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FIBER-BASED SECTIONAL ANALYSIS OF URM WALLS WITH SINGLE-SIDE FRCM STRENGTHENING

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Abstract. *Recently, research community has shown a growing interest in inorganic matrix composite materials (referred to as Fiber Reinforced Cementitious Matrices, FRCMs, or Textile Reinforced Mortars, TRMs, or Inorganic Matrix-Grid composites, IMGs) as an effective solution for external strengthening of existing masonry walls. Such composites are typically made of a composite grid immersed in an inorganic mortar, making their mechanical behavior different from conventional fiber reinforced polymers, FRPs. While the in-plane behavior of unreinforced masonry (URM) walls strengthened with FRCM systems has been investigated through extensive experimental campaigns and numerical approaches, a comprehensive understanding of the out-of-plane behavior is still lacking, with particular reference to failure modes, analytical formulations and effects of different FRCM strengthening systems. In the present work, the available experimental outcomes on the out-of-plane behavior of strengthened URM walls are firstly collected, encompassing different URM types, eccentric load applications, FRCM strengthening systems. Then, a fiber-based sectional model of URM walls with single-side FRCM strengthening is proposed and validated with proper experiments. The tensile behavior of FRCM systems is modelled considering different characteristic phenomena of such materials, i.e. matrix cracking and fiber sliding. The results of the fiber-based analysis are in good agreement with experiments.*

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1 INTRODUCTION

In recent years, a wide variety of strengthening techniques has been developed for existing unreinforced masonry, URM, structures often considering reversibility, low invasiveness, mechanical compatibility and sustainability as fundamental prerequisites for the structural intervention.

The use of techniques based on Fiber-Reinforced Polymers (FRPs) has become a common engineering practice over the last decade, being characterized by a number of advantages, including high strength-to-weight ratios, negligible increment of global masses, high resistance to corrosion and fatigue, ease of installation. However, issues related to low high temperature or fire resistance, high cost of epoxy resins or qualified labor, lack of water vapor permeability, mechanical incompatibility of epoxy resins with some substrate materials (especially in the case of masonry structures) have expanded the sector of materials for strengthening to alternative solutions.

A recently proposed solution consists in the replacement of the polymer-based matrix with an inorganic one, resulting in innovative strengthening systems commonly identified as Fiber Reinforced Cementitious Matrix systems (FRCM), or, depending on the nature of the constituent materials, as textile-reinforced mortar (TRM), textile-reinforced concrete (TRC), cementitious matrix-grid (CMG), inorganic matrix-grid systems (IMG), carbon fiber cement matrix (CFCM), steel reinforced grout (SRG) systems. Such composites are typically made of a composite grid (made of synthetic fibers such as glass, carbon or PBO, or of natural fibers such as flax or hemp) immersed in an inorganic mortar (based on cement, lime or geopolymer material), making their mechanical behavior different from conventional FRPs [1-4]. The choice of the matrix and reinforcing material along with the determination of total thickness of the composite system mostly depends on the type of substrate and mechanical contribution requested from the intervention. For instance, cement mortar is commonly used for concrete constructions, while lime mortar is mainly employed for strengthening historical and masonry buildings. Indeed, the interaction between similar materials ensures better chemical, thermal and mechanical compatibility between the strengthening system and the substrate.

Experimental procedures for FRCM mechanical characterization along with appropriate design criteria for their engineering use are still discussed in the field of study of structural retrofit [5, 6]. The major difficulty lies in handling their heterogeneous nature which yields a complex non-linear mechanical behavior, making the interaction with the substrate onto which FRCMs are applied even more complex.

At the scale of the structural application, numerous experimental and numerical activities have been conducted so far, and were mainly aimed to determine the increase in shear strength of URM walls strengthened with FRCM systems through diagonal compression tests [7-9]. In particular, it was found that the employment of FRCM systems typically led to an increase in shear strength in a variable range between 50% and 500% compared to the URM, also considering that the lower was the shear strength or stiffness of the non-reinforced samples, the greater increase in the reinforced samples was achieved. Minor influence on the same mechanical properties was observed for wall panels reinforced with different percentages of eternal FRCM reinforcements, mainly before matrix cracking. On the contrary, it was found that the FRCM strengthening systems had a major influence on the in plane post-peak behavior, providing a higher residual shear strength after cracking associated with a stress redistribution in tension, allowing the masonry to achieve significant values of deformation capacity. In many cases, the effect on the deformation capacity was attributed to a pseudo-ductile behavior.

In addition, it was observed that some of the failure mechanisms of FRCM are different from traditional FRP and may be activated under certain load conditions. In particular, the failure of the fibrous/grid systems within the FRCM was rarely attained in terms of fiber breakage while the most frequent failure mechanisms consisted in delamination/detachment from the masonry substrate or grid sliding inside the cementitious/inorganic matrix which might be at the basis of the aforementioned pseudo-ductile behavior.

Despite extensive works have been conducted so far on the in-plane behavior of URM strengthened with FRCM systems, a comprehensive understanding of the out-of-plane behavior is still lacking, with particular reference to failure modes, analytical formulations and effects of different FRCM strengthening systems. The available experimental outcomes were devoted to the determination of the flexural strength of URM strengthened with different single-side FRCM systems, and can be grouped in 4 different types of tests:

1. application of eccentric compressive load [10-11];
2. application of airbag loading [12];
3. three or four points bending [13-14].

For cases involving single side strengthening, the effectiveness of different FRCM systems, the effect of the number of applied layers and the possibility of having physical connectors were also investigated. Overall, it was found that most of the strengthening systems investigated were able to provide a considerable gain in terms of flexural strength. The failure under flexural loads was frequently characterized by a progressive loss of strength once reached the maximum applied load, achieving a satisfactory deformation capacity. With reference to FRCM systems, it was reported that fibers/grids characterized by low stiffness (e.g. natural fibers) allowed for a homogeneous spread of tensile crack onto the strengthened surface. On the contrary, in strengthening systems using stiff FRP grids the failure progression was characterized by the opening of a single crack at the mid-height of the strengthened masonry wall, resulting in grid sliding inside the FRCM system or mortar matrix detachment from the reinforcing grid/fabric/textile.

In the present work, we implement a fiber-based sectional approach for URM walls with single-side FRCM strengthening based on proper constitutive laws for masonry and FRCM systems. In the following sections the approach is validated with suitable experiments.

2 FIBER-BASED SECTIONAL ANALYSIS

The proposed fiber-based sectional analysis can be applied to URM walls with single-side FRCM strengthening and subjected to out of plane flexural loads. The mechanical analysis includes two different materials characterized by non-linear constitutive behaviors, offering the possibility of evaluating both the flexural strength and deformability/ductility of the target cross-section. The strengthened URM cross-section is divided in $i = \{1,\ldots n\}$ finite elements of reduced size, with areas A_i and distances d_i from the centroid of its cross-section. The discretization of the section is employed to calculate the average strain of each fiber and corresponding level of stress for each constituent material (URM and FRCM). The following assumptions have been made for the sectional analysis:

1) Plane sections remain plane and normal to the structural element axis after deformation (Euler–Bernoulli beam theory assumption);
2) Non-linear constitutive behavior of the constituent materials (i.e. masonry and FRCM);
3) The stresses in each finite element/fiber are dependent only on the level of average deformation they undergo;

4) The application of the load and the consequent deformation are monotonic;
5) Each FRCM layer is concentrated at a depth equal to its mid thickness;
6) Perfect bonding between the FRCM and the masonry substrate is assumed while the reinforcing grid of the FRCM can slide inside of it.

The numerical integration is then developed considering the strain values at the center of gravity of discrete elements corresponding to each *i*-th fiber of the strengthened cross-section. In particular, the complete logic scheme adopted for the determination of the analytical resisting moment vs curvature relationship of single side strengthened URM is showed in Figure 1. The flexural capacity at the ultimate limit state is evaluated with reference to the center of gravity of the entire section making use of equilibrium equations. For each value of axial force and moment acting on the section being considered (i.e. applied eccentricity), the moment-curvature relationship is established by incrementally increasing the curvature of the section and iterating through horizontal and rotational equilibrium equations until tolerance verification is satisfied for each curvature step (Figure 1). The resulting moment-curvature analytical relationship is finally normalized with respect to the URM mechanical and geometrical properties, i.e. the axial force associated with the peak compressive strength N_m and height H_m of the masonry wall. Therefore, the curves obtained were plotted in the dimensionless space $M/(N_m \cdot H_m)$ vs $\phi \cdot H_m$.

To model the stress–strain relationship of URM and FRCM materials, non-linear constitutive behaviors are considered. In particular, the URM material model refers to the works conducted by Parisi and Augenti [15, 16] and includes both compression and tensile behavior. The details of this constitutive model can be found in [15] while a representative behavior is reported in Figure 2a where the stress-strain values are normalized with respect to the peak values σ_p and ε_p (dimensionless compression and traction to peak). The constitutive behavior of FRCM material herein proposed is based on mechanical evidences derived from experimental campaigns conducted on different FRCM systems [17-19]. A representative behavior is showed in Figure 2b in terms of normalized force, f/f_u, vs normalized strain $\varepsilon/\varepsilon_{fu}$, where f_u and ε_{fu} are the ultimate force and strain at failure of the reinforcing fibers only (or, more in general, of the reinforcing grid embedded in the FRCM system). The constitutive behavior is composed of the three main stages. In the first stage, the FRCM material behaves as a linear elastic material in which the stiffness is determined through the rule of mixture applied to mortar (matrix) and FRP grid constituents of each FRCM layer. After reaching initial major matrix cracking (second phase), the resisting force progressively reduces to the tensile force of the reinforcing system embedded in the FRCM by means of possible tension stiffening or crack diffusion between matrix and reinforcing grid. Depending on the type of matrix and reinforcing grid adopted in the FRCM system, the third phase may alternatively lead to grid sliding/detachment form the mortar or grid tensile failure.

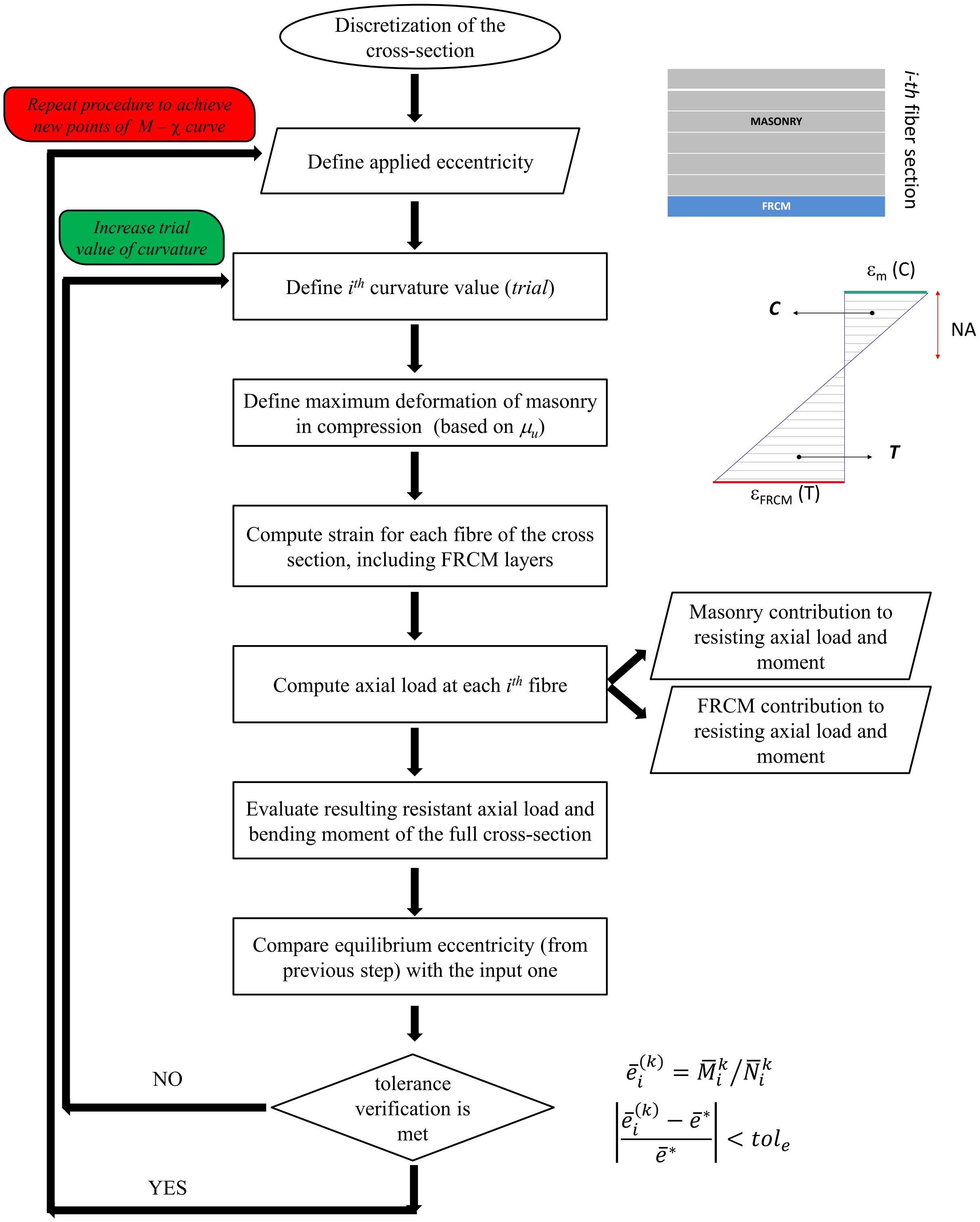

Figure 1: Logic scheme of the fiber-based sectional approach

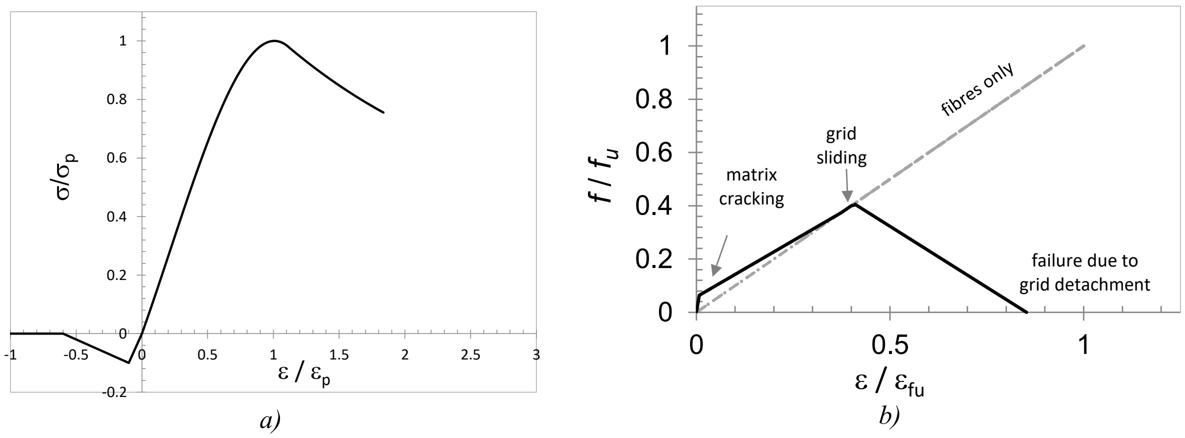

Figure 2: Normalized stress or force vs strain behavior of (a) URM and (b) FRCM material

3 RESULTS

The fiber-based sectional analysis is applied to the results of the experimental campaign conducted by Cevallos et al. [10]. In that study, three different types of masonry panels were considered and made of clay bricks bonded with a natural hydraulic lime mortar combined with a flax or polyparaphenylene benzobisoxazole (PBO) fabric-reinforced cementitious matrix (FRCM) composite used as external strengthening systems. The flexural behavior was assessed by applying concentric and eccentric loads to the URM and FRCM-strengthened masonry walls. As general outcome, it was found that both strengthening systems were able to improve strength and deformability of the URM panels; however, they reported that the strength of the composite system was not a decisive factor. For a sake of length, we report only on representative data of PBO-FRCM system for which major considerations can be made on the effectiveness of the model itself. The model parameters for the URM constitutive material model were retrieved from the uniaxial compressive tests conducted by the same author [10]. On the other side, FRCM material properties were determined on the basis of available experimental tests on PBO fibers and PBO based FRCM systems [17-19].

In Figure 3 normalized momentum vs curvature curves are showed and referred to URM experimental sample (black line), single side strengthened masonry panel (red line) and analytical results of strengthened URM. In terms of experimental results, the strengthened URM was characterized by an increase of flexural capacity of approximately 20% and a relatively wide post peak response. The analytical fiber-based sectional model was able to satisfactorily reproduce the flexural behavior of the strengthened samples. In particular, the model captured the initial variation of flexural stiffness related to the mortar-based matrix cracking and diffusion in the FRCM system. With regard to the maximum bending moment, the predicted normalized value resulted very close to the experimental one, being equal to 0.122 and 0.129 for experimental and analytical case, respectively. It’s worth noting that, by implementing the fiber-based sectional model, it was possible to identify the level of strain and stress in the FRCM system in correspondence of the maximum bending moment and, consequently, evaluate the effectiveness of this system. In detail, it was found that the effective strain of the FRCM system at the maximum value of the bending moment was in the order of magnitude of the 10% of the failure strain of the PBO reinforcing grid, demonstrating the limited effectiveness of very stiff reinforcing systems adopted for FRCM when applied to masonry structures. This result is in accordance with the considerations made by authors [10] according to which the higher stiffness and lower strain capacity of the PBO fibers greatly affected the efficacy of the PBO-FRCM.

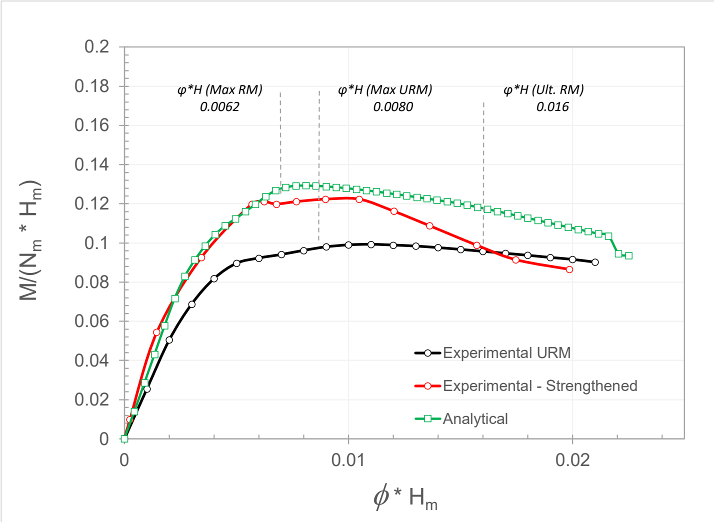

Figure 3: Comparison between of analytical and experimental results [10] in terms of normalized momentum vs curvature curves

4 CONCLUSION

In this study, we reported on the implementation of a fiber-based sectional model suitable for the analysis of the flexural behavior of URM walls with single-side FRCM strengthening. The analytical procedure is based on a logic scheme in which an incremental increase of the curvature of the section is made while iterating through horizontal and rotational equilibrium equations until tolerance verification is satisfied for each curvature step. Proper constitutive laws for masonry and FRCM systems were considered and based on experimental-based non-linear constitutive behaviors. By applying the proposed analytical approach to available experimental tests, it was found a satisfactory matching between numerical and analytical normalized momentum vs curvature curves, either for the prediction of the flexural capacity and for post peak response. In addition, by identifying the level of strain and stresses within the FRCM system in reference to the applied flexural loads, it was possible to verify the effectiveness of the FRCM system itself in increasing the flexural capacity of the URM. The outcomes achieved with regard these aspects, were in agreement with results obtained by several authors reporting that the higher stiffness and lower strain capacity of some reinforcing systems greatly affected the efficiency of the FRCM itself.

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