

## Unbonded CFRP Bar System for External Post-Tensioning

by

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### Abstract

The use of externally post-tensioned steel tendons is an attractive option to correct strength and serviceability problems in bridge and building structural members. Alternative solutions have been recently developed using post-tensioned carbon fiber reinforced polymer (CFRP) tendons, thus ideally utilizing their high tensile strength, small relaxation, corrosion resistance, and light weight.

In this paper, an innovative unbonded CFRP bar system for external post-tensioning is presented. The ability of the dead- and live-end steel anchors to develop the full tensile strength of the bars was demonstrated through laboratory testing of bar-anchor subassemblies. Intermediate deviators were developed that can be extended to achieve a profiled bar configuration and impart uplift forces at selected locations. The system is simple to install and operate, and time-consuming procedures such as bonding of post-tensioned elements and applying post-tensioning forces using hydraulic actuators are avoided. A design example is outlined to address relevant structural implications of the proposed rehabilitation method. A step-by-step installation is also documented as performed in a demonstration project by a team of engineering students at the University of Miami.

### Introduction

Externally post-tensioned (EPT) high-strength steel tendons have long been a viable choice for the structural rehabilitation of bridges (Daly and Witarnawan 1997)

and buildings (Krauser 2006). EPT systems have been implemented to increase the design loads or to correct strength and serviceability deficiencies, such as relieving tensile overstresses under service loads, reducing fatigue-induced stresses, and controlling short- and long-term deflections. Field applications are becoming more common due to the growing demand of structural upgrades because of aging, deterioration from exposure to harsh environments (e.g., deicing salts in bridges and parking garages, proximity to salt water in coastal regions), changes in use requiring greater design loads and/or more stringent serviceability requirements, and in order to correct design and construction errors. Typical advantages include the ability to perform field installations with minimal or no disruption to service, and the tailorability of design strategies enlisting straight threaded rod or profiled wire strand configurations depending on specific objectives and economical considerations. In the latter instance, saddles or deviators are positioned to impart uplift forces to the structural member at selected locations between the end anchors (Krauser 2006), thus pairing the optimal use of high-strength steel with efficient force systems. Tradeoffs are usually the cost of anchor systems and of specialized equipment needed to apply the post-tensioning (PT) forces, as well as time-consuming installation procedures that may also require the assistance of specialized personnel.

Recently, alternative EPT systems have been developed with carbon fiber reinforced polymer (CFRP) tendons. CFRP bars, plates, and strands lend themselves as post-tensioned elements due to the high tensile strength (typically in excess of 260 ksi), small relaxation (typically below 3% of the initially applied stress), and resistance to corrosion. On the other hand, concerns are posed by the vulnerability of CFRP tendons to intentional vandalism and post-installation work, and fire resistance, which may be evaluated and addressed on a case-by-case basis.

Very few field implementations have been reported, where near-surface bonded or unbonded CFRP plates are used together with complex anchorages mounted on the soffit or sides of slabs or girders (Basler et al. 2004, Andr a and Maier 2005, Zoghi 2006). Unbonded straight EPT CFRP bars were used in a demonstration project on a three-span continuous steel bridge in Iowa to relieve tensile stresses in the I-girders under service loads (Phares et al. 2003). Straight bars with diameter of 3/8" were used, which were connected to steel stiffened angles at the ends via steel-tube anchors and couplers.

### Significance

An innovative EPT CFRP system is presented herein. The system consists of unbonded CFRP bars whose connection to the stainless steel anchors at the dead- and live-end was engineered to allow the bars to

develop the full tensile strength. No hydraulic jacks are needed to apply the PT forces at the live-end. Extendable deviators were designed and prototyped for use in profiled configurations, such as the classical “king post” in Fig. 1, where the bending moment produced by the eccentric PT forces acts together with the uplift force at the mid-section. The installation of the EPT system performed by a team of engineering students is herein documented and shows the constructability characteristics of the proposed solution.

The original contribution is twofold: first, profiled bar solutions that use FRP tendons can be implemented when required by the owner, thus covering such gap with respect to steel wire strands. Second, and most important, constructability is significantly improved with respect to existing steel and FRP solutions.

### Description of EPT System

The basic EPT system includes a set of two pultruded CFRP bar assemblies, each with a dead- and a live-end forged stainless steel anchor, and an intermediate deviator. The bars are used in pairs to improve stability when profiled configurations are adopted. Fig. 2 depicts a trial installation onto the soffit of a reinforced concrete (RC) slab.

The bar assemblies terminate at both ends with a steel thread adapter and a threaded rod equipped with a clevis end-fitting that connects to forged T-shaped steel anchors by means of a 7/8” HEX bolt, thereby allowing free rotation. In addition, the arrangement of the live end features an AS2545 turnbuckle that is mounted between two steel threaded rods from the adapter connected to the bar assembly, and a threaded rod with a clevis end-fitting that connects to the forged T-anchor similar to the dead end. A schematic of the live-end and a photograph of a dead-end are shown in Fig. 3 and Fig. 4, respectively. Mechanical or adhesive bonded high-strength steel threaded rods may be used to secure the T-shaped anchors to concrete surfaces. In the latter instance, structural adhesives suitable for overhead applications may be selected under circumstances as in Fig. 2. Mechanical connections with high-strength steel bolts can be used on metallic structural members.

Fig. 5 depicts the specially designed deviator, to be installed directly onto the member to be rehabilitated between the end anchors. It comprises two high-strength steel threaded bolts that react on a steel base plate, and run through a bent plate in contact with the CFRP bars. A wrench or a socket wrench may be used to operate the spreader heads of the bolts to displace the contact plate as desired. In order to provide a low-friction and yet abrasion-resistant contact surface with the CFRP bars, the plate includes a bent ultra-high molecular weight polyethylene cover. The radius of curvature of the bend

of 6’ was designed to limit the maximum strain induced by local bending of the CFRP bar to 20% of the ultimate tensile strain.

Additional PT forces can be imparted by extending the contact plate, thereby progressively engaging the threaded rods of the deviator through a resultant axial force that directly pushes the structural member upwards. The deviator can be installed either on the soffit of a structural member, as in the reinforced concrete slab in Fig. 2, or bolted on the sides, as in the case of stems of T-beams. The use of an extendable deviator to combine eccentric PT forces in the CFRP bars and vertical reaction forces at specific locations provides an efficient mechanism to increase strength and to control short- and long-term deflections.

It should be noted that the system is at a prototype stage and additional details are to be optimized: for instance, the use of self-locking nuts would address concerns related to vibration effects such as in the case of bridge applications, while safety measures to prevent vandalism in case of easy accessibility should be tailored on a case-by-case basis.

### Laboratory Validation of Bar Anchors

A key challenge in the use of CFRP tendons is in the development of anchor systems that enable the tendons to attain the full tensile strength without premature failure at the end connections.

Five CFRP bar assemblies were subjected to uniaxial tensile tests to assess compliance with this criterion. Each specimen consisted of 4’ long bars connected at either end with a swage coupler and a coupler adapter. The specimens were connected to the test frame with high-strength steel threaded rods. The axial deformation was measured using an extensometer up to a load of 50% of the nominal tensile strength, when the sensor was removed to prevent damage, and the ultimate deformation was measured from the cross-head displacement of the test machine. Failure always occurred in the CFRP bar at an average load of 53.9 kip, with failure modes being rupture of the carbon fibers (brooming) and, in one case, cleavage. Fig. 6 shows a typical brooming failure.

### Design Fundamentals

*Application of PT forces* – PT forces can be imparted by operating each turnbuckle at the live-end using a wrench, and by extending the intermediate deviator. In the first instance, the linear relation between the PT force per bar  $PT_{end}$  and the turnbuckle intake  $\Delta_t$  is expressed as

$$\Delta_t = \frac{PT_{end}}{E_f A_f} L_b,$$

where  $E_f = 18$  msi = longitudinal elastic modulus of CFRP,  $A_f = 0.1963$  in<sup>2</sup> = cross sectional area of CFRP bar, and  $L_b$  = length of CFRP bar. The turnbuckle intake is plotted with respect to  $PT_{end}$  in Fig. 7, where  $0.55F_u$  indicates the total allowable force (ACI 440 2004). The configuration attained can replicate that of straight near-surface tendons, thus providing a comparable performance for similar axial stiffness of the selected tendons.

When the PT force or part of it ( $PT_{dev}$ ) is imparted by engaging an intermediate deviator, the nonlinear relation between  $PT_{dev}$  and the deviator extension  $\Delta_d$  can be straightforwardly determined by imposing the basic equations of force equilibrium and compatibility of deformations. In the basic case of a king post layout (Fig. 1), the relation is given by

$$\Delta_d = \sqrt{\left[ \frac{L_b}{2} \left( 1 + \frac{PT_{dev}}{E_f A_f} \right) \right]^2 - \frac{L_b^4}{4}},$$

and is plotted in Fig. 8. It should be noted that vertical clearance becomes a major factor in the design of a profiled EPT system. The presence of false ceilings that accommodate air conditioning ducts and utility lines and equipment may enhance the possibility to extend deviators up to 8" without interfering with the usable space. In addition, the availability of considerable reserve capacity in the CFRP bars provides the flexibility to adjust the PT forces if needed (e.g., when additional post-tensioning is desired to recover part of the sustained loads other than the dead load, or if the actual slab stiffness proves to be greater than expected). This can be attained by acting at either the live end or the deviator.

*Anchorage design* – Designing effective anchorages onto the structural member to be upgraded is instrumental to the structural efficiency of an EPT system. Implementations on metallic members, such as steel bridge girders, may require mechanically fastened anchorages (Phares et al. 2003) whose design is comprehensively addressed in the AISC Specifications (AISC 2001).

In the case of concrete members, the ACI 318-05 Building Code (ACI 2005) only covers post-installed and cast-in-place mechanical anchorages. Adhesive anchorages are benefiting from dramatic advances in material science and are extensively used in practice. Design guidelines are usually provided by the manufacturers and, for the case of combined tension and shear forces, typically follow the failure criterion adopted by the AC58 product evaluation standard accepted by ICC-ES (ICC Evaluation Service 2005), given as

$$\left( \frac{V}{V_{all}} \right)^{\frac{5}{3}} + \left( \frac{N}{N_{all}} \right)^{\frac{5}{3}} \leq 1,$$

where  $V$  and  $N$  = combined shear and tension forces in the anchor, respectively, and  $V_{all}$  and  $N_{all}$  = allowable forces for different embedment lengths and anchor diameters. Fig. 9(a) and Fig. 9(b) show the force components on a T-shaped anchor for design against the allowable CFRP bar strength  $0.55F_u$  (ACI 440 2004), where  $N_d$  is the tension force produced by the couple  $0.5(0.55F_u \sin \alpha)d$  ( $d$  = minimum distance between the center of the anchor eye and the contact surface between the anchor base plate and the concrete), and the associated combined failure criterion in the  $V$ - $N$  domain, respectively.

## Design Example

Detailed design calculations and methodology are outside the scope of this paper and are presented elsewhere (Matta et al. 2007). However, the following example is intended to help the reader understand the potential structural implications of the technology described herein for the case of the symmetric one-way continuous RC floor slab in Fig. 10(a).

The objective is to reduce the maximum (midspan) long-term deflection and compression stresses by recovering the deflection produced by 100% of the uniformly distributed dead load of 0.32 kip/ft, and 25% of the live load of 0.33 kip/ft. The flexural stiffness of the cracked RC section,  $EI = 3991$  kip-ft<sup>2</sup>, is assumed constant, which may be reasonable when the area of one-way slab of interest is subjected to significant additional sustained loads (such as cladding, or as a result of a change in use), or in the case of excessive deformations due to early removal of the formwork. Continuity at the intermediate supports is idealized by rotational springs with stiffness  $k_\phi = 12EI / L = 3173$  kip-ft. The midspan vertical deflection of a 1 m wide strip to be recovered is 0.26". The following straight and profiled bar design alternatives use No. 3 EPT CFRP bars with tensile strength of 290 ksi (capacity  $F_u = 29.2$  kip) and longitudinal modulus of 17.4 msi.

*Straight bar design* – A straight bar option as sketched in Figure 10(b) is first devised. The end anchors are positioned at a distance of 8" from the ends, thus well within the region where the concrete is under compression, which extends until about 2-1/2'. A short-term deflection recovery of 0.29" > 0.26" can be determined as produced by two sets of two CFRP bars each, with a PT force of 8.8 kip (30% of ultimate).

*Profiled bar design* – A profiled bar design as sketched in Figure 10(c) is proposed as follows, where the total PT force and position of the end anchors replicate those of the straight-bar design. Assuming a PT force per bar imparted by superimposing  $PT_{end} = 0.2F_u$  applied at the live end, and  $PT_{dev} = 0.1F_u$  applied by engaging the deviator, the extended height of deviator is

computed as 4.8”, which is compatible with typical false ceilings. This configuration provides the same uplift capacity of the straight-bar counterpart while requiring half of the EPT bars, that is, one set of two CFRP bars.

### Demonstration of System Installation

One set of two CFRP bars has been installed onto a concrete surface as part of a research program aimed at characterizing the long-term behavior of the EPT system under sustained PT forces. The installation has been performed by a team of students of the American Society of Civil Engineers-University of Miami chapter (ASCE-UM) as a project for the course CE 590 – Infrastructure Strengthening with Composites. The team has been trained on-site to use the materials and working tools in compliance with the material safety data sheets and the Occupational Safety and Health Administration (OSHA) requirements, and completed the job in four hours.

The hands-on experience is documented step-by-step in Fig. 11, and provides a demonstration of the constructability features of the EPT system presented. The fact that no complex and time-consuming operations are needed that may be impractical in some instances, such as adhesive bonding of post-tensioned elements and operating hydraulic jacks and other special tools, added to the ease and rapidity of installation and of application of the PT forces. Further trials are obviously needed to comprehensively characterize and document the constructability advantages and disadvantages as compared to alternative systems and configurations, irrespective of the tendon materials.

### Conclusions

An innovative EPT system for structural strengthening and repair has been presented. Unbonded CFRP bars are used as tendons and are connected to end-anchors engineered to allow the development of the full bar strength. The PT forces can be applied from the live-ends and by engaging intermediate extendable deviators. The ability of the bar anchors to allow the attainment of the CFRP tensile strength has been assessed through laboratory testing of five bar assemblies. Design fundamentals that cover the practical computation of PT forces and the design of adhesive anchors in concrete have been presented and discussed. A practical design example has been outlined to help the reader understand relevant structural implications. A demonstrative installation performed by a team of engineering students at the University of Miami has been documented and highlights the constructability advantages of the proposed solution.

Research is underway to advance the validation process of the EPT CFRP system presented. In particular, the effectiveness of post-installed adhesive anchors into rehabilitated RC members are being investigated, as

well as the long-term behavior of EPT CFRP bars under sustained PT forces.

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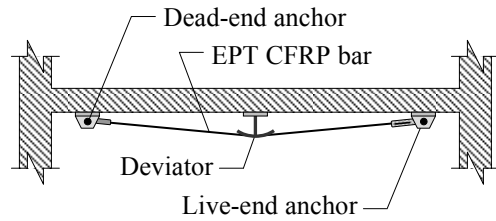
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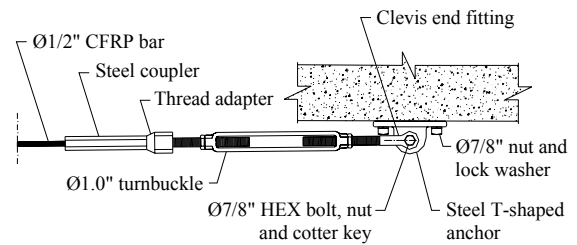
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**Figure – 1. EPT king post configuration.**



**Figure – 2. Trial installation onto soffit of a reinforced concrete slab.**



**Figure – 3. Schematic of live-end of CFRP bar assembly.**



**Figure – 4. Photograph of dead-end of CFRP bar assembly.**



Figure – 5. Photograph of extended deviator with CFRP bars.



Figure – 6. Brooming failure of CFRP bars assembly.

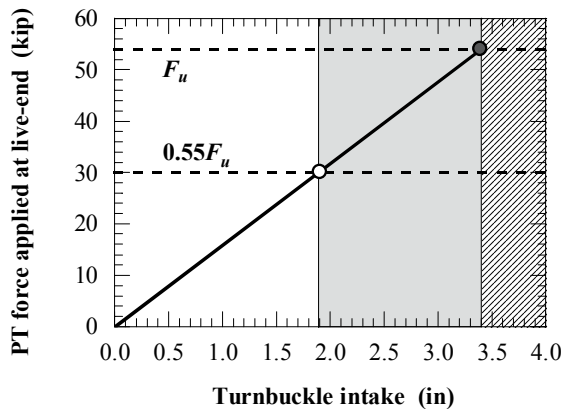


Figure – 7. Relation between PT force applied at live-end and turnbuckle intake.

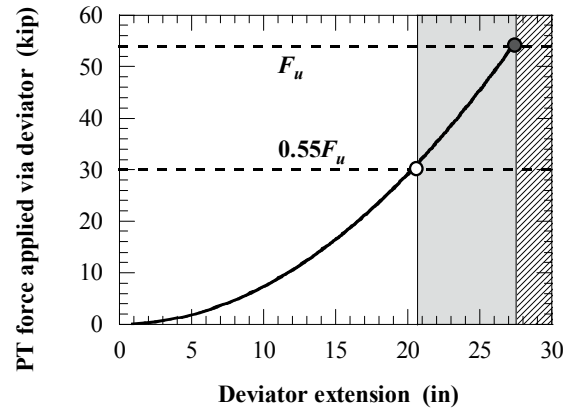
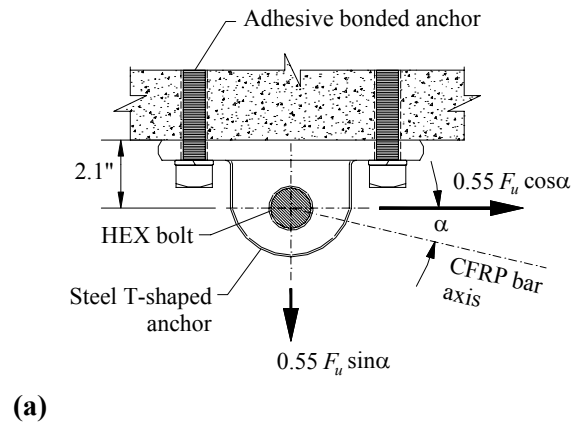
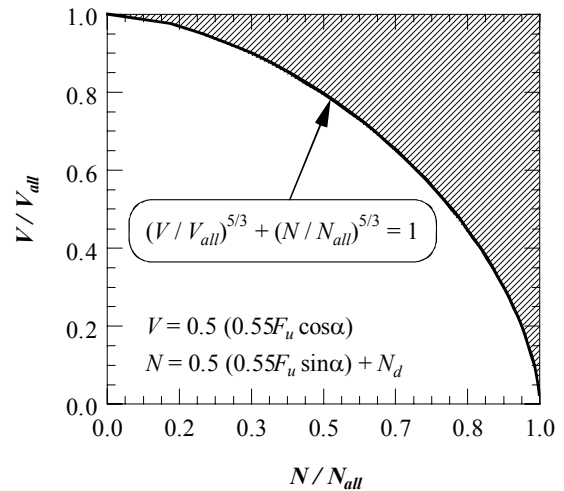


Figure – 8. Relation between PT force applied via deviator and deviator extension.

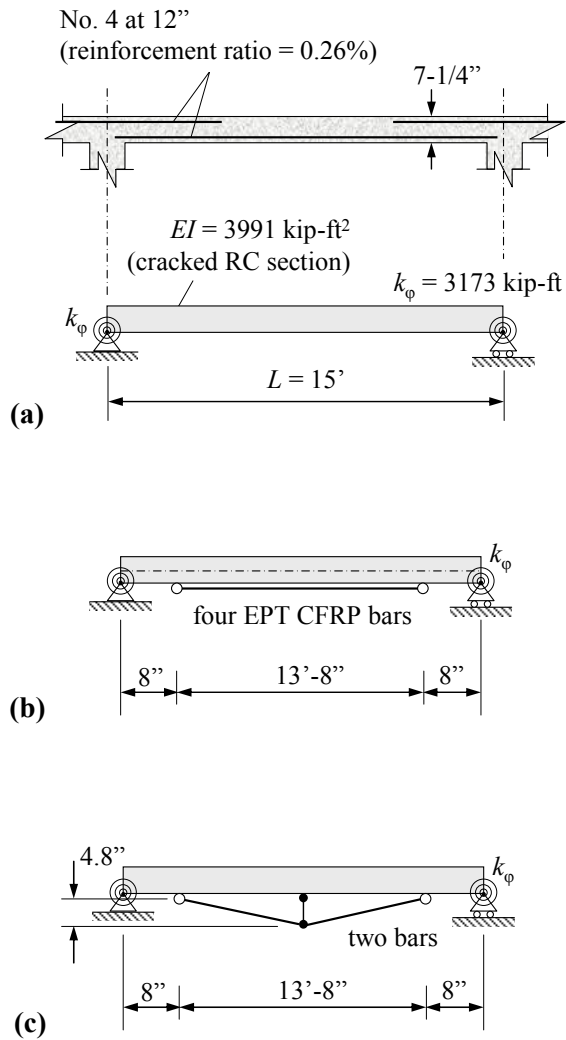


(a)

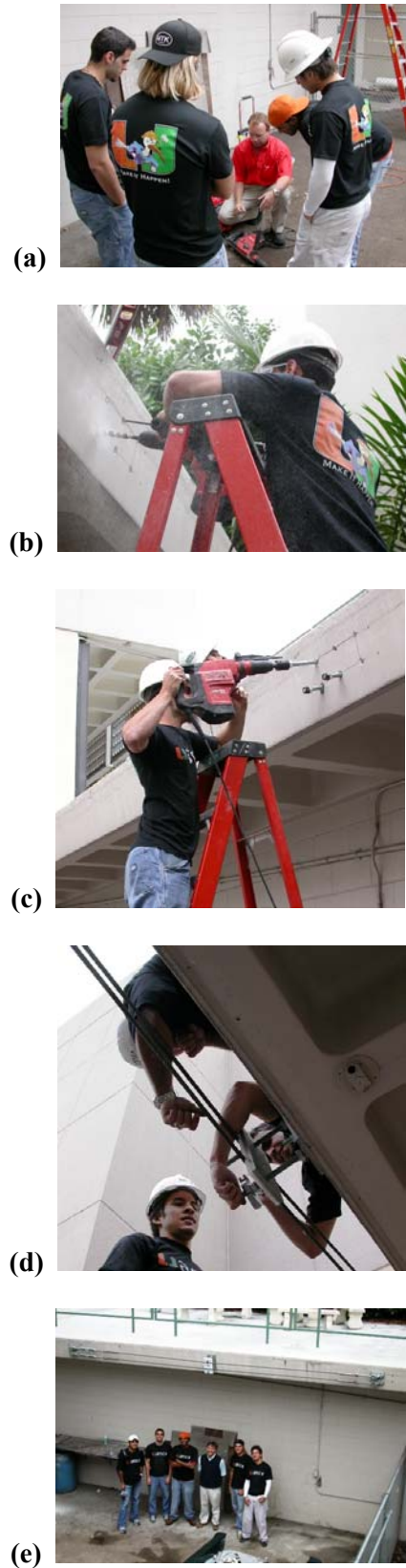


(b)

Figure – 9. Design of adhesive anchors in concrete for combined tension and shear: (a) forces on T-anchor; and (b) failure criterion.



**Figure – 10. Continuous one-way RC floor slab in design example: (a) Schematic and structural model; (b) straight EPT bar option; (c) profiled EPT bar option.**



**Figure – 11. Demonstrative installation of EPT system: (a) training of ASCE-UM student team for use of construction materials and tools; (b)**

**drilling holes for installation of anchorages and deviator; (c) insertion of adhesive-bonded threaded anchors; (d) application of PT force at the deviator; (e) completed installation.**

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