EXPERIMENTAL STUDY ON THE FLEXURAL BEHAVIOR OF BONDED PRESTRESSED CONCRETE BEAMS STRENGTHENED WITH CFRP SHEETS

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ABSTRACT: This paper presents an experimental study on the flexural behavior of bonded prestressed concrete (PC) beams strenthening using CFRP sheet. Two (PC) beams were fabricated, with overall dimensions of 150 × 200 × 2700 mm. One specimen served as an unstrengthened control, while the other was strengthened using CFRP sheets to enhance flexural performance. The specimens were simply supported and subjected to a four-point bending test until failure, allowing assessment of their flexural behavior. The results show that the CFRP-strengthened PC beams exhibited a 24% increase in load-bearing capacity compared to the control specimen. The stiffness of the strengthened beams was also significantly enhanced, leading to a reduction in deflection. Based on the obtained results, it is evident that the application of CFRP sheets for strengthening PC beams is a viable solution.

KEYWORDS: Concrete, CFRP sheets, Prestressed, Flexural behavior, Cracking, Stiffness.

1. INTRODUCTION

In modern construction, bonded prestressed concrete (PC) beams are commonly used to achieve extended spans in construction and enhance durability of buildings. The reduction of the flexural capacity of existing PC beams due to the change of building functionality or prestress losses emphasized the necessity for structural strengthening. In recent years, besides traditional strengthening methods, the utilization of Carbon fiber-reinforced polymer (CFRP) sheets to enhance the flexural performance of beams has become increasingly common. This material possesses superior characteristics such as high strength, high elastic modulus, lightweight, and corrosion resistance. The technique for applying this strengthening method is simpler and can be completed within a short construction timeframe. In the case of flexural strengthening, the CFRP sheets are bonded externally to the tension face of the members so that the high tensile strength of CFRP sheets can be utilized. On the other hand, the guidelines for designing and constructing structural members strengthened by FRP sheets, esstablished by numerous countries and international associations, underscore their substantial contribution to expanding the application of this novel strengthening technique.

While numerous studies have been conducted on flexural RC members [1-11], there remains a scarcity of research focused on prestressed concrete (PC) beam. Experimental studies on the behavior of PC beams strengthening with CFRP sheets have been somewhat conducted in previous research, with several of these studies being documented [12-15]. Despite of some existing experimental studies, the obtained experimental results are often limited in scope. The experimental study presented herein aims to provide such lacked information based on the test on two PC beams, including one un-strengthened control PC beam and one strengthened PC beam. The findings of this study will be of interest to engineers who are involved in retrofitting and strengthening PC beams with CFRP sheets. The experimental program has been carried out in the Laboratory of Construction Testing and Inspection, Hanoi University of Civil Engineering (HUCE).

2. EXPERIMENTAL STUDY

2.1. Detail of test beams and materials

For this experimental study, two bonded prestressed concrete beams were cast with indentical geometric dimensions, prestressed reinforcement, steel reinforcement layout, concrete. The length of the test beams was 2700 mm and had a specific cross-sectional size of $b \times h = 150 \times 200$ mm. Detail of test beam are presented in Figure 1. A control beam, denoted as BC-2 and not strengthen was designed, while the other beam, strengthened in flexural with CFRP sheets, was labeled as

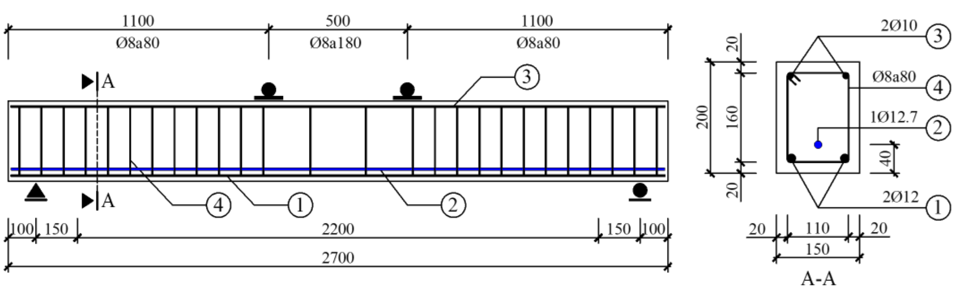
BS-2. The beams were pretensioned with a 12.7 mm strand, and the initial prestress of the strand is 1080 MPa (equivalent to prestressing force of 108 kN), which is about 0.6 times of the yielding stress. The CFRP sheets had a width of 120 mm, thickness of 0.167 mm, and length of 2200 mm. All test beams have been cast with the same concrete batch. The mix proportions for concrete are shown in Table 1 along with the actual 28-day compressive strength of concrete material. The yielding strength of longitudinal steel reinforcement Ø10 and Ø12 was 596 MPa and 580 MPa, respectively, and the elasticity modulus of steel reinforcement was measured as 200 GPa. The CFRP sheets utilized in this study were unidirectional. The mechanical and physical properties of the CFRP sheet, are presented in Table 2.

Table 1. Mixture proportions for 1 m³ of concrete và 28-day concrete compressive strength (kg/m³)

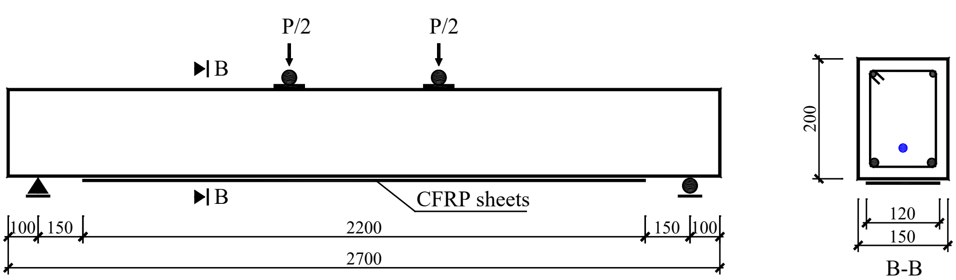
Cement (kg)	Crushed sand (kg)	Crushed stone 0,5×1 cm (kg)	Crushed stone 1×2 cm (kg)	Glenium SKY 8613 (liter)	Water (kg)	28-day compressive strength f'c (MPa)
470	800	340	730	3,9	140	60

Table 2. Mechanical properties for CFRP sheets

Thickness t_f (cm)	Modulus of elasticity E_f (GPa)	Ultimate tensile strength f_{fu} (MPa)	Ultimate deformation ε_{fu} (%)
0.167	245	3400	1.6

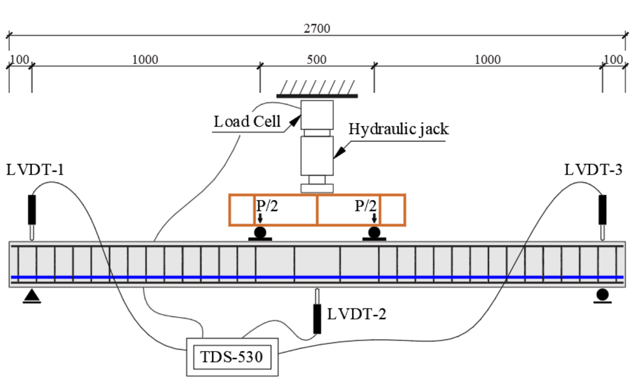


(a) Reinforcement detail



(b) Strengthened beam with CFRP

Figure 1. Details of test beams



(a) A schematic view

(b) Photo of actual test setup

Figure 2. Detail of test setup

2.2. Test procedure and instrumentation.

Figure 2 depicts the typical test setup employed for the experimental investigation, as well as a test in progress. Two beam specimens underwent testing using a four-point bending configuration. The load was applied at the mid-span of the beam using a hydraulic jack and spreader beams. An electronic force measuring instrument (load cell) was utilized to determine the applied load. Three linear variable differential transformers (LVDTs) with an accuracy of 0.001 mm, designated as LVDT-1, LVDT-2, and LVDT-3, were positioned at the two supports and in the middle of the test specimen, respectively. These LVDTs were employed to measure the displacement of the beams during loading. The deflection of the middle cross-section of the test specimens, denoted as f, was determined based on the measurements obtained from the LVDTs using Equation (1).

$$f = f_2 - 0.5\left(f_1 + f_3\right) \qquad (1)$$

The force and displacement measuring instruments were connected to a TDS 530 data logger, enabling continuous and automatic recording of experimental data at one-second intervals. The tests were conducted until the specimens failed.

3. EXPERIMENTAL RESULTS

3.1. Failure mechanism of beam specimens

Figure 3(a) and Figure 3(b) respectively present the failure modes of the control beam BC-2 and the strengthened beam BS-2. It can be seen that the overall behavior of the unstrengthened and strengthened specimens was typical. In the constant moment zone of the beams, these flexural cracks opened prominently, then these shear cracks appeared in the flexural-shear zone. As shown Figure 3, the number of crack on the strengthened beam appears to be higher than that on the unstrengthened beam in the pure flexural zone. This may be explained by the tensile participation of CFRP sheets in the tensile zone, which helps distribute cracks and limit crack growth.

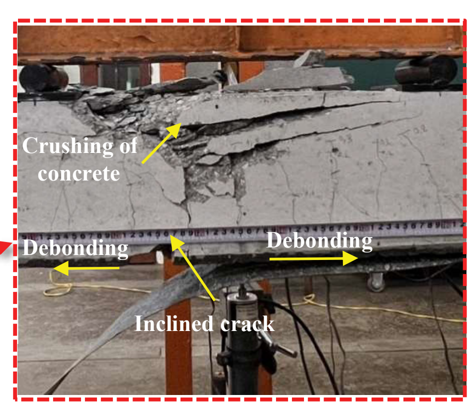
In the failure stage, the control beam exhibited a failure mode with the presence of multiple flexural cracks in the central region and inclined cracks in the bending-shear region. The flexural cracks have an average distance of about 100 mm and about 140 mm in height. As the strengthened beam BS-2, the failure occurred when the detachment of bonded sheet, prompted by flexural cracks in the constant moment region, simultaneously, there was crushing of concrete in the compressive area.

3.2. Load-deflection relationship

Figure 4 illustrates the load-displacement relationship of two test beams: the control specimen BC-2 and the BS-2 specimen. As shown in Figure 4, both test beams exhibited a similar trilinear relationship. The behavior of unstrengthened and strengthened test specimens was unchanged from the elastic stage before cracking, corresponding to O-A. Point A exhibits a slope change of the curve, showing the time at which new cracks appeared due to bending moments in the beam. Notably, the load-deflection relationship exhibited nearly identical behavior in both BC-2 and BS-2 beam specimens during this period, showing that, under low loads, the performance of unstrengthened PC beam and CFRP strengthened PC beam was similar. Evidently, during this period, the contribution of the CFRP sheets to the enhancement is minimal.

The next stage is A-B, where B is the second slope change point of the load-deflection curve, corresponding to the moment when the tensile

(a) Control beam BC-2



(b) Strengthened beam BS-2

Figure 3. Failure of unstrengthened and strengthened specimens

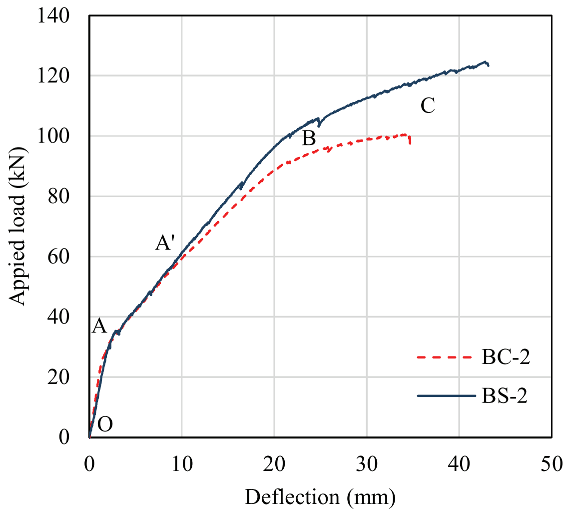


Figure 4. Load-displacement relationship

reinforcement yielded. At this point, the yielding load of prestressing steel reinforcement may be determined. In this stage, the bottom concrete was cracked and excluded from the process. Moreover, from A' point (determined at the load of 60 kN), the higher stiffness observed at this stage in the strengthened beam, as compared to the unstrengthened beam, is demonstrated by the significantly larger reduction in the deflection in the strengthened beam under the same load, compared to the unstrengthened beam. This result supports that using CFRP sheets enhances beam stiffness.

The phase from the prestressed reinforcement's yielding to complete failure (B-C). The load-bearing participation of concrete in the compression zone was negligible for the control beam, the load-bearing participation of the CFRP sheets in BS-2 beam was clearly shown at this stage. Point C corresponds the point when the CFRP sheets is unbonded and the concrete in the compression zone is crushed. At this point, the ultimate load may be determined.

Table 3 summarizes the load and corresponding deflection of the test beams at the cracking, yielding and failure points. Following the cracking stages that occurred in BC-2 and BS-2 beams were observed at the deflections of approximately 1.4 mm and 2.0 mm, respectively, the applied load in the BS-2 test exceeded that in the BC-2 test. The failure load in the BS-2 beam measured around 124.7 kN, representing a 24% increase compared to that of the BC-2 beam.

3.3. Calculation of the ultimate flexural strength of test beams

In this study, the Eurocode 2 and FIB (2010) [16, 17] are used to calculate the flexural strength of PC beams. The calculations aim to provide a deeper understanding of the contribution of CFRP sheets in enhancing the flexural capacity of PC beams. In Eurocode 2, the following assumptions were used to calculate the beam's bearing capacity: (1) Plane-section assumption; (2) The ultimate deformation value, denoted as ε_{cu}, has been attained in the outermost compressive concrete region. The value of ε_{cu} is equal to 0.0035.

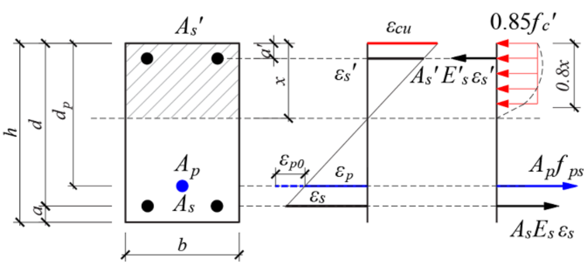


Figure 5. Strains-stress distribution of PC bending cross-section

From the compatibility conditions, as shown in Figure 5, these deformations can be expressed as:

$$\varepsilon_s = \varepsilon_{cu}\frac{d-x}{x} \le \varepsilon_y = \frac{f_y}{E_s} \quad (2)$$

$$\varepsilon_s^{'} = \varepsilon_{cu}\frac{x-a^{'}}{x} \le \varepsilon_y^{'} = \frac{f_y^{'}}{E_s^{'}} \quad (3)$$

$$\varepsilon_p = \varepsilon_{cu}\frac{d_p-x}{x} \le \varepsilon_{py} = \frac{f_{py}}{E_p} \quad (4)$$

$$\varepsilon_{p0} = \frac{N_p}{E_pA_p} + \frac{N_p}{A_cE_c}\left(1+\frac{e^2}{r^2}\right) \quad (5)$$

$$\varepsilon_{ps} = \varepsilon_p + \varepsilon_{p0} \quad (6)$$

where $f_y, f_y^{'}$ and $E_s, E_s^{'}$ are yielding strength and elastic modulus of tension and compression reinforcement, respectively; N_p is the prestressing

Table 3. Summary of loads and deflections of test beam at yielding and failure points

Specimens	Cracking load P_{cr} (kN)	Deflection corresponding to cracking (mm)	Yielding load P_y (kN)	Deflection corresponding to yielding (mm)	Failure load P_{max} (kN)	Deflection corresponding to failure (mm)
BC-2	26	1.4	90	20.6	100.8	34
BS-2	35	2.8	100	21.5	124.7	43

force; $\varepsilon_s^{'}$ is the strain in compression reinforcement; ε_s is the strain in tension reinforcement; ε_p is the tensile strain in the prestressing strand beyond decompression; ε_{p0} is the strain in the prestressing strand resulting from prestressed stress.

The stress in prestressing steel is calculated following equation:

$$f_{ps} = \begin{cases} E_p \varepsilon_{ps} & \text{for } \varepsilon_{ps} \le 0.0086 \\ f_{pu} - \dfrac{0.276}{\varepsilon_{ps} - 0.007} & \text{for } \varepsilon_{ps} \le 0.0086 \end{cases} \quad (7)$$

To predict the flexural strength of the PC beam, FIB (2010) [17] is used. This code uses the strain diagram and simplified stress distribution as presented in Figure 5.

The depth of the neutral axis, x, was determined using equation (8):

$$0.85 f_c^{'} b 0.8x + A_s^{'} E_s \varepsilon_s^{'} = A_s E_s \varepsilon_s + A_p E_p \left(\varepsilon_p + \varepsilon_{p0}\right) \quad (8)$$

In the equation, f'_c represents the concrete compressive strength; $\varepsilon_s, \varepsilon_s^{'}$, and ε_p are the strains in the tension and compression steel reinforcement, and prestressed reinforcement, respectively; ε_{p0} is the strain in prestressed reinforcement due to pre-stressing force; A_s, A_{ps}, $A_s^{'}$ are stress and area of tension reinforcement, prestressed reinforcement, and compression reinforcement.

The bearing capacity of the PC beam cross-section is determined by the following equations:

$$M_n = M_s + M_{ps} + M_s^{'} \quad (9)$$

$$M_s = A_s E_s \varepsilon_s \left(d - \frac{0.8x}{2}\right) \quad (10)$$

$$M_{ps} = A_{ps} f_{ps} \left(d_p - \frac{0.8x}{2}\right) \quad (11)$$

$$M_s^{'} = A_s^{'} E_s \varepsilon_s^{'} \left(\frac{0.8x}{2} - a^{'}\right) \quad (12)$$

where: M_s, M_{ps}, $M_s^{'}$ are contributions of tension reinforcement, prestressed reinforcement, and compression reinforcement to flexural strength of cross section; f_s and f_{ps} are stress of tension reinforcement, prestressed reinforcement; b, h, x, d, d_p, a, a' refer to Figure 5.

Similarly, according to FIB (2010), the bearing capacity of strengthened PC beam cross section uses the strain diagram and simplified stress distribution. Figure 6 illustrated the stress and strain distribution of strengthened PC beam cross section.

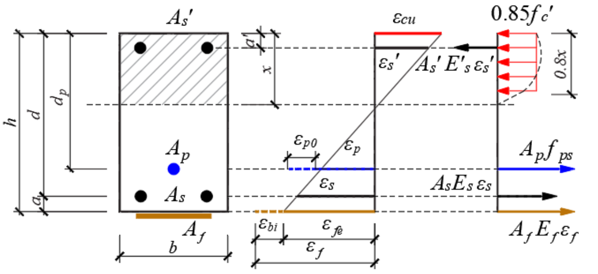


Figure 6. Strains-stress distribution of strengthened PC bending cross section

The depth of the neutral axis, x, was determined using equation (13):

$$0.85 f_c^{'} b 0.8x + A_s^{'} E_s \varepsilon_s^{'} = A_s E_s \varepsilon_s + A_p f_{ps} + A_f E_f \varepsilon_f \quad (13)$$

where ε_f is the effective strain in the CFRP sheets at the ultimate limit state can be calculated from the following fomula:

$$\varepsilon_f = \varepsilon_{fe} + \varepsilon_{bi} = \varepsilon_{cu}\left(\frac{h-x}{x}\right) + \varepsilon_{bi} \le \varepsilon_{fu} \quad (14)$$

where ε_{bi} is the initial substrate strain resulting from the prestressing force, and can be calculated through elastic analysis; ε_{fu} is the rupture strain of CFRP sheets.

The bearing capacity of the strengthened PC beam cross-section is determined by the following formulas:

$$M_n = M_s + M_{ps} + M_s^{'} + M_f \quad (15)$$

$$M_f = A_f E_f \varepsilon_f \quad (16)$$

Table 4 presents the results of calculating the flexural strength of two PC beams.

Table 4. Comparison of experimental and calculated flexural strength of test specimens

Specimens	M_{exp} (kNm)	M_{cal} (kNm)	Difference (%)
BC-2	51	52	1.9%
BS-2	63	60	4.8%

Note: M_{exp} is experiment flexural strength, and M_{cal} is calculation flexural strength, corresponding to the load values at point C in Figure 4.

A comparison with the experimental results shows that the calculation of flexural strength for PC beam consistent the result with small error.

For the strengthened PC beams, the theoretical calculations provide a lower predictive value compared to the experimental results, exhibiting a difference of 4.8%.

4. CONCLUSIONS

This paper presents an experimental study on the flexural behavior of PC beam strengthened with CFRP sheets. In the experimental investigation, two PC beams were loaded to failure using a four-point bending setup. Some conclusions can be drawn from this study:

Generally, the load-carrying capacity of PC beams can be enhanced with the CFRP strengthening method. The current tests showed that the failure load of the strengthened PC beam could be approximately 24% greater than that of the unstrengthened ones.

Notably, the effect of the CFRP sheets on the flexural behavior of the PC beam became evident at a later stage. The stiffness of the PC beam strengthening by the CFRP sheets was significantly enhanced in comparison to the unstrengthened PC beam.

Finally, for the strengthened prestressed concrete beam, the theoretical calculations predicted a predictive value lower than experimental results, offering a more conservative estimation.

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