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Masonry columns strengthened with Steel Fabric Reinforced Cementitious Matrix (S-FRCM) jackets: Experimental and numerical analysis

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ABSTRACT

The structural performances of masonry columns confined with Fabric Reinforced Cementitious Matrix (FRCM) is analysed, both experimentally and theoretically, in this paper. The analysis refers to clay brick masonry columns confined with a steel-FRCM strengthening system made by steel fiber sheets with an inorganic matrix. An experimental investigation on steel-FRCM confined clay brick masonry columns having an overall height of *770 mm* with rectangular cross-section *250 × 250 mm* was carried out. Columns were tested under axial and eccentric load until collapse. The test parameters considered in this study were the number of confining layers and the load eccentricity.

In addition, a numerical 3D model was calibrated by both results of the experimental tests of this work and results available in the literature. A numerical model was realized by the commercial code Abaqus, based on the macro-model approach in order to simulate the non-linear structural behaviour of masonry columns. The outcome of this investigation allows to evaluate the influence of considered parameters on the effectiveness of the confinement both in terms of strength and ductility.

1. Introduction

Fiber reinforced composite, especially fiber reinforced polymer (FRP) composites, by jacketing of columns is a very widespread technique in a large number of rehabilitation in the area of seismic events.

Several advantages are related to the use of FRPs to strengthen existing structures; among these the high strength to weight ratio, corrosion resistance, ease and speed of application, and minimal change of geometry. Despite all these advantages, the FRP retrofitting technique has a few drawbacks mainly attributed to the organic epoxy resins used to bind the fibers; poor fire resistance; high costs; inapplicability on wet surfaces or at low temperatures; hazards for the manual worker; diffusion tightness, poor thermal compatibility with the base material; susceptibility to UV radiation and low reversibility.

To avoid some of these problems Fabric Reinforced Cementitious Matrix (FRCM) composites consisting of fabric meshes with fibers arranged in two orthogonal directions and bonded to the substrate with a cement-based mortar can be used. The type of matrix employed in FRCM composites [1,2] is generally characterized by high resistance to fire and high temperature, resistance to UV radiation, ease of handling during application because the inorganic binder is water-based; permeability compatibility with the concrete substrate and unvarying workability temperature (between 4 °C and 40 °C). Different technological solutions were proposed varying both the type of fibres (Glass, Basalt, Carbon, PBO) and the mortar; FRCM composites are, in fact, known under different acronyms in the literature such as Textile Reinforced Concrete (TRC) [3], Textile Reinforced Mortar (TRM) [4–6] and Mineral Based Composites (MBC) [7].

Recently, a new class of composites that is being explored includes steel fiber sheets with either an inorganic matrix or an organic matrix described above, was proposed as a strengthening system of existing structures. The use of steel fibers was proposed as a lower-cost alternative to other fiber types used in FRCM or FRP previously described.

The potentialities of cement-based composite materials in improving structural performance of the concrete have been demonstrated by numerous studies and research both experimentally and theoretically. Nevertheless, some aspects of the structural behavior of FRCM strengthened structures were not completely defined; among those the load transfer mechanism at the interface between the strengthening system and the substrate, the bond-slip relationships, the failure modes and the durability. The available literature is focused on the behavior between the RC members and the FRCM composite material in order to evaluate the increase in terms of the flexural, shear and torsional capacity [8,9,10].

More limited studies have been carried out on the behavior of masonry elements strengthened with FRCM. Even if FRCM systems were

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used in strengthening existing masonry walls, arches and vaults, currently the structural performances of such systems are not completely assessed. The great variability of fibers and mortar used in FRCM systems, the different conditions of the masonry substrate and the influence of the environmental conditions do not permit to define general procedures and models able to describe the performances of strengthened masonry elements.

A valid contribution to clarify some aspects of the structural behavior of FRCM strengthened masonry elements can be furnished by experimental investigations addressed to the analysis of specific topics such as the bond between the FRCM and the plan or curved masonry substrate, the performances of masonry walls subjected to in-plane or out-of-plane loads, the performances of masonry columns subjected to axial or eccentric compression loads, the performances of arches and vaults masonry structures.

At the same time, analytical and numerical models have to be proposed and validated by comparison with experimental results in order to define adequate procedures able to predict the structural performances of FRCM strengthened masonry structures.

Experimental results and predictions of models are crucial for the definition of standard codes that provide producers, designers and contractors recommendations for testing, design, installation and control. At present a very limited number of guidelines and standards on FRCM strengthened structures are available [11].

The present paper is devoted to the analysis of masonry columns confined with Fabric Reinforced Cementitious Matrix made by steel fabrics embedded into a cement based mortar, subjected to axial loads. The analysis is developed both experimentally and numerically. The experimental investigation was conducted on clay masonry columns having an overall height of *770 mm* with square cross section, *250 × 250 mm*. Six columns were tested: 4 of these were axially loaded while the remaining two were tested under eccentric load. One column was unconfined (control specimen); axially loaded columns were confined with one (1 specimen), two (1 specimen) and three layers (1 specimen) of steel-FRCM. The columns eccentrically loaded were confined with one steel-FRCM layer. The eccentricity measured with respect to the centroidal axis of the columns, were *25 mm* and *50 mm*. The numerical analysis was conducted through a 3D approach based on a macro-model approach without the distinction between mortar and brick of the masonry. The model, calibrated on experimental results described in the following and available in the literature [12,13], simulates the non-linear structural behavior of masonry columns. The validity of the proposed model was verified by the comparison between predictions and experimental results in terms of peak load and load-strain diagrams.

2. Experimental investigation

2.1. Specimen description and preparation

An experimental investigation on the structural performances of brick masonry columns confined with steel-FRCM (or Steel Reinforced Grout, SRG) have been planned. The first part of the experimental program was described in this paper; it included *6* masonry columns, 4 of which tested under a concentric compressive loading condition while the remaining 2 columns were tested under eccentric compressive load. One column was unconfined and used as control specimen, while the remaining 3 columns axially loaded were confined with one (*1* specimens) two (1 specimen) and three layers (*1* specimens) of steel-FRCM, respectively. The two columns tested under eccentric loads were confined with one steel-FRCM layer and subjected to a load applied with eccentricity of *25 mm* (1 specimen) and *50 mm* (1 specimen) with respect to the centroidal axis.

All tested columns had dimensions of width $b = 250\,mm$ × depth $h = 250\,mm$ × length $L = 770\,mm$; geometrical details are reported in Fig. 1a.

Confined specimens were named following the designation C-X-Y-Z-E, where C indicates the confined specimen, X indicates the fiber fabric density (*12* for $1200\,g/m^2$); Y indicates the number of layers; Z indicates the specimen number and E the eccentricity value. Un-confined specimens were named following the designation CC.

Before the installation of the steel fiber sheets, the masonry columns were accurately prepared; dust and loose particles were removed from the surface and the corners were rounded to a radius of *20 mm*. The mortar adopted to build the masonry columns was chosen with the aim of reproducing the quality and the mechanical behavior of rather weak mortars usually connecting the bricks in existing masonry historical structures.

The compressive and flexural strength of the mortar were determined by tests on three *40 mm × 40 mm × 160 mm* mortar prisms casted within the same batch of mortar used to cast the masonry columns. The average compressive and flexural strength, determined by standard tests, were equal to *3.32 MPa* ($CoV = 0.07$) and *1.22 MPa* ($CoV = 0.04$), respectively.

The average compressive strength of the clay bricks, performed on *5* tests using entire masonry bricks in accordance to the EN 772-1 [14], was equal to *56.84 MPa*. The masonry columns were constructed in laboratory and stored until they were tested.

The columns were strengthened with a composite material made by steel fibers embedded in an inorganic mortar matrix. The steel fibers were in the form of a unidirectional sheet made of high-strength galvanized twisted steel micro-cords held together by a glass fiber micro-mesh. Each micro-cord consists of five filaments. Three of the five filaments are straight, and the remaining two filaments are wrapped around the other three with a high torque angle. The cross-sectional area of the cord is $0.538\,mm^2$. The matrix was a hydraulic mortar made of lime and mineral binder with fine particle size developed for concrete and masonry applications and intended for highly breathable historical masonry restoration. Mechanical properties of the matrix were determined by compression tests conducted on *3* specimens and flexural tests conducted on *5* prismatic specimens according to the EN 1015-11 [15]: obtained results were *12.85 MPa* ($CoV = 0.15$) for the compression strength and *2.65 MPa* ($CoV = 0.05$) for flexural strength. The thickness of the mortar joints was *3 mm*. After casting, the masonry columns were cured in laboratory under wet cloth for *28* days. Then, the confined columns were wetted before installing the composite jacket. The internal layer of matrix was applied, and then the steel fiber sheet was wrapped around the column. The steel fiber sheet, comes in *300 mm* wide rolls. It was cut and bent in order to confirm to the surface. Columns were strengthened with three segments of steel fiber sheets throughout the entire height, since the width is less than the height of the columns.

On the basis of the few studies present in literature an important role can be performed from the local position of the overlap of the confining layers. In this investigation, for the specimens with one layer the three segments of the fiber sheet were overlapped on the different sides of the column, in a way that does not form a vertical seam near the column corner. In particular, for specimens confined with on steel-FRCM layer, the first and the third segment of the fiber sheet are overlapped on side A (see Fig. 1b), while the second segment is overlapped on side C. For specimens confined with three SRG layers, the segments are overlapped on the single side of the columns, i.e. the first internal layer overlaps (all three segments) on side A, the second on side C and the third on side B, as reported in Fig. 1b.

2.2. Test setup

The test setup is shown in Fig. 3. The load was gradually applied by means of a hydraulic jack and measured with a local cell by means of a *1000 kN*. All columns were loaded until failure at a load rate of approximately *40 N/s*; tests were conducted through machine stroke control. Testing was completed when a significant drop in load