Numerical and Theoretical Models for NFRCM-Strengthened Masonry

Claudia Brito de Carvalho Bello¹,a*, Daniele Baraldi¹,b, Giosuè Boscato²,c, Antonella Cecchi¹,d, Olimpia Mazzarella¹,e, Emilio Meroi¹,f, Ivano Aldreghetti²,g, Giorgio Costantini²,h, Lorenzo Massaria²,i, Vincenzo Scafuri²,j, Italo Tofani²,k

¹Università IUAV di Venezia, Terese, Dorsoduro 2206, 30123, Venezia, Italy
²LabSCo, Università IUAV di Venezia, via Torino 153/a 30172 Mestre (VE), Italy

Keywords: Finite Element Model, homogenization, masonry strengthening, FRCM, NFRCM, Sisal.

Abstract. The shear behavior of masonry strengthened with natural fabric-reinforced cementitious matrix (NFRCM-strengthened masonry) is investigated through two different numerical models: a multi-layer model considering masonry and reinforcement as different materials and a multi-step homogenized model, where reinforced masonry is considered as a whole. The approaches are compared by performing nonlinear numerical pushover analysis with an increasing shear action applied to the panels. The parametric analysis shows the capacity and limits of both continuous diffused models – defined as a multi- or a single layer - to represent reinforced masonry in-plane behavior.

Introduction

In the field of masonry strengthening, particular attention would be devoted to the use of natural materials, such as fibers and bio-based matrices, for eco-compatible applications. The present research aims to extend the knowledge of mechanical behavior of innovative materials and the development of sustainable solutions for the reinforcement of existing structures, i.e. fabric-reinforced cementitious matrix (FRCM) made with natural fibers (NFRCM), starting from interpretation, by theoretical and numerical models, of experimental tests. The modelling of FRCM-strengthened masonry represents a complex task, because both masonry and FRCM are composite materials in a different way and, being an innovative strengthening technique, there is a limited number of contributions dedicated to this topic. Some authors consider the heterogeneous micro-modelling strategy by modelling separately FRCM and masonry components, to reproduce and/or predict the detailed crack patterns and nonlinear behavior of both FRCM and masonry [1]. This behavior would include the composite failure modes, such as the crack propagation in the matrix, the reinforcement textile local failure mechanisms, the bond-slip behavior between reinforcement-matrix and composite-substrate. Due to its complexity, a few studies consider this technique and some authors adopted homogenization approaches for both masonry and FRCM, in order to model large masonry structures [2, 3]. Some macro-models consider masonry components (bricks and mortar) as a homogeneous continuum, and the FRCM composites are considered as an equivalent continuum, with the textile fibers assumed as an embedded reinforcement of mortar matrix [4]. These models have also been implemented with reference to NFRCM-strengthened masonry [5]. A first FE-model is here proposed, starting from the above-mentioned hypothesis considering a multi-layer material. A second FE-model considers a whole homogenization for masonry and NFRCM [6] as a simplified alternative to the multilayered model. The two different approaches are compared and calibrated by imposing an increasing shear action on NFRCM-strengthened masonry
panels. The differences and similarities of both methods are analyzed and critically compared, aiming to evaluate the applicability and reliability of each proposed model.

**Homogenization**

A numerical 3D homogenization procedure [6, 7] is adopted to obtain the elastic properties of the materials for the multi- and single-layer models. This technique allows to define an equivalent continuum able to reproduce at the macro-scale the mechanical characteristics of the masonry panels and of the reinforcements, by considering the periodic texture of masonry and the periodicity of the NFRCM. For both materials, a representative element of volume (REV) is defined and periodic boundary conditions are applied.

**Masonry.** This work considers a square panel (1160×1160mm²) made with solid clay bricks arranged as 250 mm thick headers and 10 mm thick of mortar joints, while brick width and height are equal to 120 mm and 55 mm, respectively.

The 3D homogenization for masonry panels assumes its components - brick and mortar - as isotropic materials and adopts the mechanical parameters - E, ν - reported in Table 1. The geometrical description of REV and the boundary conditions applied are reported in Fig. 1.

Table 1 – Mechanical properties of masonry material components

| Masonry components | Young's Moduli [MPa] | Poisson's Coefficients |
|--------------------|----------------------|------------------------|
| Brick              | E = 4000             | ν = 0.15               |
| Mortar             | E = 2350             | ν = 0.20               |

![Fig. 1 – Masonry panel (a); representative Element of Volume –REV- (b); periodic boundary conditions (c)](image)

**NFRCM.** This work considers a NFRCM system constituted by a 10 mm thick mortar matrix and a Sisal plain-woven textile reinforcement (mesh 10x10mm²) placed in the middle of the whole thickness - embedded in the mortar.

Mechanical properties of NFRCM system are defined by means of 3D homogenization procedure. Both constituent materials – mortar matrix and sisal fiber reinforcement - are modeled as an isotropic material with mechanical properties in accordance to experimental tests [8] and reported in Table 2. The geometric description of REV and boundary conditions applied are reported in Fig. 2.
Table 2 – Mechanical properties of NFRCM materials

| NFRCM components       | Young's Moduli [MPa] | Poisson's Coefficients |
|------------------------|----------------------|------------------------|
| Sisal Fiber (reinforcement) | E = 3145             | ν = 0.20                |
| Mortar (matrix)        | E = 13000            | ν = 0.20                |

Fig. 2 – NFRCM system (a); representative Element of Volume –REV- (b); periodic boundary conditions (c)

Reinforced Masonry (RM). Considering the masonry panel reinforced on both sides by the NFRCM material, the homogenization of reinforced masonry is obtained by integrating the constitutive functions of masonry and NFRCM along the thickness of the wall [6]. The overall thickness of RM panel is equal to 270 mm.

Numerical models

Numerical pushover analyses of a reinforced masonry panel are performed by adopting a single-layer model (RM) and a multi-layer model, which considers a layer of homogenized masonry and a mortar layer with an embedded Sisal reinforcement on both panel sides. Results are compared also with the unreinforced case (URM) represented by the homogenized masonry. Masonry panels are subjected to an increasing shear displacement applied at the upper edge and the boundary conditions are assumed fixed at the bottom and sliding at the top. A rigid beam is positioned on the top of the panel to distribute uniformly the lateral displacements considered (Fig.3).

Fig. 3 – Case study: displacement and boundary conditions considered on masonry panel.

Multi-layer model. The modelling strategy consists in the adoption of curved layered shell elements [9] that allow the consideration of different materials arranged as layers into one single 2D
finite element. The whole thickness of the element considers one half of the RM panel subdivided into 2 layers: NFRCM and masonry, with perfect bond assumed between the layers. The NFRCM layer consists in the composite mortar with the sisal textile embedded as a reinforcement element. An eccentricity is assigned to the reinforcement, to settle it in the middle of the mortar layer. Fig. 4 shows the layered shell thickness subdivision: the whole thickness (t) mortar layer (t1), masonry layer (t2) and the reinforcement grid positioned with an eccentricity (e).

Most of the NFRCM mechanical properties are obtained through the experimental tests on the composite constituent materials: mortar (E, ν, ft, fc) and sisal fibers (E, ft) [8]. The fracture energy in compression (Gc) and in tension (Gt) are assumed accordingly to the existing literature [10]. All materials parameters used in the FE model are reported in Table 3.

![Fig. 4 – Layer thickness](image)

**Table 3 – Multi-layer model: materials parameters**

| Mechanical parameters                        | Masonry | Mortar Matrix | Sisal reinforcement |
|----------------------------------------------|---------|---------------|--------------------|
| Young’s modulus                              | E [MPa] | 3570          | 1300               | 3145               |
| Poisson's Coefficient                        | ν       | 0.15          | 0.20               | -                  |
| Tensile strength                             | Ft [MPa]| 0.20          | 0.9                | 94.3               |
| Fracture energy in tension                   | Gt [N/mm]| 0.02         | 0.03               | -                  |
| Compressive strength                         | Fc [MPa] | 4.2          | 13                 | -                  |
| Fracture energy in compression               | Gc [N/mm]| 6.7          | 20                 | -                  |

**Single-layer model.** The FE model for representing the reinforced masonry panel by considering one homogenized material adopts quadrilateral 8- noded elements in plane stress state [9]. The element thickness is equal to the whole thickness of URM and RM panels. Material elastic parameters are assigned in agreement with the third homogenization procedure described previously, and a total strain rotating crack model (TRSCM) is used for representing the nonlinear behavior, which is characterized by a parabolic response in compression and an exponential response in tension. The inelastic parameters – tensile and compressive strength, fracture energy in compression and tension – are assumed accordingly to the existing literature [10]. Elastic and inelastic parameters are collected in Table 4.

**Table 4 – Single-layer models: materials parameters**

| Mechanical parameters                        | URM    | RM   |
|----------------------------------------------|--------|------|
| Young’s modulus                              | E [MPa]| 3570 | 4384 |
| Poisson's Coefficient                        | ν              | 0.15 | 0.18 |
| Tensile strength                             | Ft [MPa]| 0.20 | 0.02 |
| Fracture energy in tension                   | Gt [N/mm]| 0.02 | 0.025|
| Compressive strength                         | Fc [MPa]| 4.2  | 5.16 |
| Fracture energy in compression               | Gc [N/mm]| 6.7  | 8.17 |

**Results Discussion and Conclusion**

In this work, the behavior of masonry panels reinforced with NFRCM has been studied by means of two different numerical simulation approaches: homogenized and multi-layered FE-models.
As illustrated in Fig. 5 both FE models are able to simulate the increase of resistance in the elastic phase and the peak load that may develop in masonry panels reinforced with NFRCM systems. The multi-layer model is able to catch the stiffness increment in the plastic and post cracking phases, due to the presence of fibre stiffness input parameter. The single-layer homogenized model is not able to simulate the ductility increment for large displacements, by reference to multi-layer model results. Therefore, it would represent a not effective tool for simulating the behavior of reinforcement systems with natural fibres, where an important ductility increment of reinforced masonry is expected.

Further analyses would consider different constitutive laws for NFRCM material, with the implementation of a residual tension strength value, to improve the reliability of RM model. Experimental tests also would give a more appropriate constitutive function to characterize material behavior. Despite this limitation, the homogenized model represents a simple efficient tool for quick predictions.

Fig. 5 – Shear force-displacement curves for reinforced and unreinforced masonry panel.

**Acknowledgments**

The research has been carried out thanks to the financial support of PRIN 2015 (under grant 2015JW9NJT_014, project “Advanced mechanical modeling of new materials and structures for the solution of 2020 Horizon challenges”).
References

[1] I. Kalker, C. Butenweg, S. Holler, B. Toll. Modelling of Textile Strengthened Masonry. In Proceedings of the 10th International Conference on Civil, Structural and Environmental Engineering Computing, Civil-Comp 15 (2005).

[2] B. Ghiassi, D. V. Oliveira, P. B. Lourenço, G. Marcari. Numerical Study of the Role of Mortar Joints in the Bond Behavior of FRP-Strengthened Masonry. Composites Part B: Engineering 46 (2013) 21-30.

[3] V. Gattulli, G. Lampis, G. Marcari, A. Paolone. Simulations of FRP Reinforcement in Masonry Panels and Application to a Historic Facade. Engineering Structures 75 (2014) 604-618.

[4] X. Wang, B. Ghiassi, D. V. Oliveira, C. C. Lam. Modelling the Nonlinear Behaviour of Masonry Walls Strengthened with Textile Reinforced Mortars. Engineering Structures 134 (2017) 11-24.

[5] C.B. de Carvalho Bello, A. Cecchi, E. Meroi, D. V. Oliveira. Experimental and Numerical Investigations on the Behaviour of Masonry Walls Reinforced with an Innovative Sisal FRCM System. Key Engineering Materials 747 KEM (2017) 190-195.

[6] A. Cecchi, G. Milani, A. Tralli. In-Plane Loaded CFRP Reinforced Masonry Walls: Mechanical Characteristics by Homogenisation Procedures. Journal of composites science and technology 64 (2004) 2097-2112.

[7] I. Aldreghetti, D. Baraldi, G. Boscato, A. Cecchi, L. Massaria, M. Pavlovic, E. Reccia, I. Tofani. Multi-Leaf Masonry Walls with Full, Damaged and Consolidated Infill: Experimental and Numerical Analyses. Key Engineering Materials 747 KEM (2017) 28-30.

[8] C.B. de Carvalho Bello, I. Boem, A.Cecchi, N. Gattesco, D. V. Oliveira. Experimental tests for the characterization of sisal fiber reinforced cementitious matrix for strengthening masonry structures. submitted to Construction & Building Materials (2018).

[9] TNO DIANA, DIANA. DIspacement method ANAlyser, release 9.4, User’s Manual.

[10] M. Angelillo, P.B. Lourenço, G. Milani. Masonry behaviour and modelling, Mechanics of Masonry Structures, CISM International Centre for Mechanical Sciences. (2014) 1–26.