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BOND BEHAVIOUR DEGRADATION BETWEEN FRP COMPOSITES AND BRICK MASONRY

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1. Introduction

Fibre-reinforced polymer (FRP) composites are being more and more used for rehabilitation or strengthening of existing civil structures. FRP composite materials are an interesting solution due to a series of advantages, namely related with high tensile strength and stiffness properties, ease of application and low weight, adaptability to curved substrates and corrosion resistance. Nevertheless, the use of FRP is often conditioned by strain limitations, related to its brittleness. Typically, FRP composite materials are externally bonded to the substrate following the wet lay-up technique. The reinforcing fibres are responsible for carrying the load while the polymeric resin matrix transfers it between the fibres and the substrate through adhesion, controls crack propagation and protects the fibres against environmental attacks.

Schwegler [1] and Saadatmanesh [2] were the first researchers to study the use of FRP for the strengthening of masonry structures. Since then, FRP composites have been extensively used to strengthen masonry components as walls, vaults, columns, including also cultural heritage constructions [3]. It is recognized that the most critical aspect controlling the success of FRP application is debonding of the reinforcing system from the substrate, which occurs in a brittle manner. Given this, the success of externally bonded FRP composites depend largely on the capacity of the FRP-substrate interface in developing an efficient load transfer mechanism [4].

The most relevant mechanical actions to be considered in externally bonded FRP strengthening systems are actions acting normal and parallel to the surface of the substrate, which mobilize the tensile bond strength and the shear bond strength, respectively. As for actions normal to the surface, the ASTM C1583 standard [5] is normally used to estimate the pull-off strength. As for actions parallel to the surface, much more frequent in current strengthening applications, specific design rules are still far from a general agreement. A comprehensive study of the debonding mechanisms found in FRP-strengthened masonry elements and the identification of important parameters for harmonizing laboratorial procedures are provided in [6]. It is worth noting that the only two guidelines internationally available, namely the CNR-DT 200 R1 [7] and the ACI 440.7R-10 [8], provide information about bond behaviour on masonry based on results obtained from studies on reinforced concrete.

Nowadays, one of the major issues associated to the use of externally bonded FRP composites for strengthening concrete and masonry structures is durability, in particular the aspects associated with fire and environmental agents. While several experimental studies exist on the effects of moisture and temperature exposures on the bond performance of external FRP-strengthened concrete elements, only a few studies have been performed on FRP-strengthened masonry. In addition, considering that the combined effect of different environmental agents may accelerate the bond degradation [9], it is of critical importance to characterize the bond degradation of FRP-strengthened masonry components under multiple effects, e.g. moisture and temperature (hygrothermal) exposure.

This paper briefly revises some of the most relevant environmental agents and their effect on the durability of FRP-strengthened constructions, followed by the discussion of a comprehensive series of accelerated ageing tests (water immersion and hygrothermal exposure) recently carried out on external GFRP-strengthened masonry units and respective constituent materials at University of Minho.

2. Environmental degradation agents

The mechanical performance of FRP strengthening systems is daily affected by exposure to certain degrading agents. The level of deterioration depends on a series of factors, in particular on the type of fibres and resin, manufacturing process and harshness of exposure conditions. Degradation is typically grouped into physical, chemical and mechanical mechanisms. These three fundamental mechanisms may interact with each other, with cumulative or subtractive effects on the material performance [10]. The interaction between the substrate and the reinforcing system in FRP-strengthened structures makes the long-term performance assessment even more difficult.

The degradation in externally bonded FRP systems occurs due to deterioration in the matrix, deterioration in the fibres or deterioration of the bond properties at the FRP-substrate interface. Deterioration of the substrate may also occur in some cases. The most relevant environmental agents concerning the deterioration of external FRP-strengthened structures consist of moisture, thermal (including freeze-thaw) cycling, alkaline environment, creep, fatigue and ultraviolet light [9]. Each of these agents may significantly affect some materials while producing negligible degradation in others. As an example, glass and aramid fibres are sensitive to moisture, while carbon fibres are relatively inert to such environment agent.

The degradation mechanisms of FRP composite materials include both physical and chemical aspects. The physical ageing is referred to reversible changes in material properties, mostly dependent on temperature, but these changes can be recovered upon drying. On the other hand, chemical ageing occurs for longer exposure periods and normally comprises irreversible modifications in the resin, the fibre and the resin/fibre interface [9].

The most pertinent aspects associated with deterioration in the material components (fibres and resin) and degradation in the bond between the FRP and the substrate, under moisture and thermal exposures, are briefly revised.

2.1 Moisture

Relevant research work has been done about moisture effects on the performance of FRP composites, typically related with the strength properties of the composite systems [9]. It is known that resins are sensitive to moisture. Degradation of resins due to water is originated by two mechanisms of different nature. Initially, the water penetration causes a reversible physical ageing (termed as plasticization), leading to a decrease of the mechanical properties of the resin and of its glass transition temperature (T_g) [11]. In addition, if a long-term exposure to water occurs, then irreversible chemical ageing (termed as hydrolysis) and micro-cracking can also take place [9].

Aramid and glass and fibres can suffer degradation when exposed to moisture. It was observed that moisture adsorption by the fibres originates a decrease in its surface energy, leading to a decrease of the cohesive strength of the fibres. Moreover, moisture attack can accelerate the rate of crack growth in glass fibres [12].

Moisture also affects the performance of the fibre-matrix interface by originating a decrease of the interfacial strength properties through chemical processes and due to the swelling of the resin caused by moisture absorption [13]. Even though carbon fibres are generally seen as not being affected by most environmental agents, its inertness does not

apply to the fibre-matrix bond and to the matrix itself, both of which can effectively be deteriorated by environmental exposure [9].

If compared with resins, FRP composites are less prone to degradation caused by moisture and thermal effects because of the presence of fibres. Nevertheless, the existence of voids and other non-uniformities in specimens prepared according to the wet lay-up technique increases the vulnerability of the composite material to moisture uptake, which then may result in its mechanical degradation [14]. Consequently, the degradation originated by moisture to resin, fibre and fibre/matrix interface may lead to significant reductions of the mechanical properties of composite materials. It is worth noting that the use of appropriate coatings can increase the durability of FRP composites subjected to moisture exposure when compared to conventional materials [9].

2.2 Thermal cycling

It is known that temperature causes a viscoelastic response in resins, which tend to soften and lose shear capacity with increased temperature exposure. In particular, a temperature increase above T_g originates an important reduction of resins' performance. As an example, the FIB report [15] suggests that T_g should be 20 ℃ above the maximum air temperature in shade, with a minimum value of 45 ℃. On the other hand, a temperature increase below T_g may increase the susceptibility to moisture absorption and also to post-curing (if the temperature is above the ambient curing temperature).

In general, fibres are resistant to temperature exposure, thus any degradation in composite materials due to temperature exposure can be assigned to the degradation of the matrix or of the fibre-matrix interface. In turn, thermal incompatibility in FRP composites and FRP-strengthened elements is a key issue that should be considered in the presence of thermal cycling [9]. The thermal incompatibility is generated by the considerable difference in terms of thermal expansion between the fibres and the polymer matrix and/or between the reinforcing system and the substrate [16]. Such differences create thermal stresses at the fibre-matrix and matrix-substrate interfaces, thus reducing bond properties in FRP-strengthened elements [17].

2.3 Freeze-thaw cycling

Usually, freezing and thawing exposures do not affect fibres, however both resin and fibre-resin interface can be affected [18]. Exposure to freeze causes embrittlement of the resin, resulting in strength and stiffness increments, but decreases damage tolerance. De-icing salt in wet conditions with subsequent freeze-thaw cycling can lead to the occurrence of micro-cracks and progressive degradation due to crystal formation and increased salt concentration. Freeze-thaw cycling can also originate micro-cracking growth in the presence of previous moisture degradation [9]. In addition, experimental results seem to indicate that the combined effect of moisture, freeze-thaw cycling and sustained loading accelerates the bond degradation [18].

From the available studies in literature and in spite of the use of distinct test procedures and different degradation trends found, it can be considered that temperature exposure reduces the bond performance of externally bonded FRP systems to a certain degree.

3. Experimental program

The effect of moisture and hygrothermal exposure on the bond behaviour of GFRP-strengthened masonry bricks was analysed recently through a series laboratorial tests carried out at University of Minho. The possible interfacial bond degradation was assessed by means of conventional pull-off and single-lap shear bond tests performed after different periods of

exposure to water immersion and hygrothermal conditions. Complementary, specimens from all material components were also submitted to the same environmental conditions in order to detect possible degradation effects in their mechanical properties.

3.1 Materials and properties

Specimens from brick, primer, epoxy resin and glass fibres were tested to characterize their properties prior to any damage induced by the environmental agents described above. Extruded solid clay bricks were used as substrate. Primer and epoxy resin specimens were cured for a period of two months in laboratory conditions. Previous studies have shown that undercure may have a relevant impact in increasing the moisture susceptibility of epoxy resins cured at ambient temperature [19]. A series of mechanical tests on material components were performed, namely compressive tests on brick specimens, tensile tests on dog-bone shaped primer and epoxy resin specimens, and tensile tests on GFRP coupons. The glass transition temperature of the trimer and epoxy resin (T_g) were characterized following the differential scanning calorimetry (DSC) method. All the details in terms of specimens' size and preparation, test setups and test procedures as well as relevant standards employed are provided elsewhere [20, 21].

Table 1 lists the average values of the properties assessed, measured on five specimens, and respective coefficients of variation (CoV). These results were also used as reference for investigating the effect of exposure conditions on the evolution of material properties. The results found for primer, resin and GFRP coupons are in agreement with those found in literature.

Table 1. Properties of the materials.

Material	Average value	CoV (%)
Solid clay brick		
Compressive strength (f_{cb}; MPa)	15.38	8
Primer		
Tensile strength (f_{tp}; MPa)	42.04	18
Young's modulus (E_p; GPa)	2.85	10
Glass transition temperature (T_{gp}; ºC)	56.3[1] / 61.7[2]	--
Epoxy resin		
Tensile strength (f_{tr}; MPa)	58.84	4
Young's modulus (E_r; GPa)	2.86	8
Glass transition temperature (T_{gr}; ºC)	54.2[1] / 66.1[2]	--
GFRP coupons		
Tensile strength (f_{tf}; MPa)	1185.14	8
Young's modulus (E_f; GPa)	58.84	5

[1] obtained from the first heating scan; [2] obtained from the second heating scan

3.2 Pull-off and shear bond tests

Specimens consisted of single solid clay bricks strengthened with unidirectional GFRP sheets following the wet layup procedure. Specimens were prepared with specific geometrical details for pull-off tests (a total of 28 specimens) and single-lap shear bond tests (a total of 70 specimens), as illustrated in Fig. 1. The bricks were initially cleaned and dried in oven at

100 ℃ for 24 h. Afterwards a primer layer was applied on the bricks' surfaces and then a layer of epoxy resin was applied followed by impregnation of the glass fibres with resin with subsequent application to the bricks' surfaces. A slight pressure was carefully applied on the GFRP surface with a roller in order to remove any possible air voids present at the interface.

Two sets of specimens were prepared for shear bond tests in order to investigate the effect of surface preparation on the bond degradation. A first group was prepared without application of any mechanical treatment of bricks' surfaces (standard preparation, here termed as ORG-specimens). A second group had the bricks' surfaces grinded for about 5 mm with a mechanical saw before application of the GFRP (denoted as GR-specimens).
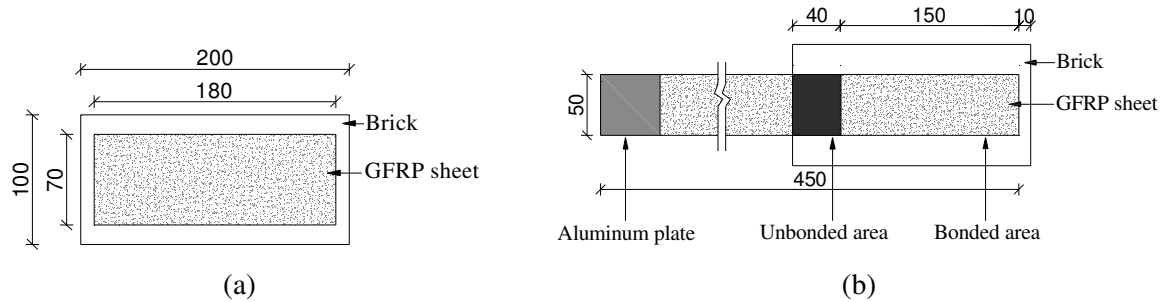

Fig. 1.   Schematic geometry for bond characterization (dimensions in mm): (a) pull-off test; (b) single-lap shear bond test.

The pull-off tests were performed following ASTM C1583 [5]. A 50 mm diameter partial core was drilled on the test zone with an approximate depth of 5 mm, as depicted in Fig. 2(a). Then, aluminium disks were glued on the GFRP surface. A servo-controlled actuator was used to apply tensile load to the disks at a displacement rate of 0.2 mm/min under monotonic regime until debonding of the disk from the specimen. The single-lap shear bond tests were carried out under displacement control at a rate of 0.3 mm/min, see Fig. 2(b). Both the applied force and the relative slip between the GFRP and the brick, measured with LVDTs placed at the free and loaded ends and at the middle of the bonded length, were recorded. A detailed description of the bond tests setups and procedures can be found in [20, 21].

Pull-off tests and single-lap shear tests were also performed on specimens before starting the exposure tests (untreated condition) in order to generate reference values.
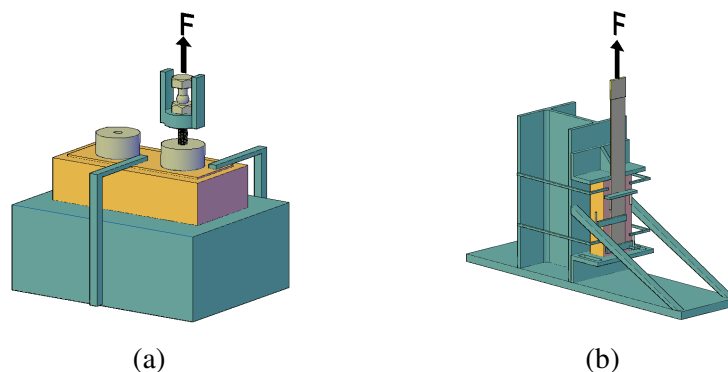

Fig. 2.   Schematic test setups for bond characterization (dimensions in mm): (a) pull-off test; (b) single-lap shear bond test.

3.3 Water immersion

Specimens were immersed in water tanks for twelve months after two months of curing in laboratory conditions. The water was kept at a controlled temperature of 20 ℃. The tanks

were solely used for these tests and were filled with pure water tap, which was changed and cleaned on a periodic basis. Based on the analysis reports from the water supplier, the water pH was in the range of 6.7 - 7.9 (with $SO_4 < 10$ mg/L, $Mg < 1$ mg/L, $Cl < 10$ µg/L and $Ca = 6$ mg/L) along the immersion period.

Specimens were taken periodically from the water tanks, visually inspected and weighed. Materials' mechanical tests and bond tests (pull-off and single-lap) were then performed on the specimens.

3.4 Hygrothermal exposure

Specimens were exposed to specific hygrothermal conditions inside a climatic chamber after 100 days of curing in laboratory conditions. The exposure included a sequence of 6 hours temperature cycles ranging from +10°C to +50°C, with constant relative humidity of about 90%, see Fig. 3. In fact, the relative humidity inside the climatic chamber dropped to 60% when the temperature reached +10°C and then went back to 90% after a short period. This phenomenon is a usual situation as it's due to the complexity of controlling the relative humidity at low temperature levels.

Five specimens of each type were taken from the climatic chamber every month (around 120 cycles and always when the chamber temperature was stabilized at 10°C) in order to perform post-ageing tests. Specimens were weighed and visually inspected, and then stored in a controlled environment room (20°C temperature and 60% R.H.) for 7 days before testing. The post-ageing tests included materials' mechanical characterization, DSC tests and bond characterization tests. The DSC tests were performed on primer and epoxy resin samples taken from tensile test specimens and on epoxy resin samples taken from delaminated FRP sheets after the debonding tests.
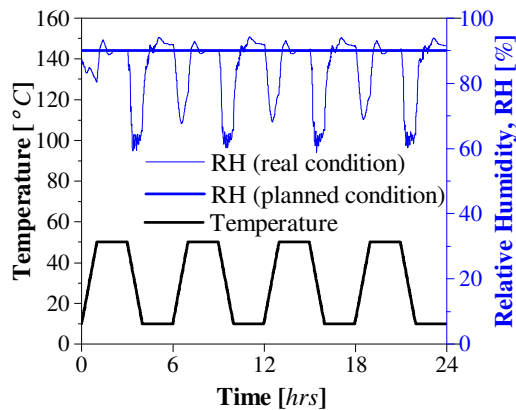

(a)   (b)

Fig. 3.   Hygrothermal exposure: (a) temperature and relative humidity conditions; (b) climatic chamber.

4. Effect of water immersion

All specimens were visually inspected upon removal from the water tank to record any visible change or interfacial delamination. It was possible to identify visually a colour change in the GFRP sheets in both groups of specimens before and after immersion, see Fig. 4. This change can be a consequence from oxidation of the ether and nitrogen groups in epoxy resin [22]. Still, no interfacial delamination was observed in any of the aged specimens.
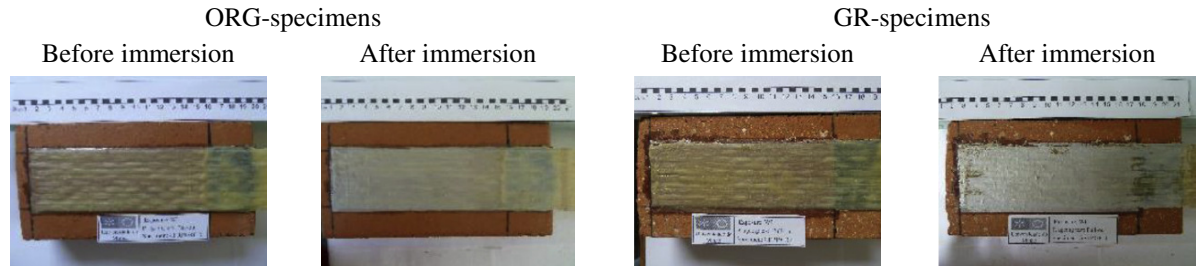
ORG-specimens		GR-specimens	
Before immersion	After immersion	Before immersion	After immersion

Fig. 4.   Typical photos of GFRP specimens taken before and after water immersion.

4.1 Post-ageing tests on components

The changes in the compressive strength of the bricks with water immersion exposure are shown in Fig. 5(a). A reduction of the brick compressive strength was recorded, with a total reduction of about 12% after twelve months of immersion. The results also show that the degradation observed cannot be reversed upon partial drying, although brick specimens lost the whole absorbed water after drying one month in laboratory conditions (around 0.3% mass water still remained after one month). The degradation observed experimentally can be due to chemical reactions of water with brick components. These reactions may lead to the formation of microcracks in brick specimens and thus reduction of mechanical properties.

Primer specimens suffered a tensile strength reduction of 10% during the twelve months of water immersion, regardless of fluctuations in the middle period, see Fig. 5(b). The primer specimens showed also larger peak strains (strain at peak stress) after immersion when compared with reference specimens, see [20] for details.

The tensile strength variation of epoxy resin specimens is depicted in Fig. 5(c). Its value for "partially dried" specimens decreased up to about 20% in the first five months and no more significant degradation was observed. The peak strain decreased with water immersion, resulting in about 11% reduction after twelve months of exposure. The observed degradation effects in the epoxy resin specimens were due to absorption of water, which is known to cause changes in the resin's structure and thus on its mechanical properties [17]. A mechanical comparison between the "partially dried" and "wet" epoxy resin specimens shows that the mechanical strength of "partially dried" specimens is slightly enhanced only in the first months of immersion [20]. Further drying may improve this enhancement.

The variation of the tensile strength of GFRP coupons is illustrated in Fig. 5(d). The maximum tensile strength dropped about 27% after four months of water immersion followed by a slight degradation until twelve months (reaching 37% loss). A relatively large coefficient of variation (CoV) was measured in the tensile strength of GFRP coupons, which is usual in wet lay-up manufactured specimens. The reduction of peak strain of GFRP coupons followed trends similar to those of the tensile strength [20]. It is known that water attack can originate corrosion of glass fibres and degradation of the fibre/epoxy interface [12, 23], which can lead to a reduction of the mechanical properties in GFRP coupons.

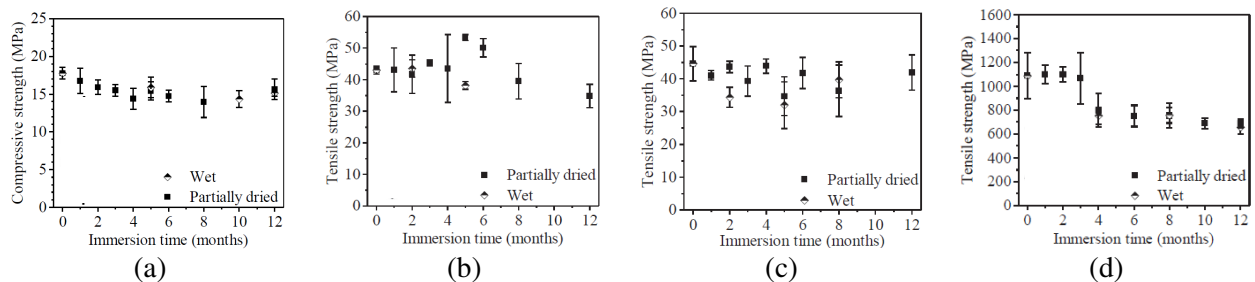(a)   (b)   (c)   (d)

Fig. 5.   Evolution of mechanical properties with immersion time: (a) brick's compressive strength; (b) primer tensile strength; (c) resin tensile strength; (d) coupons tensile strength.

4.2 Post-ageing tests on pull-off specimens

The variation of pull-off bond strength with immersion time is presented in Fig. 6(a). As indicated before, pull-off tests were performed on ORG-specimens only. A severe degradation was observed during the first four months of immersion. Subsequently, the pull-off strength reached a plateau with a total loss of 34% in twelve months.

Partial drying of the specimens did not have any reversible effect on the bond strength. The failure mode observed in all specimens, including "wet" and "partially dried" ones, was cohesive failure with the fracture inside the substrate (brick). Nevertheless, the thickness of the detached brick material continuously decreased with rise of immersion time until reaching the primer impregnated depth, as reported in [19].
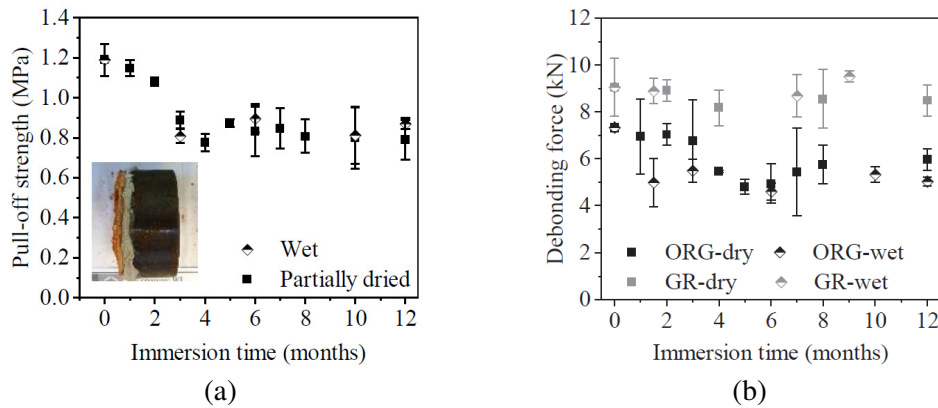

Fig. 6.   Variation of bond strength with immersion time: (a) pull-off tests; (b) single-lap shear tests.

4.3 Post-ageing tests on shear bond specimens

The evolution of the debonding force with immersion time is illustrated in Fig. 6(b) for both specimen types. An important strength degradation occurred in ORG-specimens during the first six months of immersion (around 33% loss). Afterwards, no bond degradation was observed and it seems that the shear bond strength has reached a plateau.

A minor improvement of the debonding force of ORG-specimens upon drying is observed during the first months of immersion. However, this enhancement diminishes as the immersion time increases. Contrary to ORG-specimens, GR-specimens suffered only a slight reduction of 6% after 12 months of immersion, meaning that the surface preparation followed was able to control the degradation level, as expected.

The typical failure modes of the reference specimens (both ORG- and GR-specimens) was cohesive with fracture inside a thin layer of brick material. The water immersion caused a change of the failure mode in ORG-specimens to an adhesive failure at the GFRP/brick interface. However, the failure mode observed in GR-specimens did not change due to water immersion.

5. Effect of higrothermal exposure

Possible changes in mechanical properties and moisture content of the specimens with exposure cycles are here discussed. The moisture content is measured immediately upon removal of the specimens from the climatic chamber and at the test moment, which took place after seven days of storage in controlled environmental conditions.

5.1 Post-ageing tests on components

The variation of compressive strength of bricks and moisture content along the exposure time are presented in Fig. 7(a). Changes in the bricks' compressive strength are considered as negligible. Also, the moisture absorption level (0.25% water mass after 960 cycles) is negligible. The results seem to indicate a suitable performance of the bricks under the considered hygrothermal conditions.

The variation of tensile strength and moisture content of primer specimens are depicted in Fig. 7(b). The tensile strength showed no changes during the first 240 cycles, although 2.4% moisture absorption was achieved. After this point, in which the primer seems to be saturated, the degradation starts and continues until a total drop of 42% at the end of the tests. The effect of temperature cycles and exposure to high temperatures on the degradation of primer is obvious. Further details are provided in [21].
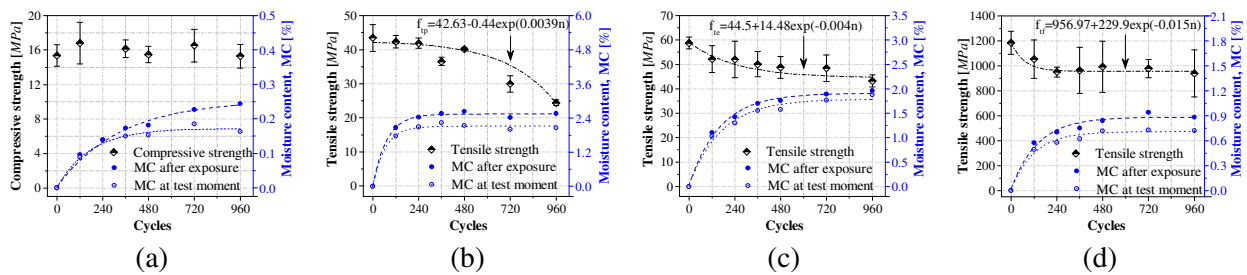

Fig. 7. Evolution of mechanical properties with higrothermal exposure: (a) brick's compressive strength; (b) primer tensile strength; (c) resin tensile strength; (d) coupons tensile strength.

Changes in tensile strength of epoxy resin and moisture content along the exposure cycles are presented in Fig. 7(c). The largest reduction in tensile strength occurred in the first 120 cycles, when the largest moisture absorption also occurred [21], with a significantly degradation rate reduction afterwards. Plasticization of epoxy resin, micro-cracking due to swelling or thermal cycles can be the responsible mechanisms for the observed degradation in mechanical properties. The total degradation in tensile strength is 26% at 960 cycles, corresponding to 1.96% water absorption. Tests showed that the behaviour of epoxy resin changed from relatively brittle (elastic until failure) to ductile (elasto-plastic) along the exposure time.

The changes in tensile strength and moisture content of GFRP coupons with the number of exposure cycles are presented in Fig. 7(d). The maximum moisture absorption of GFRP is around 0.9% for this exposure condition. Most of the degradation occurs in the first 240 cycles and then the tensile strength reaches a plateau. A 21% decrease in tensile strength is observed after 960 cycles, corresponding to 0.9% water absorption. Mechanical performance of GFRP coupons is expectedly affected by mechanical performance of epoxy, fibres and epoxy/fibre interface [12]. As glass fibres show reasonable resistance against thermal and moisture exposure, the degradation of GFRP coupons is thus ruled by degradation of epoxy resin and of the fibre/matrix interface. In fact, the fibre/matrix interface is prone to moisture ingress and transverse cracking due to thermal incompatibility between epoxy and fibres, both of which can cause degradation in the performance of GFRPs.

5.2 Post-ageing tests on pull-off specimens

All specimens were visually inspected every 60 cycles of exposure (2 weeks). A progressive GFRP delamination was observed in ORG-specimens prepared for both pull-off and single-lap shear bond tests prior to testing. The delamination generally initiated from the

boundaries and propagated from loaded end to the free end. Although the debonded area varied from one to another specimen in each exposure period, its progression pattern was similar in most of the specimens. Although delamination was significant in ORG-specimens, no delamination took place in GR-specimens thus showing the effect of surface preparation in enhancing the bond-related mechanical parameters.

The variation of pull-off bond strength with exposure cycles is presented in Fig. 8(a). The pull-off tests were performed on ORG-specimens only. A severe degradation in pull-off strength was observed. The bonded area of specimens decreased during exposure, leading to the reduction of pull-off strength up to around 100% in some locations. The failure mode was initially cohesive with fracture inside the brick. It changed then to a cohesive-adhesive failure after 240 cycles and finally to an adhesive failure after 480 cycles.

5.3 Post-ageing tests on shear bond specimens

The changes in the debonding force and delaminated area in ORG- and GR-specimens are presented in Fig. 8(b) and Fig. 8(c), respectively. While GR-specimens did not have any delamination, extensive delamination was recorded in ORG-specimens (about 50% of the bonded area after 960 cycles). Accordingly, the debonding force in ORG-specimens showed a sudden decrease (about 50%) after 120 cycles. Afterwards, degradation continued at a lower rate and reached a 72% loss at the end of exposure period.

On the contrary, a minor increase was observed in the debonding force in GR-specimens, see Fig. 8(c). These results illustrate in a clear way the major effect of surface grinding on improving the bond performance and durability. The increment of the debonding force can be attributed to the variability of the results, curing time, and possible post-curing of resin at the interface level.

As for the failure modes before and after exposure, an adhesive failure mode combined with detachment of a thin layer of brick and tiny cracks on the brick surface was observed in the reference ORG-specimens. However, the detachment occurred only at the GFRP/brick interface (adhesive failure) after 120 cycles and remained the same until the end of exposure. In contrast, the failure mode in GR-specimens was cohesive with the fracture located inside a thin layer of brick for all the exposure period. This is another evidence of the bond improvement originated by surface grinding.
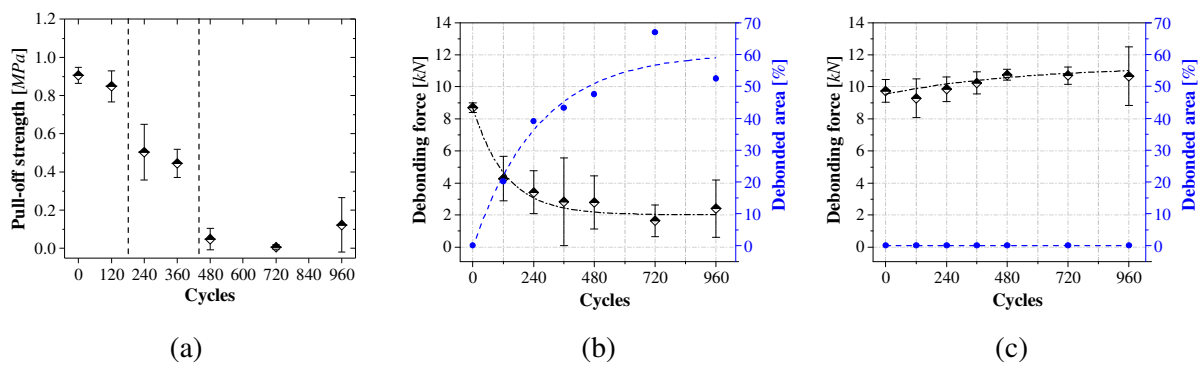

| (a) | (b) | (c) |

Fig. 8.   Variation of bond strength with higrothermal exposure: (a) pull-off tests; (b) single-lap shear tests (ORG-specimens); (c) single-lap shear tests (GR-specimens).

6. Conclusions

The experimental results showed some degradation in the mechanical strength of bricks (12%), primer (10%), epoxy resin (6%) and GFRP (37%) after the water immersion period. In primer and epoxy resin specimens, a slight improvement of mechanical properties was

possible upon partial drying in the first months of water immersion. This phenomenon can be due to the irreversibility of the induced degradation or insufficient drying of the specimens.

The changes in the bond behaviour were studied by performing pull-off tests (only for ORG-specimens) and single-lap shear bond tests. The pull-off strength significantly decreased (34%) after twelve months of immersion, but the failure mode remained cohesive with fracture inside the brick. The degradation seemed to start at two months of immersion reaching a plateau after four months. The single-lap shear bond tests showed a substantial improvement in durability for specimens prepared with grinded bricks (9% bond strength loss in comparison to 19% in ORG-specimens). The failure mode for GR-specimens kept cohesive with immersion time, with reduction of the thickness of the detached layer. Conversely, the failure mode in ORG-specimens changed progressively from cohesive to adhesive. Partial drying of specimens allowed for a slight enhancement of the bond strength in ORG-specimens for the first months of immersion. However, no strength enhancement was visible for GR-specimens.

The effect of hygrothermal exposure on the compressive strength of brick masonry was negligible. The behaviour of primer and epoxy resin changed from elastic (brittle) to elasto-plastic with reduction of strength and stiffness through time. The degradation in GFRP sheets was limited to tensile strength. DSC tests helped in identifying the governing mechanisms in degradation of primer and epoxy resin. Physical aging due to exposure to temperatures above the curing temperature had a substantial effect on the thermal behaviour of resin. On the other hand, moisture plasticization was the main factor responsible for degradation in primer and resin. Thus, the degradation in GFRP was probably due to both plasticization of resin and fibre/resin interface damage. The bond characterization tests showed that the grinding of the bricks' surfaces improves clearly the bond durability. While specimens with mechanical surface treatment did not show any bond degradation, extensive FRP delamination and degradation in bond strength was observed in specimens not submitted to surface treatment.

Acknowledgments

References

1. Schwegler G.: Strengthening of masonry with fiber composites. PhD Thesis, Federal Institute of Technology, Switzerland, 1994.
2. Saadatmanesh H.: Fiber composites for new and existing structures, ACI Structural Journal 91(3) (1994). pp 346-354.
3. Valluzzi M.R.: Strengthening of masonry structures with Fibre Reinforced Plastics: From modern conception to historical building preservation, [in:] 6th International Conference on Structural Analysis of Historic Construction, D. D'Ayala & E. Fodde (eds.): CRC Press (2008). pp 33-45.
4. Oliveira D.V., Basilio I., Lourenço P.B.: Experimental bond behavior of FRP sheets glued on brick masonry, Journal of Composites for Construction 15(1) (2011). pp 32-41.
5. ASTM C1583: Standard test method for tensile strength of concrete surfaces and the bond strength or tensile strength of concrete repair and overlay materials by direct tension (pull-off method). ASTM International, 2004.

6. Valluzzi M.R., Oliveira D.V., Caratelli A., Castori G., Corradi M., de Felice G., Garbin E., Garcia D., Garmendia L., Grande E., Ianniruberto U., Kwiecień A., Leone M., Lignola G.P., Lourenço P.B., Malena M., Micelli F., Panizza M., Papanicolaou C.G., Prota A., Sacco E., Triantafillou T.C., Viskovic A., Zając B. & Zuccarino G.: Round Robin test for composite-to-brick shear bond characterization, Materials and Structures, 45(12) (2012). pp 1761-1791.
7. CNR-DT 200 R1: Guide for the design and construction of externally bonded FRP systems for strengthening existing structures. Italian National Research Council, Rome, 2013.
8. ACI 440.7R-10: Guide for design and construction of externally bonded FRP systems for strengthening unreinforced masonry structures. American Concrete Institute, 2010.
9. Karbhari V.M.: Durability of composites for civil structural applications, CRC Press, Washington, 2007.
10. Martin R.: Ageing of composites, Cambridge, Woodhead 2008.
11. Lapique F., Redford K.: Curing effects on viscosity and mechanical properties of a commercial epoxy resin adhesive, International Journal of Adhesion and Adhesives 22(2002). pp 337-346.
12. Schutte C.L.: Environmental durability of glass-fiber composites, Materials Science Engineering 13 (1994). pp 265-322.
13. Bradley W.L., Grant T.S.: The effect of moisture absorption on the interfacial strength of polymeric matrix composites, Journal of Material Science 30 (1995). pp 5537-5542.
14. Abanilla M., Li Y., Karbhari V.M.: Durability characterization of wet lay-up graphite/epoxy composites used in external strengthening, Composites Part B 37(2/3) (2006). pp 200-212.
15. FIB: Bulletin 14 - External Bonded FRP Reinforcement for RC Structures, Fédération Internationale du Béton, 2001.
16. Ghiassi, B.: Durability analysis of bond between composite materials and masonry substrates, PhD Thesis, University of Minho, 2013.
17. Hollaway L.C.: A review of the present and future utilization of FRP composites in the civil infrastructure with reference to their important in-service properties, Construction and Building Materials 24 (2010). pp 2419-2445.
18. Benmokrane B., Mohamed H.M.: Durability Issues of FRP for Civil Infrastructure, [in:] Proc. 11th International Symposium on Fiber Reinforced Polymer for Reinforced Concrete Structures, J. Barros & J. Sena-Cruz (eds.): University of Minho, Portugal, 2013.
19. Sciolti M.S., Aiello M.A., Frigione M.: Influence of water on bond behavior between CFRP sheet and natural calcareous stones, Composites: Part B 8(32) (2012). pp 39-50.
20. Maljaee H., Ghiassi B., Lourenço P.B., Oliveira D.V.: Moisture-induced degradation of interfacial bond in FRP-strengthened masonry, Composite Part B 87 (2016). pp. 47-58.
21. Maljaee, H., Ghiassi, B., Lourenço, P.B., Oliveira, D.V.: FRP-brick masonry bond degradation under hygrothermal conditions, Composite Structures 147 (2016). pp. 143-154.
22. Stewart A.: Study of cement e epoxy interfaces, accelerated testing, and surface modification, PhD Thesis, University of Florida, 2012.
23. Hutchinson A.R., Hollaway L.C.: Environmental durability, [in:] Strengthening of reinforced concrete structures: Using externally-bonded FRP composites in structural and civil engineering, L.C. Hollaway & M.B. Leeming (eds.): Cambridge, UK, Woodhead Publishing (1999). pp 156-182.