Moisture effects on the bond strength of FRP-masonry elements

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Abstract

Moisture exposure has been observed to be one of the degrading environmental agents which affect the durability of the FRP-strengthened elements by changing the constituent material or bond properties. This paper presents the experimental investigation on the effects of moisture on the pull-off bond strength of GFRP-strengthened brick specimens. The specimens have been prepared following the wet lay-up procedure and exposed to constant moisture level of 100% R.H. at 23[C for eight weeks. The degradation in the bond performance has been investigated by performing pull-off tests on the conditioned specimens after four and eight weeks of exposure. The reversibility of the bond degradation has been also studied by storing some specimens in the laboratory conditions for one week after conditioning and before performing the pull-off tests. Comparative analysis has been performed and the main results are presented and discussed.

Keywords: Bond, degradation, FRP composite, Masonry, Moisture, Pull-off.

1. Introduction

External strengthening of masonry structures with fiber reinforced polymers (FRPs) has become a popular method in the last years. The efficiency and reliability of this strengthening technique depends intrinsically on the bond between the composite material and masonry substrate.

Although previous studies have shown the advantages of using FRP composites in strengthening the structures, the long-term performance of the bond behavior between the FRP composite and masonry support is still unknown. Therefore, investigation of the long-term durability of the bond is a key issue in performance prediction of the strengthened structures in their service life [1-2]. Extensive experimental studies have been performed on durability of bond in FRP strengthened concrete elements [3-6], while the available literature on FRP-masonry elements is still few, see e.g. [7-9].

The most common environmental factors which a strengthened element is exposed to during its service life are moisture variations, temperature variations, and alkaline and acidic environments. Moisture has been observed to be one of the main deteriorating agents in the bonded specimens. On the other hand, most of the environmental factors and deterioration processes are dependent on or coupled with moisture. Therefore a full understanding of deteriorating effects of moisture on the bond is a key step in durability modeling of FRP-strengthened masonry elements [10].

In general, it has been observed that FRP materials can tolerate environmental conditions with small reductions in mechanical properties, while the substrate and adhesive properties maybe highly deteriorated. Temperature variations and moisture exposure conditions have already been found to reduce bond shear strength, fracture energy, and peak slip in FRP strengthened concrete elements. Moreover, the force-displacement diagrams of the bond behavior have been observed to show a non-linear trend at a lower applied force. The change of the failure mode from the cohesive failure to the substrate-adhesive interface failure has also been observed. These changes are usually attributed to thermal incompatibility, extensive moisture plasticization of the polymer adhesive, and additional breakage of the interfacial bonds. Since the available experimental results on durability and degradation mechanisms in FRP strengthened masonry elements is still rare, performing comprehensive experimental and numerical studies is mandatory in this field.

The available information on FRP strengthened masonry elements shows that a significant reduction of bond strength is expected after wet-dry cycles (see e.g. [7] and [9]). Briccoli Bati and Rotunno [9] reported 17% reduction in shear strength in the CFRP strengthened masonry elements after 48 wet-dry cycles (10 hours of exposure in total). Aiello and Sciolti [7] reported 33% of reduction in shear bond strength in calcernite ashlar specimens strengthened with CFRP after 50 days of immersion in water.

In this paper, the preliminary results of a comprehensive research attributed to the durability of FRP-masonry components being carried out at University of Minho are presented. The aim of the tests performed in this stage was to investigate the bond behavior in FRP strengthened brick specimens subjected to moist environment. In this regard, the GFRP strengthened brick specimens were immersed in water and the changes in the bond strength was monitored after different periods of exposure. The effect of moisture conditioning was assessed using standard pull-off tests. Conclusions are presented regarding bond strength capacity, bond strength degradation with time, and observed failure modes.

2. Experimental tests

2.1 Test outline

The preliminary results of a comprehensive research attributed to durability of FRP-masonry components being carried out at University of Minho are presented. The aim of the tests performed in this stage was to investigate the bond behavior in GFRP-brick specimens subjected to different moisture conditions. Two different moisture conditioning protocols

have been considered, in addition to laboratory-stored control specimens. The latter provided the baseline against the results obtained from the conditioned specimens. The laboratory storage conditions were typical ambient conditions averaging 23°C and 60% RH.
The typical pull-off tests were used for investigating the tensile bond strength of the specimens. The following paragraphs describe the specimens, the moisture conditioning and the tests method considered in this study.

2.2 **Test specimens**

The specimens were made of hand-made masonry clay bricks with dimensions of 200x100x50 mm. Unidirectional glass fibers (MapeWrap G UNI-AX) were applied on the brick surface following a wet lay-up procedure. The surface of the bricks was cleaned and two layers of primer (MapeWrap Primer 1) were applied on the brick surface before application of the GFRP sheets. The GFRP sheets were glued on the prepared surface with a compatible epoxy resin (MapeWrap 31). The specimens were cured in the laboratory conditions for 15 days before exposure to moisture conditions.

2.3 **Material characterization**

The mechanical properties of masonry bricks were obtained according to the test standards UNI EN 771-1[11] and UNI EN 8942-3[12] in terms of compressive strength, f_{cb}, tensile strength, f_{tb}, and elastic modulus, E_b.
Regarding the composite materials, the mechanical properties of GFRP coupons were obtained according to ISO 527-1[13] in terms of tensile strength, f_{tf}, and elastic modulus, E_f.
Mechanical and thermal properties of the epoxy resin were investigated on samples previously cured for 15 days at room temperature. The basic tensile properties were obtained following the standard tensile tests, ISO 527-1[13]. The glass transition temperature (T_g) of the epoxy resin was obtained by means of the DSC (Differential Scanning Calorimetry) method. The epoxy samples were cured at room temperature 15 days before performing the tests. The thermal scans were carried out between 5°C and 200°C with a heating rate of 10°C/min. The T_g was calculated as the mean value of four tests.
Experimentally determined material properties of the bricks and composite material are presented in Table 1. Here, C.o.V. is the coefficient of variation.

(a) (b) (c)

Figure 1. Material characterization tests; (a) Brick specimens; (b) GFRP coupons; (c) Epoxy resin specimens.

Table 1. Material properties.

Masonry brick			C.o.V.(%)
Average compressive strength	f_{cb} (MPa)	19.8	2.5
Average tensile strength	f_{tb} (MPa)	1.95	4.0
Average elastic modulus	E_b (GPa)	1.12	3.8
GFRP coupons			
Average tensile strength	f_{tf} (MPa)	1350	11.9
Average elastic modulus	E_f (GPa)	77.1	5.3
Ultimate deformation	ε (%)	1.86	20.2
Thickness	t (mm)	0.17	-
Epoxy resin			
Average tensile strength	f_{tm} (MPa)	31.2	5.4
Average elastic modulus	E_m (GPa)	1.89	5.85
Average shear modulus	G_m (GPa)	1.64	6.1
Glass transition temperature	T_g (° C)	70	3.2

2.4 Moisture conditioning

The selected exposure is intended to investigate the influence of moisture on the bond behavior in FRP-strengthened masonry components. The test specimens were exposed to constant condition of 100% R.H. at 23° C for duration of 4 and 8 weeks. The 100% R.H. at 23° C was provided by immersing the specimens in a water tab in a temperature controlled environment.

For each exposure condition, five specimens were tested immediately after the exposure and another five were stored in laboratory conditions for one week before performing the pull-off tests. In the latter case, the aim was to investigate the reversibility of the observed degradation after moisture conditioning. Two pull-off tests were performed on each specimen resulting in ten tests in total for each moisture conditioning. Five specimens were also tested without any moisture conditioning to provide a baseline for the moisture exposed specimens.

The complete conditioning plan is shown in Table 2.

Table 2. Conditioning program.

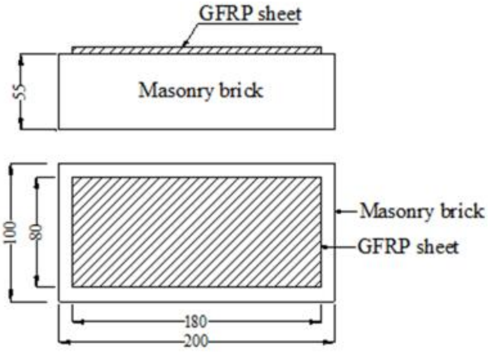
No. of specimens	Conditioning
5	No conditioning
5	100% R.H., 23°C (4 weeks)
5	100% R.H., 23°C (4 weeks)+laboratory conditions (1 week)
5	100% R.H., 23°C (8 weeks)
5	100% R.H., 23°C (8 weeks)+laboratory conditions (1 week)

2.5 Pull-off tests

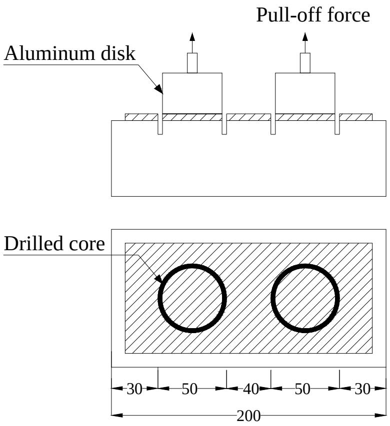
The pull-off tests were performed based on a partial coring technique. In this method the tensile load is applied to the partial core through an aluminum disk bonded to the overlay with a structural adhesive, see Figure 2. A loading device with a reaction frame applies the tensile force at a constant rate to the aluminum disk.

In this study, 50 mm cores with an approximate depth of 10 mm were drilled on the brick surfaces by means of a rotary core cutting drill with diamond bits. To avoid damage in the bricks, special care has been devoted to ensure uniform pressure when the core is being drilled. Afterwards, the aluminum disks were glued on the core surfaces by means of a structural adhesive.

The loading were applied with a DYNA Z15 instrument at a rate of 0.05±0.01 N/mm^2S^{-1}. This equipment has a capacity of 16 KN and an accuracy of 2%.



(a)



(b)

(c)

Figure 2. (a) Test specimen; (b) schematic of the pull-off test; (c) test setup.

3. Test results and discussion

Average bond strengths obtained from 10 pull-off tests for each conditioning type are normalized by the baseline specimens in Figure 3. It can be seen that a relatively large reduction is found in the bond strength after four and eight weeks. On the other hand, the bond strength was not recovered significantly after one week laboratory storage, which can be due to the irreversibility of the observed degradation in the bond strength.

The mean values of the bond strengths and their corresponding standard deviation and coefficient of variation (C.o.V.) are presented in Table 3. A relatively large scatter is found on the bond strength values which is common in this type of experimental test [14]. The strength reductions comparing to the baseline specimens are also presented in this table. In particular the reduction of the strength was 15% and 23% for four and eight weeks of immersion in

water, respectively. It can be seen that the reduction rate has been decreased in the period of four to eight weeks of exposure comparing to the period between commencement of the test and four weeks. Moreover, the bond strength was recovered about 3% in both exposure periods, after one week of laboratory storage.
As it can be observed in Figure 4, the reduction in the bond strength during the investigated period can be expressed with a linear formula. However, since the reduction rate has been reduced with time increment using an exponential decay curve with respect to the immersion time seems more reasonable, Eq. (1). Although, performing experimental tests with longer immersion times is necessary for a better understanding of the decay trend.

$$\frac{P}{P_{base}} = e^{-(2.1E-4)t} \qquad (1)$$

where P is the bond strength after t hours of immersion in water and P_{base} is the baseline bond strength.
A typical failure mode of fracture in the upper layer of the bricks was observed in all the dry specimens, see Figure 5. However, the failure was mainly observed in primer-brick interface in the moisture conditioned specimens.

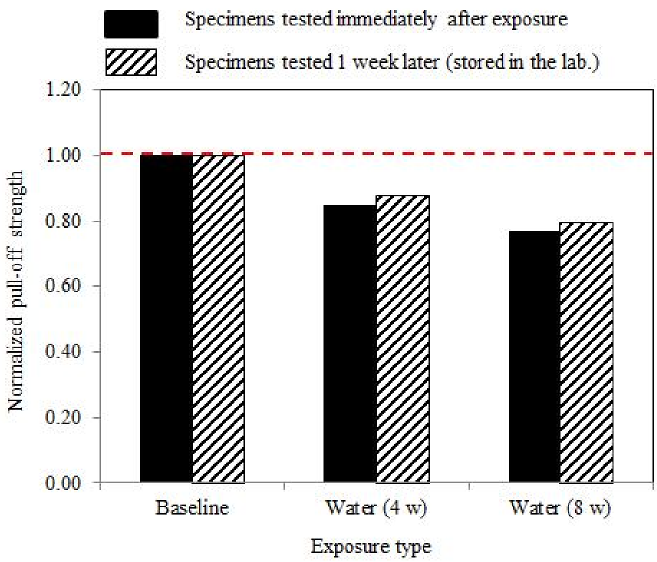


Figure 3. Average pull-off bond strength of specimens exposed to different moisture conditions.

Table 3. Average values of pull-off strengths and their variation after moisture conditioning.

Condition	Non-conditioned	Water (4 w)	Water (4 w)+ Lab. (1 w)	Water (8 w)	Water (8 w)+ Lab. (1 w)
Average	0.90	0.75	0.78	0.68	0.71
Std. Dev.	0.11	0.10	0.12	0.15	0.13
C.o.V.	7.8	13.3	15.4	21.8	17.8
Strength reduction (%)		15	12	23	20

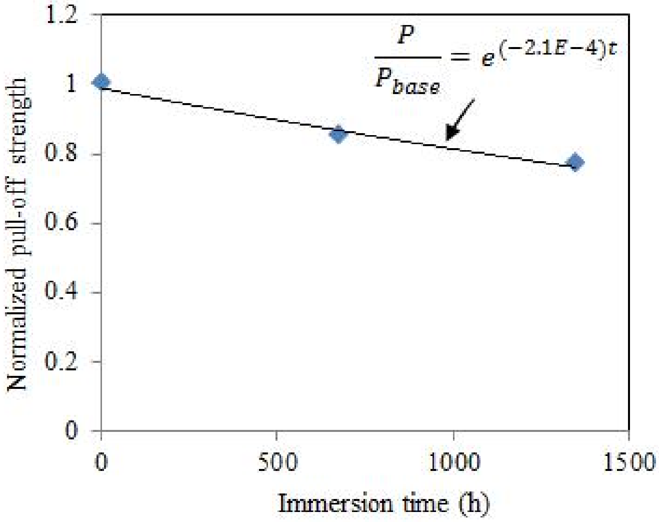


Figure 4. Bond strength decay with water immersion time.

Figure 5. Typical failure mode in the specimens.

4. Conclusions

The results of the preliminary tests performed on GFRP strengthened masonry elements exposed to moisture environment presented. The specimens were exposed to 100% R.H. at 23° C for four and eight weeks. The non-conditioned specimens provided the baseline against the moisture exposed specimens. The specimens were tested immediately after the exposure. The reversibility of the bond strength degradation has also been studied by storing some specimens in the laboratory conditions before performing pull-off tests.

In particular a large reduction of bond strength was observed in the conditioned specimens being 15% and 23% for the specimens immersed in water for 4 and 8 weeks, respectively. The bond strength recovered 3% for the specimens that were stored in the laboratory conditions before performing the pull-off test. Based on the observed degradation of the bond strength in time, an exponential decay relation was proposed.

A typical failure mode of fracture in the upper layer of the bricks was observed in all the dry specimens. However, the failure was mainly observed in primer-brick interface in the moisture conditioned specimens.

The results obtained showed that moisture can reduce the bond strength of the FRP-masonry elements largely within a short period of exposure (two months). However, further investigation is required to validate the obtained results.

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6. References

[1] Hollaway, L.C., “A review of the present and future utilisation of FRP composites in the civil infrastructure with reference to their important in-service properties.”, *Construction and Building Materials*, Vol 24, No 12, December 2010, pp. 2419-45.

[2] Karbhari, V.M., Chin, J.W., Hunston, D., Benmokrane, B., Juska, T., Morgan, R., Lesko, J.J., Sorathia, U., Reynaud, D., “Durability gap analysis for Fiber-Reinforced Polymer composites in civil infrastructure.”, *ASCE Journal of Composites for Construction*, Vol. 7, No. 3, August 2003, pp. 238-47.

[3] Dai, J.G., Yokota, H., Iwanami, M., Kato, E., “Experimental investigation of the influence of moisture on the bond behavior of FRP to concrete interfaces.” *Journal of Composites for Construction*, Vol. 14, No. 6, November/December 2010, pp. 834-44.

[4] Silva, M.A.G., and Biscaia, H.C., “Effects of exposure to saline humidity on bond between GFRP and concrete.”, *Composite Structures*, Vol. 93, No. 1, December 2010, pp. 216-24.

[5] Benzarti, K., Chatatigner, S., Quiertant, M., Marty, C., Aubagnac, C., “Accelerated ageing behavior of the adhesive bond between concrete specimens and CFRP overlays.” *Construction and Building Materials*, Vol. 25, No. 2, February 2010, pp 523-38.

[6] Tuakta, C., and Buyukozturk, O.,“Deterioration of FRP/concrete bond system under variable moisture conditions quantified by fracture mechanics.” *Composites: Part B*, Vol. 42, No. 2, March 2011, pp. 145-54.

[7] Aiello, M.A., and Sciolti, M.S., “Influence of environmental agents on bond between FRP reinforcement and calcarenite ashlars.” *4th International conference of Structural Analysis of Historical Constructions*, November 2004, pp. 875-81.

[8] Desiderio, P., and Feo., L., “Durability evaluation of EBR CFRP strengthened masonry structures.” *in Proceedings of BBFS*, 2005, pp. 481-88.

[9] Briccoli Bati, S. and Rotunno, T., “Environmental durability of the bond between the CFRP composite materials and masonry structures.” *Historical Constructions*, 2001, pp. 1039-46.

[10] Ouyang, Z. and Wan, B., “Experimental and numerical study of moisture effects on the bond fracture energy of FRP/concrete joints.”, *Journal of Reinforced Plastics nad Composites*, Vol. 27, No. 2, January 2008, 205-23.

[11] UNI EN 771-1, “Specification for masonry units. Part1: clay masonry units.”, *Ente Nazionale Italiano di unificazione*, 2005, (In Italian).

[12] UNI EN 8942-3, “Clay bricks and blocks. Test methods.”, *Ente Nazionale Italiano di unificazione*, 1986, (In Italian).

[13] EN ISO 527-1, “Plastics-determination of tensile properties- Part 1: general principles.”, ISO 527, 1993.

[14] Bonaldo, E., Barros, J.O., Lourenço, P.B., “Bond characterization between concrete substrate and repairing SFRC using pull-off testing.”, *International Journal of Adhesion and Adhesives*, Vol. 25, No. 6, December 2005, pp. 463-74.