



FRCM-confined masonry columns: experimental investigation on the effect of the inorganic matrix properties

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HIGHLIGHTS

- FRCM tensile characterization.
- FRCM confinement of masonry column.
- Analytical model for FRCM-confinement.

ARTICLE INFO

Article history:

Received 29 March 2018
Received in revised form 1 August 2018
Accepted 4 August 2018

Keywords:

FRCM
Masonry
Column
Confinement
Matrix

ABSTRACT

Nowadays, the strengthening and the retrofitting are crucial issues in the civil engineering challenge for structural conservation. Innovative techniques, using *fiber reinforced polymers* (FRPs) composites, have been proven to be very effective in a wide range of applications. However, the organic matrix appears to be inadequate because of its difficult reversibility, especially when referring to historical masonry buildings. In this perspective, a new generation of strengthening systems has been studied, known as *fabric reinforced cementitious matrices* (FRCMs). They generally consist in a dry fabric-based reinforcement (typically an open-grid or a textile) embedded in an inorganic matrix.

The present paper reports and analyses the experimental results on FRCM-confined masonry columns subjected to centred compression test. The main goal of this research consists in evaluating the role of the inorganic matrix in determining the effectiveness of FRCM-confinement. For this purpose, three different inorganic matrices, having different compressive strength, have been considered and used for confining a poor-quality masonry column. The different increases of the axial strength, due to the differences of the compressive strength of the matrices of the FRCM-system, have been assessed. Finally, the experimental results have been compared with the theoretical predictions obtained from the application of an analytical model, available in the literature.

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1. Introduction

In the field of the structural retrofitting and the seismic performance upgrade of existing buildings, recent developments have introduced a widespread use of new materials and techniques (e.g. in [1]), in addition to traditional ones. In this scenario, FRP materials had a greater diffusion in the last two decades, all over the world, especially in those regions prone to violent earthquakes. Thanks to their high-strength/high-stiffness to weight ratio, the composite materials allow to attain an increased strength and global ductility, without considerably modifying the shape and the weight of the original structural architecture. Their effectiveness is well-known for both local (involving a limited part of the struc-

ture) and global (involving the whole structural behaviour) repair/retrofitting interventions. Researches on the application of the FRPs, as reinforcement for concrete structures, appeared as early as the 1970s, [2]. However, only in the late 1980s, the wide acquired knowledge on the topic, leading to field applications, mainly addressed the use of the FRPs in forms of *externally bonded reinforcement* (EBR). At the same time, the analytical interpretation of the FRP-confinement has been assessed in different scientific researches; e.g. in [3–6].

On the other hand, the use of the FRPs, in ancient masonry constructions, has been recently questioned in terms of the mechanical (weak substrate versus strong reinforcement) and the historical compatibility (removability or reversibility not guaranteed), [7]. For these reasons, a new generation of fiber-based systems has been studied for a proper application in ancient masonry structures, namely the *fabric reinforced cementitious matrix* (FRCM), even

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if the matrix does not always contain hydrated cement powder. In the scientific literature, FRCMs are identified by several names: *textile reinforced concrete* (TRC); *textile-reinforced mortar* (TRM), *fiber-reinforced mortar* (FRM), *mineral-based composites* (MBC), *open-grid reinforced matrix* (ORM) and others. FRCM materials are now being considered as a reliable tool in the structural strengthening field of historical buildings. FRCM-systems consist in long fibers, typically in forms of $0^\circ/90^\circ$ nets or grids, embedded in an inorganic matrix (commonly lime or cement based). The function of the fibers is to bear the tensile stresses, while the matrix should be able to encapsulate and protect the fiber and also to transfer stresses from the substrate to the fiber (see [8–15]). The stress transfer from the column to the retrofitting is accomplished through the bonding between the substrate and the matrix and the mechanical interlocking between the fabric and the matrix (see [14–16]). The FRCMs cannot be considered as proper composite materials since the strain compatibility between reinforcement and matrix is lost after the cracking of the matrix (see [17,18]), even if in some cases the polymeric materials are introduced to improve the adhesion between the fibers and the mortar (i.e. adhesion promoter). At this stage, as soon as the interfacial stress increases, the slippage may occur and the interaction effectiveness remains mainly linked to the mechanical interlock and to the friction at the fiber/matrix interface. Due to this behaviour, it is reasonable to consider that the properties of the matrix plays an influential role in determining the FRCM structural performance. This aspect has been focused on a recent research regarding the FRCM-confinement of concrete, [19].

The theoretical interpretation of the “*matrix-effect*” in the FRCM-confinement has been recently addressed in [20,21] (and more recently in [22]); in which a design-oriented (DOM) and an analysis-oriented model (AOM) are reported, respectively. The properties of the FRCM-matrix (i.e. the compressive strength and the thickness) are shown to be crucial variables in the mentioned models in order to properly predict both the compressive strength and the ductility of the FRCM-column. Specifically, the DOM consists in a statistically-based empirical calibration of data collected from the literature. A multiple linear regression analysis has been performed and the importance of the parameters related to the FRCM-matrix has been critically evidenced. Moreover, a comparison with other available analytical models underlined the improved accuracy of the proposed formulation. Based on these results, an AOM has been also implemented by considering both the cracked and un-cracked phases of the FRCM-jacket during the axial loading of the confined column. In this sense, the effectiveness of the FRCM-confinement has been *step-by-step* updated and such consideration made the model able to compute both the hardening and the softening post-peak behaviour as found in experimental studies. An experimental versus theoretical comparison, in terms of the axial stress–strain curves, demonstrated the validity of the so-computed AOM. Albeit, the analytical model furnished enough accurate and precise outcomes, they were both based on different experiments, found in literature, in which the matrix-effect was not directly investigated. Whereby, the original contribution of the present paper is to investigate the mechanical role of the matrix in the FRCM-confinement of masonry column; so an experimental investigation has been planned specifically at this scope.

2. Experimental program

The experimental program included firstly the material testing for the characterization of their mechanical properties and then the structural elements, in the forms of small-scale columns; which were prepared and tested under uniaxial compression (load

without eccentricity). Eleven small-scale masonry columns have been built and tested in order to investigate on the influence of the mechanical performances of the adopted matrix on the effectiveness of the FRCM-confinement. The stress-transfer is related mainly to the interaction between the grid and the matrix; that interaction depends basically on chemical adhesion and mechanical interlocking. Generally, a significant chemical adhesion is promoted by adding a polymer within the matrix while the mechanical interlocking depends on the geometrical properties of the grid, as well as, on the mechanical characteristics of both the grid and the matrix. In all cases the crack formation and evolution are related to the stress-transfer mechanism between the matrix and the grid. At the present, the knowledge of a bond law between the matrix and the grid is not available neither experimental results that relate the interaction at the matrix-grid interface with the whole performance of strengthened structural elements. For this reason, the properties of both the grid and the matrix are considered as the most significant parameters for taking indirectly into account the mentioned interaction performance.

It should be remarked that the tensile strength of the matrix is strongly related to its mechanical grade; thus, different grades of mortars were tested and studied in this research. The column specimens have the same geometry and have been built with the same constituent materials, namely natural bricks (limestone) and mortar joints (lime-based). The columns are representative of a typical situation met in historical constructions in terms of materials and stacking. Moreover, the same dry glass fiber grid has been used in the FRCM-system. Due to the alkalinity of the inorganic matrix, an *alkaline resistant* (AR) glass type was used, including ZrO_2 in its chemical composition. On the basis of the manufacturer datasheet, the glass-grid is characterized by 120 gr/m^2 weight, $12 \times 12 \text{ mm}$ mesh, 74 GPa elastic modulus, $20 \text{ mm}^2/\text{m}$ cross-section, 28 kN/m rupture load and 1400 MPa rupture strength, corresponding to a 2.0% of elongation. Three different FRCM-systems were used, varying the mechanical grade of the inorganic matrix, while maintaining the same fiber grid. Thus, the experimental investigated variable resulted the compressive strength of the matrix considering that other mechanical properties can be accurately related to it (i.e. tensile and flexural strength). In fact, three different axial strength grades have been prepared and used: 4 MPa , 7 MPa and 23 MPa . The first two matrices (i.e. 4 and 7 MPa) were lime-based hydraulic mortars; while, the highest grade of mortar was a cement-based mortar.

The test program on the masonry columns is summarized in Table 1, in which the letter “*U*” refers to unconfined specimens, “*FRCM*” indicates FRCM-confined specimens, the letter “*M*” refers to the mortar and the last number to the nominal compressive strength of the mortar, i.e. *M4*, *M7* and *M23*.

The columns were prepared in the same hydro-thermal conditions (i.e. 65% relative humidity and temperature equal to 25°C), with the same construction schemes and handcraft. Each specimen had the dimensions of $250 \times 250 \times 500 \text{ mm}$. The bricks were placed in 13 rows, with 12 bed joints in between, as shown in

Table 1
Experimental program.

Sample label	Number	Matrix	Fiber grid
<i>U</i>	2	–	–
<i>FRCM_M4</i>	3	Hydraulic lime-based mortar (4 MPa compressive strength)	AR-Glass
<i>FRCM_M7</i>	3	Hydraulic lime-based mortar (7 MPa compressive strength)	
<i>FRCM_M23</i>	3	Cement-based mortar (23 MPa compressive strength)	

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