Strengthening of Impacted Prestressed Concrete Bridge I-Girder Using Prestressed Near Surface Mounted C-FRP Bars

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INTRODUCTION

More than 50% of bridges in North America are now constructed with prestressed concrete (PC) [1]. Among all types of prestressed concrete bridges, precast PC I-girder bridges are the most common due to their inherent durability, low maintenance and assured quality. Each year numerous PC I-girder bridges are subjected to vehicular impact due to over-high vehicles [2]. Therefore, an easy, cost effective and reliable way to repair impact-damaged bridges with minimum traffic disruption is needed.

In 1980 and 1985, a two-phase project performed by Shanafelt and Horn [3] on the evaluation of damage and methods of repair for prestressed concrete bridge members was conducted under the National Cooperative Highway Research Program. Four repair methods were suggested: external post-tensioning with concrete jacking corbels, internal splicing, metal sleeve splice and complete replacement of the damaged girders. However, these types of repair methods are relatively high costs, time consuming and vulnerable to future corrosion. In the past few years, the Missouri and Iowa Departments of Transportation have repaired several impact-damaged PC bridge girders with externally bonded carbon fiber reinforced polymers (C-FRP) [4,5]. The advantages of C-FRP include high strength to weight ratios, excellent corrosion/fatigue properties and relative ease of installation. Laboratory and field tests have indicated the effectiveness of this repair method to restore the ultimate strength of the damaged member [6,7,8]. However, this passive repair technique is unable to restore the prestress losses of the PC members or to participate in stress sharing until additional loads are applied and/or until additional deformation occurs. The asymmetrical compression stresses in the repaired PC member may also lead to unpredicted crack patterns during service conditions.

Because of their high tensile strength properties, FRP materials have great advantages for use in prestressing and post-tensioning strengthening applications. Prestressed FRP systems [9,10] can provide several advantages, besides the direct economic benefit of fully employing the high tensile strength of the materials, such as:

• Increasing live load capacity;
• Reducing dead load deflections;
• Reducing crack widths and delaying the onset of cracking;
• Reducing serviceability problems such as excessive deflection, cracking of the concrete and tensile steel stresses at serviceability;
• Improving fatigue strength by reducing tensile steel stresses;

Despite all the advantages, there are several difficulties related to prestressed FRP systems. The first relates to the gripping of the material (bars or plates), during the prestressing phase without damaging the fibres. Properly gripping the FRP bars or plates or finding ways to overcome this aspect, becomes an important focus of research which cannot be tackled in the same way as for conventional steel tendons [9]. A second but not less important issue relates to the proper anchoring of prestressed composite system. In
fact, in post-tensioned systems large longitudinal shear stresses are present within the adhesive bond when the tensioning force in the FRP composite is released and transferred into the concrete member (in non-prestressed applications shear stresses develop once the member is loaded, and they are responsible, at the ultimate limit state, for possible delamination), (see Fig. 1).

Therefore, in most cases mechanical anchorage at the ends of the FRP composite is required (e.g. Fig. 2). Gripping and anchoring devices [11,12,13,14,15], often require much preparation work (surface preparation and drilling) in order to securely anchor the prestressed FRP systems (mainly plates and sheets) onto the strengthened member, making such procedures very difficult and expensive, particularly when operating overhead. One way in which the problem of high shear stress at the ends of prestressed FRP plates might be overcome is the use of Near Surface Mounted (NSM) FRP bars [16,17], because of the larger bond surface available for the bar to transfer the shear stresses to the epoxy and then to the concrete. The use of NSM will also provide additional benefits such as: protecting the strengthening material from external damage, limited surface preparation work and, after groove cutting, minimising installation time compared with externally-bonded FRP plates. Recent studies [18] confirmed the suitability of Prestressed NSM (P-NSM) C-FRP bars for the strengthening of RC beams. Because of the benefits that P-NSM FRP can provide, similar advantages of externally bonded prestressed plates without any need of installing end-anchoring plates, with particular interest in reducing crack width opening and service state deflections, research is needed to develop a rational and easy-to-use system to achieve this.

This paper presents a pilot research project, where a PC I-girder, damaged by cutting two of the tendons at the mid-span location, was then repaired with P-NSM C-FRP bars and tested to failure. The experimental campaign aimed at proving that P-NSM C-FRP upgrade technique could allow not only restoring the original ultimate flexural capacity of the damaged girder but also the service performance of the PC girder, comparing the experimental results with a previously tested PC I-girder equally damaged and strengthened with C-FRP sheets externally applied with the conventional technique of manual lay-up [19]. The motivation for the development of the present research came from two real cases of accidentally damaged PC girders, on Bridge A10062, St. Louis County, Missouri (USA) [4], and on Bridge A5657 over the Gasconade River, South of Dixon, Missouri (USA) [6]. Tests on three specimens, one undamaged (specimen 1) and two on identically pre-damaged but differently upgraded beams (specimen 2, strengthened with C-FRP sheets, and specimen 3, strengthened with P-NSM C-FRP bars), indicate that the used upgrade technique is structurally efficient in providing the damaged beams with stiffness and strength very close to that of the original undamaged beam. In addition a prototype system to prestress NSM FRP bars, for field applications, is presented to its initial stage of development.

**Keywords:** prestressed concrete (PC), impact-damaged PC girders, NSM, prestressed NSM C-FRP, prestressing prototype, strengthening

**TEST SPECIMENS AND TEST SETUP**

Three typical PC I-girders with 11 m (36 ft) span length were fabricated at Rinker Material Corporation’s production plant in Marshall, Missouri, and brought at the University of Missouri - Rolla (UMR) facilities for testing. Fig. 3 details cross section as well as internal reinforcements of the PC I-girders. A total of 12 straight profile low-relaxation 7-wire monostrand tendons were stressed to 75 % of the yield strength and used as longitudinal reinforcement. The shear reinforcement consisted of 9.5 mm (3/8 in.) diameter steel stirrups, spaced 150 mm (6 in.) along the beam and with a 50 mm (2 in.) concrete cover. A reinforced
concrete (RC) deck measuring 810 x 150 mm (32 x 6 in.), reinforced with four deformed steel bars, was cast on top of the PC I-girders later in the lab to simulate the composite behavior in real bridge structures and it was designed in order to reach the ultimate limit state of the composite girder due to rupture of the tendons.

![Fig. 3. Girder Dimensions and Prestressing Details](image)

Tab. 1 shows the physical properties of the materials used to fabricate the PC I-girders as well as for the RC deck poured on top.

Tab. 1. Material Properties of the PC I-girder

<table>
<thead>
<tr>
<th>Material</th>
<th>Nominal Diameter, mm (in.)</th>
<th>Strand Area, mm² (in²)</th>
<th>Yield Strength, MPa (ksi)</th>
<th>Modulus of elasticity, GPa (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prestressing Tendons</td>
<td>9.53 (0.375)</td>
<td>99 (0.153)</td>
<td>1860 (270)</td>
<td>200 (29000)</td>
</tr>
<tr>
<td>Mild Steel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>413 (60)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>200 (29000)</td>
<td></td>
</tr>
<tr>
<td>Concrete*</td>
<td></td>
<td></td>
<td>27.6 (4000)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>41.4 (6000)</td>
<td></td>
</tr>
<tr>
<td>Repairing Cementitious Mortar</td>
<td></td>
<td></td>
<td>47 (6815)</td>
<td></td>
</tr>
</tbody>
</table>

* Compressive strength of concrete at 28 days

To simulate impact-damage, two specimens were intentionally damaged by cutting two tendons at mid-span and chiseling the concrete to expose the two cut tendons. A total of 132 kN (30 kips) prestress force was estimated lost, based on the total effective stress in the two cut tendons, after 15% of initial losses. Fig. 5 shows the force variation along the impact-damaged PC I-girders. The development length for the tendons being cut was 1.52 m (5 ft) according to ACI 318-02, Section 12.9.1 [21].

![Fig. 4. Damaging and Repairing the PC I-Girder Section at Mid-Span.](image)

The damaged areas were later patched with rapid setting no-shrinkage cementitious mortar before strengthening the girders (see Tab. 1 for material properties and Fig. 4 for damaging and repairing process).
Fig. 5. Force Variation after Cutting the Two Tendons at the Mid-Span

All the specimens were instrumented at the same positions and tested to failure under four point loading, with a free span of 10.3 m (34 ft) as shown in Fig. 6. Three string transducers were placed at the mid-span and under the loading points to measure vertical displacements. A 890 kN (200kips) load cell was set under one of the loading points to measure the applied force.

Fig. 6. Test Setup

Strain gauges were applied on the tendons and along the C-FRP bars, at critical locations reported in Fig. 7.

Fig. 7. Strain Gages Location

SOLUTIONS ADOPTED FOR FLEXURAL STRENGTHENING OF THE DAMAGED PC I-GIRDER

Externally Bonded C-FRP Laminates [20]

The first damaged specimen was upgraded with unidirectional C-FRP laminates applied to the bottom of the girder with fibers parallel to the beam’s longitudinal axis. Considering that FRP reinforcement was no longer needed at the cross section where the damaged strands become again fully effective, the length of the plies can be computed by determining the length at which the damaged strands transfer over their development length, assuming a linear transition between the point of zero stress and full prestress. Furthermore, to prevent the FRP delamination, C-FRP strips were U-wrapped around the bulb of the girder over the longitudinal laminates (see Fig. 10b).

Tab. 2 summarizes the physical properties of the externally bonded C-FRP laminates used to repair the damaged PC I-girder. The procedures for applying the externally bonded C-FRP laminates were as recommended by the ACI 440.2R-02 [19]. For additional details concerning all aspects of design regarding this technique please refer to Di Ludovico et al. [20].
Prestressed Near Surface Mounted C-FRP Bars

The second damaged specimen was upgraded with prestressed C-FRP bars mounted on the surface of the girder following the installation procedure as for NSM application: first grooves are cut into the concrete, then are partly filled with epoxy adhesive and lastly the FRP bar is inserted into the groove and a final injection of epoxy resin is performed to completely fill the slot (see Fig. 8 and Fig. 9 for details).

![Fig. 8. NSM FRP Installation](image)

![Fig. 9. NSM Detailing [22]](image)

The number, location and prestress force of the C-FRP bars used to repair the damaged PC I-girder were calculated in order to reestablish the stiffness, centroid and stress level of the control PC I-girder. Three C-FRP bars [22] were used and their mechanical properties are summarized in Tab. 2. The resin used for bonding the FRP bars to the concrete groove was a typical epoxy adhesive whose mechanically properties are reported in Tab. 2.

<table>
<thead>
<tr>
<th>Tab. 2. Data of the C-FRP systems used to repair the damaged PC I-girder.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar Diameter, mm (in) 9.5 (0.375)</td>
</tr>
<tr>
<td>Cross Section Area, mm² (in²) 65.2 (0.101)</td>
</tr>
<tr>
<td>Nominal Diameter, mm (in) 9 (0.362)</td>
</tr>
<tr>
<td>Tensile Strength, MPa (ksi) 2,068 (300)</td>
</tr>
<tr>
<td>Tensile Modulus, GPa (psi 10⁶) 124 (18)</td>
</tr>
<tr>
<td>Ultimate strain, % 1.70</td>
</tr>
<tr>
<td>C-FRP Rebar*</td>
</tr>
<tr>
<td>Fiber orientation Unidirectional</td>
</tr>
<tr>
<td>Area weight, g/m² (lb/ft²) 300 (0.062)</td>
</tr>
<tr>
<td>Nominal Thickness, mm (in) 0.165 (0.0065)</td>
</tr>
<tr>
<td>Tensile Strength, MPa (ksi) 3,800 (550)</td>
</tr>
<tr>
<td>Tensile Modulus, GPa (psi 10⁵) 227 (33)</td>
</tr>
<tr>
<td>Ultimate strain, % 1.67</td>
</tr>
<tr>
<td>C-FRP Sheet</td>
</tr>
<tr>
<td>Tensile Strength, MPa (psi) 27.6 (4,000)</td>
</tr>
<tr>
<td>Elongation at Break, % 1</td>
</tr>
<tr>
<td>Compressive Yield Strength, MPa (psi) 86.2 (12,500)</td>
</tr>
<tr>
<td>Compressive Modulus, GPa (psi 10³) 3.06 (450)</td>
</tr>
<tr>
<td>Epoxy Adhesive**</td>
</tr>
<tr>
<td>Tensile Strength, MPa (psi) 27.6 (4,000)</td>
</tr>
<tr>
<td>Elongation at Break, % 1</td>
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<td>Compressive Modulus, GPa (psi 10³) 3.06 (450)</td>
</tr>
</tbody>
</table>

*Values provided by the manufacturer (Hughes Brothers, Inc., 2005) [23]
*Values provided by the manufacturer (Degussa Construction Chemicals, 2005) [24]

Grooves, 2.8 cm (1¹/₁₈ in.) deep and 1.9 cm (¾ in) wide, were cut along the bulb of the damaged I-girder, following the procedure illustrated by Galecki et al. [25]. Fig. 10(a) shows the precise location of the grooves. The embedment length of the C-FRP bars was calculated according to ACI 440.1R-03, Sec. 11.1 [26], taking into account the effective bond area. The overall length of the P-NSM bar was then evaluated to be 3.66 m (12 ft) long. The three C-FRP bars was subjected to a prestressing force of 44 kN (10 kips), computed in order to restore the same level of prestress that was previously achieved by the steel strands, prior to be damaged (see Fig. 5). A strain of approximately 0.0052 was achieved after the prestressing with irrelevant losses in the in the bars after releasing the prestress force. This corresponded approximately to a stress of 680 MPa (100 ksi), 33% of the ultimate strength of the bar. Such stress level was lower than the creep rupture limits dictated for C-FRP bar according to ACI 440.1R-03, Sec. 8.4 [26].
FRP reinforcement for new and existing structures

**PRESTRESSING C-FRP BAR FOR NSM APPLICATION**

**Laboratory Test**

In order to prestress the C-FRP bar for the P-NSM strengthening solution, because no device was ready yet available for field application, a standard approach was undertaken. The C-FRP bar was gripped with a recently developed, at the University of Waterloo, Canada, steel wedge anchorage system [27]. The chuck consists of an outer stainless steel cylinder, a four-piece wedge and an inner sleeve. The installation consisted in: first filling half of the groove with epoxy resin for a length of the groove necessary to assure that the P-NSM bar was able to transfer the forces into the beam regaining the full capacity; then the bar was layed into the groove for the entire length of the beam; finally, by reacting against both ends of the beam using the chucks to grip the bar, the FRP bar was prestressed using hydraulic jacks. Once the bar was prestressed to the prescribed level of force, the groove was filled with more epoxy and the surface was levelled. Once the resin had cured, after approximately 24 hours, the prestress force was slowly released and the operation was repeated for the remaining two other bars. Throughout the installation process, strains were monitored to assure that no significant losses were occurring in the system. Fig. 10a) shows the schematic of the set-up.

**Development of a Prototype for Prestressing C-FRP Bars for Filed NSM application**

Because of the several advantages already highlighted related to prestressing FRP systems and of the several difficulties inhered to prestress FRP bars in situ, a prototype is under development in order to pursue P-NSM strengthening solution in field application. The main idea is to develop a device that allows to prestress the FRP bar prior to inserting into the groove without the need to react against the structure, as almost all available system do.

**Fig. 11. Simplified Scheme of the Prestressing Prototype**

Fig. 11 shows the proposed working scheme of the prestressing prototype system. The FRP bar to be prestressed and inserted as NSM into the concrete slot is a commonly available pultruded FRP bar. The cross section of the bar depends upon the maximum level of prestress to be achieved in the application and
will be able to vary from application to application. The bar is gripped at both ends by a flexible steel cable to form a closed belt. The gripping wedge for the FRP bar is currently under development to maximize the level of prestress achievable by the system. Tests are showing already promising results. The steel cable will be such as to have the identical axial stiffness of the FRP bar in use. By having to stress a closed belt, the prestressing frame will be a self contained extending frame that needs no anchoring on the member to be prestressed; the design of the frame is presented in Fig. 12.

![Prototype System Under Development](image)

By adopting a steel cable, the pulleys at the end of the frame will not need a large corner radius, but they will still be rounded to avoid stress concentration and possible fretting failure. Pulleys will be such as to allow insertion of the FRP bar, its ends (see Fig. 12) and the pulley into the groove cut into the concrete. Following standard NSM installation procedures, once the bar is inserted into the slot and the epoxy resin has cured, the ends of the bar will be unbolted to recover the steel cable. The locally damaged concrete, for required insertion of the FRP bar and the cable connections, will be patched with high strength non-shrink mortar to re-establish the concrete section. All pieces will be designed so that the overall weight of the system will be kept to a minimum so that two people, one at each end, will be able to raise it in the correct position into the groove, without any external help. Once in place, the prototype will be temporarily fixed on the beam with very light concrete bolts, maintaining the bar in the correct position, for the necessary time to allow the resin to cure (average curing time to achieve full strength of a standard epoxy paste is within 24 hours).

**EXPERIMENTAL TEST RESULTS**

Fig. 13 shows the load deflection curves for the control and the two repaired PC I-girders. Both repaired PC I-girders exhibited the same stiffness and cracking load, 390 kN (88 kips), as the control PC I-girder. In addition, both repaired PC I-girders also showed the same ultimate capacity, 614 kN (138 kips), as the control PC I-girder.
However, a horizontal crack between the upper flange and the web at the constant moment region, opposite the cutting side of the damaged PC I-girder repaired with externally bonded C-FRP laminates was observed after the cracking load (see Fig. 14). The crack was caused by horizontal bending due to asymmetrical prestress forces in the PC girder. The girder failed ultimately in a brittle manner, caused by the debonding of the C-FRP laminates, which was instantly followed by the rupture of U-wrapped C-FRP strips under the loading point.

![Fig. 14. Crack Pattern and Failure Modes of the PC Girder Strengthened with Externally Bonded C-FRP Laminates.](image)

The damaged PC I-girder repaired with P-NSM C-FRP bars failed in a more ductile manner compared to the former tests. Several flexural cracks appeared first in the constant moment region followed by wide open shear cracks under the loading points. When its ultimate capacity was nearly reached, the concrete cover on the side of the cut tendons, close to the edge of the P-NSM C-FRP bars, split and exposed the tendons. The splitting of the concrete cover was caused by untwisting motion of the two cut tendons (see Fig. 15). This phenomenon caused one of the P-NSM C-FRP bars under the bulb to partially debond and slowly leading to a progressive failure of the posttensioning system. Nevertheless, the repaired PC I-girder was still able to carry load and exhibited a ductile behavior before the next concrete splitting occurred and extended toward the mid-span, leading to a complete failure of the section.

![Fig. 15. Failure Modes of the PC Girder Strengthened with Prestressed NSM C-FRP Bars.](image)

The bar was carefully examined after the testing and found to have some air pockets in the grooves (see Fig. 16). This problem was caused by difficulties encountered during epoxy was applied in an overhead position.

![Fig. 16. Air Pockets in the Grooves](image)

It should be noted that the damaged PC I-girder repaired with P-NSM C-FRP bars did not presented horizontal cracks caused by bi-axial bending loads. This implies that the post-tensioning FRB bars were able to restore the full functionality of the girder.

**Strain along the Prestressed C-FRP Bars**
Fig. 17 shows the load-strain plots, respectively for each of the strain gages bonded to the outer surface of the prestressed NSM C-FRP bars, at locations reported in Fig. 7.
The load-strain curves for strain gages in C-FRP bars A and C are similar. A2 and C2 were apparently participating in stress sharing before the concrete crack and almost reached the ultimate strain at failure. The strain gages under the loading points showed signs of stress sharing after the cracking load. The strains suddenly reduced to 0.005 \% when the concrete splitting failure occurred close to the loading points.

CONCLUSION

This test showed that both repair methods, P-NSM C-FRP bar and externally bonded C-FRP sheet, are capable of restoring the ultimate capacity of the two tendons cut PC I-girder. However, the damaged PC I-girder repaired with P-NSM C-FRP performed in a more ductile manner when compared to externally bonded C-FRP sheet. In addition the use of P-NSM bars allowed to re-establish not only the ultimate capacity of the cross section, but also to gain the symmetric behavior of the cross section both at service as well as ultimate conditions.

The authors recognize that a more effective injection technique for overhead application needs to be investigated in order to avoid any problems during the application. An on-site prestressing apparatus, presented at its early stages of development, is being developed jointly between the University of Bath and the University of Missouri-Rolla to allow on-site application for such kind of applications. Complementary research is also needed to analytically derive the required bonded anchorage length based on prestress levels, groove geometries and failure modes associated with the type of FRP bar chosen.

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