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Assessment of the Bond Quality Degradation in FRP-strengthened Masonry using IR Thermography Technique

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SUMMARY

The FRP-to-masonry bond behavior in externally bonded reinforced masonry structures is the main mechanism in controlling the effectiveness of this technique. Therefore, monitoring the quality of bond during the service life of the structure is of crucial importance for structural health evaluation. The bond quality may be affected due to environmental conditions which results in local detachments at the FRP/substrate interface. These detachments can propagate along the interfacial region and affect the bond performance to a large extend. Therefore, the use of feasible non-destructive techniques for assessment of the bond quality and monitoring the debonded areas are of great interest. This paper investigates the applicability of infrared thermography technique in the assessment of the bond detachments in environmentally degraded FRP-strengthened masonry elements. FRP-strengthened specimens have been exposed to accelerated environmental conditions in a climatic chamber and the changes in the bond quality are monitored with infrared thermography technique. Infrared thermal videos were taken from the specimens after different periods of exposure to accelerated environmental conditions and the delaminated areas have been quantitatively evaluated. The obtained results are presented and critically discussed. It is observed that this technique can provide acceptable results for the system investigated in this study.

1. INTRODUCTION

External strengthening of masonry structures with FRP composites has become a popular strengthening method in the last years. Advantages such as low weight to strength ratio, high mechanical properties, and ease in application have made FRP composites a suitable solution for strengthening purposes. Extensive experimental and numerical studies have been performed on the short-term performance of FRP strengthened elements [1-3]. However, the durability and long-term behavior of these systems are still unknown and critical gaps in understanding the degrading mechanisms can be found [4].

The bond behavior between FRP composite and masonry substrate is a key parameter in performance of the strengthened element. Therefore, monitoring and evaluating the bond quality during the structure service life is of crucial importance. Environmental conditions can cause delaminations in the interfacial region which affect the structure performance. Interfacial flaws and defects can also be produced due to poor workmanship, especially in wet lay-up applications. Partial destructive tests such as pull-off tests have been conventionally used for investigating the bond quality. However, these tests are regarded as localized tests which do not allow conducting large inspections [3, 5]. Therefore, use of a nondestructive test, which can provide useful information on the bond quality is necessary. In this regard, IR thermography technique has been accepted as an effective nondestructive method for detection of bond defects and delamination in FRP composites [5-7].

This study focuses on the use of IR thermography technique for assessment of the bond quality and degradation due to environmental conditions. A quantitative IR thermography method previously used in [5] has been adopted and used for detection of the defects in FRP-strengthened masonry systems. FRP-strengthened specimens have been prepared following the wet lay-up procedure. After curing process, the specimens have been exposed to accelerated environmental conditions in a climatic chamber. The changes in the bond quality have been periodically inspected by performing IR thermography tests and the results are presented and discussed.

2. ACTIVE IR THERMOGRAPHY METHOD

IR thermography method has been extensively used for detection of defects or delaminations in FRP bonded components. Applications are mostly focused on qualitative assessment of the defects. However, once the defects have been located, it is interesting to characterize them quantitatively in order to judge their severity [8]. For this reason, quantitative IR thermography methods have been developed and used in different research subjects.

In active thermography method (AIT), an external heat source is used for applying a heat flux to the surface of the component under investigation, see Figure 1. Thermal images can be taken during the heat application or after it when the surface starts to cool down.

Main approaches used for external heating in AIT technique are pulse heating, step heating, and lock-in thermography [8]. In pulse heating method, a short burst of heat energy is applied to the specimen's surface and thermal images are captured during the cooling process. Step heating consist of application of a lower intensity heat energy in a longer duration. In this technique, the thermal imaging is conducted during the heating process. The lock-in thermography is similar to the step heating process, although the applied heat energy is sinusoidal. The pulse heating and lock-in thermography methods have been used more extensively for nondestructive evaluation purposes [9]. The former has been adopted and used in this study to perform the IR thermography tests.

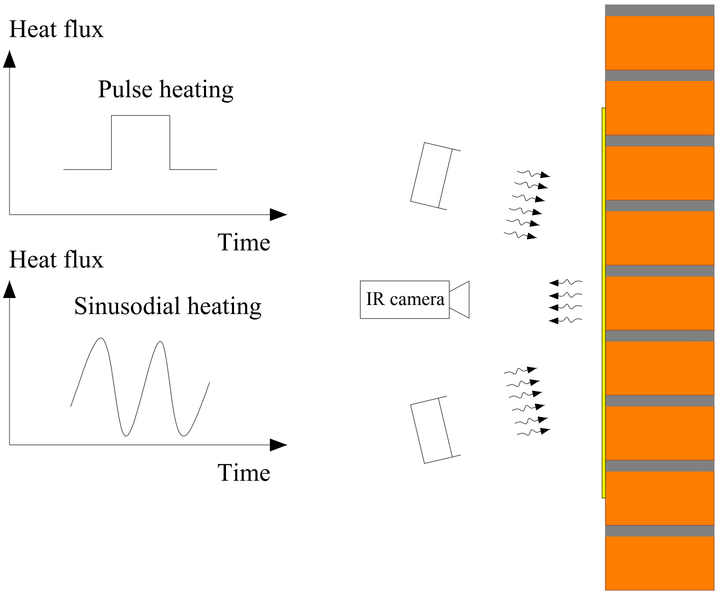

Figure 1: Different surface heating methods.

Generally, the adoption of IR thermography technique for evaluation of bond quality is based on the fact that the heat flux is transmitted at different rates in materials with different thermal properties. In a FRP-strengthened element, any defect or delamination in the interfacial region changes the thermal properties in that area. Therefore, if a heat flux is applied to the surface of a FRP-bonded element, the heat will be transferred with a different rate in the defected areas with respect to the perfectly bonded areas. This results in appearance of hot or cold spots on the surface depending on the adopted heat observation method [6, 9], see Figure 2. The heat observation methods can be categorized as reflection and transmission infrared observations. In the reflection observation method, the heat source and IR camera are placed at the same side of the specimen and the reflected heat from the specimen's surface is detected with the IR camera. In this method, the defects appear as hot spots in the thermal images. In the transmission observation method, the heat source and IR camera are located in the opposite sides of the specimen and the transmitted heat is measured on the surface under investigation. In this method, the defects appear as cold spots in the thermal images. The reflection observation method has been used in this study for performing the IR thermography tests.

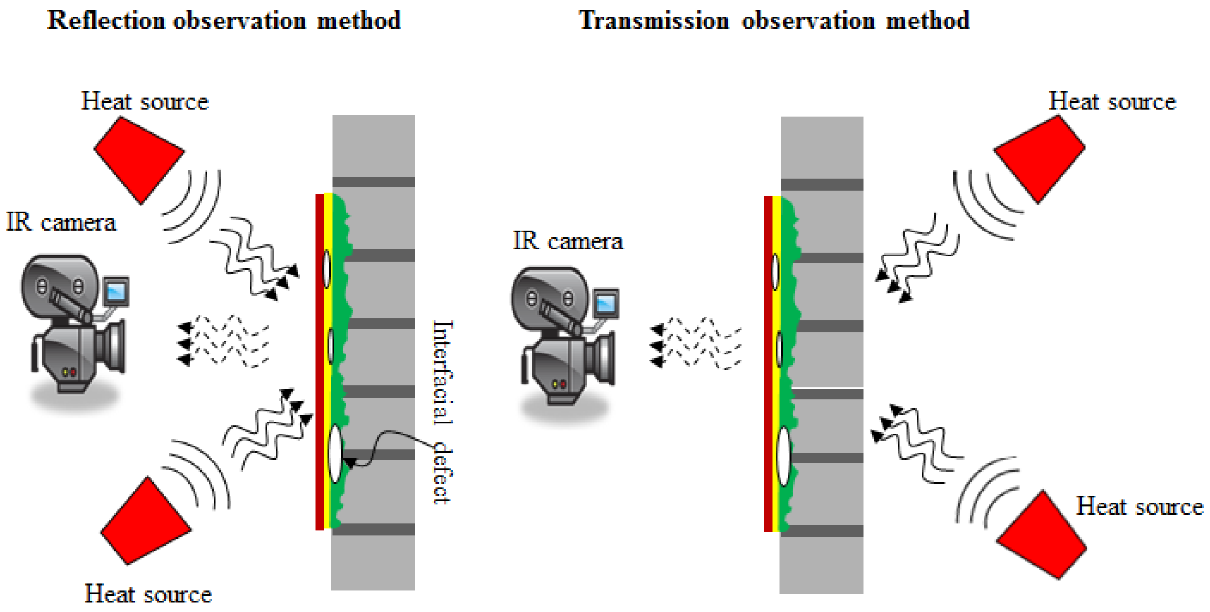

Figure 2: Different heat observation methods.

The temperature decays with time and the resolution of the observed defects in the thermograms changes at different moments. Therefore, selection of an appropriate thermogram with the best contrast and resolution is necessary to obtain the highest possible accuracy in quantitatively assessment of the defects. It is usually considered that the most appropriate thermogram is the one with the maximum thermal contrast [5, 7]. Once the suitable thermogram has been selected, the defect size can be estimated with the aim of the available analytical methods. A simple inverse method, namely two-point inflection method, has been used in this study for calculating the defects boundaries and sizes.

The thermal contrast can be obtained as [5, 10]:

$$C(x,y,t) = \frac{\Delta T_{def}(x,y,t)}{\Delta T_{sound}(x,y,t)} = \frac{T_{def}(x,y,t) - T_{def}(x,y,t_0)}{T_{sound}(t) - T_{sound}(t_0)} \tag{1}$$

where, $C(x,y,t)$ is the special thermal contrast at time t, $T_{def}(x,y,t)$ is the temperature at the defect point at time t, $T_{def}(x,y,t_0)$ is the initial temperature at the defect point, $T_{sound}(t)$ is the temperature at the sound area at time t, and $T_{sound}(t_0)$ is the initial temperature at the sound area. The maximum value of $C(x,y,t)$ is defined as the highest thermal contrast and is expected to have the best resolution for defect's size detection.

An as example, the time history curve of a sound and defected area together with the calculated thermal contrast are shown in Figure 3. The thermogram corresponding to the peak value of the thermal contrast curve is selected as the most suitable one for quantitatively assessment of the defect.

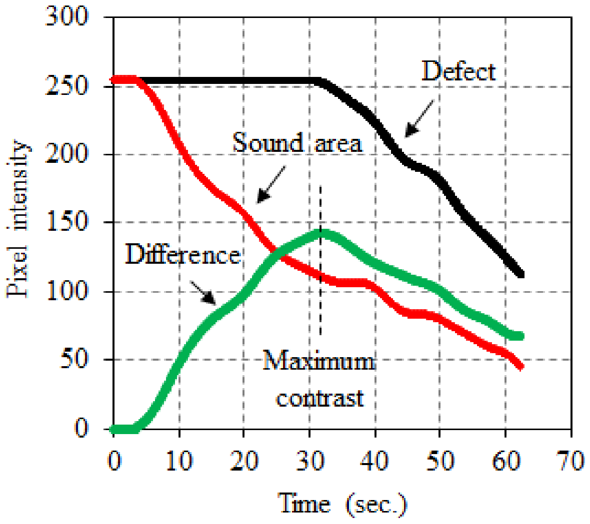

Figure 3: Thermal history curve of a sound and delaminated area.

2.1. Inflection point method

In this method, it is assumed that the boundaries of a defect are the inflection points of a 4th order polynomial curve which has been fitted through the temperature profile along the defect [5].

Figure 4 shows the longitudinal and vertical temperature profiles of a defect in a sample thermogram. The defect can be recognized as the hot spot observed in the thermogram and temperature profiles. Once the temperature profile is obtained, it can be divided into two parts from its center point as shown in Figure 5. Each part can be estimated with a 4th order polynomial curve. Two times differentiating the obtained polynomial gives the inflection point which is assumed to be the respective defect boundary. Therefore, the total length of the defect along the section under investigation is the distance between the two calculated boundaries. Following this procedure in different sections and directions, the shape and size of the defect can be obtained.

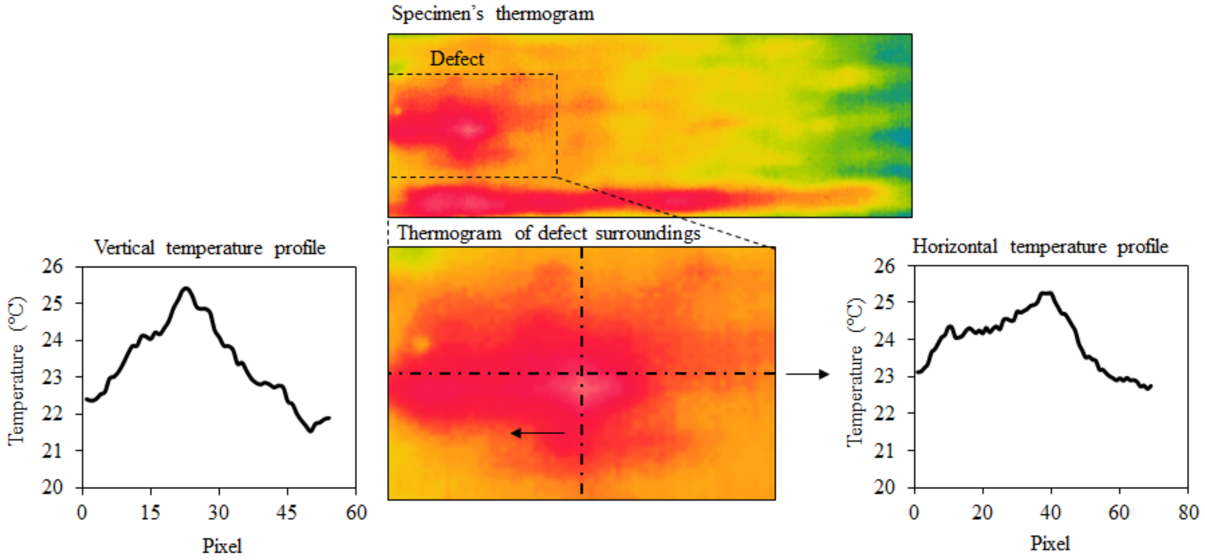

Figure 4: Thermogram of a defect.

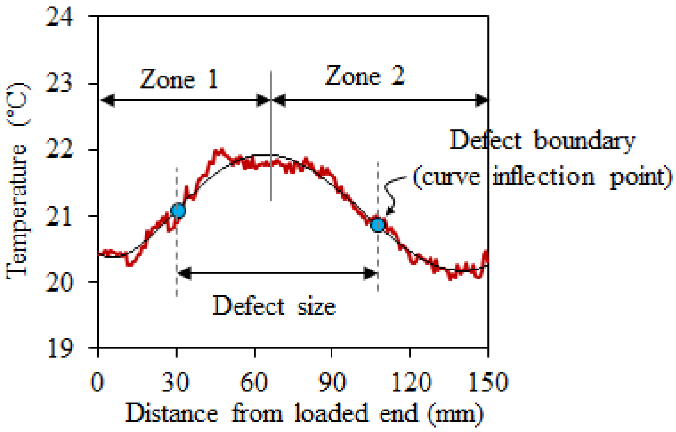

Figure 5: Defect boundaries identification.

3. APPLICATION TO DURABILITY TESTS

3.1 Specimens preparation

GFRP-strengthened brick specimens were prepared for performing the durability tests. GFRP sheets with 50 mm width were applied to the brick surface following the wet lay-up procedure, see Figure 6. 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 for adhesion to the masonry substrate. [11]

The details of the prepared specimens are shown in Figure 7. The bonded length of the strips was equal to 150 mm with a 40 mm unbounded part at the loaded end.

Figure 6: Specimens preparation.

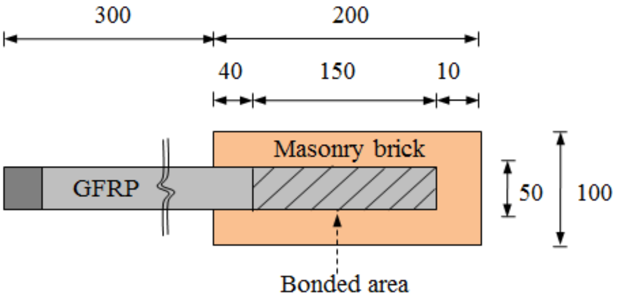

Figure 7: Geometrical details of the specimens.

3.2 Environmental exposure

The specimens were exposed to accelerated hygrothermal conditions in a climatic chamber. The aim was to investigate the degrading effects of hygrothermal conditions on the bond quality. The environmental exposures consisted of 6 hr temperature cycles from +10°C to +50°C and constant relative humidity of 90%, see Figure 8. In each cycle, the temperature was kept constant at +10°C for 2 hr. Then, it was increased to +50°C in 1 hr, followed by 2 hr constant temperature at +50°C. The temperature was decreased again to +10°C in 1 hr resulting in 6 hr cycles. The specimens were subjected to a total of 200 cycles. [11]

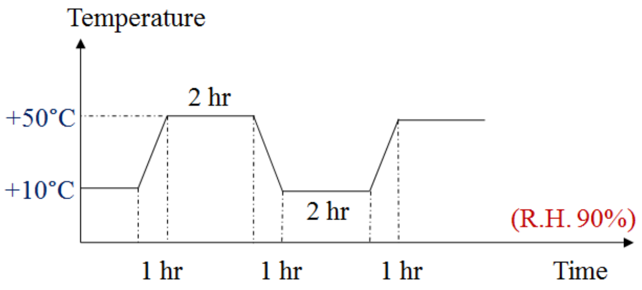

Figure 8: Hygrothermal exposure.

3.3 IR thermography test setup

The pulse heating technique together with the reflection observation method was used in this study for performing the IR thermography tests, see sec. 2. In this technique, the specimens surfaces are exposed to a thermal energy for a short period and then the changes in the surface temperature of the heated material is recorded as sequential thermal images or videos during the cooling process. Due to the thermal diffusivity properties of the material, the surface temperature decreases quickly after heating the specimens. The existence of discontinuities in multilayered materials such as interfacial defects or delaminations affects the thermal diffusivity of the material. This results in affecting the temperature decay in defect areas which can be identified as hot spots in the thermal images. The tests were performed with a FLIR ThermaCAM T400 infrared camera and thermal videos were recorded at the rate of 9 frame/sec. Two lamps with a maximum capacity of 2000 W were used as the heating sources. The lamps were placed at 50 cm distance from the surface of the specimens, Figure 9. The obtained thermal videos were then converted with a Matlab code into 8-bit digitized sequential photos of 320×240 pixels for each recorded frame. In 8-bit formatting system each pixel has a value between 0 to 255 representing different colors. This range is assumed to present temperature variations linearly. The data has been converted to 3D matrices with the size of $320 \times 240 \times t$. The third dimension of the matrix, t, represents time.

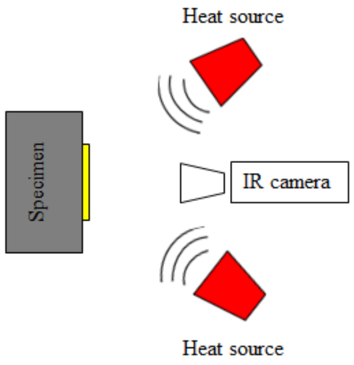

Figure 9: IR thermography test setup.

3.4 Results and discussion

After each 50 cycles of exposure, five specimens were taken out from the climatic chamber and besides the visual inspection, they were investigated with the IR thermography method.

Visual inspection and IR thermography tests showed that some FRP detachments have occurred in the specimens after exposure to accelerated hygrothermal conditions. Moreover, it was observed that the size of the detached areas increased progressively with increment of exposure cycles, see Figure 10. This progressive delamination of FRP from the masonry surface can be attributed to the thermal incompatibility problem which should be studied more extensively.

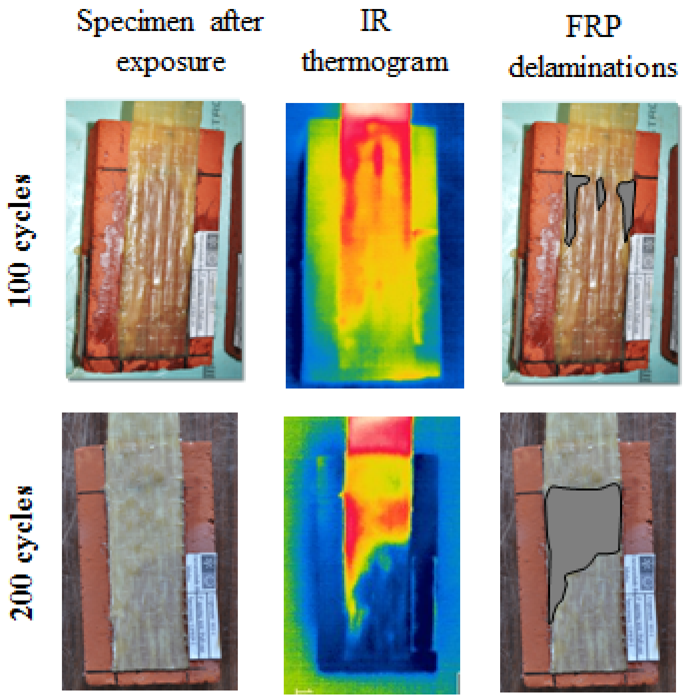

Figure 10: FRP delaminations in specimens after exposure to environmental conditions.

Figure 10 shows one representative specimen after exposure to 100 and 200 cycles of environmental conditions. The corresponding thermogram of the specimens at the maximum thermal contrast is also presented in this figure. The FRP delaminated areas have been highlighted according to the visual inspection and IR thermography analysis results.

For quantitative analysis of the defects, the temperature profiles have been obtained along the bonded length at different longitudinal and transverse sections. Then, the temperature profiles near the detached areas were fitted with a 4th order polynomial curve as described in sec. 2.1. The inflection point of the estimated curve was selected as the boundary of the FRP delamination. This process has been done for five specimens at each period of exposure and the remaining bonded area in each specimen has been calculated. The results are presented in Figure 11 as the average of the five inspected specimens. This figure presents the remaining bonded area of the specimens in each period of exposure normalized to the initial bonded area. As an example, the value of 0.7 in the specimens exposed to 150 cycles of environmental conditions means that 30% of the initial bonded area has been delaminated at this stage of exposure.

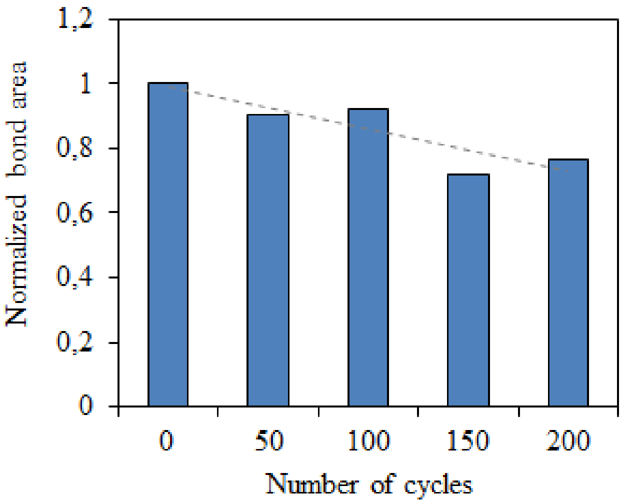

Figure 11: Reduction of the bonded area due to hygorthermal exposure.

4. CONCLUSIONS

Active IR thermography technique was used in this study for assessment of the bond quality and environmentally induced FRP delaminations in FRP-strengthened masonry elements. A quantitative IR thermography method was adopted and used for evaluating and quantifying the detected delaminations.

The specimens were exposed to accelerated hygrothermal conditions in a climatic chamber aimed at replicating high relative humidity conditions. The IR thermography tests and visual inspection of the specimens were performed periodically after each 50 cycles of exposure. A progressive delamination of FRP from the masonry substrate was observed in the specimens due to exposure time. FRP delaminated areas were detected and evaluated with the aim of IR thermography method. The results were presented and discussed.

ACKNOWLEDGMENTS

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REFERENCES

[1] Ghiassi B, Marcari G, Oliveira DV, Lourenço PB., “Numerical analysis of bond behavior between masonry bricks and composite materials.” Eng Struct, 43, 210-20 (2012).
[2] Ghiassi B, Oliveira D, Lourenço PB, Marcari A., “Numerical study of the role of mortar joints in the bond behavior of FRP-strengthened masonry.” Compos Part B, doi:10.1016/j.compositesb.2012.10.017 (2012).
[3] Oliveira D, Basilio I, Lourenco P., “Experimental bond behavior of FRP sheets glued on brick masonry.” J Compos Constr, ASCE, 15(1), 32-41 (2011).
[4] Karbhari VM, Chin W, Hunston D, Benmokrane B, Juska T, Morgan R, et al. “Durability gap analysis for fiber-reinforced polymer composites in civil infrastructures.” J Compos Constr, 7(3), 238-47 (2003).
[5] Lai WL, Kou SC, Poon CS, Tsang WF, Lai CC., “Characterization of the deterioration of externally bonded CFRP-concrete composites using quantitative infrared thermography.”, Cem Concr Compos, 32, 740-46 (2010).

[6] Tashan J, Al-mahaidi R. "Investigation of the parameters that influence the accuracy of bond defect detection in CFRP bonded specimens using IR thermography.", Compos Struct, 94(2), 519–31 (2012).
[7] Lai WL, Kou SC, Poon CS, Tsang WF, Ng SP, Hung YY. "Characterization of flaws embedded in externally bonded CFRP on concrete beams by infrared thermography and shearography.", J Nondestruct Eval, 28, 27-35 (2009).
[8] Maldague X., Theory and practice of infrared technology for nondestructive testing,. Wiley-Interscience, John Wiley&Sons Inc., 2001.
[9] Brown J, Hamilton H., "Quantitative infrared thermography inspection for FRP applied to concrete using single pixel analysis." Constr Build Mater, dor: http://dx.doi.org/10.1016/j.conbuildmat.2009.12.016 (2010).
[10] Starnes M, Carino N, Kausel E., "Preliminary thermography studies for quality control of concrete structures strengthened with fiber-reinforced." J Mater Civ Eng, 15(3), 266-73, (2003).
[11] Ghaissi B, Oliveira DV, Lourenço PB., "Experimental investigation on the long-term durability of bond between FRP and masonry substrates." In Proc of FRPRCS11, 2013.