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Procedia Structural Integrity 12 (2018) 594–601

Structural Integrity Procedia

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AIAS 2018 International Conference on Stress Analysis

Experimental evaluation of the adhesion of a FRCM-tuff strengthening system

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Abstract

Nowadays, the use of innovative materials for the reinforcement of existing buildings are the most used technological solutions. Several reinforcement systems are available currently on the market and different research groups dealt with them from experimental point of view; these systems differ both in the reinforcing fibers used and the type of matrix applied.

The most common reinforcement systems are those based on polymer matrix (FRP) provided by criteria and design rules consolidated in the application field for both new and existing buildings. In recent years scientifically-based cement matrix reinforcement systems (FRCM) are been used and experimented in the field of existing constructions. Unfortunately, there are currently no guidelines for qualification, as well as design criteria and application rules. It is a completely different reinforcement system compared to the common FRP reinforcements, in fact the cement matrix has a different mechanical behavior when applied to masonry supports. The mechanical behavior, already investigated by numerous authors, highlights the advantages that can be obtained with respect to a traditional reinforcement system. The aspect that still needs to be analyzed and studied is the adhesion between the existing support and the FRCM reinforcement system. In the present work, the attention is focused on the adhesion of a FRCM-tuff reinforcement system; for this purpose, experimental tests were carried out at the Materials and Structural Testing Laboratory of the Civil Engineering Department of the University of Calabria. The specimens consist of blocks of tuff, as regards the support, while the applied FRCM reinforcement system is based on basalt fibers and cement matrix. All results were compared with those obtained from previous research using other support materials and reinforcing fibers.

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10.1016/j.prostr.2018.11.059

Keywords: Type your keywords here, separated by semicolons ;

1. Introduction

The strengthening system for the existing structures are, at present, the civil engineering topic most developed and especially in continuous evolution. This is due to the updating of the technical standards and the progressive increase of the performance required to a structure in which structural changes have been occurred over time. Several reinforcement techniques have developed in recent decades, including those that refer to the use of fiber-reinforced composites, both applied to concrete and masonry structures. The intervention is based on the application of fabrics, made of fibrous materials with high mechanical resistance, on substrates of various properties by means of different resins. The effectiveness of these reinforcement systems is especially evident when applied to structures with poor tensile strength, such as masonry constructions; they allow to realize systems characterized by much higher resistance limits than traditional masonry and by a less fragile breaking behavior. In the application of FRP composites (based on epoxy resins), it is needed a higher level of control and site inspection due to: the reduction of performance with high temperatures, after long-term exposure to certain conditions of humidity and cycles of freezing and thawing; the impossibility of application on wet surfaces. Noteworthy are also the modest mechanical properties in the orthogonal direction to the fibers and the low elongation at break, especially for system based on carbon fibers. On the contrary, the analysis of the adhesion behavior between the substrate and the reinforcement is of fundamental importance because the bond of adhesion between the two materials is still today the topic of numerous researches. The most used fibers for the production of composite materials, applied in the civil engineering field as reinforcement of masonry structures, are those of glass and PBO. To the considerable advantages of the latter, in terms of resistance, there are problems related to the environmental pollution produced during their processing, as well as the energy necessary for disposal at the end of their life cycle (Olivito et al, 2015, 2016, Cevallos, et al, 2016, Grande et al, 2018). Sustainable development, low environmental impact and renewable technologies have led scientific research to the study of eco-sustainable composite materials. For this reason, the fibers of natural origin (especially plant or volcanic) are attracting the attention of many researchers and in some sectors are already applied with excellent results. The not negligible mechanical properties, the low cost, the high specific resistance, the eco-compatible characteristics and the biodegradability are some of the main reasons why natural fibers are considered a valid alternative to traditional composite systems based on synthetic materials. A study carried out by the authors (Codispoti et al. 2015, Olivito et al, 2017, Tiberti et al 2017, Cevallos et al, 2016) showed that among the available vegetable fibers, the flax ones offer the best combination in terms of low cost, lightness, high strength and stiffness for semi-structural applications. Basalt fibers, on the other hand, do not have any toxic reaction with air or water, as well as in the case of contact with other chemicals; they do not produce harmful reactions to health or the environment; they are not combustible and are explosion proof; they have good hardness, excellent thermal and acoustic insulation properties and considerable mechanical properties. Furthermore, the possibility of recycling basalt fibers is of great importance and, therefore they can provide a partial solution to the problem of industrial waste disposal. The basalt fibers are turning out to be the scientists, an increasingly accredited choice as a replacement for steel, glass fibers and, in some cases, carbon fibers due to their high stiffness, the limited deformation values at break and the high tenacity, characteristics that make it a material of undoubted success in structural applications (Kunal Singha, 2012, Mercedes et al, 2018).

The composite materials, called NFRCM (Natural Fiber Reinforced Cementitious Matrix) are the result of the union of fabrics of natural-origin with an inorganic matrix based on cement mortar. It is considered a cement matrix if the mortar contains a quantity of polymers less than 5% of the total weight. The main reasons for considering NFRCMs a valid reinforcement system derive from the characteristics of the cement matrix which, unlike the polymer matrix of FRP, has a better resistance to fire, a compatibility with the support, especially in the case of masonry, gives permeability steamed and can be applied on wet surfaces. The effectiveness of NFRCM is strongly influenced by the ability of the matrix to impregnate the fibers of the reinforcing fabrics, the efficiency of the bond at the interface between fibers and matrix and the bond between matrix and reinforced support. In addition, the NFRCM composite materials are made of cement mortars produced with completely recyclable natural materials, fired at low temperatures, reducing emissions and energy consumption and therefore with a low environmental impact and eco-sustainable (Carrozzi et al, 2014).

In the present work the results of experimental tests are shown. This testing campaign was carried out at the Materials and structural Testing Laboratory of the Civil Engineering Department of the University of Calabria, on masonry specimens reinforced with FRCM composite materials based on basalt fibers. The specimens submitted to adhesion tests have allowed to study in more detail the bond adhesion of the eco-compatible reinforcement system.

2. Experimental program

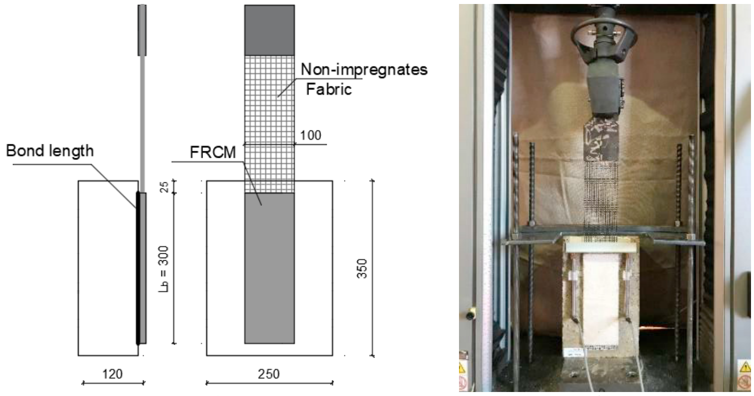
The bond behavior between masonry support and FRCM composite materials has been experimentally studied carrying out single-lap shear bond tests. These tests were performed on tuff specimens reinforced using FRCM composites based on basalt fibers. The tests have been carried out using tuff material because, with the fictile tubules bricks (Olivito et al, 2016), after the bricks and rubble masonry, tuff blocks are the most common materials used in Calabria for the construction of vaults and domes (Tiberti et al 2017).

Furthermore, the results obtained were compared with the experimental results previously obtained by the (Olivito et al, 2016) authors carrying out the same tests but using different materials: brick samples and FRCM composites based on flax and different basalt fabrics. All the tests were carried out in the Materials and Structural Testing Laboratory of the Civil Engineering Department of the University of Calabria.

2.1. Preparation of specimens and set-up tests

The specimens used to analyze the bond of adhesion were made using tuff blocks reinforced with a FRCM reinforcement system based on basalt fibers. The FRCM reinforcement consists of a single layer of fabric interposed between two layers of cement matrix, for a total thickness of about 10 mm. In particular, it is a bidirectional basalt fabric cut with a width *b* equal to 100 mm, consisting of 15 yarns.

The reinforcement was applied at a distance of 50 mm from the upper edge of the specimens and in a central position, with a bond length l_b equal to 260 mm (fig. 1.a). The unbonded fabric not inserted in the reinforcement system had a length of 300 mm. The specimens have been placed in a rigid frame, in order to prevent rotations and displacements, blocked by a steel system in order to minimize the development of normal stresses to the reinforcement-substrate interface due to eccentricity.



a) b)

Fig. **1**. a) Geometric representation of specimen, b) Set-up testing machine

Each specimen has been equipped with two aluminum tabs at the free end in order to guarantee a homogeneous distribution of the stresses and to avoid sliding phenomena during the application of the load (fig. 1.a). As regards the study of the sliding between the fabric and the support, two LVDTs transducers were positioned on both sides of the reinforcement.

The tests were carried out with a testing machine model 5582 Istron with a load capacity of 100 kN (fig. 2.b) and in the crosshead displacement control; the test speed was varied between 0.1-0.25 mm / min, while the acquisition frequency between 5-10 Hz.

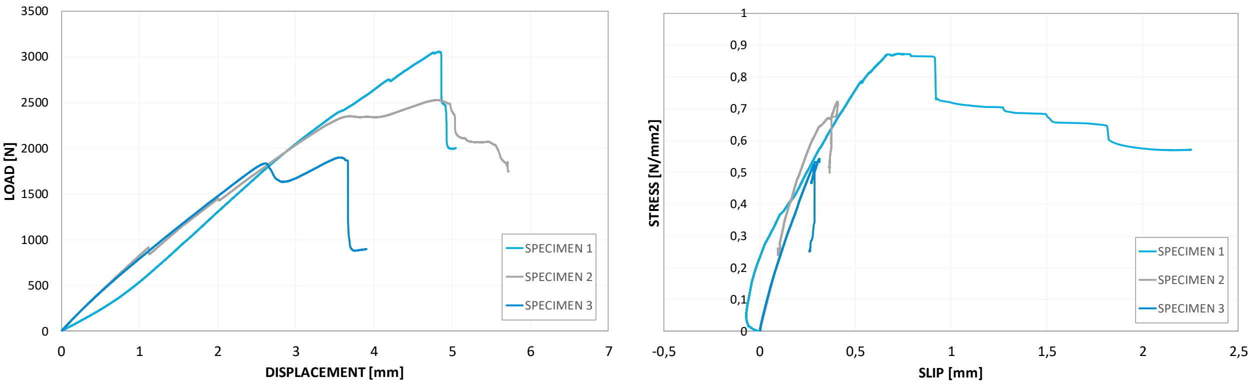
2.2. Single-lap shear bond tests

The behavior of FRCM composites and also NFRCM, is strongly influenced by the bond interface between fiber-matrix, which depends on the matrix capacity to penetrate within the single yarns of the reinforcing fabric, but also on the shape and the density of the fabric, as well as the preparation of the support. The rules for designing FRCM reinforcement system are still being tested, in fact there is still no well-defined technical document, but only the guidelines for the qualification of FRCM (Ascione, 2013).

The national (CNR-DT 200 R1, 2013) and international regulations (ACI, 2008, 2010, 2013) propose various set-up tests in this research field, in order to standardize the test phases and procedures based on the experimental results obtained by various research groups.

A typical test of adherence consists to apply a parallel and barycentric force to the warp direction of the fabric that make up the reinforcement, so called single-lap shear bond test.

First of all, elaborating the data obtained from the tests, force-displacement diagrams of the transverse were plotted (fig. 2.a) for all the samples tested. Subsequently, the stress-slip diagram (fig. 2.b), measured from the used LVTDs, was obtained calculating the stress as the ratio between the maximum force and the non-impregnated area of the fabric.



(a) (b)

Fig. 2. a) Load-displacement diagram; b) stress-slip diagram

After that, it was possible to calculate the averages of the parameters obtained, in terms of maximum force, average sliding at maximum load, maximum stress in the fabric and ratio between sliding and maximum stress (table1). The values shown refer to the three tested specimens with better results obtained than the five originally prepared.

Table 1. Experimental results

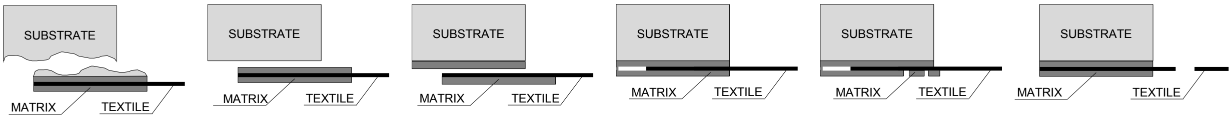
Tests	Load$_{max}$ [kN]	s_{max} [mm]	σ [N/mm2]	s_{max}/σ [%]
1	3,06	0,73	0,87	0,07%
2	2,53	0,41	0,72	0,06%
3	1,90	0,31	0,54	0,04%

Average	2,50	0,48	0,71	0,06%
CoV	23%	45%	23%	23,23%

2.3. Failure modes

During the bond tests, at the time of loading, it was found to be of relevant importance to analyze the failure modes of the specimens. As previously specified, two test speed values have been applied: 0.1 mm/min and 0.25 mm/min; this is because most of the specimens, tested at the beginning, in the unbonded area of the fabric have come to break. Consequently, it was decided to decrease the load speed, in order to better investigate the mode of failure. Indeed, the different load speed applied did not affect the final break, of the five tested specimens, only one broke for debonding between the matrix interface - with a load speed of 2.5 mm/min. In no tested specimen there was the complete detachment of the composite from the support, only micro-cracks near the interface occurred. On 5 tested specimens, only 3 were considered useful for the calculation of the average parameters reported in the table above, especially in the case of slip. It is evident that the value of the maximum force recorded during the test performed on the specimen 5, equal to 3,2 kN is clearly higher than the maximum loading forces obtained by testing the specimens 1,2 and 3, for this reason, it was excluded from the calculation. Despite this, taking into account the values of the maximum force obtained from the tensile tests of basalt fabrics, equal to 4.5 kN, only the latter test would be considered reliable for the purposes of comparison, obvious that only one value cannot representative.

The failure modes that are usually observed during delamination tests, can be classified as shown in the fig. 3: six different break modes that affect all the parts of FRCM reinforcement system. In general, from tests carried out for other researches (De Felice et al, 2017, Younis et al, 2018) and performed by the authors, the phases that characterize a break during single-lap shear bond tests can be classified as three: initially, lesions are observed in parallel to the applied load and in the thickness of the composite (fig. 4.g), subsequently as the load increases, transverse cracks to the application of the load occur in correspondence of the cement matrix layer; finally, when the matrix layer has completely broken, the first lesions are observed in the single yarns constituting the non-impregnated fabric.



A. Debonding with cohesive failure of the substrate

B. Debonding at the matrix-to-substrate interface

C. Debonding at the textile-to-matrix interface

D. Textile slippage within the mortar matrix

E. Textile slippage within the matrix with cracking of the outer layer of mortar

F. Tensile rupture of the textile (out of the bonded area)

Fig. 3. Different failures modes

In the specific case of this article, two failure modes were observed: debonding at the textile-to-matrix interface (C of fig. 3), and tensile rupture of the textile (F of fig. 3) (out of the bonded area) as shown fig. 4. a-b-c-d-e-f.. Differently from strengthening systems based on polymeric resins, mortar-based systems generally suffered a failure within the reinforcement, without involving the substrate. A cohesive failure by debonding at the textile-matrix interface was observed as shown in Fig. 4.i. In the brick specimens, the mortar did not detach from the brick surface (failure mode (A of fig. 3), while basalt fabrics slipping with mortar cover separation was observed in the sand-blasted specimens (combined failure mode (C-D of fig. 3), Fig. 4.h).

a) b) c)

d) e) f

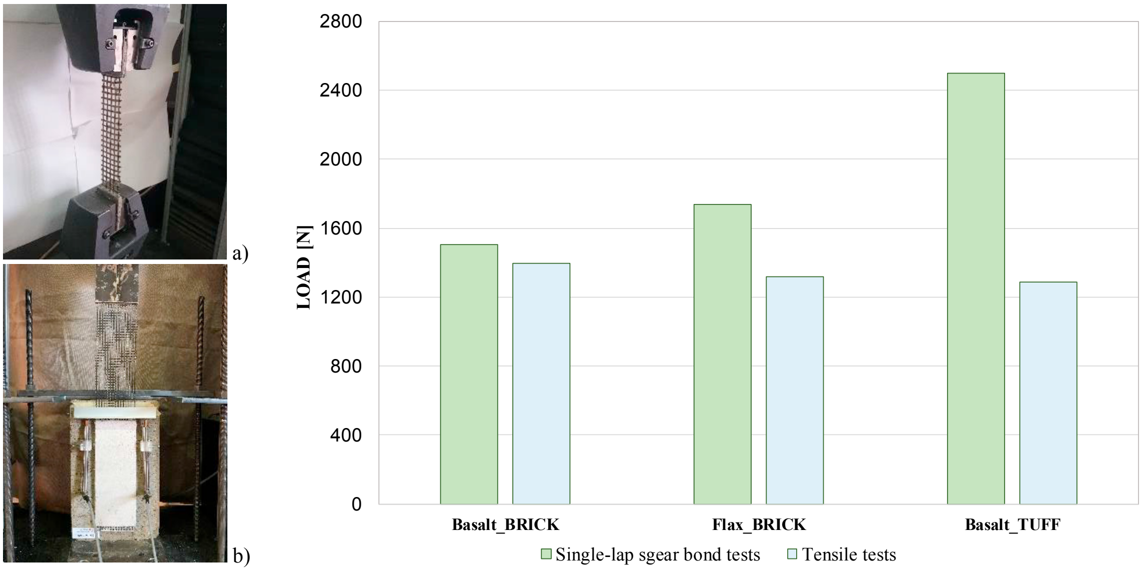
g) h) i)

Fig. 4. Different failure modes:

3. Main comparison with clay support

From previous tests carried out by the author, masonry specimens strengthened using flax and basalt fibers were investigated. In particular, the tests were performed on masonry samples consisting of 5 clay bricks and 4 layers of mortar reinforced with FRCM. The reinforcement fibers used in the FRCM composites were balanced fabrics of flax and basalt fibers, while the cementitious matrix was made with a mortar based on hydraulic binders and a specific latex replacing the total water.

Performed all the tests, it was possible to compare the results obtained with the values reached by the tensile tests on fabrics. In a particular way, the maximum force obtained from the two different types of experimental tests has been taken into consideration. As can be seen from the graph (fig. 5), the values obtained show the effectiveness of the tests carried out in terms of resistance of the non-impregnated fabric. In the adhesion tests, for both fabrics, linen and basalt, higher strength values were recorded compared to those achieved during tensile tests; same result for the tuff specimens reinforced with basalt are obtained. All results expressed in average values, were compared in the following graph (fig. 5). As can be seen from the graph, the values obtained show the effectiveness of the tests carried out in terms of resistance of the non-impregnated fabric. Finally, with regard to the maximum force obtained during the bond tests, it can be observed from the fig. 5 that the different type of support, brick and/or tuff, did not lead to evident changes in terms of maximum force. FRCM composites guarantee a good adhesion on masonry support but also because it has a rough and permeable surface, such as to underline the effectiveness of the FRCM-tuff-brick reinforcement system.



a)

b)

Fig. 5. Comparison between maximum load obtained: a) tensile tests; b) single-lap shear bond tests

4. Conclusion

The present work concerned the study of the bond adhesion between composite materials cement-based matrix reinforced with natural fibers, and masonry substrate. In particular, shear bond tests were carried out on tuff specimens reinforced with FRCM based on basalt fibers. From the analysis of the results it emerged, that the failure does not occur near the interface between reinforced materials and support, but there is a progressive cracking of the composite and the break occurs in the non-impregnated area, unlike what happens in FRP composites. This demonstrates how composites based on FRCM and natural materials have a great variety of mechanical properties compared to composites based on epoxy resins and synthetic fibers. Furthermore, the composites produced with inorganic matrices considerably increase the properties of the reinforcement systems, even more so than the resin-based organic matrix composites, given the greater compatibility between reinforcing fibers, matrix and masonry support. In conclusion, from the investigation of the failure modes, as well as from the results obtained, it is clear that the set-up test used, needs to be revised. In fact, the bond that is created between the FRCM reinforcement system and the tuff substrate, or anyway masonry substrate, is much more resistant than the strength of a fabric such as basalt. Finally, the single yarns show evident unevenness compared to glass or steel fabrics.

Acknowledgements

The work was supported by the 2017-2018 DPC-RELUIS project coordinated by prof. Luigi Ascione and prof. Marco Savoia, research sector "Innovative Materials for Infrastructural Interventions on Existing Constructions", WP2 - Composites with cement matrix (FRCM), scientific manager prof. Renato S. Olivito.

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