Composites Part B 80 (2015) 162–176

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

Effect of thermo-hygrometric exposure on frp, natural stone and their adhesive interface

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ARTICLE INFO

Article history:
Received 5 November 2014
Received in revised form
8 May 2015
Accepted 25 May 2015
Available online 3 June 2015

Keywords:
A. Polymer-matrix composites (PMCs)
B. Debonding
B. Environmental degradation
D. Mechanical testing
E. Calcareous stones

ABSTRACT

As well known, the performance of Fiber Reinforced Polymer (FRP) materials as external strengthening technique is strongly dependent on the bond behavior between FRP and substrate. Several experimental studies have been performed on this topic, however limited attention has still focused on the bond durability. In this paper, the effect of a thermo-hygrometric environment on the interface behavior FRP-calcareous natural stones isinvestigated. Each utilized materials (natural stone, adhesive, FRP sheets) was firstly exposed to the same thermo-hygrometric atmosphere; a relevant decay of mechanical properties has been found for the analyzed substrates (Lecce stone and Neapolitan tuff) while a negligible influence of the exposure has been observed for the composite reinforcements (CFRP and GFRP). The results regarding the variation of mechanical properties of the resins evidenced that the effect of the performed exposure is strictly correlated to the specific materials properties: a relevant degradation or even an improvement of mechanical performances has been,in fact, registered. The bond strength and the kind of failure were both analyzed as a function of the treatment used, as well as the strain and stress distribution at the interface. The kind of failure changed in some cases when passing from unconditioned to conditioned specimens; the bond strength, the maximum bond stress and the interface stiffness were affected by the treatment, manly depending on the adhesive resin deterioration. Finally, on the basis of the provisions given by the CNR-DT 200 R1/2013 document, the possibility of defining design relationships, able to take into account also durability aspects, is discussed.

1. Introduction

In the last decades, the use of FRP composites to repair and/or upgrade existing buildings or infrastructures proved to be an effective solution, being able to overcome some of the drawbacks experienced with traditional techniques. Many scientific papers have been published exploring the use of FRP on existing concrete structures, the most recent findings being reported in Refs. [1–4]. On the other hand, different codes or guidelines are available in several countries [5–11].

The application of FRP on masonry structures, even if considered as a promising solution, received less attention from researchers; only recently the Italian Research Council published a guideline in this field [11]. It is obvious that the assessment of design guidelines of general validity is much more difficult in this context due to the great variability of masonry and construction typologies worldwide as well as the different conservation approaches in the different countries. It is well recognized that the reliability of FRP strengthening based on EBR (Externally Bonded Reinforcement) techniques depends to a large extent on the bond between the reinforcement and the substrate, thus on the ability of stresses transfer at the interface. Generally speaking, masonry walls strengthened by external FRP sheets may undergo to crisis by both local and global failure modes, namely: the cracking of masonry in tension; the crushing of masonry in compression; the shear-sliding of masonry; the failure of the FRP reinforcement; and, finally, the delamination of FRP from masonry substrate [1–4,11]. This last mechanism is deemed particularly dangerous since it causes a brittle and premature collapse. In order to evaluate the maximum stress that can be transferred before debonding by the reinforcement to the substrate, specific bond testing and analysis procedures should be performed.

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http://dx.doi.org/10.1016/j.compositesb.2015.05.041
1359-8368/

The analysis of the bond between FRP reinforcement and masonry has been the topic of recent research works. The bond behavior and load transfer mechanisms at the FRP-masonry interface were found basically similar to those relative to FRP-concrete joints. Bond tests evidenced, in fact, the occurrence of a risky mechanism of failure due to delamination, even more marked when FRP strips are glued to historic masonry, characterized by poor surface properties [12–25]. Analogously, only few analytical studies are available, especially aimed at defining the bond behavior at the masonry-FRP reinforcement interface and at calibrating a design relationship able to predict failure modes and loads. Such a lack of knowledge is due both to the variability of the masonry supports, which makes difficult to assess general relationships valid for whatever support, and to the absence of homogeneous experimental results for each type of support, due to the intrinsic variability, in texture, characteristics, etc., of the substrate. Some efforts have been recently done in order to describe the bond behavior of FRP reinforcements-clay bricks joints both via experimental tests and numerical analyses [18,21,24].

The interface behavior can be also severely affected by environmental or other aggressive agents that could greatly compromise the efficacy and durability of the intervention. It is well recognized that the durability performance of FRP strengthening practice is very difficult to assess, since it depends on the durability of the FPR system used to rehabilitate the structure, thus on the durability of the FRP's components, on the integrity of the FRP/substrate joint and on the durability of the substrate itself. Few studies have been recently devoted to the analysis of the durability of masonry structures strengthened by FRP materials [26–31]. A finite element modeling procedure for analyzing the hygro-thermo-mechanical response of multilayered structures constructed with distinctive permeable materials was developed by incorporating structural stress analysis into the coupled moisture/temperature finite element model [26–29]. The interfacial stresses increased with the increase of the humidity diffusion time and monotonically approached the stress level at the steady-state condition of the humidity diffusion. It was also shown that, by assuming constant humidity transport properties, the analysis resulted in a significant underestimation on the maximum interfacial stresses [26]. The effect of temperature gradient on the moisture distribution resulted in an accumulation of moisture at the interface, and induced interfacial stresses even in the absence of a moisture gradient [28,29].

An experimental investigation on the changes in the bond behavior of FRP strengthened masonry elements due to saturation after water immersion is reported in Ref. [30]. Shear bond tests showed that the ductility of the bond behavior increases with immersion time of the tested specimens. The bond strength and stiffness were observed to decrease, while the debonding slip increased. It was observed that the degradation in the bond strength and stiffness diminishes with time and possibly a residual value is obtained after a certain immersion time. A similar degradation was also observed in interfacial fracture energy. The failure mode was cohesive in all the specimens, with the fracture surface inside the brick [30].

In a previous paper, the effect of a long term immersion in water on bond durability was analyzed when FRP elements were externally applied to a natural masonry substrate [31]. The obtained results showed that the bond strength reduced up to 26% passing from unconditioned to conditioned specimens, and a more fragile bond behavior was observed. In all cases, the debonding involved the first masonry layers, due to the weakness of the substrate with respect to the reinforcing system, both in standard conditions and after the aging in water. In addition, the water seems have little influence on the stiffness of the interface. The available relationships, provided by the Italian Technical document [11] for evaluating the bond strength in standard conditions, seemed to be still effective in the case of aged specimens, once the decay of the mechanical properties of the utilized materials is considered. Otherwise, an appropriate environmental coefficient should be added for taking into account the reduction of the bond strength.

In the present paper, the effect of the exposure to a thermo-hygrometric environment on the performance and durability of FRP-masonry joint was analyzed and discussed. To this aim, an investigation on the FRP sheet-natural stone bond behavior in standard conditions and after exposure to 40 °C and 90% R.H., performed in a climatic chamber, was carried out. Two types of natural stones were employed: “Lecce stone”, traditionally employed in masonry constructions of the Salentine Peninsula, and “Neapolitan tuff”, in particular “Neapolitan Yellow tuff”, characteristic of the volcanic area surrounding Naples. The commercial FRP reinforcements used were made by unidirectional one-layer carbon or glass fibers and an epoxy based matrix, applied to the stone substrate by the hand lay-up technique. Each material employed in the present study (i.e. the stone elements, adhesive and putty, composite sheets) was also exposed to the same thermo-hygrometric environment used for the FRP-stone joints in order to analyze the influence of the treatment performed on any single component. On the basis of the provisions given by the CNR-DT 200 code [11], the possibility to calibrate design relationships, able to take into account also durability aspects, is discussed.

2. Experimental investigation

2.1. Materials

Two types of natural stones, widely used in existing masonry structures of Southern Italy, were selected in the present study: the “Lecce stone” and the “Neapolitan tuff”. They are both calcareous stones characterized by high porosity, easy workability, good esthetic and satisfactory mechanical and physical properties, even if the latter are highly dependent on the quarry location. “Lecce stone” shows a widespread porosity, around 39% [32], and small pore size, while “Neapolitan tuff” displays a porosity of about 50% [33].

Two commercial FRP's, used as reinforcing systems, were analyzed: a Carbon Fiber Reinforced Polymer (CFRP) and a Glass Fiber Reinforced Polymer (GFRP). Both FRP's were manufactured through hand lay-up technique, following the procedure suggested by suppliers. The glass or carbon fiber sheets were thoroughly soaked in an epoxy adhesive, supplied by the same company, removing any excess of the resin by a roller. In each layer, the glass or carbon fibers were disposed in the lengthwise direction. The main properties of the fibers composing the two FRP systems, attained from the relative data sheets, are reported in Table 1.

The specimens of both CFRP and GFRP were manufactured in dimensions and shape according to the code relative to the assessment of tensile properties of composites, as previously reported [34].

Table 1
Main characteristics of FRP's (from supplier's data sheet).

	Thickness of sheet	Strength ASTM 3039	Modulus ASTM 3039	Density
	mm	MPa	GPa	g/cm^3
CFRP High resistance carbon fibers	0.165	3430	230	1.82
GFRP Alkali resistant glass fibers	0.230	1700	65	2.60