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Durability of CFRP-concrete bond and corresponding involved materials under different natural environmental exposures for a period of four years

Aloys Dushimimana[1*], Luís Correia[1], Ricardo Cruz[1], Susana Cabral-Fonseca[2],
João Miguel Pereira[1], José Sena-Cruz[1]

[1]Department of Civil Engineering, University of Minho, ISISE/IB-S, Guimarães
[2]Research Officer, Materials Department, Laboratório Nacional de Engenharia Civil, Av. do Brasil 101, 1700-066 Lisboa, Portugal

* Corresponding author's email: aloysdushimimana@yahoo.fr

ABSTRACT

Ageing of interfaces between Carbon Fibre Reinforced Polymer (CFRP) laminates and concrete, applied according to externally bonded reinforcement (EBR) and near-surface mounted (NSM) techniques, and their constitutive materials was investigated. That is, experimental tests on the ageing of concrete, epoxy adhesive, CFRP laminate, and the CFRP-concrete interface were performed for specimens after being exposed to different natural outdoor environments to promote degradation due to carbonation, chlorides, freeze-thaw attacks, and high temperatures. Besides, tests of the reference specimens, kept under a control environment of 20 °C and 55% RH, and of specimens continuously immersed in water with a controlled temperature of 20 °C were also included for comparison purposes. The characterization of physical and mechanical properties of the involved materials, and the degradation of CFRP-concrete interface for the specimens strengthened according to EBR and NSM techniques were assessed for a study period of up to four years. The results generally showed significant variations in the properties of the concrete and adhesive while the ageing of CFRP was found insignificant in all the studied environments. Besides, slight variations of the bond strength were observed, probably as a result of changes in the constitutive materials' mechanical properties with time and environmental exposure.

Keywords: Strengthening technique, CFRP laminate, Epoxy adhesive, Natural ageing, Bond behaviour.

1 INTRODUCTION

Carbon Fibre Reinforced Polymer (CFRP) composites have been found to possess desirable properties that are ideal for application in civil engineering such as strengthening of existing RC structures [1]. CFRP composites are generally applied through externally bonded reinforcement (EBR) or near-surface mounted (NSM) techniques [2]. In the EBR technique, the CFRP is usually applied on the surface of a RC element to be strengthened, while in the case of the NSM technique, the CFRP is inserted in a groove pre-cut into the concrete cover. Past studies show that the premature failure due to debonding in the EBR system will lead to underutilization of the materials, e.g., in [3]. Regarding the NSM technique, the existing studies show that this type of strengthening can be an effective solution to increasing the cracking, yielding and ultimate loads of strengthened elements [4], and can provide superior benefits than EBR [5]. Typical predominant failure mode for NSM can be the debonding at the adhesive-CFRP interface [1].

Although a significant number of studies exist on the durability of the materials and bond performance, most of them were conducted under laboratory conditions by performing accelerated ageing tests, which makes the existing literature lack studies that address the behaviour of the specimens exposed to natural outdoor ageing. The present study contributes towards increasing the literature on the durability of the bond between CFRP-concrete and the involved materials by performing tests on the specimens that were exposed to different outdoor environments for up to four years.

2 MATERIALS AND METHODS

The materials, namely, concrete, adhesive and CFRP used to prepare different small-scale specimens for material characterisation and bond tests are described in this section.

2.1. Description of Materials

A C30/37 XC4(P) CL 0.40 $d_{\max}$ 12.5 S4 concrete was used to cast all the specimens from a single 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. Furthermore, the commercial cold-curing epoxy adhesive trademarked as *S&P Resin 220 epoxy adhesive* by *S&P® Clever Reinforcement Ibérica Lda. Company* was adopted as a bonding agent between the CFRP strip and the concrete substrate. The elastic modulus and ultimate strength of the adhesive were 7.1 GPa and 19.9 MPa, respectively. On the other hand, the CFRP strips, produced by the same company, with the trademark CFK 150/2000 were used in the strengthening of the specimens following EBR and NSM techniques. CFRP laminates with a cross-section of 10 × 1.4 mm^2 (L10) and 50 × 1.2 mm^2 (L50) were adopted for NSM and EBR techniques, respectively. The elastic modulus and ultimate strength of CFRP were approximately 170 GPa and higher than 2000 MPa. Further details on the properties of the adhesive and CFRP used can be found in [7].

2.2. Description of Specimens with EBR and NSM Strengthening Techniques

Regarding the EBR specimens, 42 concrete prisms, each with 400 × 200 × 200 [mm] and strengthened with two CFRP laminate strips of L50 applied in opposite faces (parallel to the casting direction), were prepared and exposed to six different environments. For all the specimens, a bond length of 220 mm was adopted, with 100 mm free from the extremity of the prism to avoid premature failure by concrete rip-off ahead of the loaded end.

Regarding the NSM specimens, 42 concrete cubic blocks, each with 200 mm of edge and strengthened with CFRP laminate of L10 applied along a bond length of 60 mm, were prepared and later exposed to different aggressive environments. The CFRP strip was inserted in the centre of a 15 × 5 [mm] groove pre-cut at the surface of the concrete block.

2.3. Description of Studied Environments

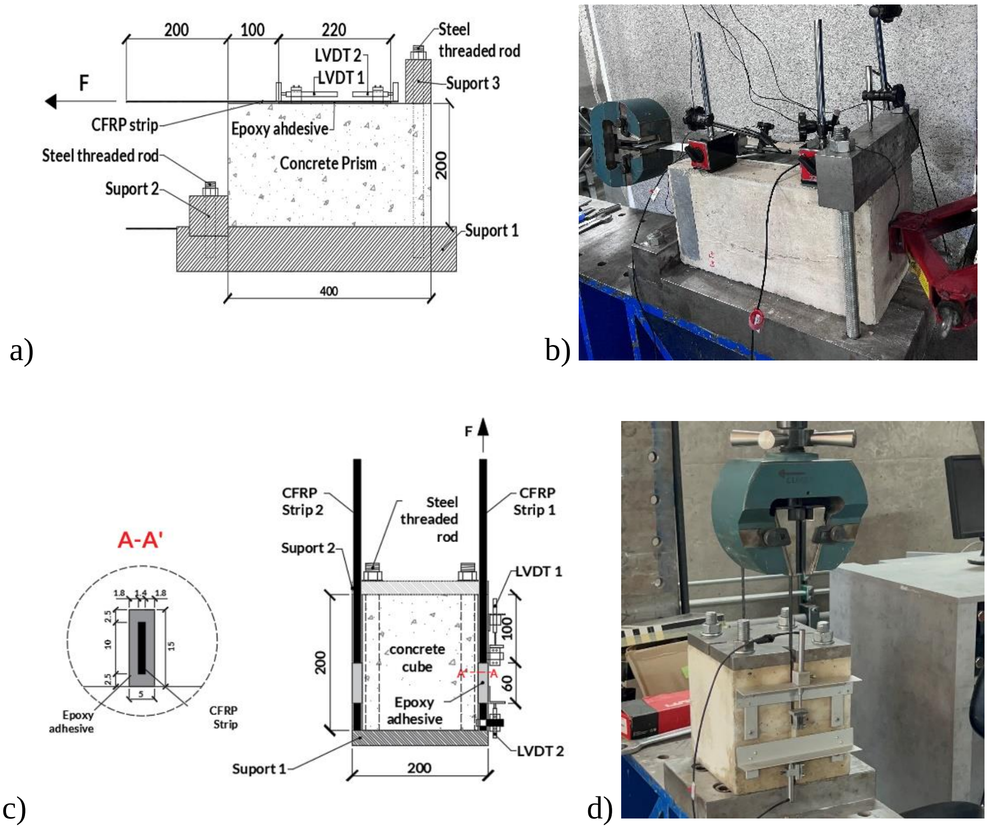
The specimens were placed in different environments (located in Portugal) in which they were exposed to different exposures (E1-E6) for up to four years. In environment E1, the specimens were placed in controlled hygrothermal conditions of 20 °C / 55% RH, while in E2 the specimens were continuously immersed in water under controlled temperature (approximately 20 °C). On the other hand, a set of specimens was placed in natural outdoor environments, namely environment E3 with high levels of concrete carbonation (experimental station near the International Airport of Lisbon), E4 with freeze-thaw attacks (i.e., specimens placed in ‘Serra da Estrela’, the highest mountain of Portugal), E5 with high elevated service temperatures and low relative humidity (i.e., specimens placed in the city of ‘Elvas’, characterized by high temperatures, especially during summer), and, E6 with high levels of chlorides concentration and relative humidity (i.e. specimens placed near the Atlantic ocean). Further details of the experimental stations can be found in [7]. Finally, each year, 2 EBR specimens and 2 NSM specimens were collected and tested at the laboratory of civil engineering, University of Minho. Details of the tests conducted in each of the consecutive four years (T1 to T4) are provided in the next section.

2.4. Description of the Tests

Compression and elastic modulus tests (for concrete specimens)
These tests were conducted on concrete cylinders as per NP EN 12390 13:2014 [8] to investigate the behaviour of concrete's compressive strength and elastic modulus with time and environmental exposure.

Tensile tests (for adhesive and CFRP laminate specimens)
Tensile tests on adhesive (as per EN ISO 527-2:2012 [9]) and CFRP (as per ISO 527-5:2009 [10]) specimens were conducted each year to assess the variation of the tensile strength of these materials with time and exposure. More details on the test setup and geometry can be found in [7].

Pull-out tests (for EBR and NSM specimens)
The pull-out 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 (see Fig.1.a, b). The tests were performed under displacement control at the loaded end with a rate of 2 μm/s. Further details of the test setup can be found in [6]. For NSM specimens, the geometry of the specimens and the respective test configuration is shown in Fig. 1 (c, d).



a) b)

c) d)

Figure 1. Pull-out tests: (a) specimen's geometry and test configuration (EBR), (b) photograph of the test (EBR), (c) specimen's geometry and test configuration (NSM), and (d) photograph of the test (NSM). Note: all units in [mm].

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.). Additional details can be found in [6].

3 RESULTS AND DISCUSSION

The results from pull-out tests performed on the EBR and NSM specimens are shown in Fig. 2. Typical average pull-out force *versus* loaded end slip relationship for EBR and NSM techniques (Fig. 2a, b) are used to compare the bond strength variation from year to year. An X_Y_Z_W notation is adopted for the legend of Fig.2a, b, where X: type of the performed test, Y: strenghening technique, Z: exposure duration, and W: exposure type. Regardless of the varitions observed in each strenghening technique, the typical responses reported in the literature can be found in these results.

Looking at the variations of the maximum pull-out force in all studied environments (see Fig. 2c, d), there are some noticeable fluctuations with time in each environment. The fluctuations tend to be more pronounced in EBR than NSM technique. A justification for such a high variation may be related to high values of the standard deviation intrinsically connected to the strengthening technique. When considering the outdoor environments (E3-E6), the highest bond strength reductions are found to be 7.5% for EBR specimens in E6 (airborne chlorides), and 9.2% for NSM specimens in E4 (freeze-thaw attacks). However, these reductions levels are not significantly high, and, in general, the bond strength degradation from all the studied environments can still be considered low, after four years of exposure.

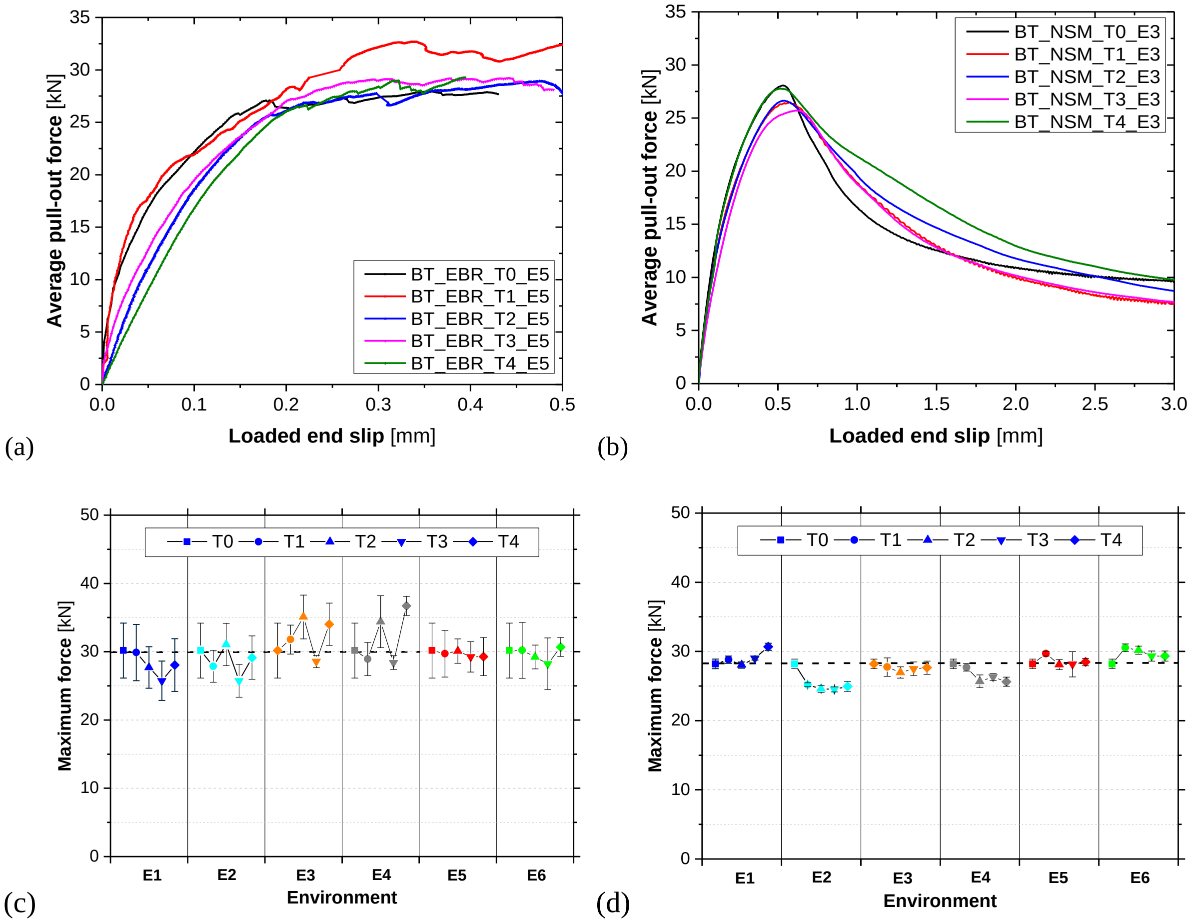


Figure 2. Bond test (BT) results for the variation of bond strength under different environmental exposures for a period of four years (Ti stands for year i, i = 0,...4): (a) EBR under elevated temperature exposure (E5) ; (b) NSM under carbonation attacks (E3), (c) EBR and (d) NSM under all studied environments.

According to the results from the tests conducted on the material characterisation (not shown here in this work due to lack of space), it was found that the variation of the material constituents' mechanical properties are also not consistent with the duration of exposure. Hence, it can be thought that the observed variations (although not high as previously mentioned) in each year mainly depend on the exposure time, type and severity along the year. Therefore, longer and severe exposures may be thought to result in more bond strength variations. In this regard, if the exposure in a certain year (T_i) is longer and harsher than that in the previous year (T_{i-1}), this can lead to higher bond strength degradation in T_i than in T_{i-1}, or lower degradation otherwise. This can be justified by the yearly-dependent bond strength fluctuations observed for each envoronment in Fig 2.c, d.

When analyzing the failure modes (FM) observed after performing the bond tests for up to four years, the FM tend to change from time to time, which can also be thought of as a result of the aforementioned variations. In general, the typical FM for both EBR and NSM systems are shown in Fig. 3. 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.

Figure 3. Typical failure modes observed after four years of exposure: (a) EBR specimens, (b) NSM specimens.

4 CONCLUSIONS

Experimental tests were conducted on the specimens that were collected from different stations where they were exposed to different environments for up to four years. The key findings from the tests are as follows:

1. After four years of exposure, there is still a low bond strength degradation for EBR and NSM specimens in some environments.
2. The experimental tests on materials (concrete, adhesive, and CFRP laminate) generally showed that the materials' strengths inconsistently vary with exposure duration and type. However, the tensile strength of CFRP laminate was found to slightly increase with time in all environments, while that of concrete and adhesive decreased in most of the studied environments.
3. The observed variation of bond strength over time is attributed to exposure type, duration, and severity, which led to fluctuations in the bond strength along the year. Additionally, exposure of specimens with EBR strengthening technique to airborne chlorides or NSM strengthening technique to freeze-thaw attacks is observed to have significant effects.

4. The failure modes observed show that EBR specimens tend to fail by a cohesive failure of concrete while NSM specimens show either CFRP-adhesive failure or CFRP-adhesive failure combined with concrete cracking or concrete splitting as the predominant failure modes.

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