# RECENT DEVELOPMENTS IN DURABILITY OF FRP-MASONRY SYSTEMS

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**Abstract**

Fiber reinforced polymers (FRPs) are being more and more used for external strengthening of masonry structures. Therefore, characterization of the short and long-term behavior of bond between FRP composites and masonry substrates in a service environment is crucial for design purposes. A full body of experimental and theoretical investigations is required for durability assessment of FRP strengthened structures. However, most of the research in this area has been devoted to FRP-concrete specimens, and the available data for FRP-strengthened masonry components is still lacking.

This paper presents recent experimental results of a large experimental campaign under development at the University of Minho. The aim is to characterize the short and long-term behavior of bond in FRP-strengthened masonry elements. Debonding tests have been performed on masonry bricks strengthened with different FRP materials for investigating the short-term aspects of the bond behavior. Accelerated ageing tests have been performed on FRP-strengthened masonry elements and the degradation of the bond due to environmental conditions is investigated. The environmental conditions consist of the coupling effect of temperature cycles and relative humidity. The degradation of bond has been measured by performing conventional single-lap shear bond tests.

## 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 system and the masonry substrate. As the bond is a key mechanism in transferring the stresses from structural elements to the composite system, 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 local phenomena is still under development in the case of masonry substrates.

Another important aspect of the bond behavior is its long-term performance. Investigating the long-term durability of the bond behavior is of crucial importance in service life prediction and structural safety evaluation [5-6]. However, few studies can be found in the literature devoted to the durability of bond in FRP-strengthened masonry [7-9] 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, see Figure 1. The behavior of the FRP matrices alone is complex and their interaction with a variety of fiber types and configurations can magnify this complexity. Moreover, FRP materials, masonry, and FRP-strengthened masonry components often have properties that vary during their lifespan due to environmental conditions. The mechanisms responsible in FRP occur at the micro-structural level, normally at the fiber-matrix interface. The bond between FRP material and masonry substrate may also be affected due to environmental agents. Moreover, 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 bio composites of flax and hemp, 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.

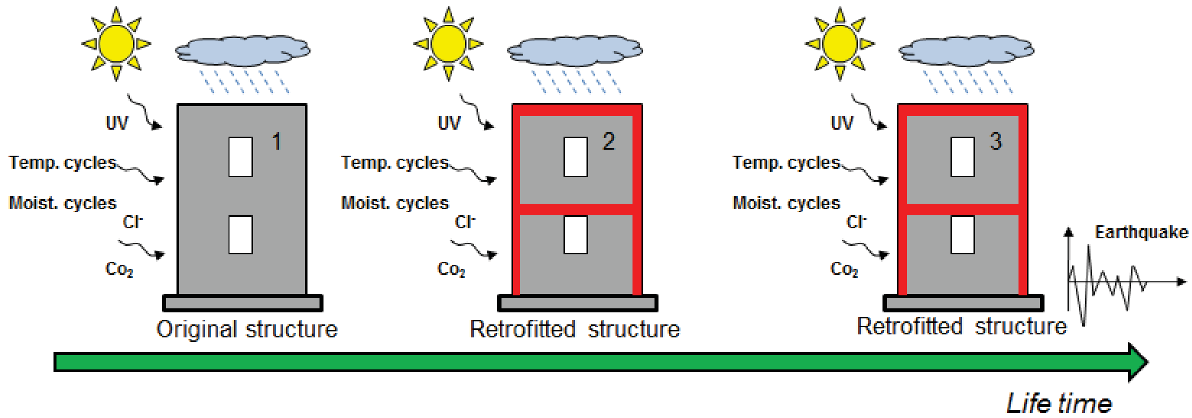



Figure 1: Service life environmental agents

Analysis of long-term behavior of FRP-masonry components involve laboratory and field testing, accelerated ageing and advanced computational strategies, but research in this area is still very few [10]. Only limited studies have been conducted on durability of FRP externally applied to masonry [7, 9, 11-13]. Available laboratory-based research on FRP composites needs therefore to be supported by materials characterization and experimental activity on FRP-masonry components in view of: (i) understanding the effects of critical degradation agents on the bond in regard to the serviceability state, (ii) assessing the bond behavior thorough accelerated ageing tests and (iii) developing feasible computational models capable to simulate degradation mechanisms and damage from accelerated aging.

It is observed that standardized durability test procedures based on accelerated ageing methods are available in literature for masonry or FRP alone (14-17). As recognized in several research works, however, the real environmental conditions cannot be accurately simulated or reproduced in laboratory-based accelerated tests. Moreover, each of these environmental conditions may affect the mechanical, physical, or chemical properties of some materials while it might not change the properties of other ones. However, accelerated aging tests represent the most common method to assess durability of building materials.

This paper presents recent advancements obtained at University of Minho in investigating the bond behavior and its durability in FRP-masonry systems. In the first part of the paper, the tests performed for characterization of the short-term bond behavior in FPR-strengthened masonry are presented and discussed. Different FRP materials have been used for strengthening the masonry bricks and their effect on local and global bond behavior is discussed and presented. The second part of the paper is devoted to the studies performed on durability of FRP-strengthened masonry elements. Accelerated hygrothermal ageing tests have been performed on FRP-strengthened masonry elements and the degradation of bond behavior has been investigated by performing debonding tests. The deboning tests have been performed after different exposure periods to obtain the bond degradation curve over time.

## 2. BOND BEHAVIOR

The short-term behavior of bond between FRP and masonry has been investigated by performing single-lap shear bond tests. The tests have been performed in the framework of RILEM TC 223-MSC [18]. Different FRP materials have been used for strengthening masonry bricks to investigate the effect of FRP properties on the bond behavior. The tests description and obtained results are presented and discussed in this section.

### 2.1. SPECIMENS PREPARATION

Single-lap shear bond tests have been performed at the University of Minho on masonry bricks strengthened with different epoxy based composite materials, namely carbon, glass, basalt, and steel. The FRP/SRP strips of 50 mm width were applied on masonry bricks following the wet layup procedure. The 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, see Figure 2.

Figure 2: Specimens preparation.

The bonded length of the strips was equal to 160 mm with a 40 mm unbounded part at the loaded end, as illustrated in Figure 3. Six specimens were tested for each type of composite material. The masonry units used as the substrate were clay bricks with dimensions of 250 × 120 × 55 $mm^3$, a mean compressive strength of 19.8 MPa (CoV=2.5%), a tensile strength of 2.0 MPa (CoV=4%), and modulus of elasticity of 5579 MPa (CoV=5.2%). The experimentally obtained mechanical characteristics of the composite materials are shown in Table 1 in terms of modulus of elasticity, $E_f$, tensile strength, $f_t$, ultimate deformation, $\varepsilon_{max}$, and composite thickness, $t_f$.

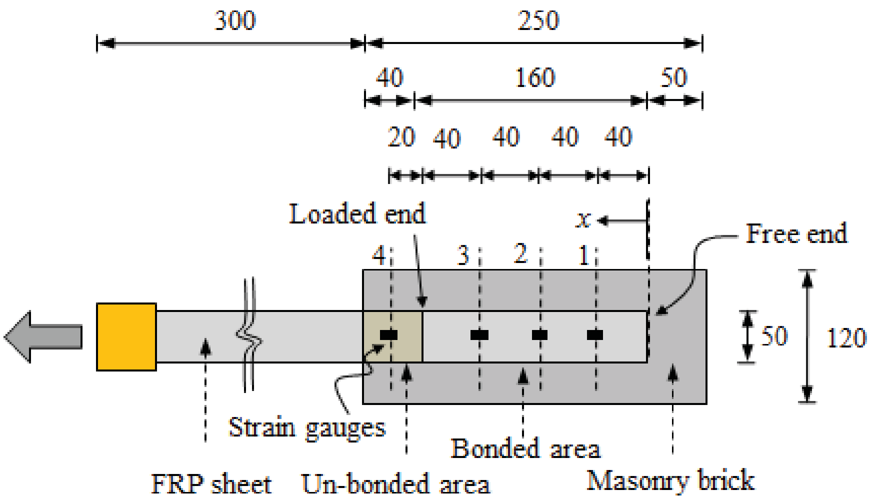



Figure 3: Geometry of the FRP strengthened masonry specimens.

Table 1: Mechanical properties of composite materials.

| Material | $E_f$ (MPa) | $f_t$ (MPa) | $\varepsilon_{max}$ (%) | $t_f$ (mm) |
|---|---|---|---|---|
| CFRP | 202070 | 2525 | 1.16 | 0.17 |
| GFRP | 77160 | 1350 | 1.86 | 0.12 |
| BFRP | 86090 | 1499 | 1.74 | 0.14 |
| SRP | 192910 | 2876 | 1.66 | 0.23 |

**2.2. TESTS DESCRIPTION AND SETUP**

The tests were performed using a closed-loop servo-controlled testing machine under displacement controlled conditions. 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 4. The displacements were imposed following a constant speed of 5μm/s at the end of the FRP strip. The resulting load was measured by means of a load cell, while the strain distribution was obtained from four strain gauges attached to the composite material surface. In particular, three strain gauges were glued on the bonded area and one was glued on the unbounded area.

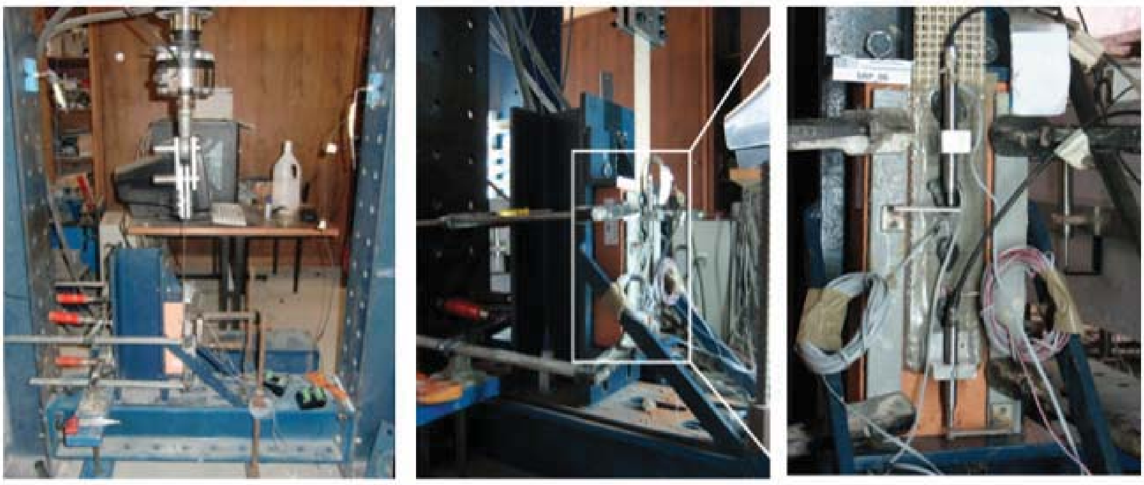


Figure 4: Single-lap shear bond test setup.

**2.3. EXPERIMENTAL RESULTS**

The results are obtained in terms of local strain distributions along the bonded length and global force-slip curves.

The obtained strain profiles are shown in Figure 5 for different load levels of 20%, 40%, 60%, 80%, and 100% of the ultimate load. As it can be seen, for low load levels the strain profiles follow an exponential curve, indicating that the load transfer occurs along a short length close to the loaded end. With increment of the load level, longer load transfer lengths are mobilized. Having the experimental strain profiles measured along the FRP reinforcement at different load levels, the local bond stress-slip (τ–s) curves which are useful in numerical modeling approaches can be obtained following the method given in [3].

The global force–relative displacement behavior of the specimens has been obtained using the force-slip values at the loaded end of the specimens in each step. The envelopes of the force–relative displacement curves are presented in Figure 6. It can be seen that the specimens strengthened with CFRP and SRP have similar global behavior, while some similarity also exists between BFRP and GFRP strengthened specimens. In general, BFRP and GFRP specimens have lower strength and higher ductility than CFRP and SRP. This result seems to be a direct consequence of the mechanical and geometrical properties of the composite materials, see Table 1. In all specimens, delamination of the FRP strip with a thin and uniform layer of brick (approximately 1 mm) was observed.

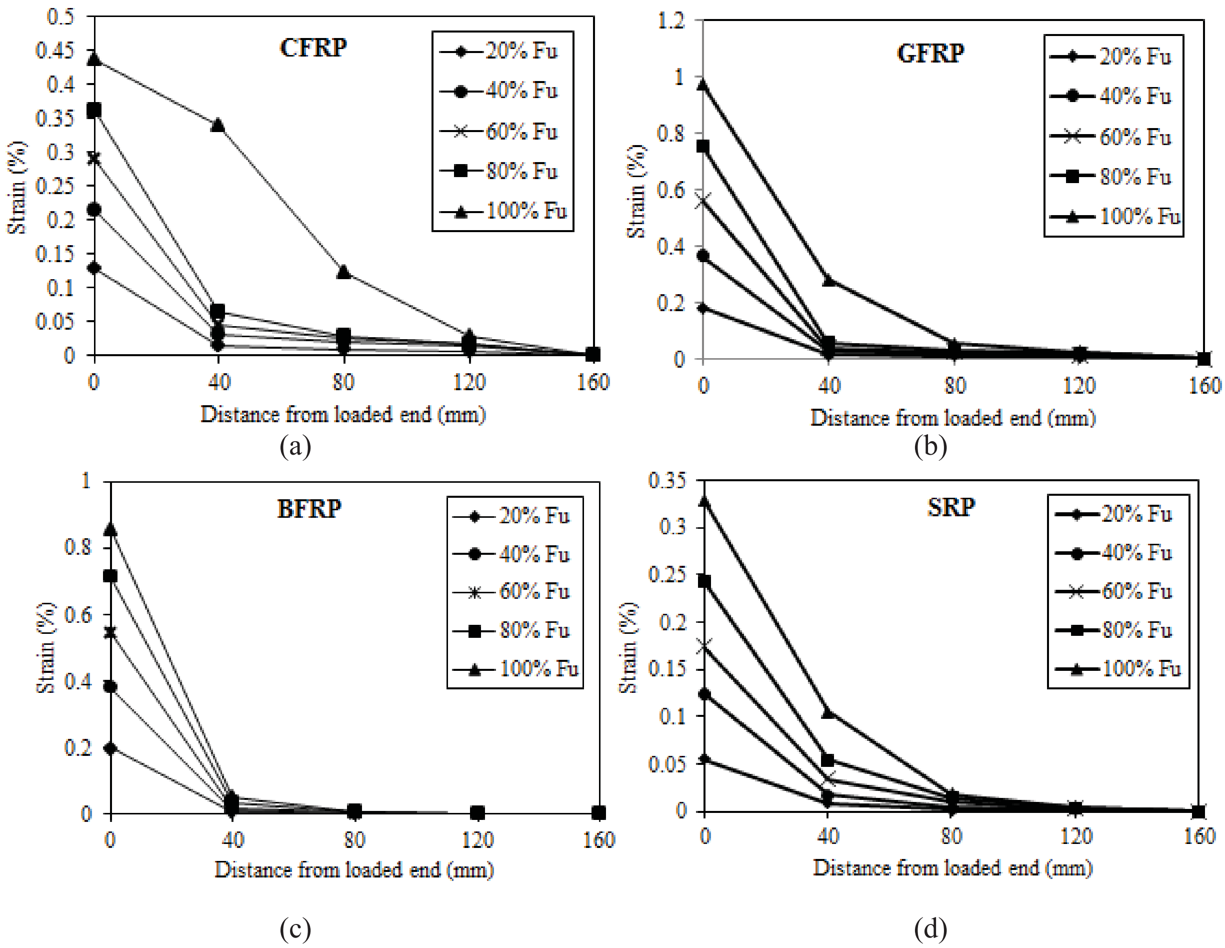



Figure 5: Strain profiles along the bonded length in different composite materials: (a) carbon fibers; (b) glass fibers; (c) basalt fibers; (d) steel fibers.

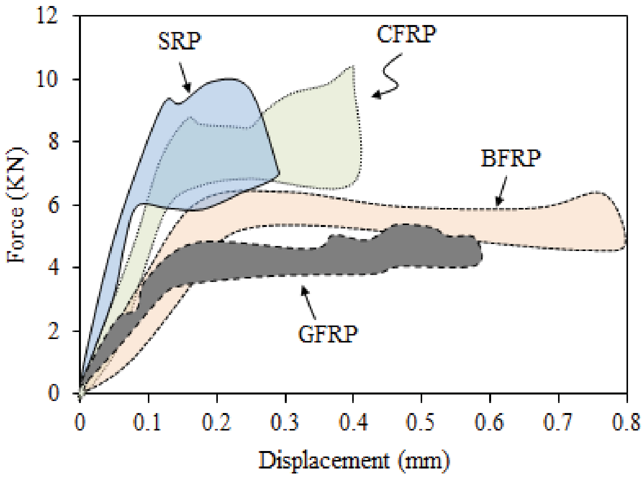



Figure 6: Envelope of experimental force–relative displacement curves for the four materials.

## 3. BOND DURABILITY

The durability of bond has been studied by performing accelerated ageing tests on GFRP-strengthened masonry specimens. The specimens were exposed to two different environmental conditions considering the coupling effect of moisture and temperature. The changes in the bond behavior have been studied by performing debonding tests on the specimens exposed to different periods of exposure.

### 3.1. SPECIMENS

The specimens consisted of GFRP-strengthened masonry bricks. The specimens were prepared following the wet-layup procedure. The details of the specimens were chosen similar to the specimens prepared for the bond characterization tests, see Figure 3.

### 3.2. ENVIRONMENTAL EXPOSURE

Environmental exposures consisted of exposing the specimens to two different hygrothermal conditions in a climatic chamber. The aim was to consider the coupling effect of temperature cycles and constant relative humidity, see Figure 7. In the first exposure, namely HT, the specimens were exposed to 6 hours. Temperature cycles between +10 ºC and +50 °C and constant relative humidity of 90%. In the second exposure, namely FT, the exposure consisted of 6 hours temperature cycles between -10 ºC and +30 °C and constant relative humidity of 90%. The specimens were exposed to 200 cycles in each of the exposure conditions.

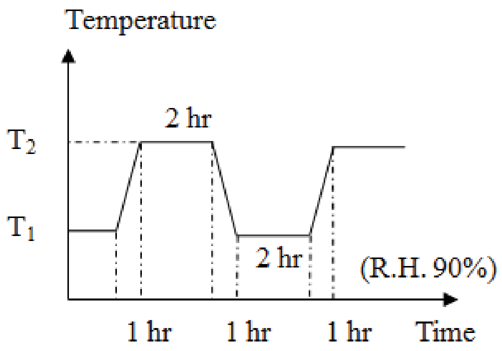


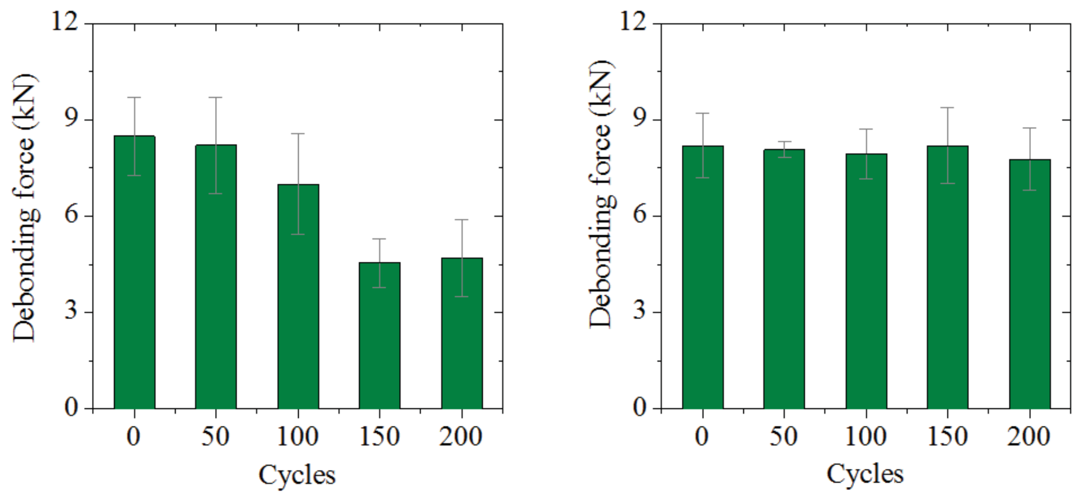

Figure 7: A schematic view of the hygrothermal cycles

### 3.3. POST AGEING TESTS

The changes in the bond behavior have been investigated by performing bond characterization tests after each 50 cycles of exposure. The bond characterization tests were conventional single-lap shear bond tests as explained in section 2.1. A minimum of 5 specimens were tested in each exposure period.

### 3.4. RESULTS AND DISCUSSION

It was observed that 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. The debonding force has been decreased 17% and 45% after 100 and 200 cycles of HT exposure, respectively. However, it has been decreased 6% and 8% after 100 and 200 cycles of FT exposure. A comparison between the obtained results shows that the HT exposure had a more degrading effect on the specimens used in this study.




(a) (b)

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

## 4. CONCLUSIONS

Recent developments obtained at University of Minho on characterization of the short and long-term behavior of bond behavior has been presented in this paper.

The short-term bond characterization has been conducted by performing single-lap shear bond tests on FPR-strengthened masonry bricks. Different FRP materials namely CFRP, GFRP, BFRP and SRP has been considered as the strengthening material. It was observed that the SRP and CFRP produced the highest debonding force, while GFRP and BFRP-strengthened specimens showed a relatively high ductility.

The results of the tests performed for characterization of the environmental degradation of bond behavior has also been presented in this paper. Accelerated hygrothermal tests were performed on GFRP-strengthened masonry bricks. The aim was to investigate the coupling effect of temperature cycles and relative humidity. It was observed that in the case of materials studied here, the degradation of the bond strength was more severe in the specimens subjected to positive temperature conditions rather than to freeze-thaw cycles.

## ACKNOWLEDGEMENTS

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