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The Effect of Cohesive Debonding Elimination on Enhancing the Flexural Performance of Damaged Unbonded Prestressed Concrete Girders Strengthened Using NSM CFRP

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ABSTRACT

This manuscript studied the effect of U-CFRP wrapped sheet anchorage on the flexural performance of unbonded post-tensioned PC members subjected to partial strand damage and strengthened using CFRP Near-Surface Mounting techniques. The program includes six girders as a control girder, a girder with strand damage of 14.2%, and four girders strengthened by CFRP laminates using the NSM technique with and without U-CFRP wrapped sheet anchorages. The testing results show that the strand damage of 14.2% has reduced the flexural strength of the girder by 5.71%. The NSM-CFRP laminate has a significant effect on flexural strength by 17.4%. On the other hand, the application of end U-CFRP wrapped sheet anchorages improves flexural strength by 27.97% and enhances ductility. The intermediate and successive U-CFRP sheet anchorages increase the flexural strength by 36.56% and 32.61%, enhancing the stiffness at all loading stages and improving the ductility. Semiempirical equations were developed to determine the actual stress of unbonded strands considering the effect of U-FRP-wrapped anchorages.

Keywords: CFRP laminate, CFRP sheet, Cover separation, Post-Tensioned girder, Strand damage.

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تاثير مقابض الفاف الكربوني على سلوك الثني للعضاء الخرسانية لاحقة الشد المتضرر والمقواة بالواح الالياف الكربونية باستخدام تقنية التركيب قرب السطح

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الخلاصة

تتناول هذه الدراسة تأثير استخدام مقابض التقوية اللف النسيجي (U–CFRP) على سلوك الثني للأعضاء الخرسانية لاحقة الشد ذات الجدائل الغير مترابطة المعرضة لتضرر الجدائل والمقواة بالواح الكربون فايبر (CFRP laminates) باستخدام تقنية التركيب القريب من السطح (NSM). البرنامج مكون من ست عينات خرسانية لاحقة الشد تتضمن عينة مرجعية وعينة معرضة لضرر جدائل بنسبة 14.2% بالإضافة الى اربع عينات مقاواة بالواح الكربون فايبر مع وبدون مقابض. بينت نتائج الاختبار بان تضرر الجدائل بنسبة 14.2% يقلل من مقاومة الثني ب 5.71%. كما وان استخدام الواح الكربون فايبر (CFRP laminates) يزيد من مقاومة الانحناء ب 17.4% من ناحية اخر تطبيق المقابض عند نهايات الواح الكاربون فايبر يزيد من مقاومة الانحناء بنسبة 27.97% وعزز مطوليه الأعضاء الخرسانية. في حين تساهم المقابض الوسطية والمقابض الموزعة على طول الاواح الكربون فايبر بزيادة مقاومة الانحناء ب 36.54% و32.61% على التوالي وتعزز الجسأة في كل مراحل التحميل وتحسن بالمطولية. تم اقتراح معادلة شبه تجريبية لتقدير الاجهاد للجدائل الغير مترابطة باخذ النظر لتاثير المقابض.

الكلمات المفتاحية: عتبات سابقة الاجهاد, فصل الغطاء الخرساني , تلف الجدائل, صفائح الكاربون فايبر, انسجة الكاربون فايبر.

1. INTRODUCTION

Post-tensioned concrete girders are an important technique in constructing bridges or structures with long spans, commonly damaged by severe weather conditions or high vehicle collisions **(Jawdhari et al., 2018)**. Traditional repair methods, such as steel jackets, external post-tensioning, and even replacement, can increase the efficiency of such structures, but they are typically complex, expensive, and often cause traffic momentum **(Kasan, 2009; Daraj and Al-Zuhairi, 2022)**. In the last 20 years, experimental studies have proven that fiber-reinforced polymers (FRP) improve the flexural capacity of reinforced concrete members, increase stiffness, and minimize crack spacing and width **(Baena et al., 2009; Abdulkareem and Izzat, 2022)**. Moreover, this material offers high tensile strength, lightweight, and weather resistance, particularly with the Near Surface Mounted (NSM) technique, as it is protected by a concrete cover, making it ideal for external repairs **(Galati and De Lorenzis, 2009; Abbas and Al-Zuhairi, 2022a).** The NSM is one of the techniques recommended in the design guidelines (**ACI Committee 440-2R, 2017).** It involves inserting FRP bars or laminates into grooves made in the concrete tension cover and bonding them together using adhesives. Therefore, this technique depends heavily on the tensile properties of the concrete cover. Given FRP's high tensile strength, FRP rupture is unlikely **(Al-Zuhairi and Al-Fatlawi, 2013; Abdualrahman and Al-Zuhairi, 2020a; Al-Zuhairi et al., 2021).** Concrete cover delimitation is a common failure mode once an NSM technique is used. U-wrapped sheet anchors with FRP strengthening techniques depend on bonding with concrete covers, such as externally bonded (ER) **(Foster et al., 2017; Wei et al., 2019; Abdualrahman and Al-Zuhairi, 2020b)**. Near-surface mounted is an easy-to-use and effective system for these techniques because they prevent concrete cover delimitation and give more chances to use the FRP's high tensile strength and improve the concrete's ductility **(Abbas and Al-Zuhairi, 2022; Naqe and Al-Zuhairi, 2020; Al-Zuhairi et al., 2022b)**. A CFRP U-wrap comprises a CFRP layer applied transversely on top of the longitudinal CFRP layer to enhance bonding force. Additionally, it postpones FRP delamination and improves concrete confinement beneath the U-wrap. The U-CFRP-wrapped anchorage has been widely investigated. (**ElSafty et al., 2014)** studied prestressed concrete members strengthened with a CFRP longitudinal layer and U-CFRP wrapped anchorages to enhance flexural capacity. According to the test, to ensure sufficient bonding between the CFRP and the concrete, the distance between the U-wraps along the span could be varied from 0.5 to 1 times the member's depth.

Unfortunately, the design guidelines in the ACI 440-R focused on strengthening procedures for bonded prestressed concrete members while neglecting the procedures for unbonded members due to the scarcity of relevant studies and the analytical complexities in calculating the strain increase for unbonded strands that determine the maximum flexural capacity **(El Meski and Harajli, 2013a; Al-Zuhairi and Ahmed, 2018; Daraj and Al-Zuhairi, 2022).**

In this experimental program, six post-tensioning concrete members were constructed and tested to investigate partial strand damage's impact and the strengthening's effectiveness using the NSM-CFRP technique, enhanced by a different profile of U-CFRP wrapped sheet anchorages.

2. EXPERIMENTAL WORK

2.1 Girder Setup

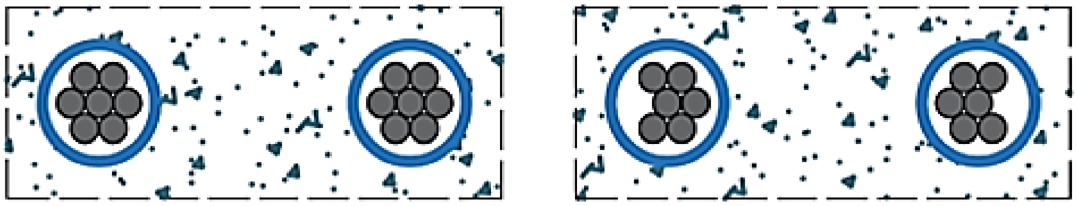
The program includes six supported unbonded prestressed concrete girders tested under two loading points. The studied variables were a damaged strand ratio of 14.2%, strengthening by CFRP laminate using a near-surface mounting technique, and various configurations of U-wrapped anchors, as illustrated in **Table 1**.

Table 1. Tested girder variables

Girders	SDR %	NSM-CFRP	End anchor	Mid-end anchors	Consecutive anchors
PR0	-	-	-	-	-
PR	14.2	-	-	-	-
PN	14.2	■	-	-	-
PNE	14.2	■	■	-	-
PNEM	14.2	■	-	■	-
PNC	14.2	■	-	-	■

SDR: Strand damaged ratio

All girders had the same dimensions of 300 mm in height, 200 mm in width, a total length of 3000 mm, and an effective length of 2800 mm. Each girder was reinforced with tensile reinforcing steel 2Ø16 mm and unbonded prestressing steel 2Ø12.7 mm. Plastic tubes (PVC) were used to pass the strands through, and the strands were anchored at the ends of the girders using steel bearing plates with strand anchor wedges. One of the peripheral wires was severed to damage the strands, as indicated in **Fig.1.**



(a) (b)

Figure 1. Undamaged and damaged Strand damage patterns of the tested beam
(a) Undamaged strand, and (b) 14.3% damaged strands with a symmetric pattern

The details of all tested girders are presented in **Figs. 2 to 7**. After twenty-eight days of concrete casting and just before strengthening, girders were post-tensioned using straight strands, as shown in **Fig. 8**. Each strand was jacked at 0.6 fpu.

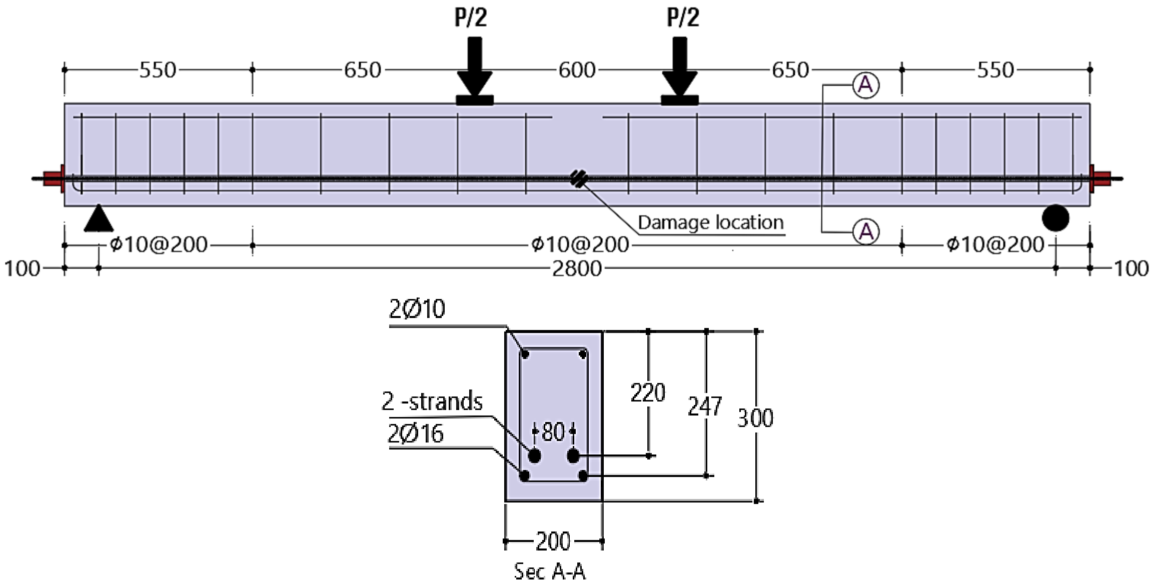


Figure 2. Reinforcement profile and stirrups distribution for tested girders

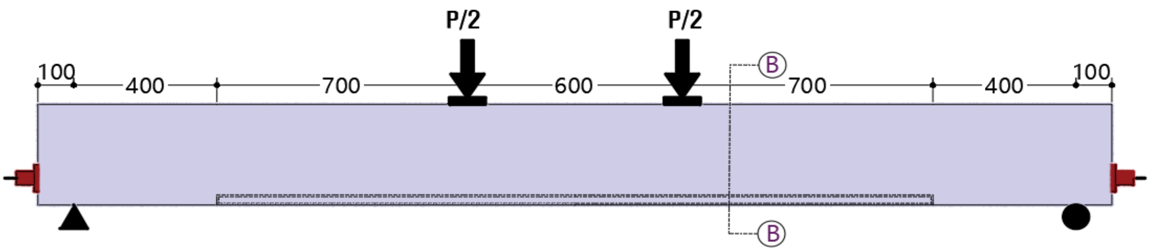


Figure 3. Strengthened girder PN.

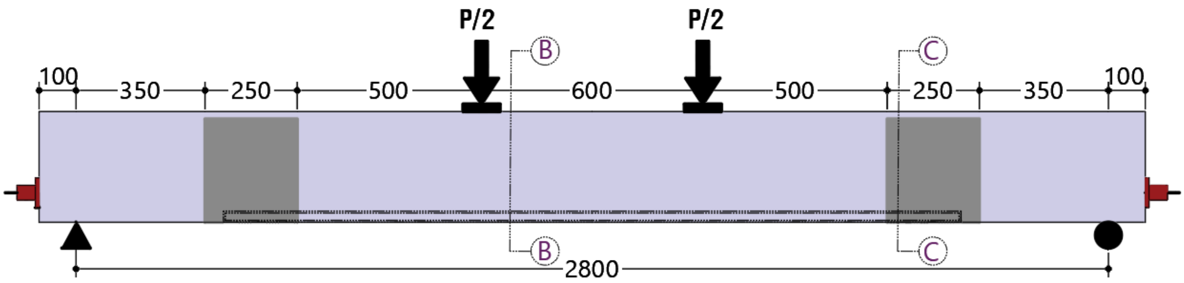


Figure 4 Strengthened girder PNE

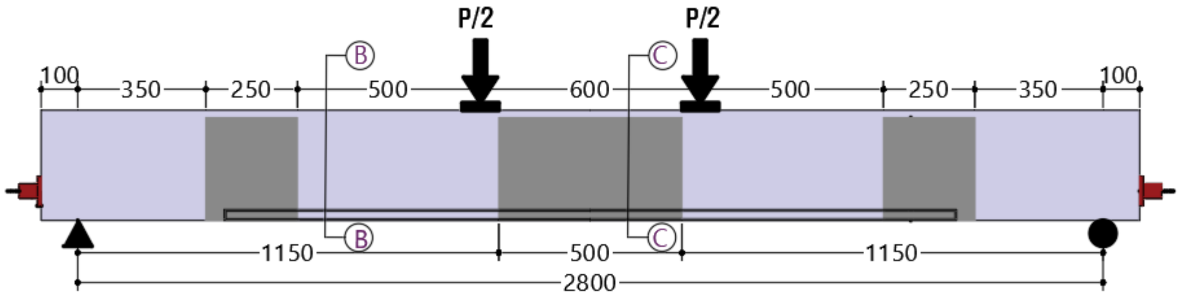


Figure 5. Strengthened girder PNEM

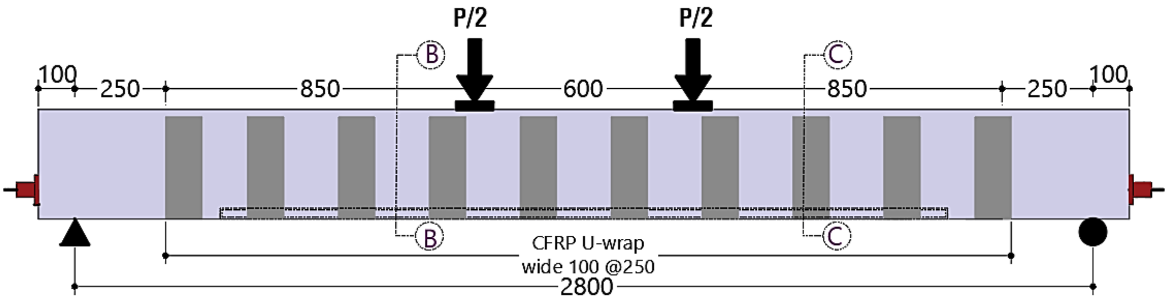


Figure 6. Strengthened girder PNC

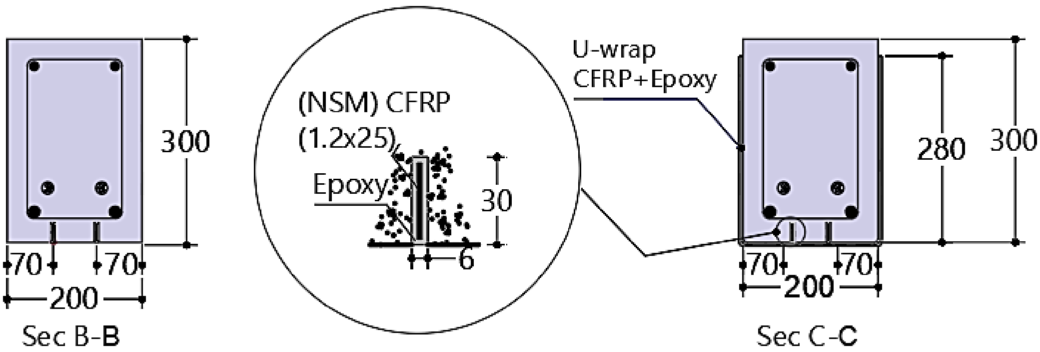


Figure 7. Cross-sectional dimensions for strengthened girders

Figure 8 . Post-tensioning girders

FRP strips with a length of 2000 mm and cross-section of 1.2 mm * 25 mm were inserted into a slot made in the concrete cover using an electrical saw with a depth of 28 mm, a width of 5.8 mm, and an overall length of 2000 mm according to ACI 440-R and bonded to the surfaces of the concrete slot using an epoxy, as shown in **Fig. 9.** The U-anchors (unidirectional CFRP sheet) were applied by removing the weak surface concrete layer and then using a primer and two resin layers before and after applying the U-CFRP sheet anchors, as illustrated in **Fig. 10.**

Figure 9 . NSM CFRP strengthening

Figure 10. U- CFRP wrapped anchorages installation

The mechanical properties of concrete, reinforcing steel, and unbonded prestressing strands are listed in **Table 2 and 3**, respectively, and the mechanical properties of CFRP laminates and sheets, as provided by manufacturers, are listed in **Table 4.**

Table 2. Concrete's mechanical properties

Compressive strength (fc') MPa	Splitting tensile strength (fct) MPa	Modulus of elasticity (Ec) MPa
43.73	3.95	31315

Table 3. Reinforcing Steel's properties

Dia. mm	Yield stress MPa	Ultimate stress MPa	Elongation (%)	Modulus of elasticity GPa
10	518.1	658.76	13.5	200
12	578.4	711.84	12.2	200
Prestressing steel reinforcement				
12.7	1725	1860	5	197.5

Table 4. CFRP's properties

CFRP	Thickness mm	Tensile Strength MPa	Tensile Modulus MPa
Laminate	1.2	3100	170000
Sheet	0.167	3482	230000

2.2 Test Procedure and Instrumentation

The girders were evaluated under a two-point load (**Fig.11**). The load was applied at 1100 mm from the closest support. Strain gauges were affixed at the mid-lengths of the FRP laminate's surface. A strain gauge was installed at the mid-length of each strand to monitor the strand's strain increase.

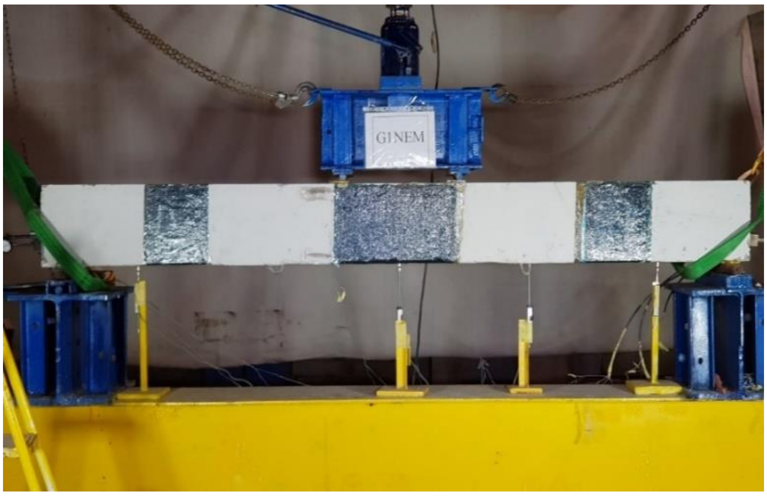


Figure 11. Test setup of experimental girders

Slots were made in the steel bearing plate before attaching the anchors to prevent gauge wire damage. One strain gauge glued at mid-length monitored steel reinforcement strain, while two strain gauges monitored concrete strain. Moreover, LVDTs were used to detect the girders' displacement. The strain gauge and LVDT data were automatically obtained using a computerized technique. A 50-ton hydraulic jack and load cell were used to steadily increase and measure the load. On the other hand, two dial gauges, one at each strand's end, monitored for strand slippage during loading.

3. RESULTS AND DISCUSSION

3.1 Modes of Failure

In post-tensioned girders, flexural cracks start at the maximum tensile stress zone and propagate throughout the girder, forming diagonal shear cracks near the girder's support. Failure occurs through the yielding of the steel reinforcement, followed by the concrete crushing at the maximum compressive strain. For NSM-strengthened girders, the failure was caused by the yielding of reinforcing steel, followed by the concrete cover separation through the development of diagonal cracks at the end of the FRP sheets. The U-wrapped anchors at the ends of FRP strips prevent concrete cover separation, whereas intermediate anchors significantly increase the concrete member's stiffness. In general, the strengthened girders have more cracks with smaller crack widths. **Fig. 12** shows the Crack Pattern at the failure of tested specimens.

3.2 Load-Deflection

Fig. 13 illustrates the flexural behavior of the investigated girders at three loading levels: elastic uncracked, elastic cracked, and ultimate load. The load-displacement correlation of the investigated girders was linear until the crack load. At this loading level, the stiffness of the control girder (PR0) gradually reduces when the girder's strand is subject to damage. The decrease in the strengthened beam's stiffness was non-significant compared to the damaged girder (PR). Moreover, the damaged girder offers a quick rate of stiffness degradation due to the loss of parts of the post-tensioning force and an increase in the crack growth rate that increases displacement when applied loads exceed the cracking load. Meanwhile, Strengthening with FRP laminates delays crack development. It slows down stiffness degradation, leading to a significant deflection reduction compared to unstrengthened damaged girders at the same loading levels.

The girder's flexural strength reduces as strand damage increases. As presented in **Table 5**, the decrease in ultimate flexural strength was 5.71%, corresponding to 14.2% strand damage. Furthermore, in the case of reinforced girders, NSM strengthening enhances stiffness along the cracked stage and increases flexural strength by 11.12%. However, the concentration of high tensile stresses at both ends of the FRP strips causes the concrete cover to separate and limits the effectiveness of this technique.

The effect of the U-wrapped anchors at the ends of the FRP strips is restricted to the advanced loading phases, as it eliminates the concrete cover separation, increases flexural capacity by 21.23%, and enhances ductility. On the other hand, the intermediate U-wrapped sheet anchors improve stiffness and flexural strength (25.64% to 29.05%) by enhancing the tension stiffening for advanced loading levels, which in turn reduces the strand strain increase.

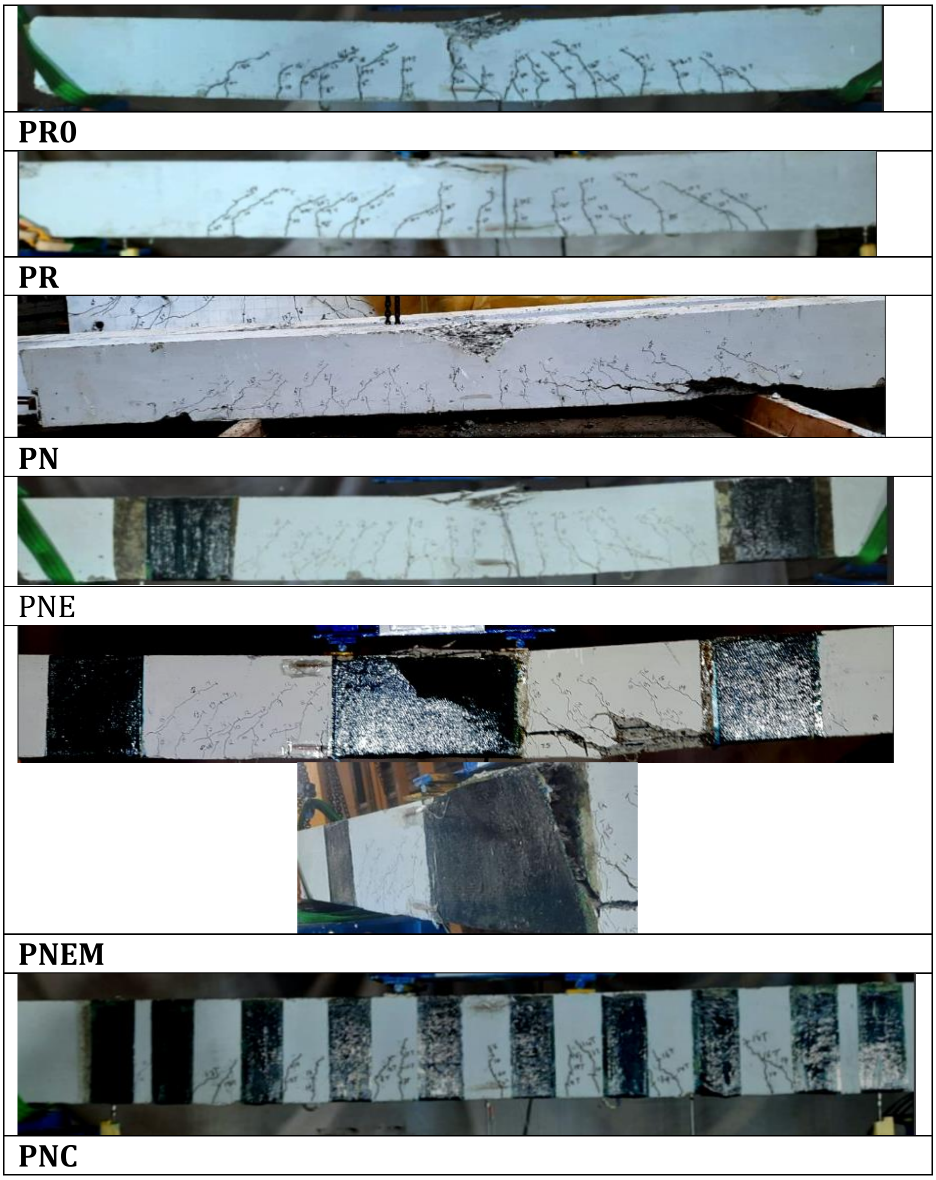


Figure 12. Crack Pattern at the failure of tested specimens

Table 5. Test result

Girders	Cracking load (kN)	Failure load P_u (kN)	Mid-Span Deflection at Failure load (mm)	Increase In P_u %	Reduction in P_u %	Failure modes
PR0	55.0	166.3	26.88	-	-	SY-CC
PR	52.0	157.3	25.48	-	5.71	SY-CC
PN	57.0	184.7	23.43	11.12	-	SY-CCS
PNE	58.0	201.3	26.86	21.23	-	SY-CC
PNEM	67.0	214.8	29.98	29.05	-	SY-CC
PNC	60.0	208.6	27.86	25.64	-	SY-CC

SY: steel yielding; CC: Concrete crushing; CCS: Concrete Cover Separation

4. Analytical Approach for Computing the Flexural Strength of CFRP Strengthened Unbonded Prestressed Member

Calculating the flexural strength of unbonded prestressed RC members is complicated due to the difficulties in measuring the strain increase in unbonded strands **(Naqi and Al-Zuhairi, 2020; Al-Zuhairi and Taj, 2018; Abdualrahman and Al-Zuhairi, 2020b).** Several researchers presented analytical approaches based on experimental studies to predict the strand strain increase and evaluate the flexural strength **(El Meski and Harajli, 2013b; Nguyen-Minh et al., 2018; Ahmed and Al-Zuhairi, 2018).**

$$M_n = A_{ps} f_{ps}\left(d_p - \frac{\beta_1 c}{2}\right) + \Psi_f A_f E_f \varepsilon_f \left(d_f - \frac{\beta_1 c}{2}\right) + A_s f_s \left(d_s - \frac{\beta_1 c}{2}\right) \quad (1)$$

The strand strain increase For girders without end anchors:

$$\Delta_{\varepsilon ps,CFRP} = \Omega \varepsilon_c \left(\frac{d_p - c}{L_0}\right) \times \left(1 + 100\frac{A_f\, E_f\, \varepsilon_{fe}}{A_c\, E_c \varepsilon_{fuu}}\right)^{0.59} \quad (2)$$

The strand strain increase For girders with end anchors:

$$\Delta_{\varepsilon ps,CFRP} = \Omega \varepsilon_c \left(\frac{d_p - c}{L_0}\right) \times \left(1 + 100\frac{A_f\, E_f\, \varepsilon_{fe}}{A_c\, E_c\, \varepsilon_{fuu}}\right)^{1.35} \quad (3)$$

where:
M_n is the ultimate flexural strength, kN.m
$\Delta_{\varepsilon ps,CFRP}$ is the Strand strain increase
ε_{fe} *is the* actual strain in CFRP laminates
ε_{fuu} is the rapture strain in CFRP laminates
A_{ps}, A_f, and A_s are the area of the unbonded strand, reinforcing steel, and CFRP laminates, respectively.
c is the depth of the natural axis, mm
d_p, ds, and d_f are the depth of unbonded strand, reinforcing steel, and CFRP laminates to extremes compression concrete fibers.
E_f is the modulus of elasticity of CFRP laminates, MPa.
f_{ps} is the strand stress increase calculated according to **(Oukaili and Buniya, 2013),** MPa
f_s is the stress in reinforcing steel, MPa
The flexural strength of tested girders was predicted according to the analytical approaches presented by **(Nguyen-Minh et al., 2018; Hernoune et al., 2020)**. The comparison included the 16 unbonded prestressed members strengthened by CFRP laminates using the externally bonded technique (ER) investigated in **Fig. 14 (El Meski, 2012).** From **Table 6**, the mean value is 0.942 and COV is 0.067, indicating the accuracy of theoretical strand strain values and their feasibility for predicting the flexural capacity of NSM-CFRP unbonded prestressed girders without and with U- CFRP anchors**. Fig. 14** illustrates the variation of the experimental flexural capacities with the predicted values. A linear variation is shown till 90 kN.m.

Table 6. Predicted and experimental flexural capacities

Strengthened UPC members **(El Meski and Harajli, 2013a)**			
Specimens	M_{u-P}	M_{u-E}	M_{u-P} / M_{u-E}
Girders			
UB1_H_F1	41.36	41.80	0.99
UB1_H_F2	51.38	54.30	0.95
UB1_P_F1	34.75	41.40	0.84
UB1_P_F2	51.68	55.60	0.93
UB2_H_F1	54.85	50.50	1.09
UB2_H_F2	63.86	65.50	0.97
UB2_P_F1	50.79	58.50	0.87
UB2_P_F2	58.91	63.30	0.93
Slabs			
US1_H_F1	22.37	21.40	1.05
US1_H_F2	27.32	26.90	1.02
US1_P_F1	19.70	21.60	0.91
US1_P_F2	28.31	30.10	0.94
US2_H_F1	25.44	26.60	0.96
US2_H_F2	30.69	35.80	0.86
US2_P_F1	27.42	29.80	0.92
US2_P_F2	31.68	37.40	0.85
Average			0.941
Standard of deviation			0.070
COV			0.075
NSM-CFRP strengthened UPC girders (Current work)			
PR0	91.43	91.07	0.992
PR	86.49	86.09	0.991
PN	101.51	100.47	0.984
PNE	110.66	101.22	0.909
PNEM	118.09	101.18	0.984
PNC	114.79	101.22	0.975
Average			0.939
Standard of deviation			0.063
COV			0.067
For all members			
Average			0.942
Standard of deviation			0.067
COV			0.072
M_{u-P} is the predicated moment capacity, and M_{u-E} is the experimental moment capacity.			

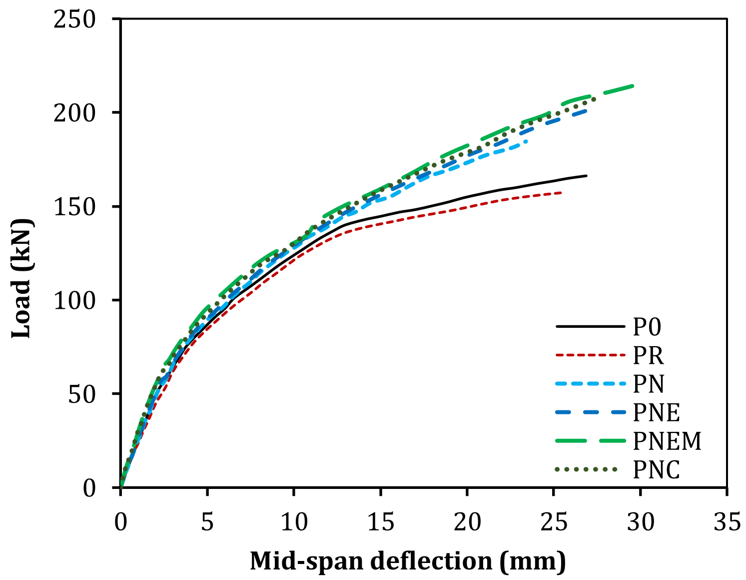


Figure 13. Load-deflection curves

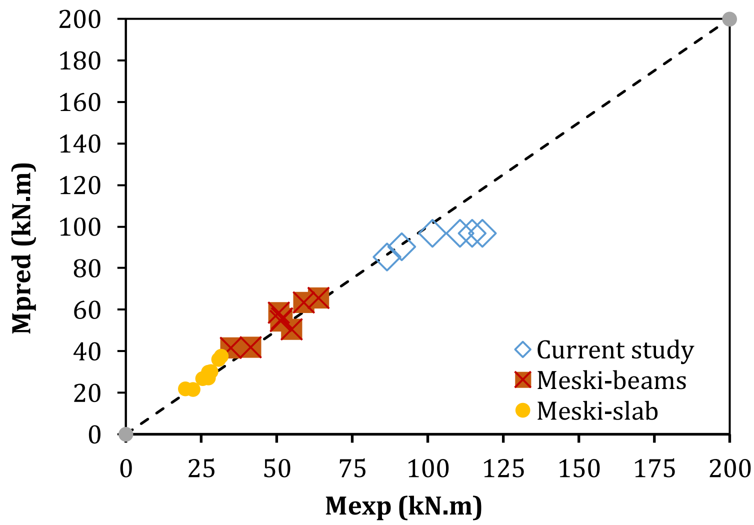


Figure 14. Experimental vs. predicted values of flexural capacities

5. CONCLUSIONS

This work researched and evaluated the behavior of post-tensioned concrete girders subjected to partial strand damage and strengthened by NSM-CFRP laminates with and without U-CFRP wrapped sheet anchorages. The following conclusions are derived from this study's experimental results:

1- With strand damage of 14.2%, the reduction in flexural strength of unbonded prestressed RC members was 5.71%, and the deflection increased at all loading stages.

2- Strengthening unbonded prestressed RC members by CFRP strips using the Near-Surface mounting technique improves the flexural capacity by 17.41%, corresponding to a damaged strand ratio (SDR) of 14.2%.

3- U-CFRP anchorage at the ends of CFRP strips prevents the concrete cover separation, improves flexural performance, and enhances ductility. The flexural strength increased by 27.9%, corresponding to an SDR of 14.2% using the end anchorage system.

4- The intermediate U-CFRP sheet anchors or those distributed successively along the CFRP laminates significantly increase the bending capacity and enhance the stiffness and ductility. The intermediate and successive U-CFRP sheet anchorages increase the flexural strength by 36.6% and 32.63%, respectively, corresponding to SDR 14.2%.

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