Construction and Building Materials 377 (2023) 131047

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Durability of bond of EBR CFRP laminates to concrete under real-time field exposure and laboratory accelerated ageing

Ricardo Cruz [a], Luís Correia [a], Susana Cabral-Fonseca [b], José Sena-Cruz [a,*]

[a] University of Minho, ISISE/IB-S, ARISE, Department of Civil Engineering, Guimarães, Portugal
[b] National Laboratory of Civil Engineering, Materials Department, Lisbon, Portugal

ARTICLE INFO

Keywords:
Durability
Bond
EBR
Real-time field exposure
Laboratory accelerated ageing
CFRP laminate
Epoxy adhesive
Concrete

ABSTRACT

The durability of bond between carbon fibre-reinforced polymer (CFRP) laminates and concrete with the externally bonded reinforcement (EBR) technique was investigated under real-time field exposure (RTFE) and accelerated ageing. The experimental program, over two years, includes four outdoor environments inducing carbonation, freeze–thaw attack, extreme temperatures, and airborne chlorides from the ocean. A laboratory environment (20 °C/55% RH) was used as reference environment. Additionally, a water-immersion environment (20 °C) was also considered. Relatively low values of bond degradation were observed, where the maximum pullout force varied between −4 % and +16 % under RTFE, while on water–immersed specimens, the maximum pullout force decreased by ~8 %.

1. Introduction

The application of the externally bonded reinforcement (EBR) technique using carbon fibre–reinforced polymer (CFRP) materials for strengthening reinforced concrete (RC) structures has become a widespread practice, especially over the last two decades. With the EBR technique, CFRP laminates or sheets are externally bonded to the tensile surface of the RC element, as a solution for flexural and/or shear strengthening. EBR with CFRP sheets has also been used for confining RC columns and joints. Epoxy adhesives are usually used as the bonding agent. Given the relevance of these strengthening techniques, several codes, e.g. ACI 440.2R-17 [1], CAN/CSA-S6-06 [2] include provisions for their design, while future ones, e.g. prEN 1992–1-1 [51] plan to include them.

The durability aspects of RC structures strengthened with CFRP systems have been investigated mainly at laboratory employing accelerated conditioning protocols (ACPs), whereas the investigations under real-time field exposure in outdoor environments are very scarce. Therefore, it represents an important lack of knowledge. Furthermore, the relationship between the effects of laboratory accelerated ageing and real-time field exposure is another critical issue in the literature and needs to be better understood, e. g., [4,5]. From the existing research, some studies only address the durability under real-time field exposure and others, include both types of exposure and attempt to correlate the effects of laboratory accelerated ageing versus real-time field exposure. Ambiguous results concerning the relationship between field exposure and laboratory ageing on FRP composites have been reported [6]. Some researchers have reported higher degradation in laboratory accelerated ageing than in field exposure, e.g., [5,7] while others have observed higher degradation under field exposure, e.g., [8–10].

A clear knowledge on the durability and long-term behaviour of the bond between EBR-CFRP laminates and concrete is essential for the long-term design of this strengthening system, as the bond assures the stress transfer between the strengthening system and the concrete substrate. The lack of consistent knowledge of these systems has been mentioned as a critical obstacle to the extensive use of these systems and materials in civil engineering applications, e.g. [11]. Additionally, up to now, design codes addressing the particular case of the durability of bond of the EBR-FRP in RC structures are not available, and therefore, it represents an additional difficulty for the use of these systems; nevertheless, there are various design guidelines developed in different countries [6]. It should be highlighted that the short-term behaviour of the EBR-CFRP to concrete system has already been widely investigated, e. g., [12–15].

Several investigations addressing the durability of the materials that compose the EBR-CFRP to concrete systems (CFRP laminate, adhesive, and concrete) have been conducted. Moisture, thermal variations, UV radiation exposure, and chemical attacks are the most important

* Corresponding author.
E-mail address: jsena@civil.uminho.pt (J. Sena-Cruz).

https://doi.org/10.1016/j.conbuildmat.2023.131047
Received 7 October 2022; Received in revised form 3 March 2023; Accepted 12 March 2023
Available online 27 March 2023

environmental degradation factors that affect these materials, acting individually or in combination. Nevertheless, the EBR-CFRP to concrete bond system is a complex multilayer system composed also by the corresponding interfaces between these three materials. Therefore, the assessment of the durability of the bonded joints became a complex process, as it is not as simple as studying the durability of each of the system components separately [6]. The bonded joint is generally the most critical aspect that affects the system's efficiency [16]. According to Tatar and Milev [6], exposure to moisture has been reported, in general, as the most detrimental degradation factor for adhesion properties. The following works provide relevant studies on the durability of EBR-CFRP to concrete system.

Kabir et al. [17] developed an investigation on the time-dependent behaviour of bond between EBR-CFRP strips (made by wet lay-up with two plies of CFRP sheet) and concrete under three environments: (i) temperature cycles (5 h at a constant temperature of 40 °C followed by 7 h at gradual decrease to 30 °C); (ii) wet-dry cycles (one week at around 95% RH and 30–32 °C followed by one week at normal lab condition at 20–23 °C) and (iii) outdoor environment of Sydney, Australia, for up to 18 months. The authors used a single-lap shear test to evaluate the bond strength of control (unexposed) and exposed specimens and concluded that the maximum bond strength degradation (15.2%) was observed in the outdoor environment, which was attributed to the degradation of epoxy mechanical properties. Temperature cycles led to a non-significant deterioration, probably due to the lower range of cyclic temperatures applied (30–40 °C), which were set below the glass transition temperature (T_g) of epoxy resin ($T_g = 47$ °C). Wet-dry cycles led to a minimal deterioration of the bond strength of EBR-CFRP to concrete (maximum reduction of ~5% after one year of exposure). The failure modes changed in the cases of wet-dry cycles (from thick concrete to a very thin concrete layer attached to the FRP) and outdoor exposure (from a thick layer of concrete to almost no concrete attached to debonded FRP), but not with thermal cycles (a thick layer of concrete attached to the epoxy adhesive of the debonded FRP). The effective bond length increased due to exposure to all environments.

Hassan et al. [18] studied the bond behaviour of EBR-CFRP laminates to concrete systems under various environmental conditions based on the natural tropical climate of Malaysia (an extremely hot/wet environment). Double lap concrete-CFRP joints were prepared and then subjected to diverse types of exposure, including: (i) outdoor exposure under Malaysia's natural tropical climate (the temperature and relative humidity varied between 23 and 35 °C and 60–95%, respectively); (ii) wet/dry cycles in plain water (24 cycles); (iii) wet/dry cycles (24 cycles) in salt water and, (iv) laboratory conditions (with relative humidity between 75 and 90% and room temperature of 25–32 °C), up to 6 months. After exposure, the double-lap shear tests were performed to investigate the bonding characteristics in detail. The results showed that the average bond strength degradation was minor (~2.1%) after exposure for 6 months to tropical outdoor conditions and even increased with wet/dry cycles in plain water and wet/dry cycles in salt water (average increase of ~6.7%).

Mohd Hashim et al. [19] investigated the effect of exposure to natural tropical climate on the interfacial bonding performance of EBR-CFRP to concrete system. Concrete prisms with two CFRP laminate strips bonded on opposite sides were exposed for 3, 6, and 9 months under (i) laboratory conditions, (ii) natural tropical climate exposure, (iii) wet-dry cycles (3 days wet followed by 4 days dry – 1 cycle/week) with 3.5% saltwater solution at room temperature and at 40 °C and, (iv) dual exposure composed by wet-dry cycles (room temperature and 40 °C) with 3.5% saltwater solution followed by tropical climate exposure (3 days wet/4 days dry at laboratory followed by 7 days of tropical climate exposure – each cycle lasted 2 weeks). The results demonstrated that the combination of climate effects can improve the curing of the bonded joints and therefore leading to a better performance. Therefore, the bonding system was only slightly affected by the exposure to tropical climate/salt solution. No specific trend of bond strength evolution along the testing times (3, 6 and 9 months) was observed.

From the works previously described, it can be concluded that is not clear the comparison between the levels of aggressivity caused by laboratory versus real-time field exposure. It should be noted that with the laboratory-based accelerated ageing protocols it is impossible to reproduce all the environmental degradation factors that act under real-time field exposure (natural). Additionally, the real-time field exposure requires longer test periods to extract valuable results of degradation in the system. Many authors have tried to establish comparisons between the effects caused by both types of ageing, e. g., [10,17–19]. Nevertheless, in several cases, the matrix of environmental degradation factors and times of exposure established by the authors are not adequate to directly compare the effects of both ageing types (natural and artificial accelerated in laboratory). Despite such difficulties, it is of paramount relevance to develop real-time field exposure tests, as only this type of tests can provide effective knowledge on the real degradation mechanisms [10].

Existing guidelines accounts for the deleterious effects of environmental exposure. While codes, e.g. ACI 440.2R-17 [1] and CNR-DT 200 R1/2013 [20] consider explicitly these durability effects through environmental conversion factors (also known as reduction factors), other codes only refer the need of considering durability effects, e.g. CAN/CSA-S6-06 [2], AASHTO FRPS-1 [21], ISIS Design Manual 4 [22], JSCE CES41 [23] and TR55 [24].

Considering the aforementioned statements, various gaps in the knowledge of the durability of the EBR-CFRP to concrete systems need to be investigated, namely: (i) the performance of these systems under different real-time field exposure environments and ageing periods; and (ii) the relationship between the effects of real-time field exposure and laboratory accelerated ageing. Thus, this investigation aims at studying the durability of a EBR bonding system by means of an experimental work that includes exposure to four outdoor environments for real-time field exposure (natural ageing mainly by carbonation, freeze–thaw attack, extreme temperatures, and airborne chlorides from the ocean) for up to two years. A reference (control) environment (20 °C/55% RH) and a water immersion environment under controlled temperature (20 °C) were also considered. The specimens were tested at three time points of ageing: after production (T0), and after one (T1) and two (T2) years of exposure. A database composed of results of laboratory accelerated conditioning tests collected from the literature was created and compared with the results of real-time field exposure from this work. Finally, new insights in predicting the service life of the EBR-CFRP to concrete systems and suggestions for improving the existing guidelines, such as ACI 440.2R-17 [1] and CNR-DT 200 R1/2013 [20] were also developed.

2. Experimental program, constitutive materials, and methods

2.1. Experimental program

This work presents the durability assessment of the bond between EBR–CFRP laminates and concrete and is linked with the investigation of Cruz et al. [25], where the durability of epoxy adhesives and CFRP laminates were studied. Both works were performed in the scope of the FRPLongDur project, which further details are presented in Cruz et al. [25]. For the easier comparison between the results of the involved materials on the EBR–CFRP to concrete system and the durability of the system itself, this work also includes a selection of relevant results (epoxy adhesive and CFRP laminate) of Cruz et al. [25].

The specimens were exposed to a total of six environments, including two laboratory environments and four outdoor environments. Fig. 1 presents the relevant characteristics of these six environments and their geographical locations. The laboratory environments included a (i) reference/control (E1 environment) with controlled hygrothermal conditions (20 °C/55% RH) and (ii) immersion in fresh water (E2 environment) with controlled temperature (20 °C). The environment E2 was

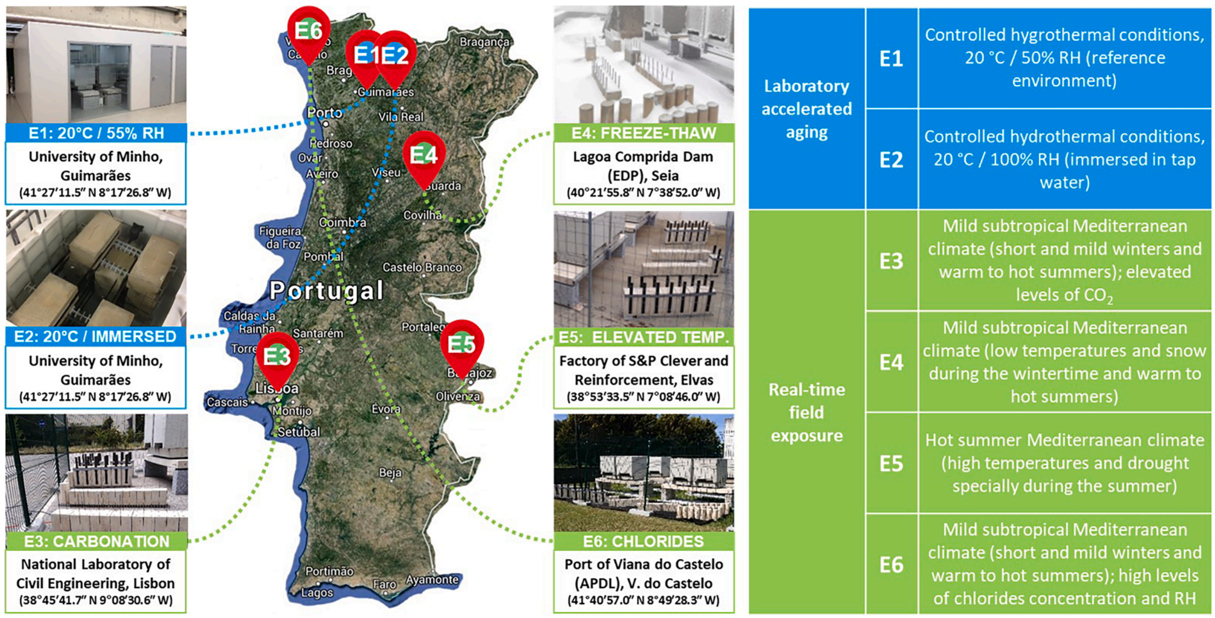


Fig. 1. Environments considered in this investigation. (Base map © Google, Map data ©2022 Inst. Geogr. Nacional; Images by authors).

implemented as an extreme conditioning of moisture (in general design guidelines do not allow continuous water immersion of FRP systems without appropriate protection) and also to allow comparisons with the other environments adopted in this investigation. The four real-time field exposure (outdoor/natural) environments were considered giving the specific characteristics that can be found in Portugal to achieve specific conditioning effects, namely: (iii) high levels of concrete carbonation (E3 environment), due to the elevated levels of concentration of anthropogenic CO_2 in this location, which is near to a highway with high traffic load and is also close to the International Airport of Lisbon; (iv) freeze–thaw attack (E4 environment), since specimens were installed in the highest mountain of Portugal ('Serra da Estrela'), where typically low temperatures and snow are observed during the wintertime; (v) extreme service temperatures and lower values of relative humidity (E5 environment), characteristics of the climate of Elvas; and, (vi) high levels of airborne chlorides from sea water in the air and high relative humidity (E6 environment), since the test specimens were placed nearby to the Atlantic Ocean, in the coast of Viana do Castelo.

The air temperature and relative humidity were continuously monitored at each location (technical details of these sensors can be found in Cruz et al. [25]). Fig. 2 shows the diary average temperatures and relative humidity recorded between 2018 and 2020 in each experimental station.

A timeline with the main steps developed in this work is presented in Fig. 3. Specimens were produced and then stored in the laboratory premises (~15 months) with an average temperature of 20.5 °C (min. 10.0 °C; max. 30.5 °C), and 54.9% RH (min. 20.0% RH; max. 86.0% RH) before exposure to the abovementioned environments. During this period, an experimental campaign (T0) was performed to evaluate the initial mechanical properties. The determination of the tensile properties of the CFRP laminates was performed when they arrived from the producer company (March 2017), whereas the mechanical characterization of the epoxy adhesive was performed 7 days after the production of specimens (the curing age typically used for epoxy adhesives). The elastic modulus and compressive strength of concrete were evaluated 28 days after casting (December 2016), whereas its tensile strength was only assessed at ~2 years of age (October 2018), due to technical issues. The bond characterization of EBR-CFRP to concrete specimens was performed 8 months after the strengthening application (October 2017). The ageing of the bond specimens and material samples started between June and December of 2018. It should be highlighted that in real-time field exposure (E3 to E6 environments), all bond specimens used the same orientation: one CFRP laminate positioned to the sunrise direction and the other to the sunset direction to get the maximum solar exposure.

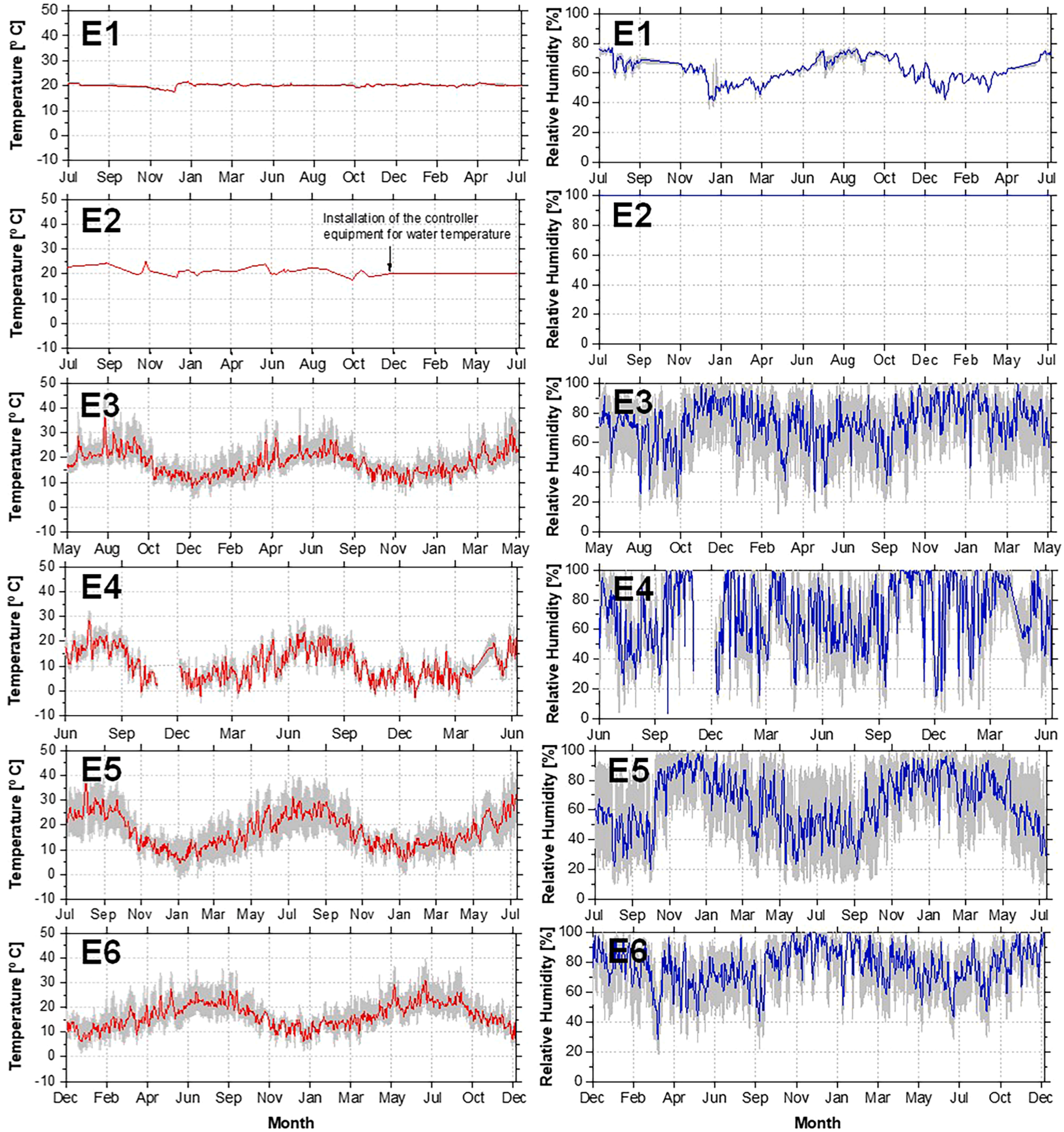
A set of materials samples and bond specimens were taken every year from each experimental station to be characterized at the laboratory after one (T1) and two (T2) years of exposure. Each set was composed of CFRP laminate strips, epoxy adhesive specimens, concrete cylinders, and EBR-CFRP to concrete bond specimens. After collecting these specimens, a desorption period of three weeks prior to the tests was adopted. This desorption phase was adopted to avoid the effect of punctual and instantaneous high level of humidity (e.g., rain) that the specimens may faced at the time of their collecting. The desorption was achieved by placing the collected specimens inside a climatic chamber, with the E1 hygrothermal conditions. E1 specimens were kept under the same laboratory conditions during this period, while E2 specimens were kept fully immersed in water until testing (without a desorption period before testing), in order to evaluate the actual mechanical properties (saturated conditions). This protocol was adopted in both T1 and T2 times.

2.2. Materials

This section presents a detailed characterization of the materials used in this work, namely the CFRP laminate, epoxy adhesive, and concrete.

2.2.1. CFRP laminate

A CFRP laminate prefabricated by pultrusion and composed by unidirectional carbon fibres (fibre content higher than 68%) and by a vinyl ester resin matrix was adopted in this work. This CFRP laminate has a black and smooth external surface. The rectangular cross-section geometry is 50 mm wide by 1.2 mm thick. It should be mentioned that this type of cross–section geometry is commonly used in EBR-CFRP strengthening applications. According to the technical datasheet provided by the supplier [26], this CFRP has a characteristic elastic modulus greater than 170 GPa and a characteristic tensile strength higher than 2000 MPa.



Notes: For each environment is presented the daily mean values (line) and the envelope extreme minimum and maximum values (grey line); E2: A controller equipment for the temperature of the water was installed on the experimental station in December 2019, setting the temperature at 20 ºC; E4 and E5: values provided by IPMA (IPMA's station is located 9 km apart from E4 and 560 m apart from E5).

Fig. 2. Air temperature and relative humidity recorded in the environments.

2.2.2. *Adhesive*

A commercial cold-curing epoxy adhesive was adopted as the bonding agent to fix the CFRP laminate to concrete. Based on the previous work [25], this epoxy adhesive presents a tensile strength of ~20 MPa, an elastic modulus of ~6.5 GPa (both mean tensile properties after 7 days of curing at 20 °C) and a T_g of 46.2 °C (after 7 days of curing at 23 °C). Furthermore, according to the datasheet provided by the supplier [27], the adhesive's flexural elastic modulus is higher than 7.1 GPa. Further details regarding the characteristics of this epoxy adhesive can also be found in Cruz et al. [25].

2.2.3. *Concrete*

A single batch of concrete was used to cast all the specimens: (i) cylinders for compression tests and, (ii) prisms for bond EBR-CFRP to concrete specimens. The later specimens were also used to assess the concrete's tensile properties and its carbonation depth. For that purpose, a ready-mix concrete was ordered with the following characteristics: standard cylinder compressive characteristic strength of 30 MPa (37 MPa in standard cube), exposure class XC4(P) (cyclic wet and dry), water/cement ratio (CL) of 0.40, maximum aggregate size of 12.5 mm, slump class S4 (Eurocode 2 [3]/EN 206–1 [28]).

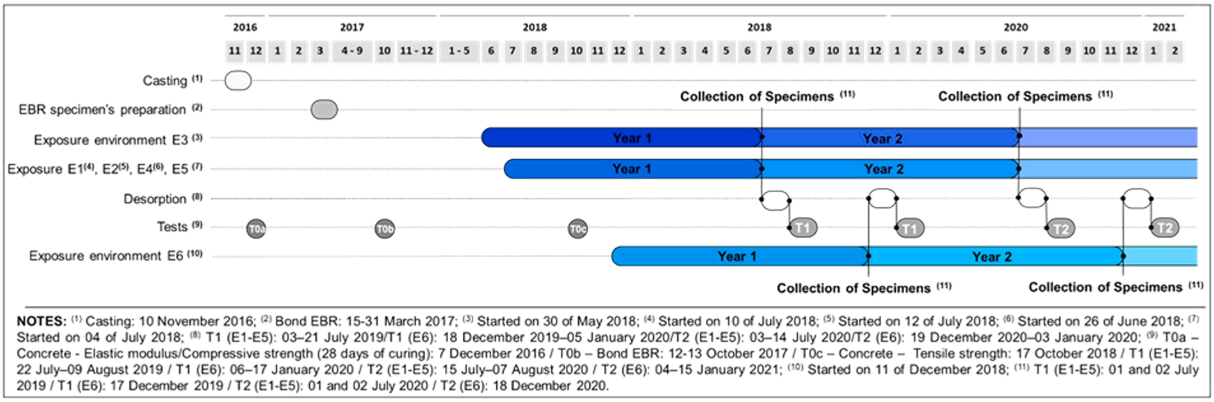


Fig. 3. Timeframe of the work carried out.

2.3. Test methods

Different methods were adopted depending on the material or property to be evaluated on both unaged (reference/control) and aged specimens.

2.3.1. CFRP laminate and adhesive

The elastic modulus (E_a and E_f) and tensile strength (f_a and f_f) of the epoxy adhesive and CFRP laminate were assessed following the ISO 527–2:2012 [29] and ISO 527–5:2009 [30], respectively. Per stage (T0, T1 and T2) and environment (E1-E6), at least five epoxy specimens and six CFRP laminates were tested. Additional information regarding other physical and mechanical properties assessed are detailed in Cruz et al. [25].

2.3.2. Concrete

The elastic modulus (E_{cm}) and compressive strength (f_{cm}) of concrete were assessed using cylinders of 150/300 mm (diameter/height), according to NP EN 12390–13:2013 [31] and NP EN 12390–3:2011 [32] standards, respectively. The initial characterization (T0 tests) was conducted 28 days after casting, using 4 specimens (see Fig. 3). After one and two (T1/T2) years of conditioning, 3 specimens per environment were tested.

The tensile strength of the concrete (f_{ctm}) was determined by means of pull-off tests conducted on the bottom face (perpendicular to the cast direction) of concrete prisms according to EN 1542:1999 [33] standard. For each environment (E1-E6) and time of testing (T0, T1 and T2), four tests (two per concrete prism) were performed. The tests were conducted using a machine Matest E142, with a capacity of 16 kN (maximum pull-off force), accuracy of 1% and resolution of 10 N. These tests were carried out with a loading rate of 1 MPa/s and using a dolly of 50 mm diameter.

The carbonation depth of concrete was determined according to LNEC E391:1993 [34] standard. The method is based on the pH reduction that occurs on the carbonated concrete caused by the CO_2 of the atmosphere. A solution of phenolphthalein indicator was used to measure the carbonation depth. This solution becomes pink in contact with basic (alkaline) concrete (pH higher than 9) while continues transparent at lower levels of pH. This characterization was conducted after one and two (T1 and T2) years of conditioning but not on the initial characterization (T0). Two samples of concrete of 50/100 mm (diameter/height) were extracted from the concrete prisms per environment and testing time.

2.3.3. EBR-CFRP to concrete bond tests

Fig. 4 presents the geometry of bond EBR-CFRP to concrete specimens and the corresponding single–lap shear test configuration. Concrete prisms of 400 mm × 200 mm × 200 mm were adopted with two CFRP laminates (of 50 mm × 1.2 mm cross-section) bonded in each opposite face of the concrete prism and parallel to the casting direction, according to the EBR technique (2 laminates/prism). Prior to the CFRP application, the concrete surface was prepared using the sandblast method. A bond length of 220 mm was adopted, remaining 100 mm free (unbonded) from the extremity of the concrete prism to avoid premature

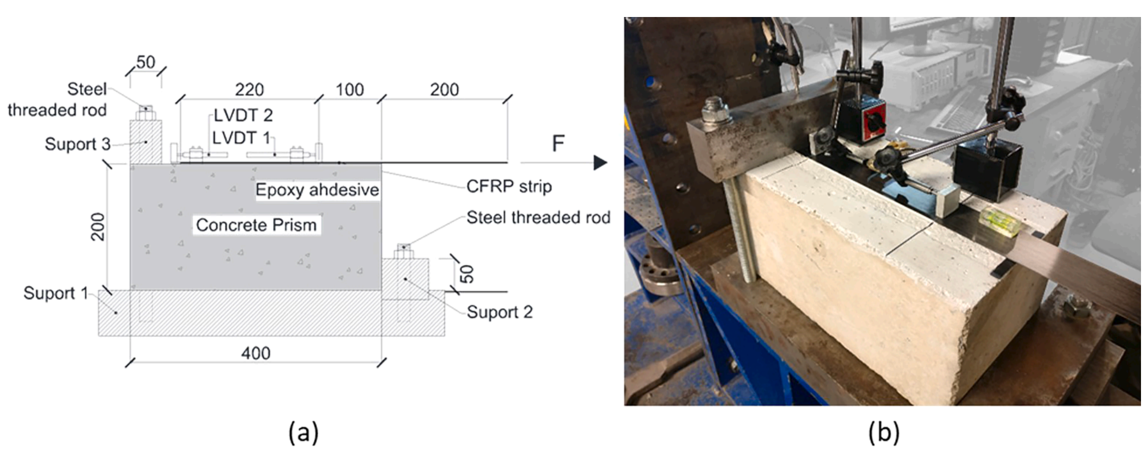


Fig. 4. Pull-out shear test of bond EBR-CFRP to concrete: (a) specimen's geometry and test configuration and (b) photograph of the test. Note: All units in [mm].

failure by concrete rip off at the loaded end. The adopted bond length (220 mm) is higher than the theoretical effective length (l_e) which is equal to 101 mm according to the CNR-DT 200 R1/2013 [20]. The tests were conducted with the specimens installed horizontally on a steel plate with 70 mm × 300 mm × 550 mm (Support 1), fixed to a stiff testing steel closed frame system. Other steel plate (Support 2) was designed to ensure negligible horizontal displacements in the loading direction. A prismatic steel bar (Support 3) was placed in the rear top part of the specimen to minimize vertical displacements. The tests were performed using a servo-controlled equipment. The applied force (F) was measured through a load cell with a maximum load-carrying capacity of 200 kN (linearity error of 0.05% F.S.), installed between the actuator and the grip used to pull the CFRP strip. The relative displacement between the CFRP and the concrete (slip) at the loaded end section (s_l) and free end section (s_f) was measured using two linear variable displacement transducers (LVDTs), LVDT1 and LVDT2 respectively, with a stroke of ± 10 mm (linearity error of 0.24% F.S.). The tests were performed under displacement control at the loaded end through LVDT1 with a rate of 0.12 mm/min. For each environment (E1-E6) and testing time (T0, T1, and T2), 4 tests were performed (see Fig. 3).

3. Results and discussion

3.1. Materials

The results obtained from the evaluation of the mechanical properties of the materials over the time are presented and discussed in this section. In this publication, the values of the material's mechanical properties are presented graphically. The detailed presentation of the nominal values is available elsewhere [25].

3.1.1. CFRP laminate

Fig. 5 shows the average values of elastic modulus (E_f) and tensile strength (f_f) obtained for the CFRP laminates at times T0, T1 and T2.

In the initial characterization (T0) of the CFRP laminate, an elastic modulus (E_f) of 190 GPa (CoV = 9.3%) and a tensile strength (f_f) of 2527 MPa (CoV = 10.8%) were obtained. These values fit with the characterization published by the CFRP producer [26]. Regardless of the type of exposure and duration, small variations in the tensile mechanical properties of the CFRP laminate were observed, particularly on the elastic modulus with a tendency of decreasing with the time. Between T0 and T1, in all environments, a decrease in the elastic modulus was observed, which was statistically significant according to the ANOVA test. The maximum p-value of the 6 series (T0 against each one of the 6 environments of T1) was 0.004 (p-value < 0.05 means that the mean results differ significantly between series). This decrease continued for the second year of exposure (between T1 and T2) for specimens exposed to laboratory environments, but not for the real-time field specimens, which showed an almost negligible variation. A general increase in tensile strength was observed in the period T0-T1 (significant statistic differences between mean values were verified according to the ANOVA test – maximum p-value = 0.007) whereas in the period T1-T2, a decrease in all the environments was observed, especially in specimens of laboratory environments. The increase observed in the period T0-T1 can be a consequence of the matrix post–curing phenomenon that may have occurred in the CFRP laminate from the sun exposure, since this material presents a dark surface that leads to elevated temperatures inside the material (higher than the air temperature). Therefore, it is probable that the detrimental effects of the environmental degradation factors have been balanced by the post-curing during the first year of exposure. The general decrease in the tensile mechanical properties of the CFRP in the period T1-T2 seems percentual higher in tensile strength than in elastic modulus, as also observed by Fernandes et al. [10]. This finding can be attributed to the environmental degradation factors that acted on the CFRP laminate in T1-T2. On the contrary to T1, during T2, the post-curing phenomenon that could occur is probably not sufficient to overcome the environmental degradation factors. Finally, it should be highlighted that the evolution of the mechanical properties over time is very similar, regardless of the type of exposure.

3.1.2. Adhesive

Fig. 6 shows the average values of the elastic modulus (E_a) and tensile strength (f_a) obtained in the epoxy adhesive at times T0, T1, and T2.

In the initial characterization (T0), an elastic modulus (E_a) of 6.5 GPa and a tensile strength (f_a) of 19.9 MPa were obtained. Excluding E2, between T0 and T1, the tensile properties of the epoxy adhesive have shown small variations (the highest increase was observed in the E5 environment – E_a increased ~15% and f_a increased ~10 %, when compared with T0). These improvements can be explained by the post–curing that may have occurred during the first year due to the temperature exposure to the sun. The tensile properties of the adhesive specimens exposed to E2 drastically decreased (up to 75% in E_a). The difference in E_a and f_a between T0 and T1 for E2 specimens is statistically significant by performing a variance analysis ANOVA test. This finding can be also related with testing specimens in a saturated state (without a desorption phase). From the existing literature, e.g. [16,35], the incorporation of water by the epoxy adhesives can cause swelling

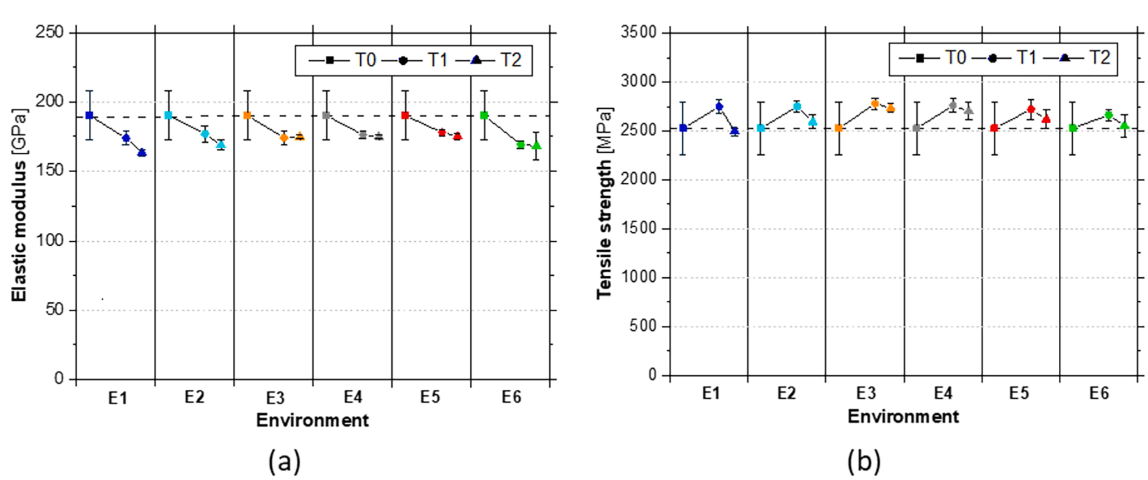


Fig. 5. CFRP laminate tensile properties: (a) elastic modulus and (b) tensile strength at the initial characterization (T0) and after one and two years (T1/T2) of exposure to environments E1-E6. Source: Data from Cruz et al. [25].

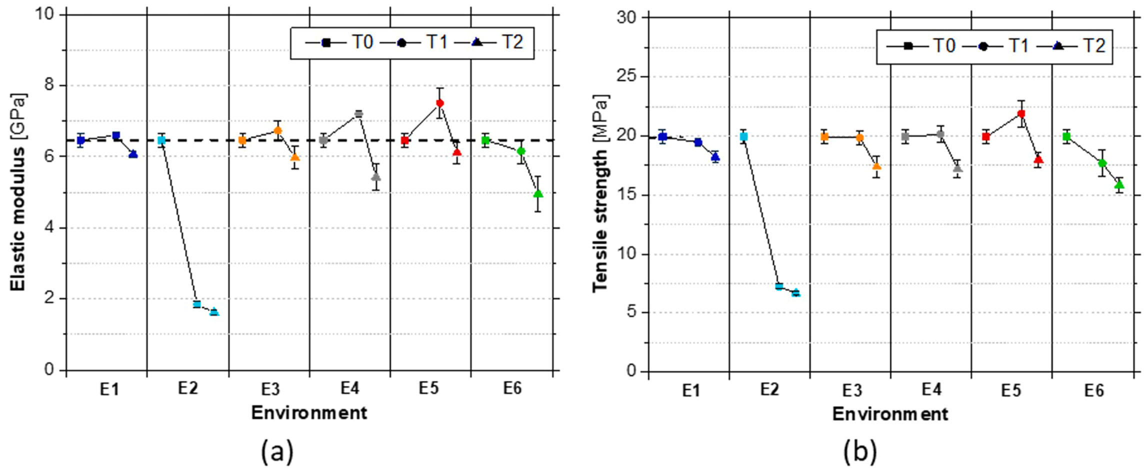


Fig. 6. Adhesive tensile properties: (a) elastic modulus and (b) tensile strength at the initial characterization (T0) and after one and two years (T1/T2) of exposure to environments E1-E6. Source: Data from Cruz et al. [25].

and plasticization, yielding to the reduction of the E_a and F_a. Between T1 and T2, a general reduction in the tensile properties was observed (the maximum f_a reduction was registered in the E5 environment – 17.8% while the maximum E_a reduction was registered in the E4 environment – 25.0%). The high humidity recorded in E4 experimental station (see Fig. 2) is probably the main cause for the reduction observed in the E_a for these specimens. The ANOVA test confirmed that both E_a and f_a differ significantly between T1 and T2 for all the environments.

3.1.3. Concrete

Fig. 7 presents the average results of the elastic modulus (E_{cm}), compressive strength (f_{cm}), tensile strength (f_{ctm}) and carbonation depth

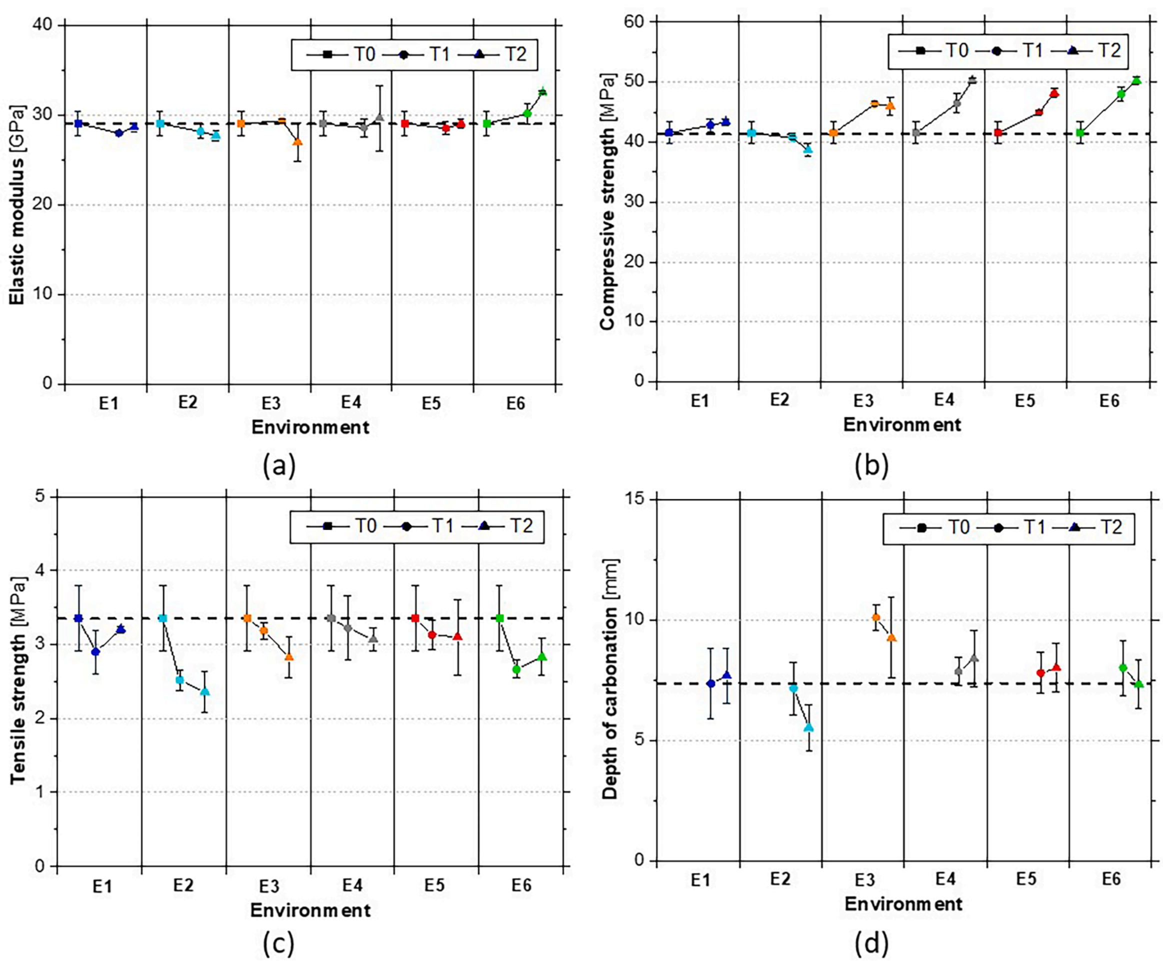


Fig. 7. Concrete's mechanical/physical properties: (a) elastic modulus, (b) compressive strength, (c) tensile strength and (d) carbonation depth obtained at the initial characterization (T0) and after one and two years (T1/T2) of exposure to environments E1-E6.

on the initial characterization (T0) and after one and two years (T1 and T2) of exposure.

In the initial characterization of the mechanical properties of concrete (T0), conducted at 28 days of age, an elastic modulus (E_{cm}) of 29 GPa and a compressive strength (f_{cm}) of 42 MPa were obtained. The impact of the ageing on f_{cm} is higher than on E_{cm}. Small E_{cm} variations were observed in specimens exposed to laboratory environments that, according to an ANOVA test, were statistically insignificant between T0 and T1 and between T1 and T2. However, the real-time field exposure led to E_{cm} variations in between −7.2% (E3 at T2) and +12.0% (E6 at T2) when compared with T0 results. This latter E_{cm} increase can indicate an improvement due to the exposure to a high-humidity conditioning. The real-time field exposure led to an increase in the concrete's compressive strength (comparing with T0). The highest f_{cm} increase was obtained in E4 (+21.2%) and E6 (+21.0%) environments at T2 (comparison with T0). This finding can be explained by the higher relative humidity (see Fig. 2), which is in agreement with other authors, e.g. [36]. The f_{cm} did not increase considerably in E1 environment (maximum increase of ~4% at T2). In the case of the E2 environment, a f_{cm} decrease was recorded, especially at T2 (6.7% in relation to T0), which can be explained by the lower compressive strength of saturated concrete when compared with dry concrete [37,38]. However, it should be highlighted that f_{cm} variations in E1 and E2 specimens are not statistically relevant from the ANOVA test performed.

Contrary to the compressive strength (f_{cm}), a general decrease in the tensile strength (f_{ctm}) was obtained at T1 and T2 conditioning times in comparison with T0. This finding indicated a higher decrease in the superficial mechanical properties when compared with the core's mechanical properties, as shown by Rozsypalová et al. [39]. The highest f_{ctm} reduction was verified in the E2 environment at T2 (-29.5%), however, these specimens were also tested saturated. The presence of water in concrete pores decreases f_{ctm}, as referred by Jin et al. [40]. A considerable f_{ctm} decrease was also verified in the E6 environment at T1 (-20.6%). Similar values were obtained in the remaining environments (E1/E3-E5). It should be highlighted that the variations between T0-T1 and between T1-T2 (except E2) are not statistically relevant based on the ANOVA test performed.

The real-time field exposure caused higher levels of carbonation depth than laboratory accelerated ageing. Concrete exposed to the E3 environment presented the highest carbonation depth (~10 mm), as expected, due to its location (near a highway and the International Airport of Lisbon). An average increase of ~ 30% was registered in the testing times T1 and T2 when compared with the E1 (used as reference). In the remaining series, a carbonation depth of ~ 7.5 mm was obtained, which is in line with similar investigations, e. g., [41,42]. Material exposed to the E2 environment for 2 years (T2) recorded the lowest value, probably due to the reduced contact with CO_2 due to the immersion in water. Smaller increases in carbonation depth compared to the values verified in E1 (a maximum increase of 9.6% in E6 at T1) were obtained in the remaining outdoor environments. In fact, the outdoor environments lead to minor carbonation depth variations between T1 and T2, which can be a result of the reduction in the air concentration of anthropogenic CO_2 due to the confinement imposed by the COVID-19 pandemic during the second year of exposure.

3.2. EBR-CFRP to concrete bond tests

Table 1 presents the main results (average values of four tests) of the single-lap shear tests from the initial characterization (T0) and after one and two years (T1/T2) of exposure to environments E1-E6, namely: K is the initial stiffness of the force versus loaded end slip curve (F_l – s_l) – obtained from the slope of a linear fitting performed on these curves in between 0 and 10 kN; F_{max} is the maximum pull-out shear force reached by the specimen during the whole test; s_{lmax} is the loaded end slip attained at F_{max}; FM represents the failure modes observed. Fig. 8(a) and Fig. 8(b) present the average F_l – s_l per series, for laboratory and real-time field exposure, respectively (average curves). Fig. 8(c) shows a typical force versus loaded end slip relationships (F_l – s_l). These curves presented the following behaviour: first, an ascending branch appears until the debonding load is reached (maximum load supported by the effective length according to CNR–DT 200 R1/2013 CNR [20]); this branch with decreasing stiffness is initially linear up to 30–40% of F_{max}; the debonding that begins to occur beyond this value of 30–40% of F_{max} is responsible by the stiffness degradation, which starts to occur when the shear strength is reached at the loaded end [14]; second, the slip at the loaded end increases until failure, with an almost constant force, as already observed in similar investigations [13,14,43]. In some tests, after the debonding load, a sudden decrease in force and increase in loaded end slip were observed as a result of a sudden detachment of an initial bonded zone, which probably corresponds to the effective bond length (see Fig. 8(c)).

Fig. 8(d) presents the maximum force obtained from the bond tests

Table 1
Main results of the pull-out shear tests on the bond EBR-CFRP to concrete system at the initial characterization (T0) and after one and two years (T1 and T2) of exposure to environments E1–E6.

Env.	Hygrothermal ranges		K [kN/mm]			F_{max} [kN] (CoV [%])			s_{lmax} [mm] (CoV [%])			FM		
	Temp. [°C]	RH [%]	T0	T1	T2	T0	T1	T2	T0	T1	T2	T0	T1	T2
E1	+17.0 to + 22.0	36 to 80	292.8 (14.6)	241.5 (2.7)	282.1 (13.0)	30.2 (13.3)	29.9 (13.8)	27.7 (11.0)	0.5 (28.7)	0.4 (16.6)	0.3 (25.9)	C + F/A [2]; C [2]	C [1]; C + F/A [3]	C [4]
E2	+17.6 to + 25.0	–		275.6 (20.3)	311.7 (38.4)		27.9 (8.4)	31.1 (10.0)		0.2 (12.4)	0.2 (8.7)		C (4)	C [3]; C + F/A [1]
E3	+3.3 to + 46.2	11 to 100		302.7 (9.5)	329.5 (39.5)		31.8 (6.7)	35.1 (9.1)		0.4 (44.7)	0.4 (28.1)		C [3]; C + F/A [1]	C [4]
E4	−4.7 to + 32.4	4 to 100		355.6 (26.0)	305.5 (8.8)		28.9 (8.4)	34.4 (11.1)		0.2 (32.6)	0.3 (6.1)		C [4]	C [4]
E5	−1.9 to + 44.6	10 to 100		240.6 (6.2)	251.9 (6.1)		29.7 (11.5)	30.1 (5.9)		0.4 (29.8)	0.4 (25.0)		C [2]; C + F/A [2]	C [4]
E6	+1.5 to + 39.5	18 to 100		276.0 (15.5)	373.8 (11.1)		30.2 (13.5)	29.2 (6.0)		0.3 (15.3)	0.3 (31.0)		C [4]	C [4]

Failure modes (FM): C = cohesive failure of concrete; C + F/A = cohesive failure of concrete and debonding at laminate-adhesive interface; the value between square brackets is the number of specimens where the failure mode was observed.

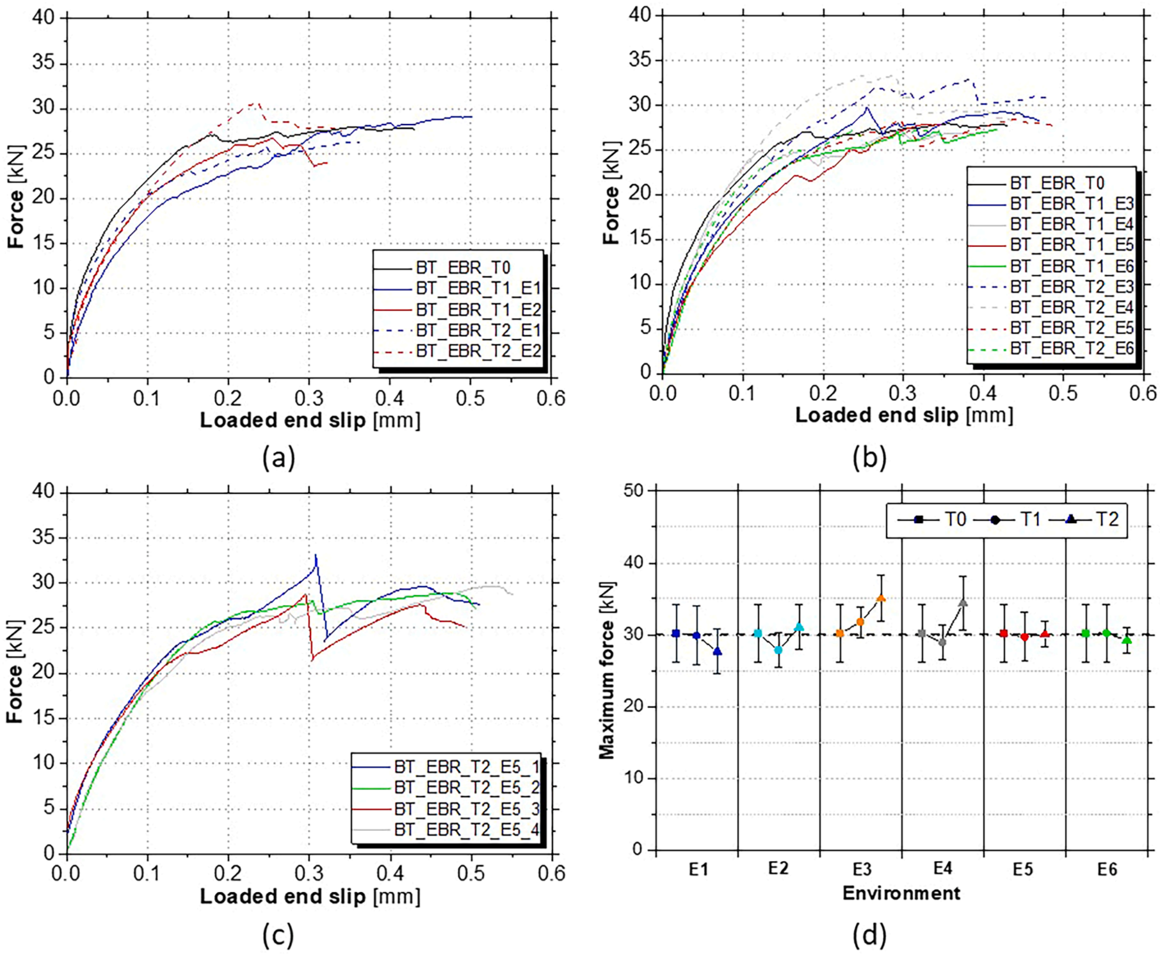


Fig. 8. Results of single-lap shear tests on bond EBR-CFRP to concrete specimens: (a) Force *vs.* loaded end slip (average curves of 4 specimens/environment) for laboratory accelerated ageing; (b) Force *vs.* loaded end slip (average curves of 4 specimens/environment) for real-time field exposure; (c) Force *vs.* loaded end slip for E5 environment at T2; (d) Maximum pull-out shear force at the initial characterization (T0) and after one and two years (T1 and T2) of exposure on the environments E1-E6.

Fig. 9. Failure modes observed in the pull-out shear bond EBR tests: (a) C – cohesive failure of concrete and (b) C + F/A - cohesive failure of concrete and debonding at laminate-adhesive interface.

performed at T0, T1, and T2.

Fig. 9 presents the two types of failure modes observed in bond EBR-CFRP to concrete tests: (i) cohesive failure in the concrete (C), which was the dominant failure mode, and (ii) cohesive failure in the concrete with simultaneous debonding at the laminate-adhesive interface (C + F/A), also observed in some test specimens (see Table 1).

The initial characterization (T0) of the bond EBR-CFRP to concrete specimens provided results in agreement with related preceding works, e.g. [14,43]. An average maximum force of 30.2 kN was reached, with cohesive failure of the concrete (C) as the dominant failure mode. In two specimens, the detachment at the laminate-adhesive interface (F/A) was also observed in approximately half of the bond length. The average maximum tensile stress obtained in the CFRP laminate was 503 MPa (~20% of the ultimate tensile strength of the CFRP strip), which is in agreement with the result obtained using the formulation proposed by the CNR–DT 200 R1/2013 [20] (505 MPa). The initial stiffness (K) varies with the environment and period of exposure. In general, the real-time field exposure leads to a higher initial stiffness. A tendency of F_{max} increase was verified in specimens of E3 and E4 environments (specially in E3, where F_{max} increased 16.2% at T2 in comparison with T0). The increase in the time of exposure seems to cause the change of the failure mode, from C + F/A to C.

3.2.1. Effect of the environmental exposure type

A decrease in the initial stiffness (K) was observed between the initial characterization (T0) and T1 for the E1 environment. The E2 environment does not seem to affect the initial stiffness. In general, the real-time field exposure has led to an increase in the initial stiffness (in comparison with T0 or with E1 at T1 and T2), except in the case of E5 series, which has shown lower K values.

The exposure to the E1 environment caused only a negligible variation in F_{max} after one year (T1) of exposure. However, a F_{max} decrease of 8.3% was observed at T2. The specimens immersed in water (E2) recorded a F_{max} decrease at T1 (6.7%) followed by an increase at T2 (12.2%) when compared with the E1 environment (reference) for the same period of exposure. The F_{max} on specimens from E1 and E2 environments did not statistically differs significantly with the ANOVA test between T0-T1 and T1-T2. It should be highlighted that the tensile properties of the epoxy adhesive faced a strong reduction in the E2 environment, justified by plasticization and swelling effects, that had not been observed in the bond EBR–CFRP to concrete system. Therefore, for the studied period, it seems that the overall behaviour of the bond of EBR-CFRP to concrete systems does not fully depend only on the mechanical properties of the adhesive, as the magnitude of strength reduction observed in the adhesive was not verified in the bonding system. Furthermore, due to the small variations in the mechanical properties of the remaining constitutive materials, the overall durability of the EBR system is probably not substantially dependent on the individual properties of each material, even with water absorption and testing in a saturated state. The F_{max} increase observed at T2 can be related to the adhesive plasticization, which may reduce the interfacial peaks of shear stress (responsible for the premature debonding of the CFRP laminate) and lead to a better and more uniform distribution of the shear stresses along the whole bond length (also observed by Hassan et al. [18]) yielding to an increase in the maximum force, as already observed in EBR-CFRP strengthening using flexible adhesives, e.g. Kwiecień [44].

Regarding the real-time field exposure (environments E3-E6), F_{max} did not change significantly after one year of conditioning (T1) in comparison with the reference E1. Variations of F_{max} between + 6.4% (E3) and −3.3% (E4) were observed. Higher variations were observed after two years of conditioning (T2), with strong F_{max} increases of + 26.7% and + 24.2%, respectively, in E3 and E4 environments (comparing to E1 at T2). Therefore, after a two-year conditioning (T2), the maximum strength has increased in immersed (E2) and outdoor (E3 and E4) environments, which indicates a bond strength improvement of the EBR-CFRP to concrete system in the conditions of this study. Nevertheless, by performing the ANOVA test between T0–T1 (minimum p-value = 0.424 for the E2 environment) and T1-T2 (minimum p-value = 0.081 for E4 environment), it was possible to conclude that F_{max} did not significantly statistically differs on outdoor specimens.

Considering only the evolution of the mechanical properties of the constitutive materials exposed to outdoor environments (see "Materials" section), the observed F_{max} increase in the EBR-CFRP to concrete system can be related with the: (i) increase in the compressive strength of concrete (also observed by Kabir et al. [17]), (ii) decrease in the superficial tensile strength of concrete, (iii) improvement of the interface characteristics, and (iv) reduction of the elastic modulus of the adhesive. As stated before, the reduction of the adhesive's elastic modulus allows for a better and more uniform distribution of the shear stress along the active bond length, which leads to an increase in the maximum strength [44,45]. The daily and seasonal fluctuations of temperature and humidity faced in outdoor exposure can lead to the development of shear stresses at the interfaces due to the different thermal expansion coefficients of the constitutive materials. These stresses can lead to bond damage and even the debonding of the CFRP strip. However, the temperature and humidity of the tested environments do not seem to be significant to the point where they impact the interfaces. As stated by Cabral-Fonseca et al. [16], the effects of freeze–thaw cycles are controversial, as some authors found deterioration of the bonding system and others stated small effects on the FRP-concrete bond. In the present investigation, the bond strength observed in the E4 environment increased after two years of exposure. The non-deleterious effects may be justified by the reduced range of extreme temperatures and the corresponding number of cycles faced by this outdoor environment, when compared with other works from the literature. Finally, for a given testing period (T1 or T2), the same failure modes were observed in all environments, even in the E2 environment (where specimens were tested saturated).

3.2.2. Effect of time of exposure

During the first year of exposure (between T0 and T1), a general decrease in the initial stiffness (K) was observed, except for the E4 environment. Then, on the second year (between T1 and T2), a tendency of increase in the initial stiffness (K) occurred, regardless of the environment. The highest increase was verified in the E6 environment (35%), which can be related to the increase in the elastic modulus of concrete in E6 at T2. Nevertheless, the E4 environment induced a reduction of the initial stiffness in this interval.

The maximum force remained almost constant over time in E1, E2, E5, and E6 environments (maximum decrease of ~ 8.3% in E1 at T2), whereas F_{max} increased in E3 and E4 environments, especially during the second year of exposure (maximum increase of ~ 16.2% in E3). After two stages of evaluation (T1 and T2), no clear trend of evolution in F_{max} was observed in E2, E4, E5, and E6 environments. Nevertheless, a continuous F_{max} decrease and a continuous F_{max} increase was observed in E1 and E3 environments, respectively.

Comparing the failure modes observed on series corresponding to T0, T1, and T2, it became clear that the C + F/A tends to change to cohesive in the concrete (C) as the exposure time increases. This finding may be related to the change in the mechanical properties of the concrete surrounding the adhesive-concrete (A/C) interface and to the improvement of laminate-adhesive (F/A) interface over time.

4. Laboratory versus field exposure and design guidelines

A database of laboratory accelerated ageing tests was established to perform comparisons between the results of laboratory accelerated ageing (collected in the existing literature) and real-time field exposure (obtained in the present work). Therefore, the results of EBR systems obtained on EBR-CFRP to concrete bond tests were gathered. This database presents the following main characteristics:

- Database size: 50 test results, collected from five research works [46–50];
- Type of FRP: pultruded CFRP laminates with thicknesses between 1.2 and 1.4 mm and elastic modulus between 155 and 176 GPa;
- Type of adhesive: epoxy adhesives;
- Concrete compressive strength: between 25 and 50 MPa;
- Bond lengths: ranging from 100 to 600 mm;
- Test configurations: single-lap shear test and beam test;

- Types of exposure conditions: freeze–thaw cycles (in water and 90% RH), immersion in water (tap and salt water), sun exposure (thermal cycles) and saline splash exposure (salt fog cycles);
- Periods of exposure: up to 18,000 h (~2 years).

A preliminary analysis of the database's results and attempts of correlating the bond strength retention observed for each specific accelerated ageing type (found in literature) with real-time field exposure conditions were performed. The bond strength retention was computed as the ratio between the strength after exposure and reference strength (before exposure). Nevertheless, no specific correlations could be obtained due to the significant dispersion of the results and reduced number of test results.

Fig. 10(a) presents the relationship between the evolution of bond strength retention and time of exposure, obtained for the results of laboratory accelerated conditioning that compose the database. The results of laboratory accelerated ageing of the E2 environment (black circles) and the results of real-time field exposure of the E3-E6 environments (red circles) are also presented. In general, a considerable dispersion of the results can be observed, without a clear trend of evolution with time. The dispersion in real-time field exposure is lower than in laboratory accelerated ageing, with a retention value close to 1.0 (RTFE). Accelerated ageing protocols by water immersion tends to yield lower values of bond strength retention when compared with real-time field exposure, whereas thermal cycles (sun exposure) tend to give higher values, even for short periods of exposure. When only bond strength retention values lower than 1.0 are considered, average retentions of strength equal to 0.84 (with a coefficient of variation, CoV = 9.4%) and 0.93 (CoV = 4.9%) are obtained, respectively, for laboratory accelerated ageing and real-time field exposure (E3-E6 environments). From these results, it becomes clear that, up to ~18000 h, laboratory accelerated ageing yields to lower bond strength retention than real-time field exposure.

Fig. 10(b) presents the relationship between the non-conservative estimated data values (percentage of the cases where the adopted conversion factor is not conservative) of the database collected and the conversion factor (only retention values lower than 1.0 were considered in this work). Based on this approach, a bond strength conversion factor of 0.75 should be used to ensure at least 10% of the non-conservative estimates with the EBR system. The suggested value of 10% of non-conservative estimates is based on engineering judgment. In the investigation developed by Cruz et al. [25], which addressed the durability of the CFRP laminate and epoxy adhesive, strength conversion factors of 0.85 and 0.55 were proposed, respectively. Comparing the conversion factor proposed in this work (0.75) for the EBR system with the values of conversion factors proposed by Cruz et al. [25] for the CFRP strips (0.85) and epoxy adhesives (0.55), it can be concluded that the degradation of the bond EBR system is higher than the degradation of the CFRP laminate itself and lower than the degradation of the epoxy adhesive.

The durability of the FRP strengthening systems is explicitly accounted in the existing guidelines ACI 440.2R-17 [1] and CNR-DT 200 R1/2013 [20]. These guidelines provide environmental conversion (or reduction) factors (C_E for the case of ACI 440.2R-17 and η_a for the case of CNR DT 200 R1/2013) to predict the service life of the FRP strengthening system considering generic types of environmental exposure. Nevertheless, these guidelines do not provide conversion factors for specific types of exposure. Furthermore, in ACI 440.2R-17 and CNR-DT 200 R1/2013, the same conversion factor of 0.85 is proposed for exterior and aggressive environmental conditions using epoxy/carbon systems (including EBR and NSM techniques). However, these design conversion factors only reduce the ultimate tensile strength/strain of the FRP material and do not consider the eventual reduction in the bond strength of the FRP-concrete systems, which, as demonstrated in this investigation, is affected by the type of conditioning. Therefore, these guidelines should be improved to consider (i) the bond strength degradation and (ii) more specific types of environmental exposure.

5. Conclusions

The results of an investigation on the durability of bond in EBR-CFRP to concrete systems under real-time field exposure was described in this paper. The experimental program included a total of six exposure environments. Two laboratory conditions under controlled hygrothermal/hydrothermal conditions were considered: (i) a control (reference) environment (E1) and (ii) water immersion environment (E2). Four types of real-time field exposure were included for inducing ageing mainly by carbonation (E3), freeze–thaw attack (E4), elevated temperatures (E5), and airborne chlorides from seawater (E6). Experimental campaigns were performed along the time to assess the evolution of the mechanical characteristics of materials and bond at specific time points, namely at an early stage (T0) before conditioning and after one and two years (T1/T2) of conditioning. The results obtained from real-time field exposure developed in this work and results of laboratory accelerated ageing from the existing literature were compared. An analysis of the appropriateness of these results when compared with the existing guidelines was also developed. From this work, the following conclusions can be pointed out:

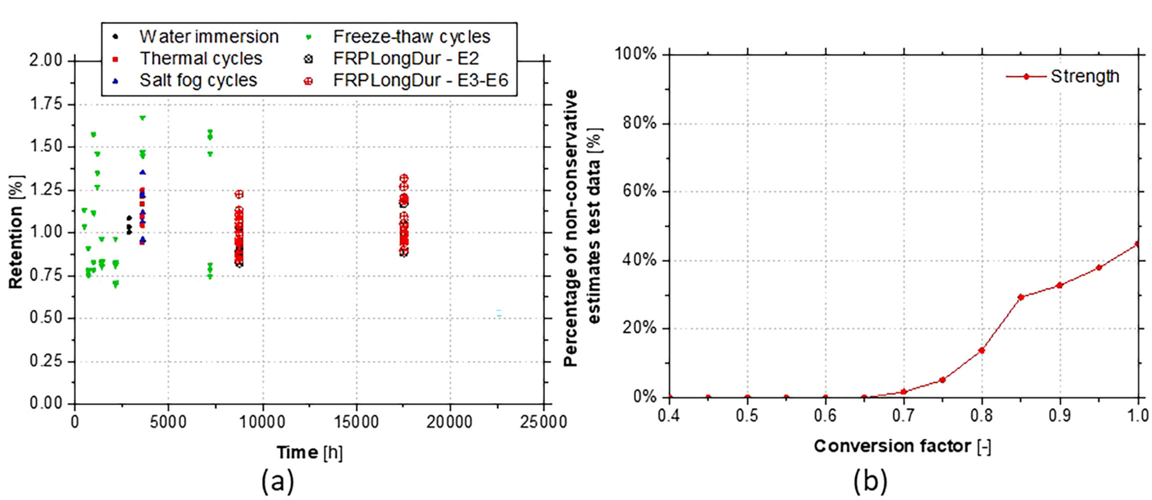


Fig. 10. Laboratory accelerated ageing versus real-time field exposure on bond EBR-CFRP to concrete systems: (a) retention values and (b) percentage of non-conservatively estimated data versus conversion factor.

5.1. EBR-CFRP to concrete bond tests

- A maximum force of 30.2 kN was obtained on the initial characterization (T0), which corresponds to only ~ 20% of the tensile strength of the CFRP laminate;
- At T1 and T2, no trend of evolution in the bond strength was obtained for laboratory ageing (E1 and E2), with a maximum bond strength variation in the E2 environment at T1 (a decrease of 8.3% in comparison with T0). Regarding to real-time field exposure, a trend of increasing in the bond strength at T2 was verified in E3 and E4 environments (with the highest increase of + 16.2% in the E3 environment in comparison with T0); negligible variations were obtained in E5 and E6 environments (a maximum decrease of ~ 3.3% in E6 at T2);
- The cohesive failure in the concrete (C) was observed in all the test specimens; In some tests, debonding at the laminate-adhesive interface (F/A) was also verified in addition to the cohesive failure in the concrete (C); This complementary component F/A was common in the first testing period (T0) and it tends to disappear with the exposure and increase in the time of exposure.

5.2. Laboratory versus field exposure and design guidelines

- Despite the dispersion of results, for similar periods, the real-time field exposure yielded higher values of bond strength retention than laboratory accelerated ageing (considering only retention values lower than 1.0);
- An environmental conversion factor of 0.75 is suggested for the case of exterior or aggressive environmental conditions for accounting the bond strength durability of the EBR-CFRP to concrete system (for design purposes, the real bond strength should be reduced by 25%). The existing guidelines should be improved to account for the bond strength degradation.
- Two years is a short period for field exposure with consistent test results. Longer exposure times can lead to higher degradation rates and may provide results closer to those observed under laboratory accelerated ageing. Therefore, it is possible that the values of the conversion factor converge to those observed in laboratory if longer periods of exposure to natural ageing are adopted. This should be pursued in future research works.

CRediT authorship contribution statement

Ricardo Cruz: Methodology, Investigation, Formal analysis, Writing – original draft. **Luís Correia:** Methodology, Investigation, Formal analysis, Supervision, Writing – original draft. **Susana Cabral-Fonseca:** Methodology, Investigation, Formal analysis, Supervision, Writing – original draft. **José Sena-Cruz:** Conceptualization, Methodology, Supervision, Writing – review & editing, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This work was carried out in the scope of the project FRPLongDur POCI-01-0145-FEDER-016900 (FCT PTDC/ECM-EST/1282/2014) and DURABLE-FRP (PTDC/ECI-EGC/4609/2020) funded by national funds through the Foundation for Science and Technology (FCT) and co-financed by the European Fund of the Regional Development (FEDER) through the Operational Program for Competitiveness and Internationalization (POCI) and the Lisbon Regional Operational Program and, was partly financed by FCT/MCTES through national funds (PIDDAC) under the R&D Unit Institute for Sustainability and Innovation in Structural Engineering (ISISE), under reference UIDB/04029/2020, and under the Associate Laboratory Advanced Production and Intelligent Systems ARISE under reference LA/P/0112/2020. The first author wishes also to acknowledge the grant SFRH/BD/131259/2017 provided by Fundação para a Ciência e a Tecnologia (FCT).

The authors also like to thank all the companies that have been involved supporting and contributing for the development of this study, mainly: S&P Clever Reinforcement Iberica Lda., Portuguese Institute for Sea and Atmosphere, I.P. (IPMA, IP), Sika Portugal – Produtos Construção e Indústria, S.A., Hilti Portugal – Produtos e Serviços, Lda., Artecanter – Indústria Criativa, Lda., Tecnipor – Gomes&Taveira Lda., Vialam – Indústrias Metalúrgicas e Metalomecânicas, Lda., Laboratório Nacional de Engenharia Civil (LNEC, IP), EDP – Energias de Portugal and APDL - Administração dos Portos do Douro, Leixões e Viana do Castelo, SA.

References

[1] Aci, Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures, ACI 440.2R-17, American Concrete Institute. Farmington Hills (MI), 2017.
[2] CSA, Canadian Highway Bridge Design Code, CAN/CSA-S6-06. Canadian Standards Association. Toronto, Toronto, 2006.
[3] IPQ, NP EN EN 1992-1-1. Eurocode 2: design of concrete structures - Part 1-1: general rules and rules for buildings, Instituto Português da Qualidade (IPQ). Caparica, Portugal, 2010.
[4] W. Ashraf, Carbonation of cement-based materials: Challenges and opportunities, Constr. Build. Mater. 120 (2016) 558–570.
[5] J. Tatar, H.R. Hamilton, Comparison of laboratory and field environmental conditioning on FRP-concrete bond durability, Constr. Build. Mater. 122 (2016) 525–536.
[6] J. Tatar, S. Milev, Durability of Externally Bonded Fiber-Reinforced Polymer Composites in Concrete Structures: A Critical Review, Polymers 13 (5) (2021) 765.
[7] M. Lettieri, M. Frigione, Natural and artificial weathering effects on cold-cured epoxy resins, J. Appl. Polym. Sci. 119 (3) (2011) 1635–1645.
[8] V.M. Karbhari, K. Ghosh, Comparative durability evaluation of ambient temperature cured externally bonded CFRP and GFRP composite systems for repair of bridges, Compos. A Appl. Sci. Manuf. 40 (9) (2009) 1353–1363.
[9] G.M. Odegard, A. Bandyopadhyay, Physical aging of epoxy polymers and their composites, J Polym Sci B 49 (24) (2011) 1695–1716.
[10] P. Fernandes, J. Sena-Cruz, J. Xavier, P. Silva, E. Pereira, J. Cruz, Durability of bond in NSM CFRP-concrete systems under different environmental conditions, Compos. B Eng. 138 (2018) 19–34.
[11] V.M. Karbhari, J.W. Chin, D. Hunston, B. Benmokrane, T. Juska, R. Morgan, J. J. Lesko, U. Sorathia, D. Reynaud, Durability gap analysis for fiber-reinforced polymer composites in civil infrastructure, J. Compos. Constr. 7 (3) (2003) 238–247.
[12] A. Bilotta, F. Ceroni, M. Di Ludovico, E. Nigro, M. Pecce, G. Manfredi, Bond efficiency of EBR and NSM FRP systems for strengthening concrete members, J. Compos. Constr. 15 (2011) 757–772.
[13] C. Mazzotti, A. Bilotta, C. Carloni, F. Ceroni, T. D'Antino, E. Nigro, C. Pellegrino, in: C. Pellegrino, J. Sena-Cruz, RILEM (Eds.), State-of-the-Art Reports, 19, Springer Netherlands, Dordrecht, 2016, pp. 39–96.
[14] I. Iovinella, A. Prota, C. Mazzotti, Influence of surface roughness on the bond of FRP laminates to concrete, Constr. Build. Mater. 40 (2013) 533–542.
[15] C. Pellegrino, J. Sena-Cruz, Design Procedures for the Use of Composites in Strengthening of Reinforced Concrete Structures : State-of-the-Art Report of the RILEM Technical Committee 234-DUC, 2016. https://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=1056106.
[16] S. Cabral-Fonseca, J.R. Correia, J. Custódio, H.M. Silva, A.M. Machado, J. Sousa, Durability of FRP - concrete bonded joints in structural rehabilitation: A review, Int. J. Adhes. Adhes. 83 (2018) 153–167.
[17] M.I. Kabir, R. Shrestha, B. Samali, Effects of applied environmental conditions on the pull-out strengths of CFRP-concrete bond, Constr. Build. Mater. 114 (2016) 817–830.
[18] S.A. Hassan, M. Gholami, Y.S. Ismail, A.R.M. Sam, Characteristics of concrete/CFRP bonding system under natural tropical climate, Constr. Build. Mater. 77 (2015) 297–306.
[19] M.H. Mohd Hashim, A.R. Mohd, M.H. Sam, Experimental investigation on the effect of natural tropical weather on interfacial bonding performance of CFRP-concrete bonding system 11 (2016) 584–604.
[20] CNR, CNR-DT 200 R1/2013. Guide for the design and construction of externally bonded FRP systems for strengthening existing structures, 2013.

[21] Aashto, Guide Specifications for Design of Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements, AASHTO-FRPS-1, American Association of State Highway and Transportation Officials, Washington, DC, USA, 2010.
[22] ISIS, in: K.W. Neale (Ed.), Strengthening Reinforced Concrete Structures with Externally-Bonded Fibre Reinforced Polymers (FRPs), Design Manual 4 (Man. No. 4). FRP Rehabilitation of Reinforced Concrete Structures. Intelligent Sensing for Innovative Structures (ISIS). ISIS Canada, University Sherbrooke, Sherbrooke, QC, Canada, 2012.
[23] Recommendations for Upgrading of Concrete Structures with Use of Continuous Fiber Sheets, Concrete Engineering Service 41, Japan Society of Civil Engineers, Tokyo, Japan, 2001.
[24] CS, Design Guidance for Strengthening Concrete Structures Using Fibre Composite Materials, Concrete Society TR55. 3rd ed.; Concrete Society Technical Reports 55 (TR55); Camberley, Surrey, UK, 2012.
[25] R. Cruz, L. Correia, A. Dushimimana, S. Cabral-Fonseca, J. Sena-Cruz, Durability of Epoxy Adhesives and Carbon Fibre Reinforced Polymer Laminates Used in Strengthening Systems: Accelerated Ageing versus Natural Ageing, Materials 14 (6) (2021) 1533.
[26] S&P, S&P CFRP Laminates. Technical Datasheet, Seewen, Switzerland, 2014.
[27] S&p,, S&P 220 Resin epoxy adhesive, Seewen, Switzerland, 2015. Technical Data Sheet.
[28] CEN, EN 206-1. Concrete — Part 1: Specification, performance, production and conformity, European Committee for Standardization (CEN), 2000.
[29] ISO, ISO 527-2. Plastics—Determination of Tensile Properties. Part 2: Test Conditions for Moulding and Extrusion Plastics, International Organization for Standardization (ISO): Genève, Switzerland, 2012.
[30] ISO, ISO 527-5. Plastics—Determination of Tensile Properties. Part 5: Test Conditions for Unidirectional Fibre-Reinforced Plastic Composites, International Organization for Standardization (ISO): Genève, Switzerland, 2009.
[31] NP IPQ. EN 12390-13.Testing Hardened Concrete. Part 13: Determination of Secant Modulus of Elasticity in Compression, Instituto Português da Qualidade (IPQ), Caparica, Portugal, 2013.
[32] NP IPQ. EN 12390-3. Testing Hardened Concrete. Part 3: Compressive Strength of Test Specimen, Instituto Português da Qualidade (IPQ), Caparica, Portugal, 2011.
[33] BSI, Products and systems for the protection and repair of concrete structures - Test methods - Measurement of bond strength by pull-off, EN 1542. STANDARD by British-Adopted European Standard. British Standards Institution (BSI), 1999.
[34] LNEC, Concrete – Determination of carbonation resistance. E391-1993, Portuguese specification from LNEC, 1993.
[35] J.M. Sousa, J.R. Correia, S. Cabral-Fonseca, Durability of an epoxy adhesive used in civil structural applications, Constr. Build. Mater. 161 (2018) 618–633.
[36] Z. Mi, Y. Hu, Q. Li, Z. An, Effect of curing humidity on the fracture properties of concrete, Constr. Build. Mater. 169 (2018) 403–413.
[37] G. Zhang, C. Li, H. Wei, M. Wang, Z. Yang, Y. Gu, Influence of Humidity on the Elastic Modulus and Axis Compressive Strength of Concrete in a Water Environment, Materials 13 (24) (2020) 5696.
[38] J.-K. Zhou, N. Ding, Moisture effect on compressive behavior of concrete under dynamic loading, J. Cent. South Univ. 21 (12) (2014) 4714–4722.
[39] I. Rozsypalová, P. Daněk, O. Balkanský, The bond strength by pull-off and direct tensile strength of concrete damaged by elevated temperatures, IOP Conference Series: Materials Science and Engineering 385 (2018), 012047.
[40] L. Jin, X. Du, G. Ma, Macroscopic effective moduli and tensile strength of saturated concrete, Cem. Concr. Res. 42 (12) (2012) 1590–1600.
[41] N.B. Bouzoubaâ, A.B. Bilodeau, B.T. Tamtsia, S.F. Foo, Carbonation of fly ash concrete: laboratory and field data, Can. J. Civ. Eng. 37 (12) (2010) 1535–1549.
[42] M. Otieno, J. Ikotun, Y. Ballim, Experimental investigations on the effect of concrete quality, exposure conditions and duration of initial moist curing on carbonation rate in concretes exposed to urban, inland environment, Constr. Build. Mater. 246 (2020), 118443.
[43] S. Soares, J. Sena-Cruz, J. Cruz, P. Fernandes, Influence of Surface Preparation Method on the Bond Behavior of Externally Bonded CFRP Reinforcements in Concrete, Materials 12 (2019) 414.
[44] A. Kwiecień, Stiff and flexible adhesives bonding CFRP to masonry substrates—Investigated in pull-off test and Single-Lap test, Archives of Civil and Mechanical Engineering 12 (2) (2012) 228–239.
[45] K. Benzarti, S. Chataigner, M. Quiertant, C. Marty, C. Aubagnac, Accelerated ageing behaviour of the adhesive bond between concrete specimens and CFRP overlays, Constr. Build. Mater. 25 (2) (2011) 523–538.
[46] P. Colombi, G. Fava, C. Poggi, Bond strength of CFRP–concrete elements under freeze–thaw cycles, Compos. Struct. 92 (4) (2010) 973–983.
[47] K. Al-Tamimi Adil, A. Hawileh Rami, A. Abdalla Jamal, A. Rasheed Hayder, R. Al-Mahaidi, Durability of the Bond between CFRP Plates and Concrete Exposed to Harsh Environments, J. Mater. Civ. Eng. 27 (9) (2015) 04014252.
[48] M.F. Green, L.A. Bisby, Y. Beaudoin, P. Labossière, Effect of freeze-thaw cycles on the bond durability between fibre reinforced polymer plate reinforcement and concrete, Can. J. Civ. Eng. 27 (5) (2000) 949–959.
[49] Y. Pan, G. Xian, H. Li, Effects of Freeze-Thaw Cycles on the Behavior of the Bond between CFRP Plates and Concrete Substrates, J. Compos. Constr. 22 (3) (2018) 04018011.
[50] F. Al-Mahmoud, J.-M. Mechling, M. Shaban, Bond strength of different strengthening systems – Concrete elements under freeze–thaw cycles and salt water immersion exposure, Constr. Build. Mater. 70 (2014) 399–409.
[51] CEN, prEN EN 1992-1-1. Eurocode 2: Design of concrete structures - Part 1-1: General rules - Rules for buildings, bridges and civil engineering structures, European committee for standardization (CEN), 2021.