DURABILITY OF CFRP-CONCRETE BOND IN EBR AND NSM SYSTEMS UNDER NATURAL AGEING FOR A PERIOD OF THREE YEARS

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Abstract: *Carbon Fibre Reinforced Polymer (CFRP) composites have been shown to possess desirable properties for strengthening of reinforced concrete (RC) structures. The application of CFRP composites is mainly through Externally Bonded Reinforcement (EBR) or Near Surface-Mounted (NSM) techniques. The main objective of the present work was to provide insights on durability of bond between concrete and CFRP strips installed according to EBR and NSM techniques under the effects of ageing induced by outdoor conditions for a period of three years. Specimens were placed in four different outdoor environments (E3-E6) with ageing mainly induced by freeze-thaw attacks, carbonation, airborne chlorides, and elevated temperatures. Besides, the study included a reference environment (E1: ≈20 ℃ / 55% RH) and another environment (E2: ≈20 ℃ / water immersion). The bond test results for the specimens collected from the aforementioned outdoor environments showed a low degradation of the CFRP-concrete bond after three years.*

Keywords: *bond; EBR; NSM; durability; natural outdoor ageing*

1. Introduction

Carbon Fiber Reinforced Polymer (CFRP) composites possess desirable properties for strengthening of existing RC structures [1, 2]. CFRP composites can mainly be applied through EBR or NSM techniques [3]. In the former, the CFRP is applied on the surface of a RC element to be strengthened, while in the latter the CFRP is inserted in a groove cut into the concrete cover of the RC element. The adhesion between FRP and concrete substrate in EBR generally controls the ultimate capacity of the strengthened element [4]. However, the premature failure due to debonding will lead to underutilization of the materials [5]. On the other hand, NSM technique is an effective solution to increase cracking, yielding and ultimate loads of strengthened elements failing in bending [6]. Besides, experimental observations from different past studies have revealed that NSM has superior benefits than EBR [7, 8]. This is attributed to a better CFRP-concrete bond performance which leads to a more efficient use of CFRP strain [9].

Regarding the durability of the CFRP-concrete bond, the bond strength can be affected by various factors, mainly by ageing of the constituent materials, environmental exposure conditions, or due to loading conditions. Negligible variations of NSM CFRP-concrete bond strength were found after 240 days of exposure to water immersion, water immersion with chlorides, wet/dry cycles in tap water with chlorides, and freeze-thaw cycles [1]. However, the latter exposure changed the failure mode from debonding at the CFRP/adhesive to adhesive/concrete and cohesive failure of concrete [1]. Furthermore, some studies show that the glass transition temperature (T_g) of adhesive can significantly affect the failure mode [10], and the exposure to temperature cycles can improve the bond strength (due to post-curing phenomena), while temperatures higher than the T_g can reduce it [11, 12].

A comparative analysis on the bond performance using data from the available literature can contribute to further understanding of EBR and NSM systems when considering their service life and long-term benefits. Referring to existing data on accelerated ageing conditions, a comparative perspective in [1], showed a significant degradation of the bond strength up to 68% for EBR and 1.4% for NSM when exposed to moisture, and up to 25% and 5%, respectively, when exposed to freeze-thaw cycles. However, a comparable bond strength reduction was found when EBR and NSM were exposed to natural outdoor environments, but further studies were suggested for confirmation [1]. In fact, most of the existing studies on the durability of the CFRP-concrete bond have been conducted under laboratorial conditions using accelerated ageing protocols [13], and little is known on whether such conditions can provide an appropriate estimate of what normally happens in the real (natural) outdoor conditions. Hence, there is a need to conduct further studies under natural ageing conditions, perform comparative analysis, and gain an increased understanding on the behavior of EBR and NSM systems with time. In this regard, this work presents the durability of the EBR and NSM CFRP-concrete bond after three years of natural outdoor exposure to different aggressive environments, particularly, the maximum pull-out force and the type of failure mode are the main parameters investigated.

2. Materials and Methods

2.1. Description of materials, EBR and NSM specimens

A description of the materials involved in the preparation of the specimens for bond tests and the prepared specimens is provided in this section.

Materials: In this work, the commercial cold curing epoxy adhesive, trademarked as S&P Resin 220 epoxy adhesive by S&P® Clever Reinforcement Ibérica Lda. Company, was used as the bonding agent between the CFRP strip and the concrete substrate. The CFRP strips, also produced by the same company, with the trademark CFK 150/2000 were adopted to strengthen the specimens according to EBR and NSM techniques. In the latter technique, CFRP laminates with a cross-section of 50 × 1.4 mm^2 (L10) were adopted, while CFRP laminates with a cross-section of 50 × 1.2 mm^2 (L50) were adopted in the former. The concrete with C30/37 XC4(P) CL 0.40 d_{max} 12.5 S4 as per [14] was used to cast all the specimens from a single concrete batch of about 12 m^3. The average elastic modulus and compressive strength of concrete after 28 days were 29.1 GPa and 41.5 MPa, respectively. The elastic modulus and ultimate strength of CFRP and adhesive were approximately 170 GPa and higher than 2000 MPa, 7.1 GPa and 19.9 MPa, respectively. Further details on the properties of the adhesive and CFRP can be found in [13].

EBR specimens: 40 concrete prisms each with 400 × 200 × 200 [mm] and two CFRP laminate strips with a cross-section of L50 applied in opposite faces (parallel to the casting direction) were prepared from different environments for testing. A bond length of 220 mm was adopted, with 100 mm free from the extremity of the concrete prism to avoid premature failure by concrete rip-off ahead of the loaded end. According to [15], the used bond length (220 mm) should be higher than the theoretical effective length, L_e, of 101 mm.

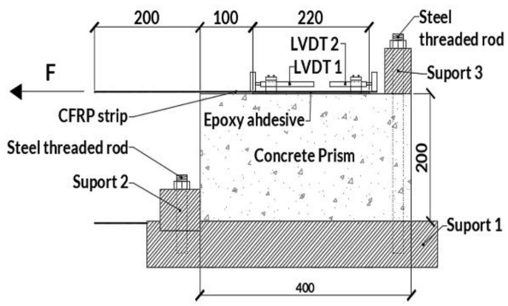
NSM specimens: 40 concrete cubic blocks, each with 200 mm of edge and CFRP strip (L10) applied along a bond length of 60 mm, were prepared according to NSM system. The CFRP strip was inserted in the center of a groove with 15 × 5 [mm] opened at the surface of the concrete block.

2.2. Description of experimental stations

After the preparation of the EBR and NSM specimens, the specimens were placed in different regions of Portugal for ageing until three years of exposure, that is, the specimens were kept in two artificial environments (E1 and E2), and four outdoor environments (E3-E6). In E1, the specimens were placed in controlled hygrothermal conditions of 20 °C / 55% RH, while in E2 the specimens were continuously immersed in water under controlled temperature (approximately 20 °C). On the other hand, specimens were placed in E3 characterized by high levels of concrete carbonation (station near the International Airport of Lisbon), E4 characterized by freeze-thaw attacks (i.e., specimens placed at the highest mountain in Portugal), E5 characterized by high elevated service temperatures and low relative humidity (i.e., specimens placed in Elvas city), and E6 characterized by high levels of chlorides concentration and relative humidity (i.e. specimens placed near the Atlantic ocean). Additionally, sensors were installed close to the materials in order to control the temperature and relative humidity in each environment. Further details on the experimental stations can be found in [13]. Finally, each year, 2 specimens of EBR and 2 specimens of NSM were collected and tested in the laboratory of civil engineering, University of Minho. Details on the tests conducted in each of the consecutive three years (namely T1 for year1, T2 for year 2, and T3 for year 3) are provided in the next section.

2.3. Pull-out tests for EBR and NSM specimens

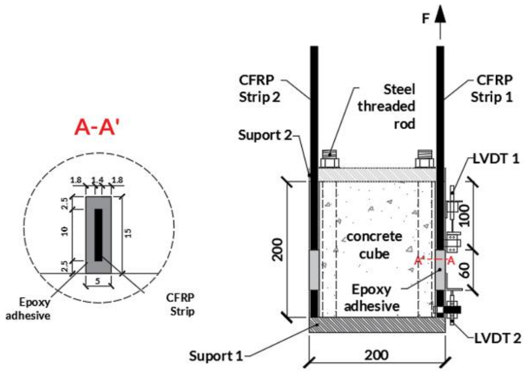
In order to perform the pull-out tests, the EBR specimens were placed horizontally on a steel plate with 70 × 300 × 550 [mm] identified as Support 1 (see Fig. 1), fixed to the stiff base of the testing steel frame system through eight M16 steel threaded rods. A steel plate identified as Support 2 was placed in the bottom front part of the concrete block to assure negligible horizontal displacements of the specimen in the loading direction during the test, which acted as a reaction element at a height of 50 mm. The Support 3, which is a prismatic steel plate, was placed in the rear top part of the specimen to minimize vertical displacements during the test. Support 2 and Support 3 were fixed to Support 1 through two M20 steel threaded rods. The tests were performed using a servo-controlled equipment and the applied force was measured through a load cell of 200 kN maximum load carrying capacity (linearity error of 0.05% F.S.), placed between the actuator and the grip was used to pull the CFRP laminate during the test. The relative displacement between the CFRP and the concrete (slip) at the loaded end section (s_l) and free end section (s_f) were measured using the linear variable displacement transducers (LVDT) 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 2 μm/s. Additionally, a series of four strain gauges TML BFLA-5-3-3L were placed along the CFRP laminate centerline to measure the longitudinal strains during the loading process.

a) 

b) 

Figure 1. (a) Specimen's geometry and test configuration, and (b) photograph of the EBR bond test. Note: all units in [mm]

On the other hand, the geometry of NSM specimens and the respective test configuration is shown in Fig. 2. A servo-controlled equipment was used to apply the load, and the slip at the loaded and free end, was measured using two LVDTs (range ±2.5 mm and linearity error of ±0.05% F.S.) i.e. LVDT1 and LVDT2, respectively. The load was measured by a load cell placed between the grip and the actuator, with a static load carrying capacity of 200 kN (linearity error of ±0.05% F.S.). These tests were also performed under displacement control at the loaded end section (LVDT1), at a rate of 2 µm/s.

a) 

b) 

Figure 2. (a) Specimen's geometry and test configuration, and (b) photograph of the NSM bond test. Note: all units in [mm]

3. Results and Discussion

The average curves for EBR force *versus* slip relation in each of the studied environments after T3 are presented in Fig. 3a. It can be seen that the E1 and E2 environments have the lowest maximum force, E5 shows the highest force and slip compared to other environments. When comparing the results for the maximum pull-out force (pullout strength) from T1 to T3 (Fig. 3b), it can be seen that there was an increase in the pullout force from T1 to T2, followed by a reduction from T2 to T3 in the environments E2-E4, while a reduction can be noticed from T2 to T3 in all environments. After T3, the force is generally lower than the initial value at T0, mainly in the artificial environments (E1 and E2), and a low degradation of bond strength can be seen in outdoor environments.

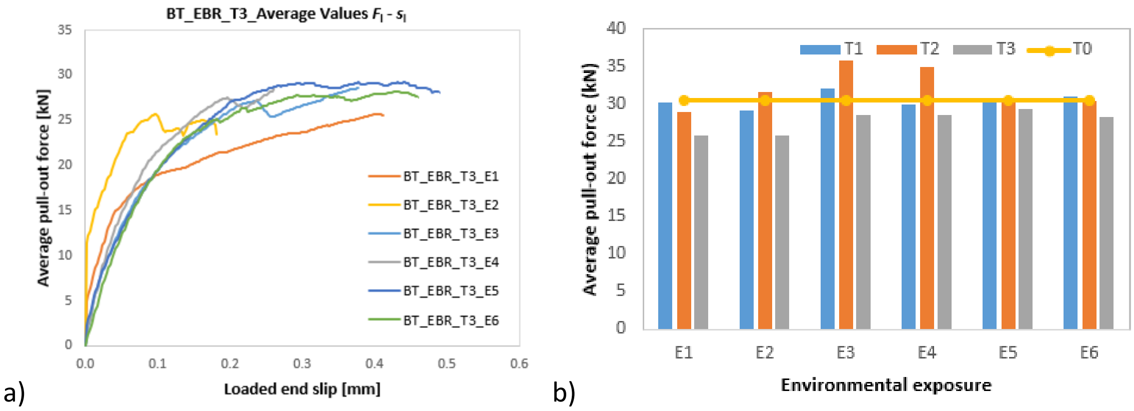


Figure 3. Results obtained from EBR systems for the different environments: (a) average curves for pullout force vs. slip for T3, (b) average values of pull-out force from T1 to T3

Looking at the results for NSM system in different environments (Fig. 4), it can be seen that specimens continuously immersed in water (E2) show the lowest maximum pull-out force, which can be attributed to the degradation caused by ingress of water through the constituent materials. On the other hand, the specimens collected in E6 exposed to airborne chlorides shows the highest pull-out force. After three years, a low degradation in E3-E5 and a slight increase in E1 and E6 can be noticed, while a significant degradation is observed in E2 (see Fig. 4b).

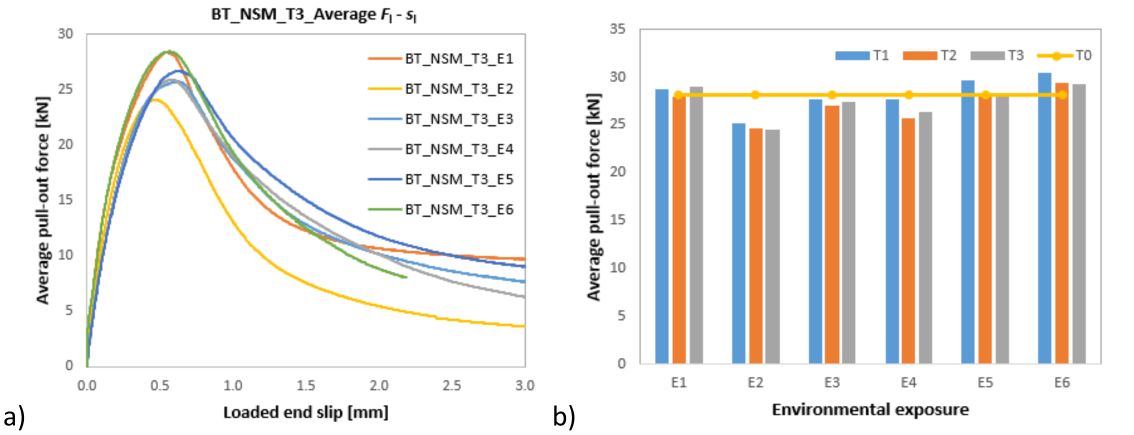


Figure 4. Results obtained from NSM systems for the different environments: (a) average curves for pull-out force vs. slip after T3, (b) average values of pull-out force from T1 to T3

In order to examine the cause of the strength variation in both EBR and NSM systems, the bond strength from EBR and NSM is plotted together with the tensile strength of the constituent materials (concrete, CFRP and adhesive) in Fig. 5 after 3 years. It can be seen that CFRP is immune against strength variation with time, while both concrete and adhesive tensile strengths tend to vary with time and environment. Mainly, the hybrid effect of the highest adhesive and concrete strength degradation is observed to cause the highest bond strength degradation for the specimens immersed in water (E2). Like what has been previously observed in [1], a comparable bond strength reduction is found between EBR and NSM systems when exposed to natural outdoor environments, except in E6.

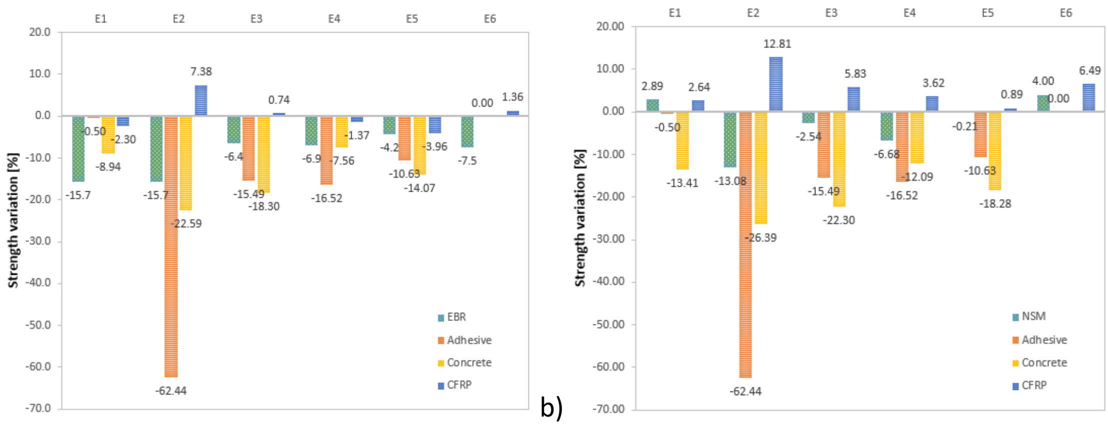


Figure 5. Comparison of strength variation between EBR (a) or NSM (b) bond strength and the constituent materials' strength in different environments after 3 years

Typical failure modes (FM) for both EBR and NSM systems are shown in Fig. 6. In the former system, the concrete cohesive failure is predominant in all environments, while in the latter the failure at CFRP-adhesive or at CFRP-adhesive combined with concrete cracking (or splitting) is predominant. In general, the failure mode is observed to vary with time and environments.

a)
b)

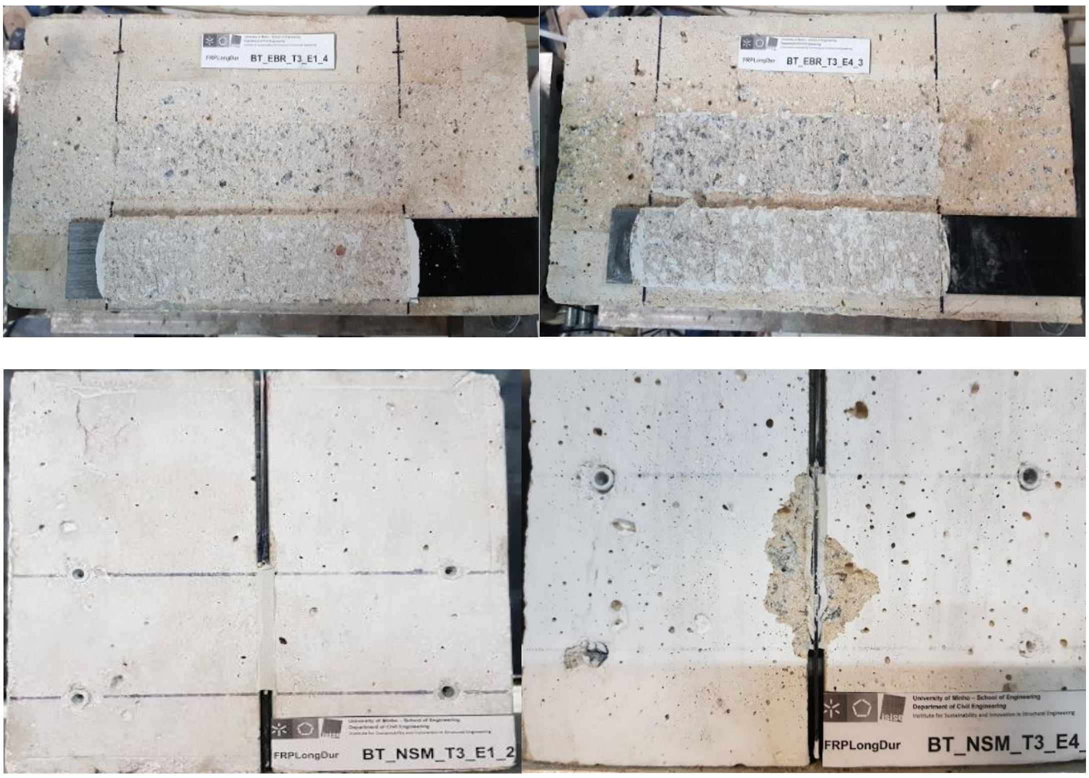


Figure 6. Typical failure modes observed after three years of exposure: (a) EBR specimens, (b) NSM specimens

4. Conclusions

In this work, pull-out bond tests were carried out for specimens strengthened according to EBR and NSM techniques. These specimens were previously placed in different environments (E1-E6) and then collected (each year) from these environments to be tested up to three years of exposure. The key findings from the tests are as follows.

1. Bond strength of both EBR and NSM systems had generally a slight variation after three years of natural exposure when compared to the value recorded at initial time. Besides, the maximum pull-out force in EBR specimens from outdoor environments tend to have a similar plateau after being exposed to different aggressive environments.
2. A slight increase in CFRP tensile strength is observed in all studied environments for NSM systems, while for the case of EBR a slight decrease is found in some environments. On the other hand, the tensile strength of both the concrete and adhesive showed a decrease in all environments, the most significant decrease being observed in specimens immersed in water.
3. The effect of strength variation of different constituent materials (CFRP, concrete, and adhesive) on the bond strength degradation in EBR and NSM systems is investigated. It is found that CFRP strength variation may have no effect on the EBR or NSM strength degradation after three years of exposure. However, the effect of adhesive and concrete strength degradation tends to lead to slight degradation of bond strength for the specimens immersed in water, exposed to carbonation, freeze-thaw cycles and high temperatures. This shows that the above environments might have significant effect on the adhesive and concrete properties with time. Particularly, the immersion of epoxy adhesive in water is observed to severely affect its strength.
4. The failure modes for EBR and NSM systems are generally different. Also, the FM are found to change with time. In general, the EBR system shows cohesive failure of concrete as the predominant failure, whereas for the NSM system the failure at CFRP-adhesive or CFRP-adhesive combined with concrete cracking (or concrete splitting) are the observed predominant failures.

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