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Experimental Investigation on the Long-term Durability of Bond Between FRP and Masonry Substrates

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SUMMARY
The characterization of long-term behavior of bond between Fiber-Reinforced Polymers (FRPs) and masonry substrates in a service environment is a crucial issue for design purposes, which requires a full body of experimental and theoretical information. Most of the research in this area has been devoted to FRP-concrete specimens, and the available data for FRP-strengthened masonry components are still lacking. This paper presents the experimental investigation on degradation of bond between glass FRP composite sheets and masonry bricks by performing accelerated aging tests. Masonry bricks strengthened with GFRP sheets are prepared following the wet lay-up procedure and exposed to thermal cycling and constant relative humidity. Single-lap shear bond tests are finally performed for investigating the degradation of the bond after exposure to environmental conditions and the results are presented.

1. INTRODUCTION

Composite materials, such as Fiber Reinforced Polymers (FRP) and Fiber Reinforced Grouts (e.g. SRG), have been used extensively for external strengthening of masonry structures in recent years. The effectiveness of this strengthening technique is intrinsically dependent on the bond performance between the composite material and the masonry substrate. As the bond is a key mechanism in transferring the stresses from structural elements to the composite material, its failure results in deterioration of the strengthening system or premature debonding.

The short-term aspects of the bond behavior have been extensively under investigation during the last years [1-4]. However, a detailed understanding of aspects such as failure initiation, nonlinear bond mechanisms, and constituent property effects on the local phenomena is still under development in the case of masonry substrates.

Another important aspect that should be considered is the long-term performance of the bond behavior. Investigating the long-term durability of the bond behavior is of crucial importance in service life prediction and structural safety evaluations [5-7]. However, few studies can be found in the literature devoted to durability of bond in FRP-strengthened masonry [8-12] and this issue still remains open.

The durability of FRP composites or masonry itself has been the subject of considerable academic concern for the last 30 years. Relevant degradation agents that can affect the durability or long-term in service behavior of FRP or masonry include cycles of temperature and/or moisture, UV or carbon dioxide. The behavior of FRP matrices alone is complex and their interaction with a variety of fiber types and configurations magnifies this complexity. Moreover, FRP materials, masonry, and FRP-strengthened masonry components often have properties that vary during their lifespan due to environmental conditions. The bond between FRP material and masonry substrate may also be affected due to environmental agents. Moreover, the service behavior of wet lay-up applications is frequently different for each fiber-matrix combination, especially as novel matrices are combined with a range of fibers such as biocomposites of flax and hamp, basalt or steel fibers. Some fiber-matrix combinations are particularly prone to certain degradation mechanisms, while in others the dominant mechanisms are still the subject of research and debate.

Analysis of long-term behavior of FRP-masonry components involve laboratory and field testing, and advanced computational strategies, but research in this area is still very few [8-12]. The laboratory investigations can be conducted by performing real exposure or accelerated ageing tests. The real exposure tests take long time to be completed (equal to expected service life of the material) but a full understanding of the real degradation phenomena can be obtained. In comparison, accelerated tests are performed over a shorter time span, but the resulting degradation trend should be then related to real exposure conditions. Moreover, the degradation mechanisms may change in accelerated exposures with respect to real conditions. Therefore, special care should be taken in designing accelerated ageing tests and interpreting the results.

This paper presents experimental investigations performed at the University of Minho on the durability of bond in FRP-masonry elements. The aim was to investigate the coupling effect of temperature cycles and relative humidity on the bond behavior. GFRP-strengthened brick specimens have been prepared following the wet lay-up procedure. The specimens were then exposed to accelerated hygrothermal conditions in a climatic chamber. The degradation of the bond behavior has been investigated by performing conventional debonding tests after different periods of exposure. The results were obtained and presented in terms of bond degradation with time (exposure cycles).

2. LITERATURE REVIEW

Several studies have been focused on the effects of temperature and humidity variations on FRP-strengthened concrete elements and still just few studies have been performed on FRP-masonry elements. Generally, it has been observed that temperature and moisture exposures may affect the properties of epoxy resins, composites, fiber/epoxy interface, and composite/substrate interface [7] but these effects are not still well recognized and classified in FRP-masonry systems.

Epoxy resins or FRP composites tend to absorb water when exposed to humidity conditions. The water absorption is increased by formation of cracks and openings in the matrix, and can cause hydrolysis, plasticization, and saponification with irreversible or reversible changes in the polymer structure [7]. The main effects of the plasticization are decreasing the glass transmission temperature, $T_{g,}$ of the resin, and decrement of modulus of elasticity and yield strength. Moisture can also have deteriorating effects on the fiber-matrix bond. The decrease of T_g is recognized as a physical change that can be partially reversed upon drying, but it depends highly on the exposure time and also the moisture concentration level [7]. The mechanical properties of FRP composites, because of the presence and strong influence of fibers, are generally less sensitive to hygrothermal ageing as compared with those of resins [7]. However, degradation of mechanical properties of FRP composites after exposure to moist environment has been reported in some cases [7, 13].

Thermal effects include changes in the properties of the matrix due to temperatures above the curing temperature, freezing, and freeze-thaw conditions. It is well known that epoxy resins soften over the T_g which causes an increase in viscoelastic response, reduction of mechanical properties, and epoxy resin de-ageing. Exposing the epoxy resins below their T_g may result in an increase in susceptibility to moisture absorption, mechanical degradation, and also post-curing phenomenon (if it is exposed to temperatures above its curing temperature) [7, 14]. Exposure to freezing conditions results in embrittlement of the resin while it increases the effective stiffness, matrix hardening, matrix microcracking, and fiber-matrix bond deterioration [15].

An important phenomenon that should be considered in exposure to temperature cycles is the thermal incompatibility problem. The thermal incompatibility is due to the considerable difference of thermal expansion coefficient between fibers, polymer matrix, and the substrate. The majority of the epoxy resins used in FRPs have coefficients of thermal expansion in the range of 45 to 65 × 10-6 °C. Meanwhile, this coefficient is around 5 × 10-6/°C for glass fibers and in the range of - 0.2 to 0.6 × 10-6 °C for carbon fibers [16]. The thermal expansion coefficient of clay bricks has been reported to be in order of 5×10^{-6}/̊C magnitude which is similar to the one for glass fibers [17]. This large difference in expansion coefficients produces residual interfacial stresses in fiber/matrix and matrix/substrate interfaces. The case is worse in carbon fibers since it has a positive coefficient of thermal expansion in the transverse direction and negative coefficient in longitudinal direction, which usually results in debonding of the fibers from the surrounding matrix [18].

The main degradation mechanisms in epoxy resin, FRP and FRP -substrate interface due to moisture and temperature exposures are summarized in Figure 1 and Figure 2, respectively.

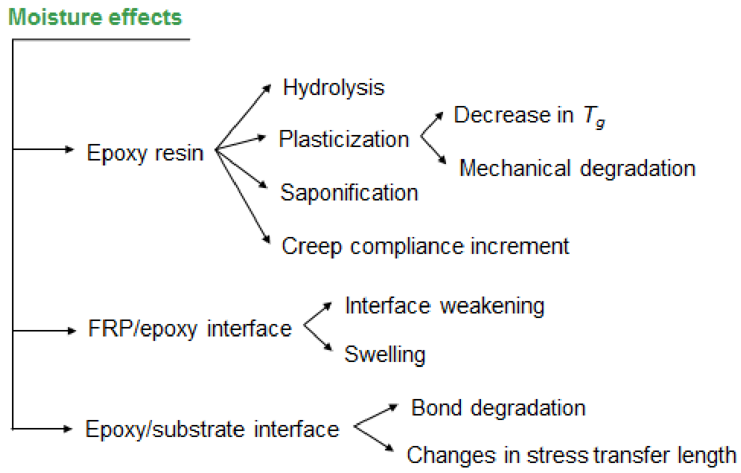

Figure 1: Moisture degrading effects on FRP-strengthened specimens.

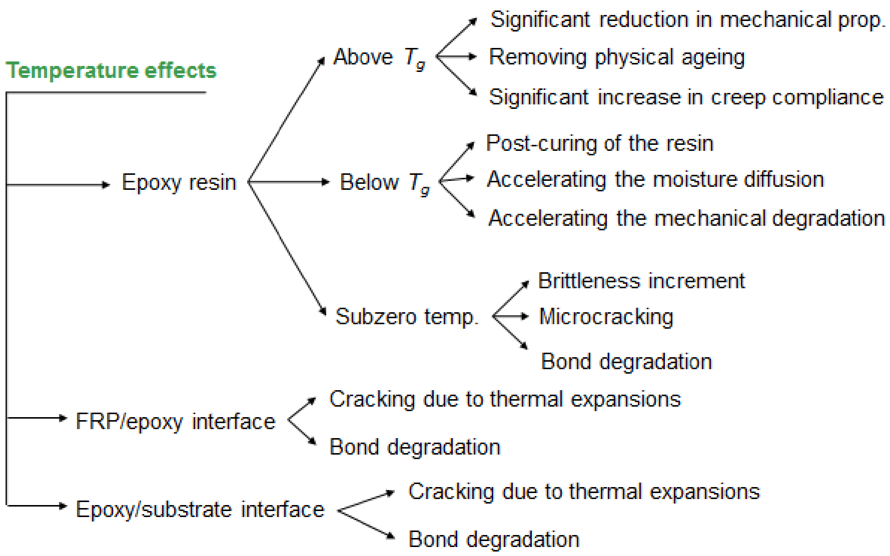

Figure 2: Temperature degrading effects on FRP-strengthened specimens.

2. EXPERIMENTAL PROGRAM

The experimental program consists of exposing the GFRP-strengthened brick specimens to accelerated ageing conditions. The aim was to investigate the coupling effect of temperature cycles and relative humidity on the bond behavior. The specimens were exposed to two different environmental conditions and the changes in the bond behavior have been investigated by performing single-lap shear bond tests.

2.1 Specimens preparation

The GFRP-strengthened brick specimens were prepared following the wet lay-up procedure, see Figure 3. The masonry bricks were dried in the oven before application of the GFRP sheets. After cleaning the brick surface, a two-part epoxy primer was applied to the brick surface for preparation of the substrate surface before GFRP application. Finally, a two-part epoxy resin was used as the matrix of the composite material and also adhesion to the masonry substrate.

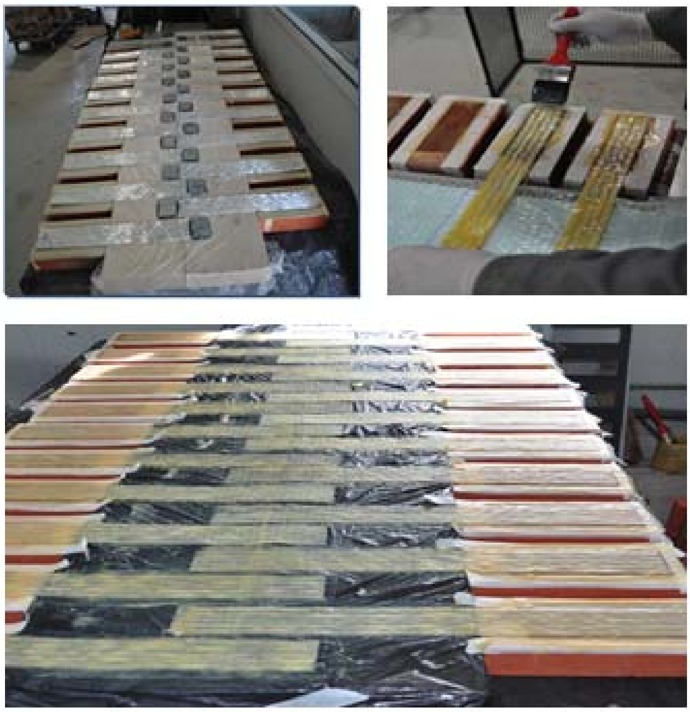

Figure 3: Specimens preparation.

The geometrical details of the prepared specimens are shown in Figure 4. The GFRP sheets were applied on the brick surface with a bonded length of 150 mm and 40 mm unbounded part at the loaded end.

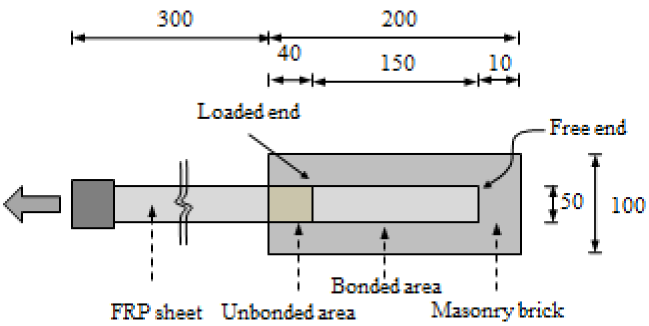

Figure 4: Geometry of the specimens.

2.2 Accelerated ageing tests

The experimental program consisted of exposing the specimens to two different environmental conditions in a climatic chamber. The aim was to investigate the degrading effect of hygrothermal conditions on the bond behavior. The details of exposure conditions are shown in Figure 5.

In the first exposure, exposure HT, the specimens were exposed to 6 hr temperature cycles from +10°C to +50°C and constant relative humidity of 90%. In each cycle, the temperature was kept constant at +10°C for 2 hr. It was then increased to +50°C in 1 hr, followed by 2 hr constant temperature at +50°C. Then the temperature was decreased again to +10°C in 1 hr resulting in 6 hr cycles of exposure. In the second exposure, exposure FT, the specimens were exposed to temperature cycles from -10°C to +30°C and constant relative humidity of 90%. The aim was to investigate the effect of freeze-thaw conditions on the bond behavior while having the minimum number of changes comparing to the first exposure. Therefore, similar exposure cycle rates have been adopted with 20°C decrement of the maximum and minimum temperatures. The specimens were subjected to a total of 200 cycles in each exposure conditions.

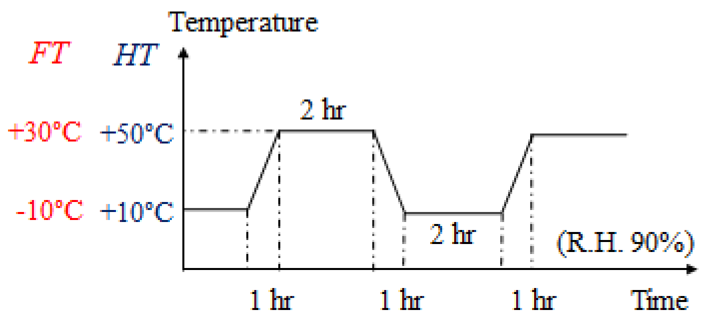

Figure 5: Hygrothermal exposure cycles.

2.3 Post-ageing tests

Post-ageing tests were performed after each 50 cycles of environmental exposure. The specimens were taken from the climatic chamber and dried in the laboratory conditions before performing the post-ageing tests. A minimum of 5 specimens were tested in each exposure period and the average results have been obtained and presented.

Single-lap shear bond tests were performed using a mechanical testing machine with maximum load capacity of 50 kN. A steel frame was used to support the specimens appropriately and avoid misalignments in load application. The specimens were placed on the steel frame and firmly clamped to it as shown in Figure 6. Tests were driven under displacement control conditions with reference to the LVDT sensor placed at the loaded end of the FRP composite. The specimens were pulled monotonically with a speed rate of 5μm/sec. The resulting load was measured by means of a load cell. The relative slip between the GFRP and the masonry substrate was measured with the LVDTs glued along the bonded length.

Figure 6: Single-lap shear bond test setup.

3. RESULTS AND DISCUSSION

The specimens were visually inspected before performing the debonding tests in order to investigate the development of any visible interfacial damages or FRP delaminations. Progressive FRP delaminations were observed in the specimens after exposure to environmental conditions, see Figure 7. The FRP detachments were severe in the specimens exposed to HT conditions, while the detachments due to exposure to FT conditions were small. The observed FRP detachments can be attributed to the thermal incompatibility problem between epoxy resin and masonry substrate as discussed in sec. 2.

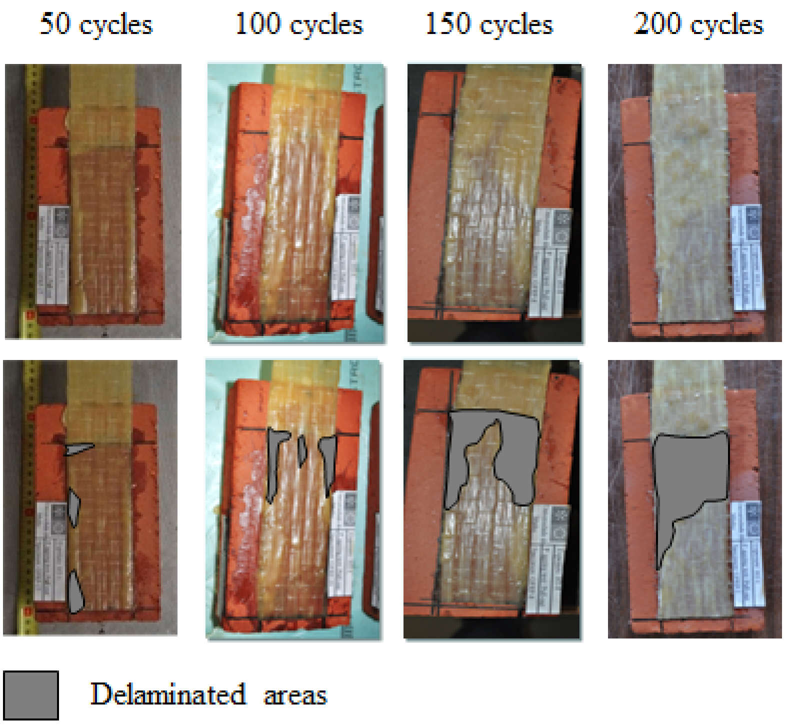

Figure 7: FRP delaminations after exposure to HT conditions

In terms of bond behavior, the debonding force and stiffness decreased with increment of exposure cycles in both environmental conditions. Moreover, the debonding behavior changed from brittle to a progressive and ductile failure mode.

The changes in the debonding force of the specimens due to exposure to both environmental conditions are presented in Figure 8. It can be observed that the debonding force has been decreased 17% and 45% after 100 and 200 cycles of HT exposure, respectively. Meanwhile, this decrease is respectively 6% and 8% in the specimens exposed to FT conditions. A comparison between the obtained results shows that the HT exposure had a more degrading effect on the specimens used in this study.

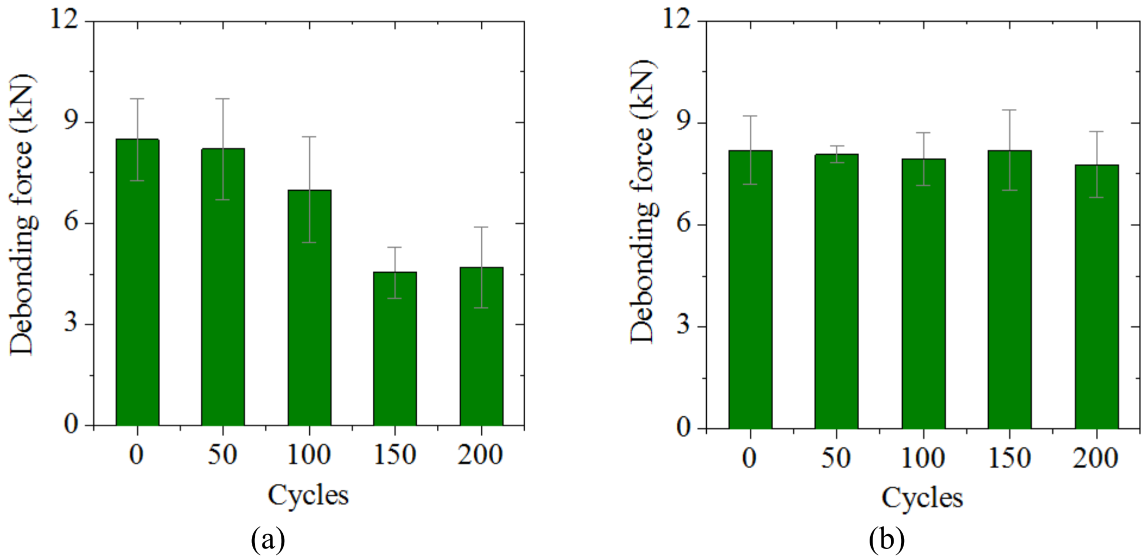

Figure 8: Changes in the debonding force after exposure to environmental conditions: (a) HT exposure; (b) FT exposure.

4. CONCLUSIONS

The results of an extensive experimental program aimed at investigating the durability of FRP-masonry systems were presented in this paper. Accelerated ageing tests were performed on the GFRP-strengthened brick specimens. Two different hygrothermal environmental conditions were considered called HT and FT exposures. HT exposure consisted of 6 hr temperature cycles between +10℃ to +50℃ (90% R.H.), while the temperature change in FT was between -10℃ to +30℃. Post-ageing tests were performed on the specimens after each 50 cycles of exposure to study the changes in the bond behavior. The post-ageing tests consisted of visual inspection and single-lap shear bond tests. Progressive FRP delaminations were observed in the specimens after exposure to hygrothermal conditions which can be attributed to the thermal incompatibility between epoxy resin and masonry substrate. Moreover, it was observed that the bond strength and stiffness decreased with time due to exposure conditions.

ACKNOWLEDGMENTS

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