ORIGINAL ARTICLE

Degradation of the EBR-CFRP strengthening system applied to reinforced concrete beams exposed to weathering

Degradação do sistema de reforço EBR-CFRP em vigas de concreto armado expostas ao intemperismo

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Abstract: Little is known about the behavior and durability of strengthening systems applied on concrete substrata and the possible loss of performance due to the degradation of the intervening materials by the structure's natural aging process and exposure of the externally strengthened elements to aggressive environments. In this context, the present work presents an experimental analysis of the behavior of reinforced concrete beams strengthened with Carbon Fiber Reinforced Polymer (CFRP), applied according to the Externally Bonded Reinforcement (EBR) technique, maintained in a laboratory environment (indoor and protected) or exposed to weathering (outdoor exposure). In addition, specimens of the intervenient materials were also molded and exposed to the same environmental conditions as the beams. The results indicate that weather-exposed epoxy adhesives present reductions up to 70% in their mechanical properties after exposure, while the CFRP composite properties remain similar. It was also found that the strengthening system provided 50% and 28% increments in the load-carrying capacity and stiffness of the elements, respectively. However, the tests conducted after 6 months of weathering exposure showed a 10% reduction in the load-carrying capacity of the strengthened elements.

Keywords: reinforced concrete beams, strengthening, CFRP, degradation, EBR technique.

Resumo: Pouco se sabe a respeito do comportamento e da durabilidade do sistema de reforço aderido ao substrato de concreto e a possível perda de desempenho frente à degradação dos materiais intervenientes face ao processo natural de envelhecimento das estruturas e, também, devido à exposição dos elementos reforçados externamente a ambientes agressivos. Neste âmbito, o presente trabalho baseia-se na análise experimental do comportamento de vigas de concreto armado reforçadas a flexão com mantas de fibra de carbono (CFRP, *Carbon Fiber Reinforced Polymer*) aplicadas segundo a técnica EBR (*Externally Bonded Reinforcement*) mantidas em ambiente laboratorial (interno e protegido) e expostas a intempéries (exposição exterior). Para além disso, corpos de provas dos materiais constituintes do sistema de reforço também foram confeccionados e expostos nas mesmas condições ambientais das vigas. Os resultados demonstraram que os adesivos epoxídicos apresentam reduções de até 70% em suas propriedades mecânicas quando expostos às intempéries enquanto o compósito de CFRP permanece com suas propriedades inalteradas após mesma exposição. Para as vigas de concreto armado reforçadas, foi verificado que o sistema de reforço proporciona incrementos de 50 e 28% na capacidade de carga e rigidez dos elementos reforçados, respectivamente. No entanto, os ensaios realizados após 6 meses de exposição às intempéries demonstraram uma redução de 10% no incremento da capacidade de carga dos elementos reforçados.

Palavras-chave: vigas de concreto armado, reforço, CFRP, degradação, técnica EBR.

1 INTRODUCTION

Strengthening a structural element means restoring or increasing its supporting conditions in relation to those for which it was initially designed. Carbon Fiber Reinforced Polymer (CFRP) strengthening systems can be applied to various reinforced concrete elements such as beams, columns, slabs. Design errors, project reading misinterpretation, changes in the structure use, or the natural weathering of buildings are some of the main reasons for strengthening a structure [1].

Among the main materials used for this purpose, Fiber Reinforced Polymers (FRPs) are of high prominence because their mechanical properties are superior to the conventional materials used in strengthening techniques. Of the main characteristics of FRPs, high strength and stiffness, and low weight are the main properties that favor their use in strengthening works [2].

CFRPs are the most widely used materials for structural strengthening [3]. One main advantage of CFRPs is the resistance to chemical agents and corrosion [4]. According to Barros [5], prefabricated and in-situ cured systems are the most used in strengthening techniques. Prefabricated systems are supplied in the form of laminates or circular section bars, with their fibers oriented in the longitudinal direction of the element. In-situ cured matrix and fiber are supplied separately, and CFRP composite manufacturing is carried out at the strengthening application site. In this case, the fibers may be either unidirectional or bidirectional in orientation and supplied in the form of sheets or fabrics.

Of the various ways of applying strengthening systems, the Externally Bonded Reinforcement (EBR) technique is widely used. It originated in Europe, proposed and developed in Switzerland, and it was first used to strengthen a bridge using CFRP sheets in the city of Lucerne in 1991. Since then, the EBR technique has continued to be used in strengthening interventions [6], [7] due to its advantages, such as the ease of application and good mechanical performance [8].

Further, the EBR technique allows for increments in bending with the bonding of the strengthening system on the tensile face of the beams, or even by shear, by strengthening the lateral faces of the beams, or with the strengthening systems working simultaneously.

According to Karbhari [9] and Gangarao et al. [10], composite materials used in civil construction can be exposed to various aggressive agents. Determining the effects of environmental aggressiveness on the adhesion of the concrete-adhesive FRP, especially over prolonged periods, is of extreme importance [11]. There is a need for further knowledge of their long-term performance, durability, and design life in the face of conditions such as moisture, seawater salinity, and thermal cycles, among others.

The present work aimed to evaluate the long-term durability and mechanical behavior of the flexural strengthening system's constituent materials, as well as reinforced concrete beams strengthened with CFRP, applied according to the EBR technique, maintained in a laboratory environment (internal and protected) or exposed to weathering (outdoor exposure).

2 STATE OF THE ART

2.1 Degradation of FRPs when exposed to weathering

All materials used in the construction industry are subject to degradation, originated by chemical, physical, or mechanical sources. Applying an FRP strengthening system to a determined concrete element, these degradation mechanisms should be considered to achieve better long-term behavior and durability [12]. Degradation mechanisms can occur either individually or together in the degradation of the composite FRP material (Figure 1).

It is generally known that degradation mechanisms directly affect the most sensitive part of the strengthened structure, i.e., the bond between the concrete substrate and the FRP composite. Bonding usually relies on epoxy-based resins, which are susceptible to degradation in harsh environments. These resins are susceptible to ultraviolet (UV) radiation, temperature, humidity, and acid rain [13]. Unless a protective layer is used, the FRP gets directly exposed to the external environment and, consequently, to the possible aggressive agents or eventualities, as shown in Figure 2.

Direct exposure to UV radiation from polymers can result in photodegradation, a mechanism that causes the decomposition or dissociation of chemical bonds between polymer chains, driven by the UV radiation present in solar waves. This radiation causes the degradation of polymers, leading to discolouration, surface oxidation, embrittlement, and polymer matrix microfissuration [12].
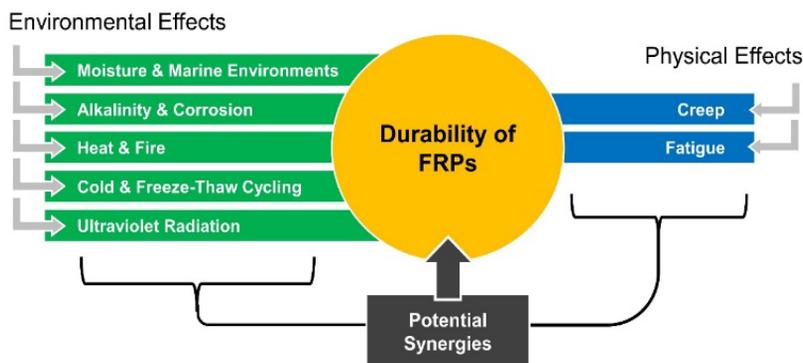
Figure 1. Degradation mechanisms of FRP systems [12]

Figure 2. Sewage station with CFRP sheets externally applied according to the EBR technique [14]

Zhao et al. [15] evaluated three types of degradation in polymeric resins (ester-vinyl, epoxy, and epoxy ester) when exposed to UV radiation. In the study, specimens with 200 mm, 20 mm, and 4 mm in length, width, and thickness, respectively, were prepared and cured for seven days at room temperature. Subsequently, they were exposed to UV radiation (280–315 nm) at a temperature of 57–63ºC and humidity of 90–95%. The radiation cycles lasted 12 hours (8 hours of UV radiation and 4 hours of condensation) for a total period of 90 days (Table 1). The ester-vinyl resin presented higher degradation, with a reduction of 65% and 69% in tensile strength and modulus of elasticity, respectively. After exposure, the resin specimens presented significant changes in their colouration.

Table 1 Mechanical properties of resins after exposure to UV radiation [15]

Exposure period	Maximum tensile stress (MPa)			Modulus of elasticity (MPa)		
	Vinyl ester	Epoxy	Ester epoxy	Vinyl ester	Epoxy	Ester epoxy
Reference	39,7	41,0	34,5	2544,7	1944,0	2024,7
30 days	17,1	39,8	30,7	1223,0	2438,9	2385,3
90 days	13,8	42,0	31,4	777,6	1547,9	1740,1

Some fiber types also suffer from degradation caused by UV radiation. According to ISIS [12], carbon and glass fibers are generally not affected by UV radiation, while aramid fibers undergo slight degradation in the face of UV exposure. Homam and Sheikh [16] studied the isolated effect of exposure to UV rays on FRP composites with epoxy

resin. In a controlled environment, CFRP and GFRP specimens were exposed to 22°C to 38°C temperature of, 40% relative humidity of radiation from UV-A lamps at 156 W/m². The specimens were tested for uniaxial tensile and shear using the single-lap bond test. Slight increases in tensile strength and stiffness were observed in the specimens of both composites exposed to UV radiation as compared to those maintained in the laboratory environment for exposure periods of 1200 and 4800 hours. Notably, exposure to UV rays did not significantly affect the shear strength of the composites. The bond between the FRP composite and the concrete substrate was susceptible to degradation due to UV radiation. Kabir et al. [17] studied the concrete/adhesive/FRP bonding in external environments. The authors report the exposure to external environments as the most harmful situation for concrete bond-adhesive-FRP.

2.2 Climate regions: Köpper–Geiger classification system

The intensity of weathering effects depends on the climate and microclimate of the place where the structure is allocated. One way to categorize the climate is through the Köppen–Geiger climate classification system, which is used worldwide in different areas (such as climatology, meteorology, geography, bioclimatology, and ecology) and takes into account the average annual and monthly values of temperature and precipitation in addition to climate seasonality. Climatic types are separated by large groups, types, and subtypes. Table 2 presents the nomenclatures and climatic types, while Figure 3 shows the climate classification of Brazil [18].

Figure 3 indicates that tropical climate (Zone A – an average temperature equal to or higher than 18°C every month and significant precipitation) is predominant in Brazil, covering 81.4% of the country's total area. Dry climate (Zone B – low precipitation throughout the year) is present in some parts of the northeastern states of Brazil, while subtropical climates are dominant in the South and Southeast [18].

According to the Brazilian Agricultural Research Company (EMBRAPA) [19], the city of São Carlos in the state of São Paulo (latitude 21°57'42" (S), longitude 47°50'28" (W), and altitude 860 meters above sea level), which is where this research was developed, has a local climate defined as humid subtropical with dry winter and hot summer (known as Cwa). Figure 4 shows other regions of the world that have similar Cfa and Cwa climate types, as per the Köpper–Geiger climate classification system, for which the results obtained in this research can also be expanded.

Table 2 Köpper–Geiger classification system [18]

Group	Type	Subtype (where applicable)
A - Tropical		**f** - Equatorial (no dry season, with precipitation ≥ 60 mm each month)
		m - Monsonic (with a drier month)
		w - Savanna with drier season in winter
		s - Savanna with drier season in summer
B - Dry	**w** - Arid	**h** -Low latitude and longitude; average annual temperature ≥18°C
		k - medium latitude and high altitude; average annual temp. <18°C
	s - Semiarid	**h** -Low latitude and longitude; average annual temperature ≥18°C
		k - medium latitude and high altitude; average annual temp. <18°C
C - Moist Subtropical	**f** - Oceanic climate, no dry season	**a** - Hot summer
		b - Cool summer
		c - Short and cold summer
	w - With dry winter	**a** - Hot summer
		b - Cool summer
		c - Short and cold summer
	s - With dry summer	**a** - Hot summer
		b - Cool summer
		c - Short and cold summer
D - Temperate Continental	**f** - No dry season	**a** - Hot summer
		b - Cool summer
		c - Short and cold summer
		d - Very cold winter
	w - With dry winter	**a** - Hot summer
		b - Cool summer
		c - Short and cold summer
		d - Very cold winter
	s - With dry summer	**a** - Hot summer
		b - Cool summer
		c - Short and cold summer
		d - Very cold winter
E - Polar		**T** - Tundra (temperature in the hottest month between 10 and 0°C)
		F - Glacial (temperature in the hottest month <0°C)
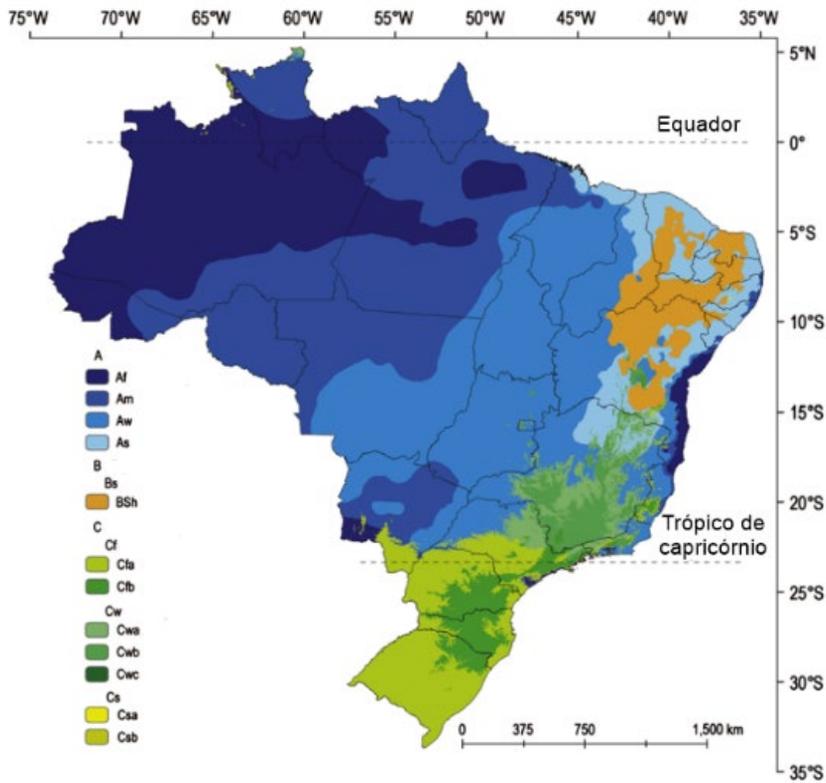
Figure 3. Brazil climate classification in the Köpper-Geiger system [18]
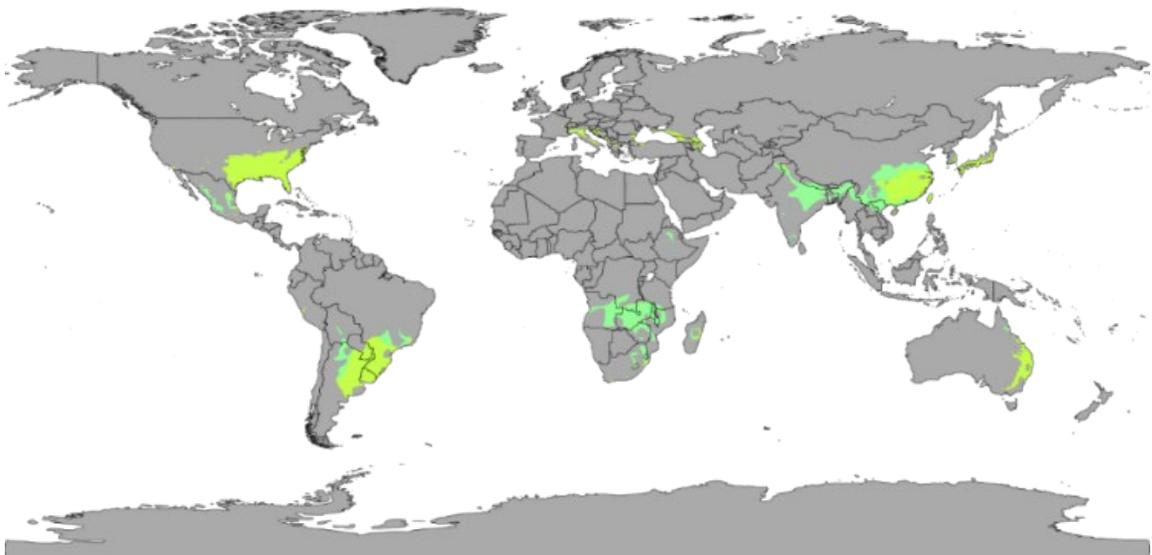
Figure 4. Humid subtropical climate Cfa and Cwa around the world [20]

3 EXPERIMENTAL PROGRAM

The research aimed to evaluate the degradation of reinforced concrete beams strengthened with CFRP sheets and exposed to weathering in a humid subtropical climate with dry winter and hot summer (Cwa) in non-accelerated tests. The beams and intervening materials (epoxy resins and CFRP composites) were exposed to two distinct environments: (a) laboratory environment (internal, protected), inside a controlled temperature and humidity chamber for a period of

6 months (reference), and (b) external environment, wherein the materials were exposed to weathering for the same period of time.

3.1 Beam geometry, degradation environments, strengthening system, and bending test configuration

3.1.1 Beams

The experimental program consisted on twelve simply supported beams of 120 x 200 x 2500 mm³, 20-MPa, and positive longitudinal reinforcement composed by two CA-50 steel bars (10-mm diameter; reinforcement ratio of 0.75%). To avoid shear rupture, CA-60 steel stirrups (5-mm diameter and 10-cm spacing) with two top longitudinal reinforcement bars of CA-50 and 6.3 mm diameter (Figure 5). The beams were designed in the deformation domain 2, based on NBR 6118 [21].
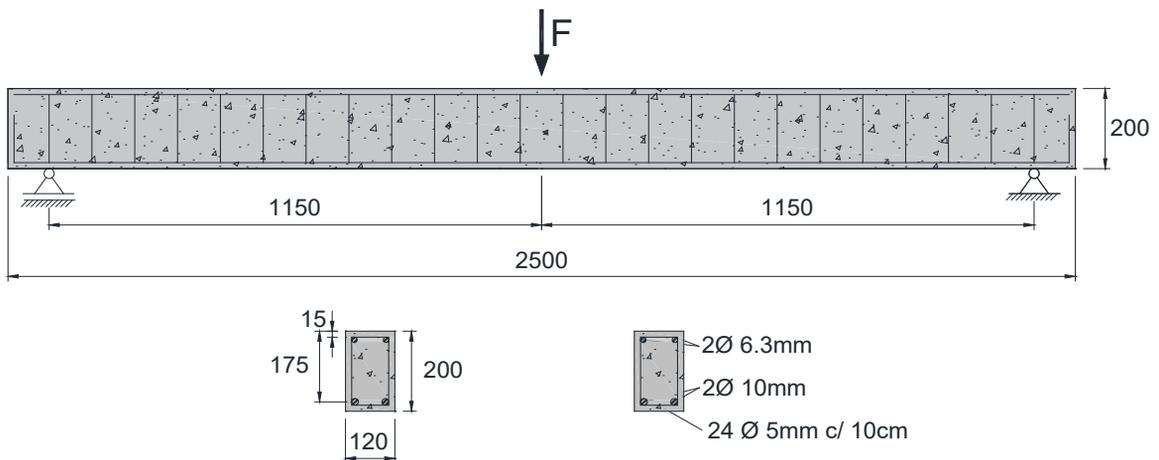
Figure 5. Characteristic of reinforced concrete beams (units in mm).

3.1.2 Strengthening system

Eight beams were reinforced with unidirectional 300-g/m² weight carbon fiber sheets of 0.13 mm thickness. The sheet was cut into 110 x 2200 mm strips to fit the tension surface of the reinforced concrete beam (Figure 6).
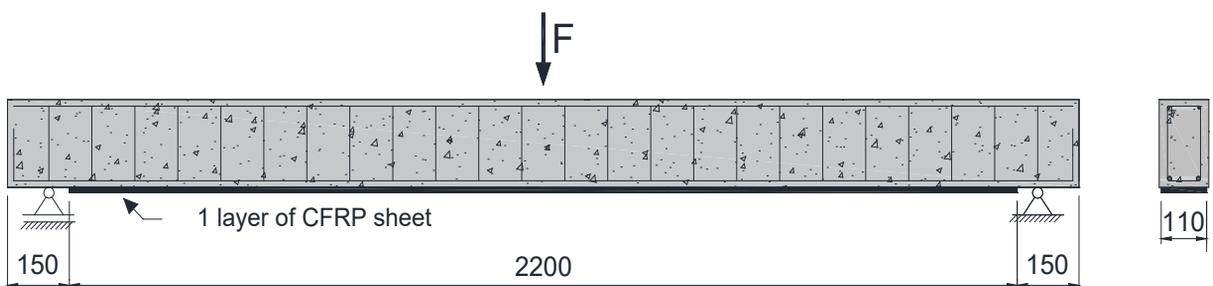
Figure 6. Details of the strengthening system (units in mm)

The CFRP sheets were applied externally to the beams when they were 186 days old. The substrate was cut with a diamond thinning disc grinder until the entire layer of cement paste was removed and the aggregates were exposed. After, compressed air was applied to the surface for disposing of any solid particles. A layer of the primer resin (Resin A) was applied to improve the adhesion conditions between the CFRP and concrete substrate. The CFRP was bonded using the epoxy lamination resin (Resin B), which was applied 45 minutes after the primer. The primer and saturation resins were

prepared into three steps: agitation of each component, mixture of component A to B in the proportion indicated by the manufacturer, and mechanical mixture until a uniform color was obtained. The primer resin was spread on the concrete surface using a brush. The CFRP sheet was covered with lamination resin and applied to the concrete substrate before the application of the strengthening system. While strengthening, we tried to ensure the alignment of the fibers in the longitudinal direction of the beam, to check the non-formation of air bubbles in the back of the CFRP composite, and to avoid the accumulation of excess resin. The steps and procedures used to strengthen the reinforced concrete beams are depicted in Figure 7.

3.1.3 Degradation environments

Of the twelve beams made, four had no strengthening, and the others were strengthened in flexure with one layer of CFRP sheet applied according to the EBR technique. Two exposure environments were adopted in this research (Figure 8), as given below.

- Laboratory environment (LAB): internal to a chamber, protected, and with monitoring of ambient temperature and humidity, which served as a reference for the other tests (Figure 8a)

- Exposure to weathering (WEA): external environment, free of obstacles that promoted shading in beams and specimens, and with monitoring of humidity, temperature, and radiation (Figure 8b).
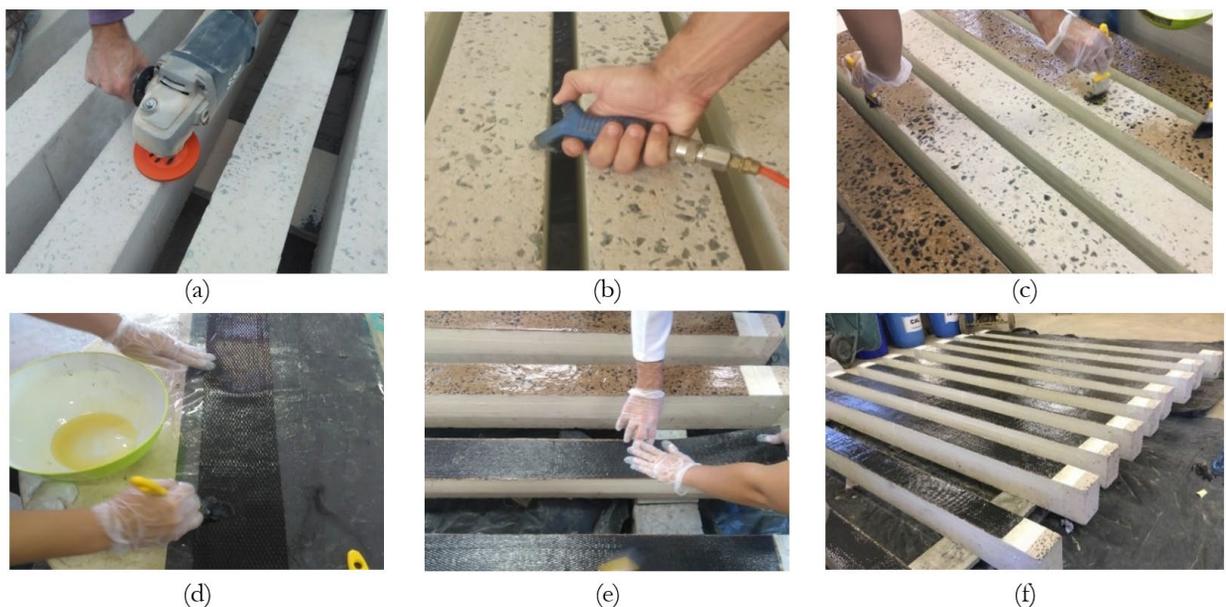
Figure 7. (a) Preparation of the concrete surface, (b) surface cleaning with compressed air, (c) application of the primer, (d) impregnation of the CFRP composites, (e) application of CFRP to the concrete substrate and (f) final aspect of the strengthened members

Each beam was identified as Vx_y_z, where "x" is the number of tested elements, "y" corresponds to the elements used as reference (REF, of *Reference),* maintained in a laboratory environment (LAB, of *laboratory*), or exposed to weathering (WEA, of *Weathering*), and "z" due to the use or not of strengthening material (0 or 1 layer of CFRP sheet). The strengthening system was also analyzed, specifically the epoxy resins and the CFRP composites. Table 3 presents a summary of the experimental program wherein Vx_REF_0 and Vx_REF_CFRP refer to the beams without and with strengthening, respectively, maintained in the same environment and tested on the same date – 200 days after concreting – which were considered as references for the other analyses. The Vx_LAB_CFRP and Vx_WEA_CFRP refer to the beams strengthened with CFRP and maintained in laboratory chamber environment or exposed to weathering, tested 6 months after the application of the strengthening. The other beams will be tested 2 years after strengthening and exposure to the environments previously mentioned.

Figure 8. Exposure environments: (a) isolated and protected chamber and (b) exposure to weather (outdoor environment)

Table 3 Test program for reinforced concrete beams

Group identification	Strengthening	Environment	Identification of beams	Condition for performing the test	Number of beams
V_REF_0	No strengthening	LAB	V1_REF_0	Test conducted at the age of 200 days	2
			V2_REF_0		
V_REF_CFRP	CFRP	LAB	V1_REF_CFRP	Strengthening performed at the age of 186 days	2
			V2_REF_CFRP	Test performed at the age of 200 days (14 days after application of the strengthening system, time considered to be the complete cure of epoxy resin)	
V_LAB_CFRP	CFRP	LAB	V1_LAB_CFRP	Strengthening carried out at the age of 200 days	2
			V2_LAB_CFRP		
V_WEA_CFRP	CFRP	WEA	V1_WEA_CFRP	Test performed 380 days after concreting (6 months after the application of the strengthening system)	2
			V2_WEA_CFRP		

3.1.4 Test configuration

The three points bending tests were performed with midspan point load, using a universal EMIC testing machine (model DL 60000 available at the Structural Systems Laboratory [LSE] of the Federal University of São Carlos [UFSCar]).

A self-reaction system was designed to allow testing the beam inside the universal testing machine. A double corbel element (Figure 9a) was designed using 31.75-mm and 25.40-mm thick. The corbel was fixed to the testing machine base and supported a 250-cm long steel section (W200 x 26.6). The corbel was screwed to the base of the test machine using six steel hexagon screws type M12, and the metal profile was mounted on it with eight steel hexagon screws type M10. The concrete beams were supported on the metal profile at a roller and at a fixed support, as shown in Figure 9b.

To measure the rotation of the supports and displacement of the steel beam ends, two Linear Variable Differential Transformers (LVDTs) with 25-mm stroke and two potentiometers with 20-mm stroke were used, positioned as shown in Figure 9b, 9c.
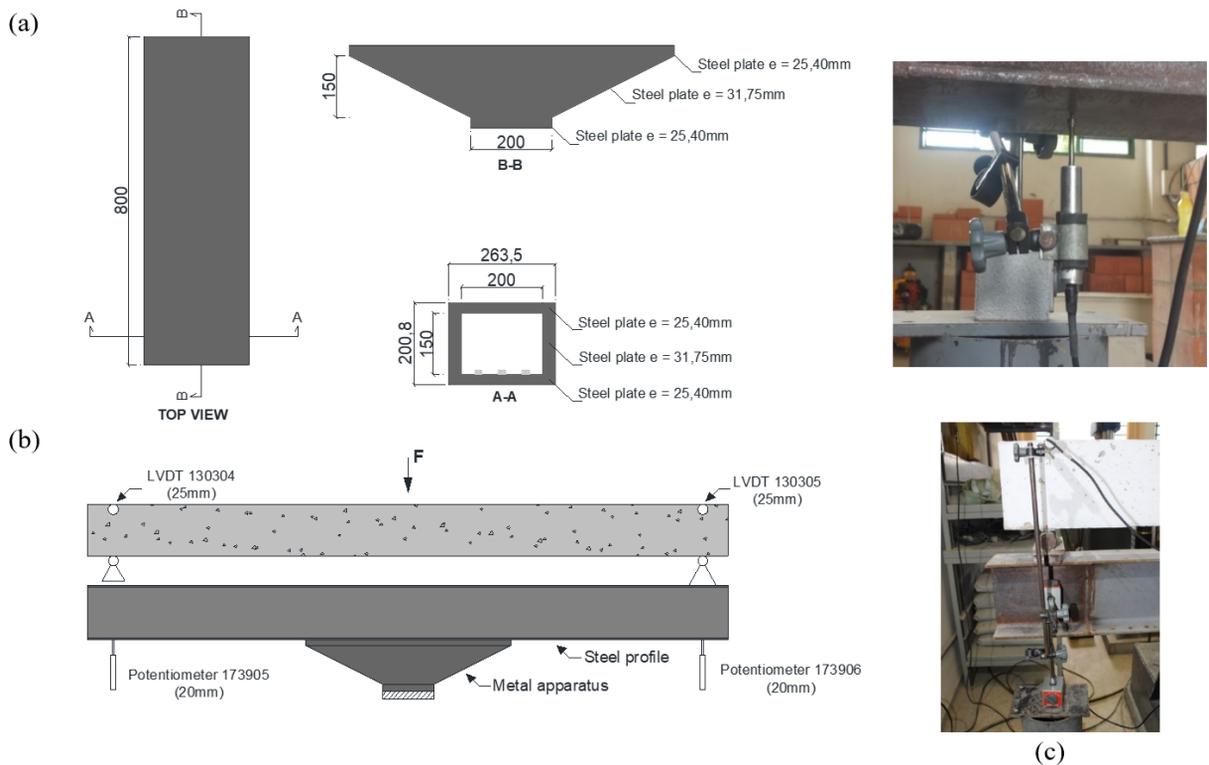
Figure 9. (a-b) Steel apparatus and (c) details of the positioning of the LVDTs and potentiometers used to measure the displacement of the metal beam and rotation of the supports (units in **Figure 9a:** mm)

The loading was applied at 0.50mm/min displacement. The load application was double recorded using an external 200-kN load cell (with reading resolution of 0.01 kN), in addition to the test machine load cell, which had a load cell with a maximum capacity of 600 kN and reading resolution of 0.1 kN. The displacements and deformations in concrete, longitudinal reinforcement and CFRP composite were recorded using an ADS-2000 model data acquisition system (manufactured by LYNX). Beam instrumentation included a displacement transducer and six electrical strain gauges. A *Vishay* displacement transducer, with a linear range of 50mm, was used to measure the vertical displacement of the beams. This was fixed to an external support and positioned at the midspan at the beams.

The deformations 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 40 mm; produced by Excel Sensors), which was positioned in the middle of the beams (SG1). The deformations in the longitudinal strengthening were measured on electrical strainers of type KFG-20-120-C1-11 (resistance of 120 Ω and length of the reading grid of 20 mm; produced by KYOWA), which was positioned in the section of the central section of one of the longitudinal strengthening (SG2). In relation to CFRP composite deformations, electrical strain gages of type KFG-20-120-C1-11 (the same used in longitudinal strengthening) and type PA-06-250BA-120 (resistance of 120 Ω and reading grid length of 6 mm; produced by Excel Sensors), positioned along the strengthening material (SG3 to SG5). Figure 10 shows the instrumentation used.

3.1.5 Characterization of materials

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 [22], and cylindrical specimens 200 mm

in height and 100 mm in diameter were molded. 24 hours after the casting, the specimens were demolded and positioned in the same environment as the beams.

The CFRP composite manufacturing system, which supplies the fiber and matrix separately, is known as the "*in situ*" cured system. In this experiment, an *in situ* cured system was used.
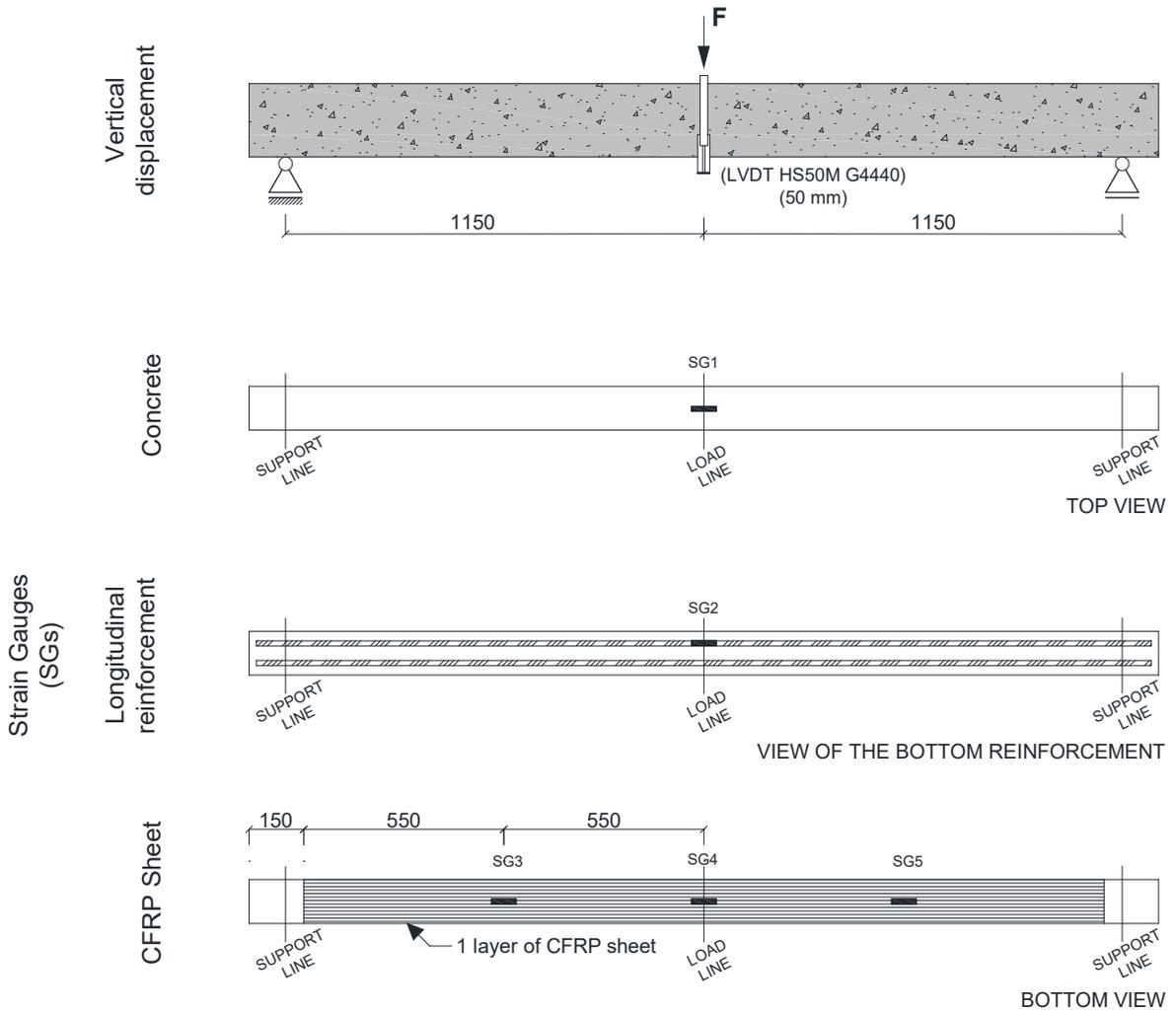
Figure 10. Instrumentation used in beam testing (units in mm)

A layer of unidirectional carbon fiber mat weighing 300 g/m^2 was impregnated with epoxy resin. The carbon fiber sheet had to have at least tensile strength of 3800 MPa, modulus of elasticity of 240 GPa, and deformation at rupture of 15.5‰. More information on the characterization of the CFRP composites and experimental results can be found in Ferreira [23].

The adhesives used to fix the composite strengthening system to the concrete substrate were supplied by the same manufacturer of the carbon fiber sheet used in this work. In the experiment, bi-component epoxy primer and lamination resins were used. The characterization tests of epoxy resins and CFRP composites were carried out at the Polymer Laboratory of the Materials Engineering Department (DEMa) of UFSCar. More information on the characterization of adhesives and the experiment results can also be found in Ferreira [23].

The mechanical properties of the steel were evaluated by axial tensile tests, according to the recommendations of NBR 6892-1 [24]. A minimum of three specimens, 50 cm in length and randomly chosen, were tested for each bar diameter used. Both steel and concrete characterization tests were performed at LSE.

4 RESULTS AND DISCUSSION

This section presents the results of the tests of characterization of the materials and the behavior of concrete beams without strengthening and reinforced with a layer of CFRP sheet.

4.1 Environmental data

The temperature and average humidity readings in the laboratory environment were 23.3ºC (± 0.03%) and 36.5% (± 0.24%), respectively. The values in parentheses represent the Coefficient of Variation (COV). For exposure to weathering (external environment), Figure 11 presents the data of temperature, humidity, and UV radiation throughout the exposure period of the beams and concrete specimens, i.e., from May to November 2018. During this period the maximum and minimum temperatures were 34.2ºC and 4.7ºC, and the maximum and minimum humidity were 95% and 16%, respectively. Regarding UV radiation, the surface weather station recorded a peak of 4112 kJ/m^2 and an average of 788 kJ/m^2 over the exposure period.
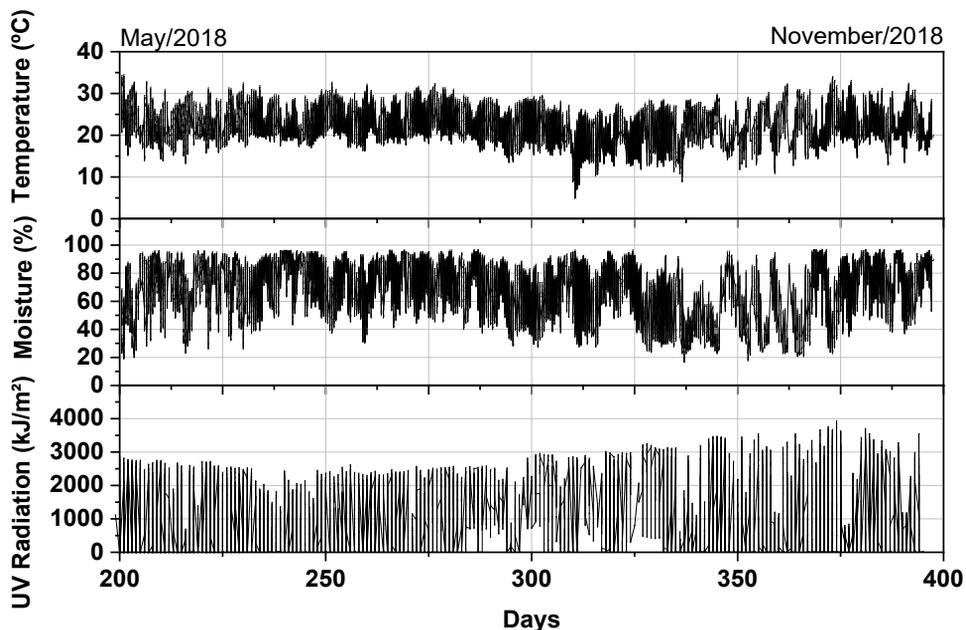
Figure 11. Weather data for the weather exposure. Source: INMET

4.2 Mechanical properties

4.2.1 Concrete

Concrete properties were tested 28 days after concreting and also on the day of the beam tests, which were performed at the age of 200 days (REF) and 380 days (LAB and WEA). The results showed the mean values of compressive strength of 22.0 MPa (± 3.50%) and 28.5 MPa (± 0.54%) and modulus of elasticity of 29.3 GPa (± 7.03%) and 31.6 GPa (± 5.32%) obtained at 28 and 200 days, respectively. For the specimens that were kept in the laboratory environment (LAB) or exposed to weathering (WEA), mean values of 27.4 MPa (± 0.50%) and 25,2 MPa (± 6.94%) for compressive strength and 31.2 GPa (± 2.87%) and 28.5 GPa (± 3.06%) for modulus of elasticity, respectively, were obtained in the test performed at the age of 380 days.

4.2.2 Steel

Regarding the characterization of steel, for bars with a diameter of 5 mm, type CA-60, an average yielding stress was observed at 2.0‰ of 646.9 (± 4.04%) MPa and a maximum tensile stress of 670.6 (± 3.62%) MPa (Figure 12a). For steel with a diameter of 10 mm, a typical behavior of CA-50 steel was verified with a plastic plateau (Figure 12b),

with an average yielding stress of 547.4 MPa (± 2.13%), mean yielding strain of 2.8‰ (± 1.59%), and a maximum tensile stress of 591.5 MPa (± 6.25). The elasticity modules verified for the 10 mm and 5 mm bars were 196.9 GPa (± 1.58%) and 191.3 GPa (± 7.19%), respectively.
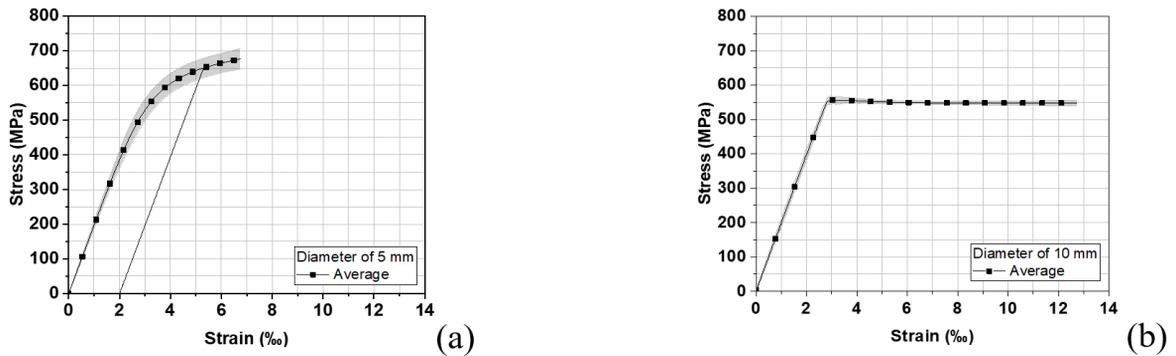
Figure 12. Stress versus deformation of materials: (a) stirrups and (b) steel of longitudinal reinforcement

4.2.3 Epoxy resins

The characterization tests for the resins were experimentally performed at the ages of 7 and 14 days and 4 and 8 months after the application of the strengthening system, as presented in Figure 13. Considering 14 days of cure for Resin A (Figure 13a), which was maintained in a laboratory environment, the material presented a small increase in maximum tension and modulus of elasticity (5.7% and 4.5%, respectively) at 4 months. After 8 months of exposure and with the results of the tests performed at 14 days as a reference, there was no major change in the maximum tensile stress of the primer, which presented a small reduction of 2.9%. However, a 9.1% reduction in the modulus of elasticity was verified in the assays. There was also a small reduction in the ductility of the specimens after 8 months of exposure in a laboratory setting. Therefore, there were no significant changes in the mode of rupture and stress-strain behavior throughout the exposure period in the laboratory environment.

Considering the exposure to weather of Resin A (Figure 13b) and with the tests performed at 14 days as a reference, a reduction of 39.1% in tensile strength and 4.5% in the modulus of elasticity was noted at 4 months. At 8 months of exposure, a sharper reduction in tensile strength (about 51.0%), while the modulus of elasticity showed a reduction of 9.1%. It was also verified, for both ages, that the reduction of ductility of the specimens with alteration in the mode of rupture from ductile to fragile without a defined plasticization interval. Further, Resin B, which was maintained in a laboratory environment (Figure 13c) did not present major changes in its mechanical properties (reduction of only about 3.1% of tensile strength) up to 4 months of exposure. However, after 8 months, there was a considerable reduction of 23.8% and 19.2% in tensile strength and modulus of elasticity, respectively. This reduction in tensile strength and modulus of elasticity did not alter the behavior of the stress-strain diagram, and the maximum stress level continued to be reached with close deformations. At 7 days of cure, the tensile strength was already close to that obtained in the complete cure indicated by the manufacturer (14 days). For Resin B's exposure to weather (Figure 13d), the stress-strain diagrams did not present major changes at 7 and 14 days, only a small increase in the maximum tension. After 4 months, there were remarkable losses in its mechanical properties, with a reduction in its tensile strength and modulus of elasticity of 63.3% and 9.1%, respectively. At 8 months, the maximum tensile strength decreased sharply (about 69.2%), while the modulus of elasticity showed a reduction of 18.2%. Observed, also, the reduction of ductility for both ages of exposure with alteration in the mode of rupture, which occurs abruptly and without any stretch of plasticization. Unlike Resin A, Resin B yielded a considerable loss in its mechanical properties after 8 months of exposure to the laboratory environment. Another divergence found in the epoxy resins is related to their mechanical properties at 14 days of curing. It was noted that both the tensile strength and modulus of elasticity of Resin B were higher (about 16%) than those of Resin A despite the equivalent curing time.
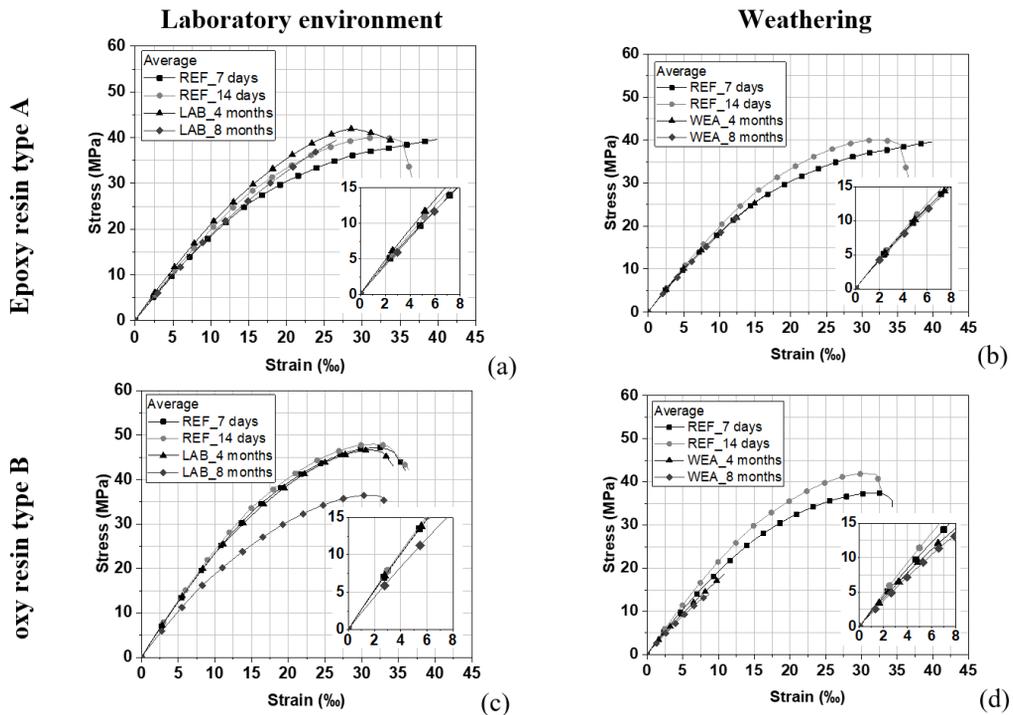
Figure 13. Stress versus strain relationship of primer (a-b) and saturation (c-d) resins maintained in a laboratory environment or exposed to weathering

In a study carried out by Fernandes et al. [25], epoxy resins were also kept in a laboratory environment for a period of 2 years. The results, as in the present study, also showed small reductions in their mechanical properties, specifically 5.5% and 6.9% in tensile strength and modulus of elasticity, respectively. The findings for the epoxy saturation resins (Resin B) exposed to weather were also verified in a research conducted by Escobal [26]. The author evaluated the degradation of epoxy saturation resins exposed to weather (external environment with monitored temperature and humidity) for a total period of 4 months. The results showed losses of 44% in tensile strength after 4 months of exposure. Escobal [26] also evaluated the same epoxy resins exposed to accelerated aging cycles, contained by UV radiation, temperature of 60ºC, and water vapor at 50ºC. The results showed a considerable reduction in the tensile strength of the resins (about 60%), as verified in the present work for resins A and B exposed to the weather. The results found by Zhao et al. [15] were also similar to those in this study. The authors evaluated epoxy resin specimens exposed to UV radiation cycles (simulating exposure in an external environment) for a period of 90 days. At the end of the trials, the authors verified a maximum reduction of 20.4% in the modulus of elasticity of the specimens.

4.2.4 CFRP composites

For CFRP composites (Figures 14a, 14b), the specimens presented a linear elastic behavior until their rupture, typical of fragile materials. Regarding their exposure to the laboratory environment (Figure 14a), a more significant variation was seen in the behavior of the specimens after the ages of 4 and 8 months. Further, a greater reduction in the tensile strength of the specimens occurred after 4 months of exposure (reduction of about 15% of tensile strength). During this same period, there was a small reduction of 1.73% in the modulus of elasticity. After 8 months of exposure, the CFRP composite specimens gained resistance and showed a lower loss in tensile strength, at about 11%, while the modulus of elasticity reduced by only 3.3%. The last deformation also showed reductions of 14% and 7% over 4 and 8 months' exposure to the laboratory environment, respectively. It was verified that a greater loss occurred in the test performed at 4 months.

For weather exposure (Figure 14b), and taking as reference the tests performed at 14 days, a reduction in tensile strength, modulus of elasticity, and last deformation of 18%, 4.9%, and 13.3%, respectively, after 4 months of exposure was verified. At the age of 8 months, the specimens of the CFRP composite presented reductions of 1.4%, 1.3%, and 0.7% in tensile strength, modulus of elasticity, and last deformation, respectively. Once again, there was a significant

variation in the behavior of the samples for the analyzed ages. Although the properties of CFRP composites present reductions over exposure time, these oscillations do not mean that the material has degraded. Therefore, it is important to verify the coefficient of variation in the properties of the samples, which, as mentioned before, present considerable variation.

Cromwell et al. [27] also found that the exposure of CFRP laminates to aggressive environments, such as constant humidity and saline solution, does not cause major changes in their tensile strength and modulus of elasticity or ultimate deformation.

In another research by Dalfré [28], there was no significant change in tensile strength and modulus of elasticity of CFRP composite specimens exposed to cycles of constant humidity and humidity for a total period of 2 years.
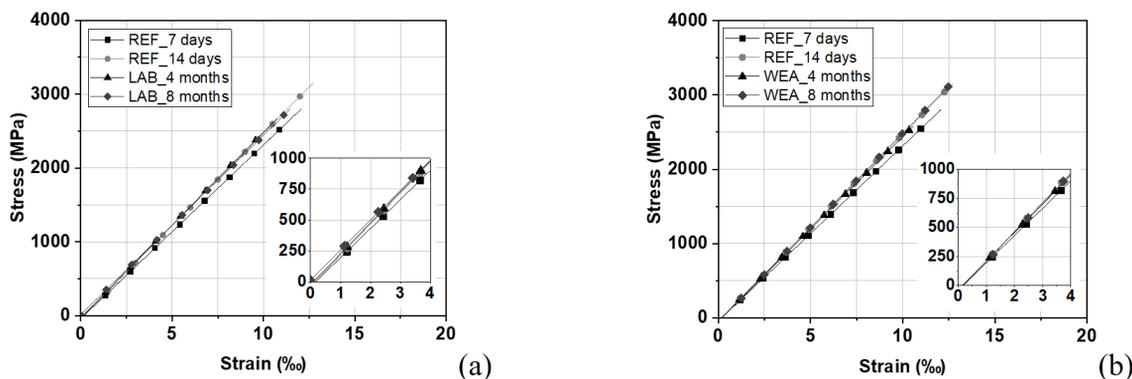
Figure 14. Stress versus strain relationship of CFRP composites maintained in laboratory environment (a) or exposed to weathering (b)

4.2 Concrete beams behavior

The behavior of the reinforced concrete beams (with and without strengthening) exposed to the laboratory environment and weathering was analyzed based on ductility, increased load capacity, deformation of materials (concrete, steel, and CFRP), and rupture mode of the strengthening system.

The stop criterion adopted for the reference beams tests without strengthening was established in terms of the deformation of the bending strengthening (at the time the deformation in the steel reached the average value of 11‰), while that adopted in the reinforced beams of reference and exposed in laboratory environment and weather was established in terms of the failure of the strengthening system, followed by a sudden loss of load and detachment of the material.

Table 4 presents a summary of the average results obtained in the tests of the beam sets for the yielding of the steel reinforcement (ε_{sy}), for the concrete crushing ($\varepsilon_{c,esm}$), and the instant that the beams reach maximum loading (F_{max}). The indicator of effectiveness of the bending strengthening system in terms of increased load capacity (IR) is also presented, which was obtained by analyzing the average load ($F = (F_{V1} + F_{V2})/2$) recorded for the beams without strengthening and strengthened (reference and exposed to the environments), respectively.

Table 4 Resume of the average experimental results

Group of beams	Yielding of the steel reinforcement (ε_{sy})					Concrete crushing ($\varepsilon_{c,esm}$)					Maximum force recorded					
	F_{sy} kN	u_{sy} mm	ε_c ‰	$\varepsilon_{f,max}$ ‰	IR %	$F_{c,esm}$ kN	u_{esm} mm	ε_{sy} ‰	$\varepsilon_{f,max}$ ‰	IR %	F_{max} kN	$u_{F max}$ mm	ε_c ‰	ε_s ‰	$\varepsilon_{f,max}$ ‰	IR %
REF_0	21.8	10.3	1.8	----	----	25.4	15.6	5.2	----	----	27.0	25.2	6.1	11.4	----	---
REF_CFRP	26.1	9.3	1.8	2.9	19.7	31.5	13.3	5.5	----	24.0	40.6	32.7	9.8	13.5	9.9	50.0
LAB_CFRP	22.8	8.6	1.2	3.1	4.6	25.4	16.0	8.3	----	0.0	38.0	39.9	3.2	17.4	----	40.7
WEA_CFRP	23.9	9.0	*	2.9	9.6	----	----	----	----	----	36.5	32.5	----	11.6	----	35.1

*Mechanically damaged strain gauge

In order to evaluate the effectiveness of the strengthening system with CFRP sheets applied according to the EBR technique, Figure 15 presents a comparison between the Load and vertical displacement of the reference beams without strengthening (V1_REF_0 and V2_REF_0) and strengthened (V1_REF_CFRP and V2_REF_CFRP). Upon analysis of Table 4 and Figure 15, it is possible to verify the effectiveness of the CFRP EBR strengthening system for the reinforced beams without strengthening and the increase in the load capacity of the strengthened beams.
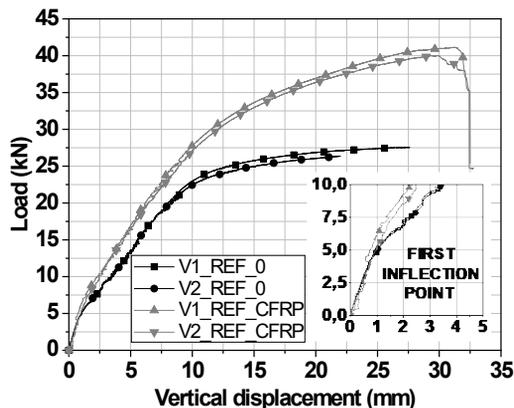
Figure 15. Load versus displacement of reference beams without strengthening and strengthened

In relation to the beginning of the steel yield, it was verified that the strengthening provided an increase in the load capacity corresponding to the beginning of the longitudinal steel yielding and the maximum force of 19.7% and 50%, respectively. In addition, a reduction in the average vertical displacement of 9.7% for the strengthened reference beams, compared to the reference beams without strengthening due to the reduction of cracking that the strengthening system promotes, restricting the reduction of element inertia was observed.

As failure modes, the reference beams without strengthening, V1_REF_0 and V2_REF_0, designed in Domain 2, presented a ductile rupture characterized by the yielding of the longitudinal tensile reinforcement and later crushing of the compressed concrete. All the strengthened beams (V1_y_CFRP and V2_y_CFRP), after great deformation and high curvature of the elements, showed appearances of cracks parallel to the strengthening material in the moments before the failure of the element. Therefore, it appears that the use of the CFRP EBR strengthening system alters the failure mode of the strengthened elements. The failure, which was previously ductile and ruled by the deformation of the longitudinal strengthening, became almost fragile with the detachment of the CFRP sheet adhered to the concrete substrate. Figure 16 presents a comparison between Load and vertical displacement relationship of the reference beams without strengthening (V1_REF_0 and V2_REF_0) and strengthened (V1_REF_CFRP and V2_REF_CFRP), with those exposed in laboratory environment (V1_LAB_CFRP and V2_LAB_CFRP) and to weathering (V1_WEA_CFRP and V2_WEA_CFRP), respectively.

(a)   (b)
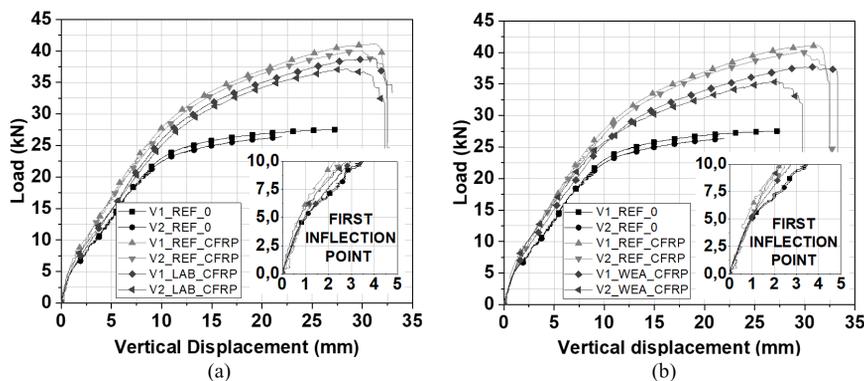
Figure 16. Relationship between Load versus vertical displacement of reference beams exposed to the environments: (a) laboratory and (b) weathering

For the yielding of the steel reinforcement of the strengthened beams maintained in laboratory environment or exposed to weathering, an average increase in load capacity of 4.6 and 9.6%, respectively, was observed in relation to the yielding of the steel in the beams without strengthening. For the maximum strength, an average increase in load capacity of 40.7 and 35.1% in the reference beams without strengthening (REF_0), respectively, was observed. Analyzing the yielding of the steel reinforcement of the exposed beams and considering the results obtained in the tests of the strengthened reference beams (REF_CFRP), it was noted that the elements maintained in laboratory environment and exposed to weathering presented a reduction of the average load of 12.6 and 8.4%, respectively. It was also observed that the maximum force recorded in the strengthened beams exposed to weathering suffered a reduction of 6.4 and 10.0%, respectively, when exposed to the environments previously presented. Finally, taking into account the maximum force recorded in the tests with the strengthened beams (Table 4), exposure to weather was more aggressive for the strengthening system, since its ultimate load was lower than that of the elements maintained in laboratory environment.

Concerning the failure load of the strengthened elements exposed to the environments, it was verified that there were no changes comparing it to the strengthened reference beams, presenting an almost fragile failure, preceded by pops and a lower load than verified for the strengthened reference beams, with the detachment of the CFRP sheet adhering to the concrete substrate (Figure 17).

Figure 17. Verified failure mode on the strengthened beams

5 CONCLUSIONS

This work reports findings from an experimental program conducted to evaluate the efficiency of the EBR technique in increasing the load capacity of reinforced concrete beams strengthened in flexure with CFRP composites and also to evaluate the behavior of EBR-CFRP strengthening systems when exposed to weathering. Two exposure environments were adopted in this study (laboratory and weathering). Beams maintained in laboratory condition for 200 days, with and without strengthening, were considered as reference (REF), while the remaining beams were exposed to degradation environments and tested at the age of 380 days. The results obtained allowed for the following conclusions to be obtained:

- The efficiency of the EBR technique in increasing the load capacity of bending reinforced concrete beams with CFRP sheets was verified by means of significant increases in the load capacity of the strengthened elements. In relation to the steel reinforcement yielding, it was verified that the strengthening provided an increase in the load capacity corresponding to the beginning of the longitudinal strengthening yield and the maximum force of 19.7% and 50%, respectively. In addition, there was a reduction in the average vertical displacement of 9.7% for strengthened reference beams, compared to those without strengthening, respectively, due to the reduction of cracking that the strengthening system promotes, restricting the reduction of the element's inertia;
- Analyzing the beginning of the steel yielding of the exposed beams and taking into account the results obtained in the tests of the strengthened reference beams (REF_CFRP) showed that the elements exposed to the laboratory environment and those exposed to weathering presented a reduction in the average load at steel yielding of 12.6 and 8.4%, respectively. It is also possible to observe that the maximum force recorded in the strengthened beams exposed to these environments suffered a reduction of 6.4 and 10.0%, respectively.
- Moreover, it was noted that the evolution of the curing time from 7 to 14 days of the primer and saturation epoxy resins maintained in laboratory environment resulted in statistically equivalent values, i.e., the curing time affected neither the mechanical properties of the specimens nor the behavior of the stress-deformation diagram.

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- Also, in relation to the epoxy resins maintained in laboratory environment, it was observed that the saturation resin presented losses of 23.8% and 19.2%, respectively, in tensile strength and modulus of elasticity after 8 months of exposure in addition to an alteration in the failure mode, while the primer resin's properties remained statistically unchanged.
- The analysis of primer epoxy resin exposed to weathering was observed for the tests performed after 4 and 8 months of exposure reductions of 39 and 50% of tensile strength, respectively, in addition to the change in the failure mode of the specimens, while the modulus of elasticity resulted in statistically equivalent values.
- From the analysis of the saturation epoxy resin exposed for 4 and 8 months to the weathering, it was found that the tensile strength reduced by about 64 and 70%, respectively, from the reference condition with 14 days of cure, and the failure mode changed from ductile to fragile without a plasticization interval. Regarding the modulus of elasticity, it was observed that the values were statistically similar up to 4 months of exposure, but after 8 months, a reduction of 18.2% in the modulus of elasticity was verified, as compared to the reference condition.
- The CFRP composites exposed to the laboratory environment and weathering showed no increase in their mechanical properties over the temporal evolution of the curing time from 7 to 14 days, and the results of the tests were statistically equivalent.

ACKNOWLEDGEMENTS

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