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EXPERIMENTAL ASSESSMENT OF PRE-CRACKED RC BEAMS STRENGTHENED WITH PASSIVE AND PRESTRESSED CFRP LAMINATES

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Abstract

An experimental program was carried out with three reinforced concrete beams subjected to four-point bending tests until failure, where one of the beams had no strengthening (reference), and two were flexurally strengthened with externally bonded passive and prestressed CFRP laminates, where the two strengthened beams was subjected to pre-cracking. The results showed that passive strengthening leads to an increase in yielding load of up to 8.3% compared to the unstrengthened beam. Also, an increase of up to 23.3% was observed at the ultimate load compared to the reference beam. However, the use of prestressed strengthening led to an increase of up to 30.7% and 36.0% in the loads at the yielding of the steel reinforcement and at the ultimate load, respectively, compared to the reference beam. The use of prestressed laminate is more effective in increasing the load-carrying of the elements. Regarding the strains in the strengthening material, considering that the CFRP laminate showed an estimated maximum strain of approximately 14.6‰, an effectiveness of up to 44.4% and 68.4% was obtained for the passive and prestressed strengthening, respectively. Thus, the ability of the prestressed strengthening system to attain higher strain levels to the strengthening material compared to passive strengthening is highlighted. Furthermore, the use of the prestressed CFRP laminate strengthening system also reduced vertical displacements and pre-existing crack openings in structural elements.

Keywords: Laminate; prestressed CFRP; Passive CFRP; structural strengthening; reinforced concrete; real scale beam.

1. Introduction

Various experimental programs have demonstrated the effectiveness and structural performance of applying fiber-reinforced polymer (FRP) laminates or sheets for passive flexural strengthening of reinforced concrete elements using the externally bonded technique (EBR) [1–4].

Despite the favorable structural performance of the passive FRP strengthening, the elements often exhibit failure modes characterized by detachment of the strengthening material at load levels corresponding to only 20% to 50% of its ultimate strength. This premature failure limits the material's potential, as the load transfer between the concrete substrate and the FRP strengthening relies on adhesion mechanisms, which are prone to early debonding [4, 6]. Moreover, passive FRP strengthening does not significantly enhance the stiffness of the structural element, leading to larger deflections under loading conditions.

To optimize the performance of FRP strengthening, numerous studies have focused on the behavior of prestressed FRP strengthening systems [1–5]. The use of prestressed FRP laminates integrates the passive EBR technique with prestressed concrete principles, particularly external prestressing. This approach introduces a compressive load in the concrete prior to the application of external loads, thereby increasing the load-bearing capacity under both service and ultimate load conditions.

The pre-applied tension in the CFRP contributes to closing existing cracks and delays the formation of new ones, thereby improving the durability and long-term performance of the structure by mitigating crack-induced damage. Additionally, prestressed CFRP laminates utilize end anchorages, enabling the material to achieve higher stress levels before failure. Consequently, this technique is particularly recommended for retrofitting and rehabilitating structures such as bridges, buildings, and other infrastructure subjected to increased service loads, deterioration, or design deficiencies [1, 5–7].

In this context, the present study investigated and analyzed, through an experimental program, the behavior of full-scale reinforced concrete beams strengthened in flexure with both prestressed and passive CFRP laminates. This research is justified by the limited knowledge and application of prestressed FRP reinforcement techniques in Brazil, as well as the lack of experimental programs on the topic in the country, particularly regarding full-scale structural elements.

2. Experimental program

2.1. Beam geometry

The present study aims to analyze the structural behavior of full-scale reinforced concrete beams strengthened in flexure with passive or prestressed CFRP laminates. Thus, an experimental program was conducted with five reinforced concrete beams (Figure 1) subjected to four-point bending tests until failure, where two of them underwent pre-cracking. The identification code BX-Y-Z was adopted, where “B” refers to the term "Beam", “X” corresponds to the number of the tested element, “Y” indicates if the beams were subjected to pre-cracking (“PC”) or not (“NPC”), and “Z” represents the type of strengthening, with “0” for the unstrengthened element and “P” standing for Prestressed and “NP” for Non-Prestressed CFRP laminate.

Due to space limitation, this paper only deals with three beams, namely: (i) the unstrengthened beam (B1-NPC-0), which served as a reference for comparison with the strengthened beams; (ii) the beam subjected to pre-cracking and later strengthened in flexure with externally bonded passive CFRP laminate using the EBR technique (B3-PC-NP); and (iii) the beam subjected to pre-cracking strengthened in flexure with externally bonded prestressed CFRP laminate (B5-PC-P). More information, including the results of the other beams, can be found elsewhere [8].

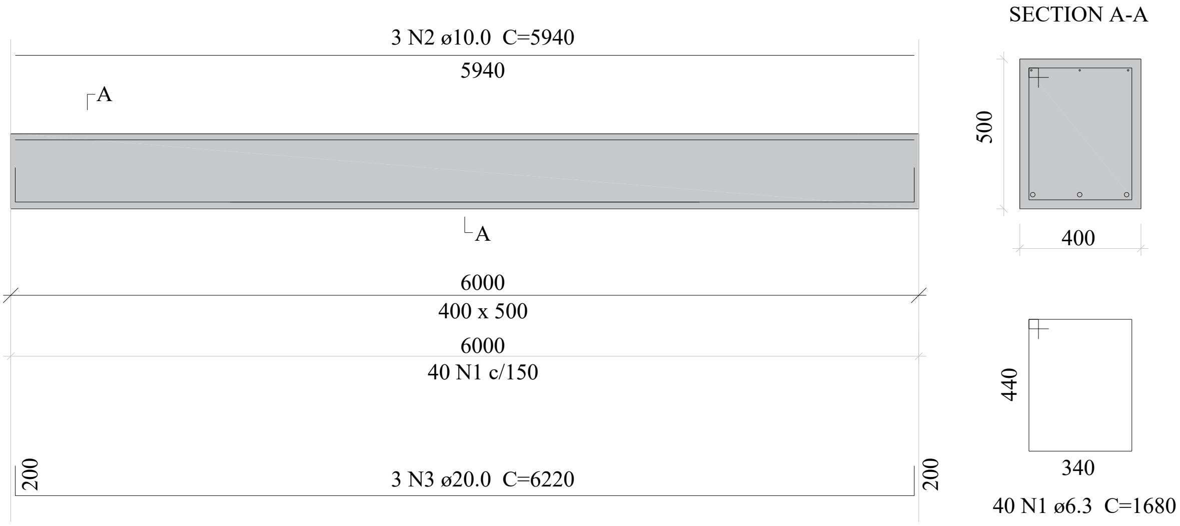


Figure 1. Dimensions (in mm) and steel reinforcement arrangement [8]

2.2. Strengthening system

One of the beams had no strengthening (B1-NPC-0), while the other two beams herein presented were strengthened in flexure with CFRP laminates. According to the manufacturer, the laminate has a thickness of 1,4 mm, an average modulus of elasticity of 170 GPa, an average tensile stress of 2800 MPa and ultimate strain of 16 ‰. In this work, B3-PC-NP and B5-PC-P were strengthened with passive (Figure 2a) and prestressed CFRP laminates (Figure 2b), respectively. The main steps of the passive and prestressed strengthening systems, respectively, can be found elsewhere [5]. Note that a prestrain of 4‰ was applied to the CFRP laminate.

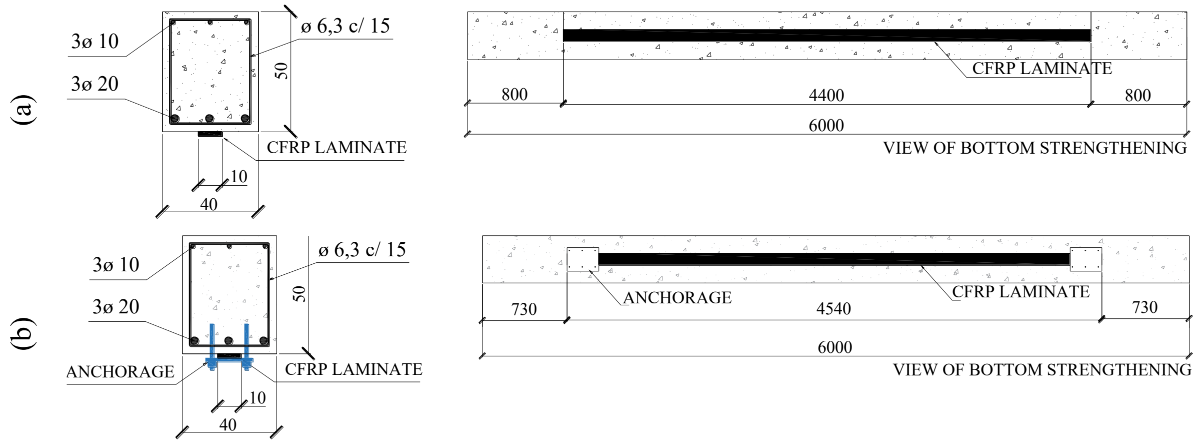


Figure 2. Strengthening arrangement of (a) B3-PC-NP and (b) B5-PC-P. Dimensions in mm [5]

2.3. Test configuration and instrumentation

The four points bending tests were performed at Center for Study and Technology in Precast Concrete (NetPre) of the Federal University of São Carlos (UFSCar) by using metal frames with a capacity of 500kN, along with an Enerpac hydraulic actuator, model RC-506 (capacity of 500kN), which was connected to an electric hydraulic pump for the application of incremental monotonic loading. Figure 3 shows the test setup and instrumentation used in the experimental program.

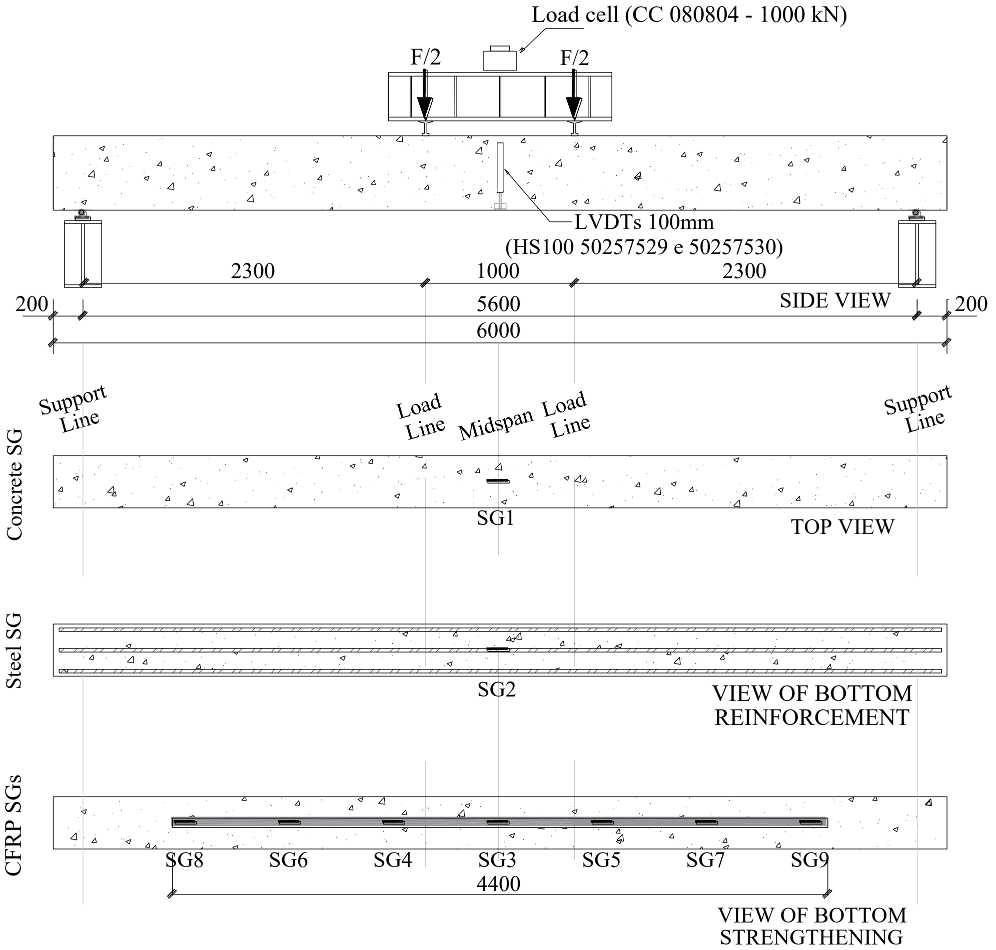


Figure 3. Test setup and instrumentation (Dimensions in mm)

Two different flexural tests were conducted in the beams analyzed in this work. The first test used a single-loading stage procedure, where the beam B1-NP-0 was subjected to loading until failure. The second was divided into three stages: the first involved pre-cracking, where the beams B3-PC-NP and B5-PC-P were loaded until reaching the vertical displacement corresponding to L/250 (5600/250 = 22.4mm), followed by unloading; the second stage consisted of applying the passive/prestressed CFRP laminate and the pause for the cure of the epoxy adhesive (7 days); and the third stage involved loading the beams until failure.

The load application was recorded using a 1000 kN load cell (with a reading resolution of 0.246kN). The displacements and strains in concrete, longitudinal reinforcement and CFRP composite were recorded using an ADS-2000 model data acquisition system (manufactured by LYNX). Beam instrumentation included two displacement transducers and electrical strain gauges. Thus, two *Vishay* displacement transducers, with a linear range of 100 mm, were used to measure the vertical displacement of the beams, fixed to an external support, and positioned at the midspan at the beams.

The strain in the concrete were measured on an electric strain gauge of type PA-06-1500BA-120 (resistance of 120 Ω and length of the reading grid of 40mm, produced by Excel Sensors), which was positioned in the middle of the beams (SG1). The strains in the longitudinal strengthening were measured on electric strain gauges of type KFG-20-120-C1-11 (resistance of 120 Ω and length of the reading grid of 6mm, produced by Excel Sensors), which was positioned in the midspan of one of the longitudinal strengthening (SG2). Concerning the CFRP laminate strains, electrical strain gages of type KFG-20-120-C1-11 (resistance of 120 Ω and length of the reading grid of 10mm, produced by Kyowa), were used and positioned along the strengthening material (SG3 to SG8).

Finally, the crack opening of the beams was also measured on a digital microscope with a focus range of 0-40 mm and magnification up to 1600x when the target vertical displacement (L/250) was reached.

2.4. Materials characterization

Characterizing the concrete included an analysis of the axial compressive strength and modulus of elasticity. Molding and curing procedures were performed, as prescribed by NBR 5738 (ABNT, 2016), and cylindrical specimens 200mm in height and 100mm in diameter were molded. The mechanical properties of the steel were evaluated by axial tensile tests, according to the recommendations of NBR 6892-1 (ABNT, 2018). The CFRP laminates and the epoxy adhesive were evaluated according to the recommendation of ISO 527-1 (2012).

3. Results and discussion

3.1. Materials characterization

3.1.1. Concrete

Concrete properties were tested 28 days after casting and on the last beam test (age of 156 days). The results showed the average values of compressive strength of 44.7 MPa (0,78) and 47.5 MPa (2.95) and modulus of elasticity of 32.4GPa (4.5%) and 31.1 GPa (5.5%) obtained at 28 and 146 days, respectively, where the values in parentheses indicate the coefficient of variation (COV).

3.1.2. Steel bars

Regarding the characterization of steel, bars with a diameter of 6.3mm, type CA-50, presented an average yielding stress of 535.3 MPa (2.4) at 2.0‰ and a maximum tensile stress of 611.7 MPa (2.8). For steel with a diameter of 10mm, a typical behavior of CA-50 steel was verified with a plastic plateau, with average yielding stress of 571.9 (0.2) MPa, mean yielding strain of 3.1‰ (1.6), and maximum tensile stress of 706.4 MPa (0.4). Finally, the 20mm steel bar, type CA-50, presented an average yielding stress of 535.3 MPa (2.4), mean yielding strain of 2.7‰ (3.6) and maximum tensile stress of 730.2 MPa (3.3). The elastic modulus verified for the 6.3, 10 and 20mm bars were 182.1 GPa (2.8), 192.1 GPa (0.55) and 196.3 GPa (0.3), respectively.

3.1.3. CFRP laminates and epoxy adhesive

The CFRP laminates presented linear-elastic behavior until failure, presenting an average maximum tensile stress of 2316.6 MPa (5.1), average elastic modulus of 158.8 GPa (2.4) and average ultimate strain of 14.6‰ (6.8). An average tensile stress of 14.1 MPa (13.8) was obtained for the epoxy adhesive.

3.2. Beams

Figure 4 presents the applied load versus vertical displacement diagrams for the tested beams, while Figures 5 and 6 show the strains in steel and CFRP laminate throughout the loading process. It is important to note that the pre-cracking test of B3-PC-NP and B5-PC-P was conducted while the beam was unstrengthened and that none of the beams presented concrete crushing during the test. Table 1 summarizes the main results, including the applied load (F), average vertical displacements (δ), and strains in concrete, steel, and CFRP (ε_c, ε_s and ε_f), respectively, at the first crack formation ($_{cr}$), reinforcement yielding ($_y$), and ultimate load ($_u$). Note that the flexural test was concluded at a vertical displacement of approximately 57 mm.

From the analysis of the applied load versus midspan displacement diagrams (Figure 4), it is observed that all beams in this study exhibited three typical behavioral stages: the first represents uncracked concrete, the second corresponds to cracked concrete with the steel in the elastic regime, and the third corresponds to cracked concrete with yielding of the longitudinal tensile reinforcement. In the case of the strengthened beams, after the steel yielded, the strengthening system contributed to an increase in the load capacity of the beams. This explains the linear behavior of the curve, resulting from the elastic-linear behavior of the CFRP laminate.

Regarding reinforcement yielding, the beam with passive strengthening (B3-PC-NP) presented an 8.3% increase in the load-carrying capacity and a 1.5% reduction in vertical displacement compared to the reference beam. For the maximum applied load, an increase of 23.3% in load and 10.9% in vertical displacement was observed in comparison to the reference beam.

The beam with prestressed CFRP laminate (B5-PC-P), regarding reinforcement yielding, showed an increase in the load-carrying capacity by 30.3% and the vertical displacement by 2.9%. This indicates that the prestressed strengthening system yielded at a higher yielding load than observed in the reference beam. At the maximum applied load, the prestressed CFRP laminate led to a 36.0% increase of the load-carrying capacity when compared to the reference beam and up to a 10.3% increase when compared to the beam with passive strengthening. This confirms the ability of the prestressed CFRP laminate to enhance the ultimate capacity of the strengthened element, with a higher level of improvement than that achieved with passive strengthening, even in the presence of pre-existing damage in the strengthened element.

In terms of ultimate conditions, the prestressed strengthening system also led to higher maximum loads compared to the passive system. Moreover, an analysis of the diagrams in Figure 4 shows that beam B5-PC-P exhibited a lower initial residual displacement at the onset of loading, compared to B3-PC-NP, due to the camber effect induced by prestressing. In this beam, the prestressed strengthening reduced the average residual displacement from 6.2 mm (caused by pre-cracking) to 2.9 mm, representing a 110.9% reduction in vertical displacement. This confirms the ability of the prestressed CFRP laminate to reduce pre-existing displacements in structural elements. In contrast, passive strengthening did not result in any reduction in displacement at the time of application.

Regarding the flexural stiffness of the beams in the first stage (uncracked concrete), a comparison of the parameters K_I presented in Table 1 shows similar values for all the beams since the strengthening system was inactive in the first stage. A similar behavior was observed in the second stage (cracked concrete with steel in the elastic regime), where the analysis of the parameter K_{II} shows that the beams with passive CFRP laminate did not exhibit increases in flexural stiffness compared to the reference beam. However, B5-PC-P showed a stiffness increase of 16.8% when compared to beam B1-NP-0. Notably, the stiffness increase is attributed to the prestressed system's ability to reduce or close pre-existing cracks.

Table 1. Resume of the experimental program

Beam	Stifness		First crack					Yielding of the steel reinforcement					Maximum aplied load				
	K_I	K_{II}	F_{cr} (kN)	δ_{cr} (mm)	ε_c (‰)	ε_s (‰)	ε_f (‰)	F_y (kN)	δ_y (mm)	ε_c (‰)	ε_s (‰)	ε_f (‰)	F_u (kN)	δ_u (mm)	ε_c (‰)	ε_s (‰)	ε_f (‰)
B1-NPC-0	26.08	9.50	46.16	1.77	-0.16	0.22	---	185.90	26.04	-1.31	4.39	---	199.94	40.94	-2.08	m.d.	---
B3-PC-NP	29.32	7.67	34.60	1.18	-0.03	0.13	---	201.23	25.65	-0.53	3.49	2.69	246.50	45.42	-0.86	m.d.	6.48
B5-PC-P	30.40	11.10	45.90	1.51	-0.10	0.09	---	243.02	26.82	-0.92	3.02	6.83	272.00	39.62	-1.35	3.45	9.18

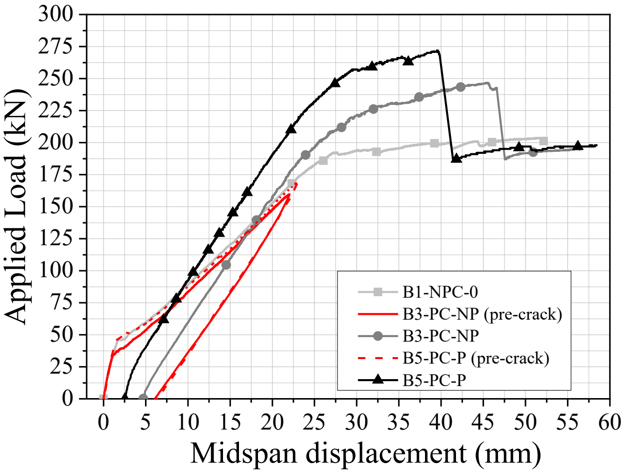


Figure 4. Relationship between Applied load versus midspan displacement [8]

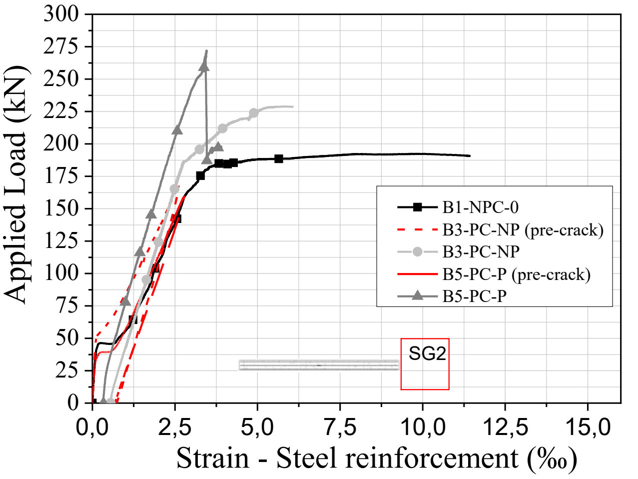


Figure 5. Relationship between Applied load versus strain in the steel reinforcement – SG2 [8]

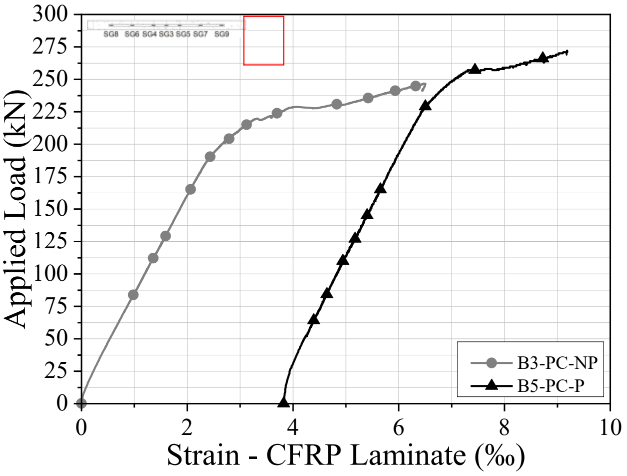
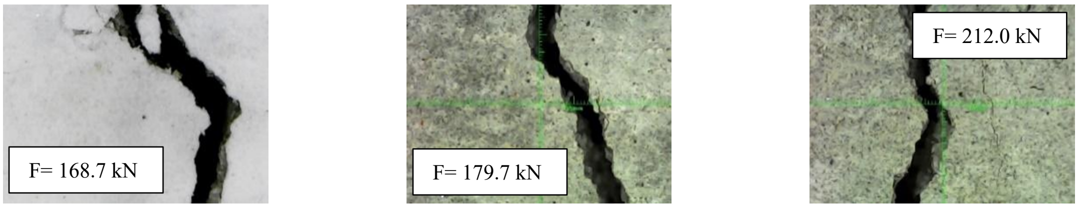


Figure 6. Relationship between Applied load versus strain in CFRP laminates – SG3 [8]

Regarding the strains in the strengthening material, considering that the tested laminate showed an average ultimate strain of approximately 14.6‰, an effectiveness of up to 44.4% and 68.4% was obtained for the passive and prestressed strengthening, respectively. Thus, the prestressed CFRP laminate was found to provide a higher level of utilization of the strengthening material when compared to the passive one, which is attributed to the load-level imposed on the CFRP laminate during prestressing, combined with the anchoring system that provides better fixation of the strengthening material to the concrete substrate compared to passive CFRP laminate, which depends solely on adhesive bonding to the substrate.

Figure 7 shows the load levels at which the crack widths were measured at midspan for L/250. The measured values were 0.40 mm (6.3), 0.35 mm (11.7), and 0.33 mm (14.1) for B1-NP-0, B3-PC-NP, and B5-PC-P, respectively, where the values in parentheses indicate the coefficient of variation (COV). By analyzing the images and the obtained results, reductions in the average crack spacing of the beams with the application of strengthening systems can be observed when compared to the reference beam. It was found that passive strengthening reduced the crack opening by up to 12.5%, while the prestressed CFRP laminates achieved a reduction of up to 17.5%. Thus, the results indicate that, for the same level of displacement, the strengthening systems resulted in smaller crack openings, with the prestressed strengthening standing out as having the smallest openings recorded during the tests.



(a) (b) (c)

Figure 7. Examples of crack openings of B1-NP-0 (a), B3-PC-NP (b) and B5-PC-P (c)

Regarding the failure modes governing the behavior of the simply supported reinforced concrete beams evaluated in this research, the unstrengthened beam (reference) failed due to the yielding of the tensile reinforcement. The beams with passive strengthening exhibited a failure mode characterized by the brittle detachment of the CFRP laminate. Finally, the prestressed CFRP laminate exhibited a failure mode characterized by detachment and partial rupture of the laminate in one of the anchoring zones. It was observed that the use of metal anchors change the failure mode of the strengthening system when compared to passive CFRP laminate, postponing the collapse of the strengthening material and resulting in higher levels of stress on the CFRP laminate.

4. Conclusions

An experimental program was carried out with three reinforced concrete beams subjected to four-point bending tests until failure, where one of the beams had no strengthening (reference), and two were flexurally strengthened with externally bonded passive and prestressed CFRP laminates, where the two strengthened beams was subjected to pre-cracking.

The results obtained allowed the following conclusions to be obtained:

- Regarding the types of strengthening applied in this research, passive strengthening led to a strength increase at the yielding of the steel reinforcement of 8.25% when compared to the unstrengthened beam. Additionally, an increase of 23.29% was observed in the maximum force obtained during the test compared to the reference beam. The use of prestressed strengthening promoted increases of 30.73% and 36.04% for the yielding of the steel reinforcement and strengthening collapse, respectively, when compared to beam B1-NPC-0;

Regarding the strains in the strengthening material, considering that the laminate showed an average ultimate strain of approximately 14.6‰, an effectiveness of up to 44.4% and 68.4% was obtained for the passive and prestressed strengthening, respectively;

- Regarding crack openings, the results showed that, for the same level of displacement, the strengthening systems provided smaller values, with prestressed CFRP laminate showing the smallest

recorded crack openings during testing, confirming the ability of the prestressing system to delay concrete cracking and resulting in higher flexural stiffness compared to the passive system;
- The prestressed CFRP laminate showed a better in-service performance, with higher load increments observed at the yielding of the reinforcement, as well as increased flexural stiffness due to the prestressing load applied to the strengthened element;
- The prestressed CFRP laminate delays the detachment of the strengthening material due to the anchoring system; and
- The prestressed CFRP laminate showed the ability to reduce pre-existing displacements in structural elements.

Acknowledgments

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