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Effect of elevated temperatures on the bond strength of FRP-strengthened bricks

João P. Pereira
Master student
ISISE- Guimarães

Hamid Maljaee
PhD student
ISISE- Guimarães

João M. Pereira
Postdoctoral researcher
ISISE- Guimarães

Bahman Ghiassi*
Postdoctoral researcher
ISISE- Guimarães

Paulo B. Lourenço
Professor
ISISE- Guimaraes

ABSTRACT

Fiber Reinforced Polymer (FRP) composites have received extensive attention in the last years for Externally Bonded Reinforcement (EBR) of masonry structures. It is well known that the FRP-to-masonry bond behavior is a critical mechanism in this strengthening technique. Several experimental and numerical investigations have thus been devoted to investigation of the bond behavior. However, aspects such as long-term performance and durability of these systems under different environmental conditions are still unknown.

This study aims at experimentally investigating the effect of elevated temperatures on the bond strength in FRP-strengthened masonry components. The specimens consist of GFRP-strengthened bricks prepared following the wet lay-up procedure. The specimens, after curing in the laboratory conditions, are exposed to constant temperature conditions from 70°C to 500°C and the changes in the bond strength are investigated by performing pull-off tests at different exposure times. The effect of application of a rendering mortar layer on the bond degradation at elevated temperatures is also investigated. The experimental observations and results are presented and discussed.

Keywords: Bond; FRP; Masonry; Elevated temperature; Degradation; Durability.

1. INTRODUCTION

Fiber Reinforced Polymers (FRPs) have been increasingly used for externally bonded reinforcement of masonry structures during the last years. Advantages such as light weight,

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*Autor correspondente – ISISE, Dep. Civil Engineering, University of Minho, 4800-058 Guimaraes.
E-mail: bahmanghiassi@civil.uminho.pt

high mechanical properties and easy processing have made this material a suitable choice for strengthening purposes. It is known that the efficacy and reliability of this strengthening technique depends intrinsically on the bond between the composite material and the masonry substrate and therefore its characterization and deep understanding is of crucial importance.

The bond behavior has been extensively studied in FRP-concrete systems, but in case of FRP-masonry it has only recently received attention [1–4]. However, the durability and long-term performance of bond still remains a challenge for both masonry and concrete substrates [5,6]. Available information regarding the bond durability are mostly devoted to FRP-concrete systems under aggressive environments or moisture conditions, see e.g. [7–9] and only few studies can be found regarding the FRP-masonry, see e.g. [10,11].

An important aspect in durability of FRP-strengthened components is resistance against fire and elevated temperature conditions [12]. The mechanical properties of epoxy resins, usually used as the adhesive in this strengthening technique, are largely influenced by service temperature. Above the glass transition temperature (T_g), the epoxy resin changes to a rubbery-like material leading to a significant drop of mechanical properties. This can affect the bond performance in FRP-strengthened components under sustained loads to a large extent. Little information is available regarding the residual strength of FRP-strengthened components after exposure to elevated temperatures. Few available experimental results, performed on FRP-concrete elements [6,13], show significant reduction of strength occurred in the specimens. However, the effect of elevated temperature conditions on the bond performance in FRP-strengthened masonry components is still unknown and is the main aim of this study.

This experimental program consists of performing conventional pull-off tests on specimens exposed to different constant temperatures and durations. The effectiveness of application of conventional repair mortars on the FRP surface in protecting the strengthening system is also of concern of this study. 50 FRP-strengthened brick specimens are prepared in total following the wet lay-up procedure. A 15 mm mortar layer is applied on the FRP surface of 25 specimens to investigate its effectiveness in protecting the strengthening system. The specimens, after curing in the laboratory conditions, are exposed to constant temperature conditions of 70°C, 100°C, 280°C and 500°C for up to four hours in an oven. The residual bond strength is obtained by performing pull-off tests on the specimens after 1, 2.5 and 4 hours of exposure. The results and experimental observation are presented and discussed.

2. EXPERIMENTAL PROGRAM

The experimental program aims at investigating the effect of elevated temperatures on the bond performance between FRP composites and masonry substrates. The tests consist of performing conventional pull-off tests on the specimens after exposure to different constant temperatures and different periods. The specimens are kept in room temperature for at least one day after each exposure condition (and before performing the post-aging tests). The effectiveness of application of a simple rendering mortar on the FRP surface in protection of the strengthening system is also investigated. 50 specimens are prepared and tested in total. Material properties and specimens' preparation as well as testing procedures are presented and discussed in this section.

2.1. Materials and specimens

The specimens are made of solid clay bricks (200×100×50 mm^3) strengthened with Glass Fiber Reinforced Polymer (GFRP). A unidirectional E-glass fiber (MapeWrap G UNI-AX) is used as the strengthening material. A two-part epoxy primer (MapeWrap Primer 1) is used for preparation of the bricks surfaces and a two-part epoxy resin (MapeWrap 31) is used for impregnation of the FRP sheets and adhesion to the bricks. Mechanical tests are performed on the materials following the applicable test standards [14–17] and the results are presented in Table 1.

Table 1. Material mechanical properties.

Masonry brick			CoV(%)
Compressive strength	f_{cb} (MPa)	14.3	4.0
GFRP coupons			
Tensile strength	f_{tf} (MPa)	1250	15.0
Elastic modulus	E_f (MPa)	79200	6.8
Ultimate deformation	ε (%)	3.0	20.2
Epoxy resin			
Tensile strength	f_{tm} (MPa)	53.8	9.7
Elastic modulus	E_m (MPa)	2500	9.5
Glass transition temperature (four specimens only)	T_g (°C)	70.0	3.2

The bricks are initially dried in the oven and cleaned with an air compressor. The GFRP sheets are then applied on the bricks surfaces following the wet lay-up procedure. The primer is then applied to the brick surface for preparation of the substrate surface before GFRP application. Finally, the epoxy resin is used as the matrix of the composite material and also adhesion to the masonry substrate. 50 specimens with the geometrical details shown in Figure 1 are prepared in total.

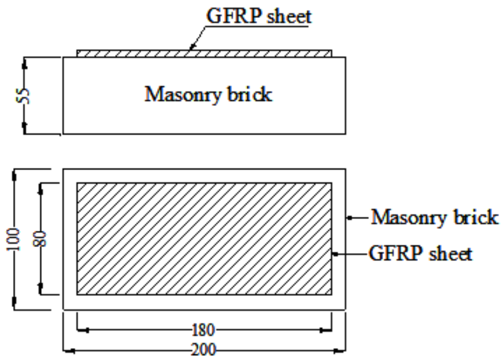

Figure 1: Geometrical detail of the specimens.

A conventional lime-based mortar with 15 mm thickness is applied on the FRP surface of 25 specimens to investigate the effectiveness of a normal rendering layer in protecting the strengthening system, see Figure 2.


Figure 2: Specimens with and without mortar layer.

2.2. Exposure program

The specimens are exposed to four constant temperatures of 70°C, 100°C, 280°C and 500°C for up to four hours in an oven. Given that the glass transition temperature (T_g) of the epoxy resin is 70°C, see Table 1, the exposure temperatures represent T_g, 1.4 T_g, 4 T_g and 7 T_g, respectively. The specimens are taken from the oven after 1, 2.5 and 4 hours in each exposure condition to investigate the changes of the bond performance with exposure time. Two specimens with rendering and two specimens without rendering are taken from the oven at each exposure time resulting in four pull-off tests for each exposure time and specimen type.

2.3. Pull-off tests

Pull-off tests are usually performed for evaluating the bond performance as an in-situ test method even if the results obtained represent the local adhesion strength between composite

material and the substrate, and are not representative of the global bond behavior. However, this test is selected in this study to investigate the bond degradation at elevated temperatures.
The specimens are kept in room temperature for at least one day before performing the pull-off tests to obtain the residual bond strength after different exposure conditions. The pull-off tests are performed following suggestions provided by the ASTM D4541-09 [18]. A 50 mm diameter partial core was drilled on the test zone with an approximate depth of 5 mm, see Figure 3. Then, aluminum disks are glued over the GFRP surface with a high strength adhesive. Two pull-off tests are performed on each specimen as shown in Figure 3.
The tests are performed using a closed-loop servo-controlled testing machine with maximum load capacity of 25 kN. A rigid supporting steel frame was used to support the specimens appropriately. The specimens are placed on the steel frame and firmly clamped to it. The disks are then pulled monotonically with a speed rate of 3μm/sec under displacement control conditions and the resulting load is measured by means of a load cell.

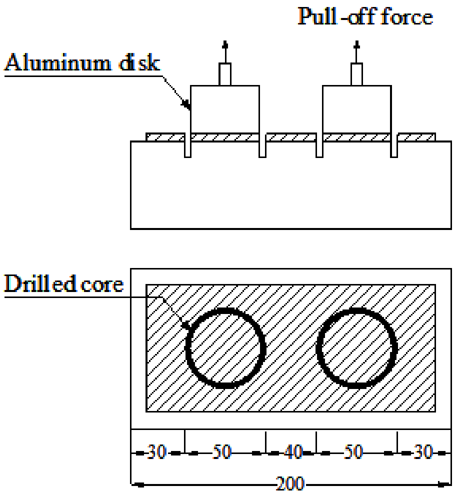

Figure 3: Pull-off tests specimen preparation.

3. RESULTS AND DISCUSSION

In general, no change of color or visible damage was observed in the specimens exposed to 70°C and 100°C. In specimens exposed to 280°C, the epoxy resin burnt in all exposure durations in the specimens without rendering, see Figure 4. However, burning occurred only after 2.5 hours of exposure in the specimens with rendering layer. The significant burning of epoxy resin in the specimens without rendering after 2.5 and 4 hours of exposure resulted in detachment of the fibers from the brick surface and therefore pull-off tests are not performed on these specimens. 500°C exposure resulted in complete burning of the epoxy resin and detachment of the glass fibers from the brick surface in all the specimens and exposure durations.

Figure 4: Typical specimens after exposeure to 280°C

The variation of the Pull-off strength of the specimens in different exposure conditions is shown in Figure 5 and Figure 6. The results are presented as normalized to the pull-off strength of the reference specimens. It can be seen that in both specimen types (with and without rendering) the residual pull-off strength is increased with time after exposure to 70°C and 100°C. This increase can be due to the epoxy re-curing and cross linking improvement. Significant reduction of pull-off strength can be observed in the specimens exposed to 280°C. The pull-off strength of the specimens without rendering has completely deteriorated at 2.5 hours of exposure. However, 30% and 75% reduction of the bond strength is observed in the specimens with rendering after 2.5 and 4 hours of exposure, respectively. The results show that the rendering layer has been effective in protecting the strengthening system at this temperature. The pull-off tests are not performed on the specimens exposed to 500°C due to the complete detachment of the fibers from the brick surface after the exposure.

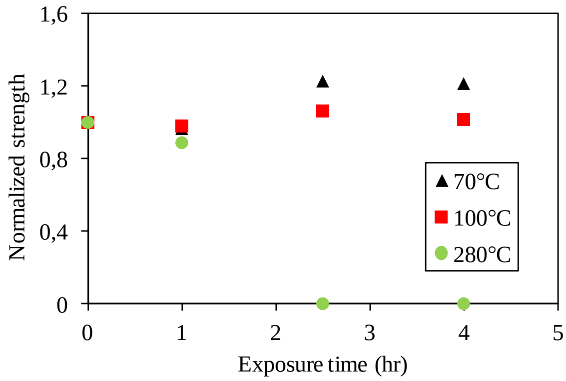

Figure 5: Variation of the pull-off strength in specimens without rendering layer.

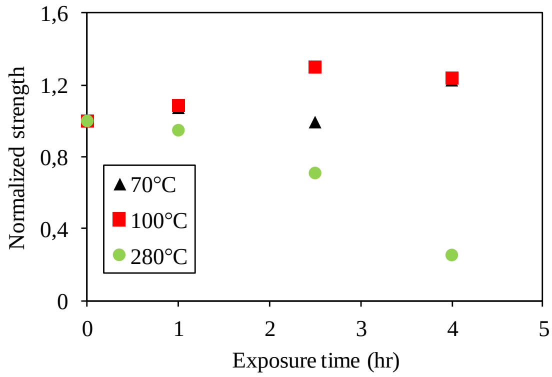

Figure 6: Variation of the pull-off strength in specimens with rendering layer.

The failure modes of the specimens were mostly cohesive failure with the fracture inside the brick, see Figure 7. Only in the specimens (with rendering) exposed to 4 hours of 280°C, an adhesive failure at the fiber/brick interface was observed.

(a) (b)

Figure 7: Failure modes: (a) cohesive failure inside the brick; (b) adhesive failure at fiber/brick interface.

4. CONCLUSIONS

The preliminary results of an extensive experimental program aiming at characterization of the bond performance in FRP-strengthened masonry at elevated temperatures were presented in this study.

The experimental program consisted of exposing GFRP-strengthened brick specimens to constant temperature conditions of 70°C, 100°C, 280°C and 500°C corresponding to the epoxy resin T_g, 1.4 T_g, 4 T_g and 7 T_g, respectively. 50 specimens were prepared and tested in total. A 15 mm mortar layer was applied on the FRP surface of 25 specimens to investigate its effectiveness in protecting the strengthening system.

A slight improvement of the residual pull-off strength was observed in the specimens after exposure to 70°C and 100°C. This increase can be due to the re-curing of the epoxy resin and cross linking improvement. On the other hand, significant reduction of pull-off strength was observed in the specimens exposed to 280°C. The pull-off strength of the specimens without rendering completely deteriorated after 2.5 hours of exposure. However, 30% and 75% reduction of the bond strength was observed in the specimens with rendering after 2.5 and 4 hours of exposure, respectively. The results showed that the rendering layer was effective in protecting the strengthening system at this temperature. The pull-off tests were not performed on the specimens exposed to 500°C since the fibers were completely detached from the brick after the exposure. The failure modes of the specimens were mostly cohesive failure with the fracture inside the brick. Only in the specimens (with rendering) exposed to 4 hours of 280°C, an adhesive failure at the fiber/brick interface was observed.

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