NUMERICAL SIMULATIONS OF IN-PLANE BEHAVIOR OF TUFF MASONRY STRENGTHENED WITH CEMENTITIOUS MATRIX–GRID COMPOSITES

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ABSTRACT

Masonry is one of the oldest construction materials and in particular tuff buildings are a significant part of the Mediterranean cultural heritage. These historical buildings need to be preserved especially in seismic areas. Tuff masonry buildings fail in the case of earthquakes mainly because of their low tensile and shear resistance. These structures can be retrofitted with FRP composites to increase their seismic performance. Previous experimental studies, conducted by some of the authors, on in-plane response of tuff masonry walls strengthened with an innovative cementitious matrix composite grid (CMG) system confirmed that the CMG system satisfies basic design requirements such as compatibility with the support, high bond properties and reversibility of the intervention. Finite element models (FEM) were analyzed, and the experimental data were used to calibrate the numerical model. Micro modeling was adopted for the analysis of masonry walls and some parametric analyses were conducted.

FEM results were compared to experimental data and were found to be in good agreement with the test data. Significant improvements in strength and ductility of panels were achieved by installing different layouts of the CMG grid, while a negligible influence on the initial stiffness of the strengthened walls, that is reduced impact of the intervention on the existing structure, was observed. Further numerical investigations on calibrated FEM models are in progress to assess the effectiveness of the proposed strengthening solution when applied to different brickwork and structural layouts.

KEYWORDS

cementitious matrix composite grid, finite element model, shear, strengthening, tuff masonry.

INTRODUCTION

Masonry is one of the oldest construction materials and is a generic term standing for a structure made by a large number of small blocks mortared together in many different arrangements. Tuff buildings are a significant part of the Mediterranean cultural heritage. These historical buildings, presenting load-bearing walls, represent an important part of the existing buildings and need to be preserved especially in seismic areas. Tuff masonry buildings fail in the case of earthquakes mainly because of their low tensile and shear resistance. The development of structural steel and reinforced concrete has led to non load-bearing walls, such as partitions and infill walls in frame constructions. These kinds of walls affect the strength and stiffness of the in-filled frame structures. In seismic areas, under lateral loads, the infill walls dramatically increase stiffness, resulting in a possible change in the seismic demand. In the last few decades, significant experimental research has been carried out to investigate the cause of damage and develop technologies suitable for seismic retrofit and rehabilitation of existing masonry buildings (Tomaževič, 2000).

In the case of an earthquake, the most relevant in-plane loads for a structure built with masonry walls are the series of cyclic horizontal, seismic actions. Structural walls, the critical resisting elements to seismic loads, may be damaged, and if they have not been properly designed and detailed to withstand inelastic deformation and to dissipate energy, the induced inertia forces might cause heavy damage or even collapse of the building. The seismic behavior of masonry walls is characterized by three failure modes depending on the geometry of the wall (height/width ratio), quality of materials, boundary restraints and loading scheme (Tomaževič, 2000).
The typical seismic failure mode is the diagonal cracking mode when the principal tensile stresses developed in the wall under a combination of vertical and horizontal loads exceed the tensile strength of the masonry materials. Peak strength is governed by the formation and development of inclined diagonal cracks, which may follow the path of bed- and head-joints or may go through the bricks, depending on the relative strength of mortar joints, brick-mortar interface, and bricks.

In the case of low vertical load and poor quality mortar, the seismic loads cause sliding shear failure, dividing the wall into two parts with sliding of the upper part of the wall on one of the horizontal mortar joints, while in the case of improved shear resistance and high moment/shear ratio, crushing of compressed zones at the ends of the wall usually takes place (flexural failure).

Masonry Strengthening using Advanced Composites

Frequently masonry strengthened with FRP materials is treated in the same manner as reinforced concrete structures due to lack of specific knowledge (Triantafillou, 1998). Further studies are required to characterize the in-plane behavior of masonry walls strengthened with FRP, in particular to better understand shear behavior.

Based on the principles of capacity design, undesirable modes of failure in the structural masonry walls should be avoided. Application of FRP reinforcement can modify the failure mode from brittle shear to flexural failure. Typically, flexural failure in masonry walls strengthened at a high reinforcement ratio is due to compressive crushing. FRP rupture is less desirable than masonry crushing, being a more brittle failure mode (Triantafillou, 1998).

Analysis of simple cases of FRP strengthened walls has led to the following conclusions (Bakis et al., 2002):

- The in-plane shear capacity of masonry walls strengthened with FRP may be quite high especially in the case of low axial loads.
- The in-plane bending capacity depends on the amount and distribution of FRP reinforcement: reinforcement placed near the highly stressed zones yields a significant strength increase.
- The achievement of full in-plane strength depends on the proper anchorage of the FRP reinforcement: improper anchorage may result in premature failures.

The matrix plays a significant role to ensure good bonding of the reinforcement; typically it is a polymer matrix with outstanding bonding characteristics, both with the fibers and with the substrate, but also with advantages such as sensitivity to high temperatures, moisture impermeability, and flammability.

A cement-based matrix is compatible with the masonry substrate in terms of bonding, moisture permeability, and thermal properties, avoiding most of these critical issues. It is not only noncombustible, but protects the embedded fibers against direct fire exposure. The limited bonding (chemical) characteristics with the fibers are minimized through the penetration of the mortar between the fibers (mechanical interaction). Also buckling phenomena, commonly seen in thin resin-based FRP plies, are reduced since cement-based systems are thicker. Sufficient mechanical properties for load transfer, good bonding characteristics and consistency for embedding the fibers, workability and environmental compatibility are some of the requirements for the cement-based matrix.

EXPERIMENTAL BEHAVIOR

A comprehensive experimental program on tuff masonry panels is presented in Prota et al. (2006). Twelve diagonal compression tests were performed on tuff panels; four were tested as-built and eight were tested using different CMG strengthening configurations. Tests were carried out under displacement control in order to measure in-plane deformations and strength properties, including the post-peak softening behavior of the specimens.

A cement-based matrix-coated alkali-resistant glass grid system, CMG, was used to strengthen tuff masonry walls; different CMG layouts were selected, and overall performances were compared with those of as-built ones. All panels were built with the same size and type of mortar and masonry units (supplied from the same local quarry). The stones (370 × 120 × 250 mm³) were laid in a running bond such that a final mortar joint thickness of 15 mm mortar was attained. Each panel was built with a compact frame (single-leaf wall) made of roughly squared tuff blocks overlapped on eight alternate courses; the panel width was two-and-a-half tuff blocks. The resulting dimensions were 1030 × 1030 × 250 mm, as shown in Figure 1a.
The bi-directional ARglass coated fabric, has a tensile strength 1700 MPa, Young’s Modulus 72 GPa and ultimate strain equal to 2.4%. The grid cross sectional area per rib is 0.896 mm$^2$ (based on glass cross-sectional area), where “ribs” are defined as continuous elements of a grid, and the spacing is about 25.4 mm. The cementitious matrix is a polymer modified glass fiber reinforced mortar, which is compatible with masonry applications. The mechanical properties of the matrix are compressive strength 13.9 MPa and tensile strength 1.2 MPa. The composition of the CMG system is layered and one or two grids are embedded in the matrix (thickness of 8 mm and 12 mm respectively) on one only or on both sides of the masonry wall (Fig. 1b). The layered construction provides a large surface of the fibers for the stress transfer.

**NONLINEAR MODELING**

One of the aims of this study was to develop finite-element models (FEM) that could simulate the behavior of tested specimens in diagonal compression, evaluate and confirm the CMG retrofitting effectiveness. Masonry is a material which exhibits distinct directional properties due to the mortar joints which act as planes of weakness. The large number of influence factors, such as anisotropy, material properties of the bricks and mortar, arrangement of bed and head joints and quality of workmanship, make the simulation of masonry structures extremely difficult.

The experimental data were used to calibrate the numerical model. Micro modeling was adopted for the analysis of masonry walls and some parametric analyses were conducted. At the micro level, the interaction between mortar joints and brick units is analyzed in depth using a discrete nonlinear model of single elements layered according to different patterns. Page (1978) made the first attempt to use a micro-model for masonry structures. Hand preparation and defects of workmanship lead to nonuniform mortar thicknesses of the joints. To simulate these defects, the mechanical properties of the mortar were changed both in terms of elastic modulus and of ultimate strength in a well defined range (table 1).

Numerical simulations have been conducted under plane-stress assumption. This assumption is almost good for as-built panels and when even plies of reinforcement are used and applied symmetrically over both sides of the masonry wall. The analysis of displacements recorded on the opposite surfaces of the tested symmetrically reinforced specimens showed that load-displacement distributions were very similar on both sides, or rather that the out of plane displacements were negligible. Panels strengthened with CMG grids on one side only showed the activation of evident out-of-plane deformation that the FEM model is unable to simulate. However, two-dimensional modeling is preferred here to three-dimensional modeling in order to reduce computational effort, especially in highly refined mesh discretizations.

**Finite Elements Analysis**

In-depth analysis was performed using multipurpose finite-element analysis software TNO DIANA v9.1, which can handle nonlinear material behavior. The panels were modeled by about 32,000 nodes and about 10,400 CQ16M elements (Fig. 2). The CQ16M element is an eight-node quadrilateral isoparametric plane stress element. It is based on quadratic interpolation and Gauss integration. At the micro level, a detailed modelling strategy in which brick units and mortar joints are modelled separately according to a smeared-crack approach with linear softening in tension and ideal Mohr-Coulomb plasticity in compression is preferred to a meso-level approach.
where the bricks are modeled with elastic continuum elements and the joints with nonlinear interface elements. According to a linear stress cut-off criterion, a crack arises (both in the bricks as in the mortar) if the major principal tensile stress exceeds the minimum of tensile strength, $f_{ct}$, or a value linearly reduced to account for the lateral principal stress (at least the tensile strength is zero if the lateral principal stress is equal to the strength in compression, $f_c$).

The parameters for the ideal Mohr-Coulomb plasticity model, cohesion $c$ and friction angle $\phi$, are evaluated from tensile and compression strength according to the well known equations (Eqs. 1):

$$c = \frac{f_t - f_c}{2}$$  \hspace{1cm} (1a)  

$$\phi = \frac{1}{2} \sqrt{\left(\frac{f_t - f_c}{f_c}\right)^2 - 4\left(\frac{f_t - f_c}{f_c}\right)}$$  \hspace{1cm} (1b)

CMG is modeled as an equivalent elastic material bonded to the masonry panel. In all tests, the wall’s structural integrity at failure was ensured by the CMG strengthening system, revealing the high bond performance between CMG and the support even without any mechanical anchorage (Prota et al., 2006). This suggests that the strengthening system can be perfectly bonded (simulated with a second series of about 10,400 CQ16M elements over the first masonry substrate mesh, connecting the same nodes) to the masonry panel in the FEM simulations. Numerical analyses were carried out under displacement control measuring in-plane deformations and stress evolution; the failure modes in terms of crack pattern were also checked. The load has been applied through two steel devices put at the two opposite corners of the panel. These steel devices have been also modeled by means of about 350 three-node triangular elements, each. Mechanical and geometrical properties adopted for FEM analyses are reported in table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Tensile Strength $f_t$ [MPa]</th>
<th>Compressive Strength $f_c$ [MPa]</th>
<th>Young Modulus [MPa]</th>
<th>Thickness [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tuff</td>
<td>0.35</td>
<td>3.70</td>
<td>2,000</td>
<td>250</td>
</tr>
<tr>
<td>Mortar</td>
<td>0.17-0.23-0.30</td>
<td>0.50-1.2-2.00</td>
<td>500-2,000</td>
<td>250</td>
</tr>
<tr>
<td>CMG system [1ply/1side]</td>
<td>60.6</td>
<td>97.0</td>
<td>72,000</td>
<td>1.15</td>
</tr>
<tr>
<td>CMG system [2plies/1side]</td>
<td>80.1</td>
<td>99.5</td>
<td>72,000</td>
<td>1.68</td>
</tr>
<tr>
<td>CMG system [1ply/2sides]</td>
<td>60.6</td>
<td>97.0</td>
<td>72,000</td>
<td>2.29</td>
</tr>
<tr>
<td>CMG system [2plies/2sides]</td>
<td>77.3</td>
<td>96.0</td>
<td>72,000</td>
<td>3.47</td>
</tr>
</tbody>
</table>

The equivalent thickness $S_{eq}$ of the CMG system (Eq. 2a) is the homogenized thickness of the cement matrix and composite grid with respect to the Young modulus $E$ of the Glass fibers. The strength is evaluated as (Eq. 2b):

$$S_{eq} = \frac{E_{Cement-matrix}}{E_{Glass-grid}} \cdot S_{Cement-matrix} + \frac{S_{Glass-grid}}{E_{Glass-grid}}$$  \hspace{1cm} (2a)  

$$f_{eq} = \frac{f_{Cement-matrix} \cdot S_{Cement-matrix} + f_{Glass-grid} \cdot S_{Glass-grid}}{S_{eq}}$$  \hspace{1cm} (2b)
A comparative analysis between as-built and strengthened panels is presented. The behavior of tested panels can also be analyzed in terms of shear stress-average strain, and shear stress-average shear strain curves. The shear stress, \( \tau \), can be obtained as \( \tau = 0.707 \frac{V}{A_n} \), where \( V \) is the diagonal load and \( A_n \) is the net section area of the un-cracked section of the panels (\( A_n = 0.257 \text{ m}^2 \) in the present case).

The average vertical and horizontal strains, \( \varepsilon_v \) and \( \varepsilon_h \), were computed as the average displacement over the same gauge length (400 mm) along the compressive and tensile diagonals, respectively, as considered in the experimental phase. The shear strain, \( \gamma \), can then be computed, according to the ASTM E519-81 standard method, as \( \gamma = \varepsilon_v + \varepsilon_h \).

**As-Built Panels**

Figures 3a, 3b depict a parametric analysis to simulate workmanship defects and variability of mortar mechanical and geometrical properties. The tensile strength and compressive strength (Figs. 3a, 3b) of the mortar are changed simultaneously from the lower values to the higher ones given in table 1. The corresponding shear stress-average strains and shear stress-average shear strain curves are plotted (an increase in mortar strength corresponds to increasing panel shear strength) and compared to experimental as-built panel outcomes (in dashed lines).

All the numerical analyses showed that the compressive strength of the mortar, simulating workmanship defects, can greatly influence the global response of the as-built panel, while its behavior is less sensitive to tensile
strength. Linear behavior was detected up to a shear stress of about 0.15 MPa, when cracking occurred in the mortar joints causing nonlinear behavior. The beginning of noticeable diagonal cracking is almost always associated with the attainment of the peak force after which strength degradation takes place.

**Strengthened Panels**

In the case of strengthened panels, the shear strength is mainly governed by the amount of reinforcement, while it does not appear sensitive to the mechanical properties of the mortar (whereas as-built panels were sensitive mostly to the mortar’s compressive strength). The numerical curve for the panel strengthened with two plies on one side (figure 4a) shows the linear behavior, for both as-built and strengthened panels, identified at low stress levels. The presence of the CMG system determines that panel response is almost linear up to about 60 % of the shear strength.

Panels strengthened with the CMG grid on one side showed the activation of evident out-of-plane deformation that led to a more brittle failure and consequently to a lower strength increase. The initial stiffness of the panel is also reduced due to the out-of-plane behavior with respect to numerical FEM analysis (the FE model is unable to simulate out-of-plane behavior in plane stress assumption).

By contrast, when double CMG layers were applied on both sides (Fig. 4b), the strength increment was limited by a corner crushing failure mode. This is a local failure with crushing of at least one loaded corner usually associated with weak masonry blocks surrounded by strong loading devices. For this reason, the ultimate values determined with the tests represent a lower bound of the assessed numerical shear capacity. Experimental curves are plotted in dashed lines in Fig. 4.

![Graph](image-url)

Figure 4. Parametric analyses. Numerical behavior of strengthened panels under diagonal compression test
In figure 5 the numerical curves for the as-built and strengthened panels with different amounts of reinforcement (one or two plies) show that the shear capacity of the strengthened walls was substantially increased by the CMG system, with a gain in strength ranging from about 82% (one ply on one side) to 214% (two plies on two sides). Importantly, the FE plane-stress model is unable to simulate the out-of-plane behavior. Consequently, two plies on one side gave similar behavior as one ply on both sides (the equivalent strengthening system is similar) while experimental results showed that asymmetrical reinforcement activated out-of-plane deformations that led to a more brittle failure and lower shear strength.

The CMG system reduces the anisotropy of the as-built panels; the strengthened wall is then made of two components: the CMG system that ensures the required tensile strength, and the masonry substrate providing the compressive strength. The results indicate that considerable increases in shear strength can be obtained using CMG reinforcement, especially when two plies are applied on both sides of the panel. This configuration also provides a better post-peak response and a significant increase in ductility.

![Graph showing shear stress vs. average diagonal strain for different configurations of reinforcement](image)

Figure 5. Parametric analyses. Numerical behavior of strengthened panels under diagonal compression test

Crack Pattern

The composite fibers led to a better redistribution of the stresses in the panel, and a more uniform and diffused crack pattern was achieved, instead of few localized cracks allowing for higher shear strength and better performance. The load applied to the panel passes through the matrix and induces tension forces in the FRP grid. Figure 6a shows the crack pattern at ultimate for the as-built panel predicted by FE analysis. At ultimate, shear capacity and the failure of the as-built panel is governed by the few cracks that follow the mortar bed and head joints (weak lines), rather than the diagonal line where the splitting load acts. Figure 6b shows multiple and spread cracking of the panel after the CMG system application, which confirms the better stress distribution and hence better energy absorption provided by the reinforcing grid.

![Images of crack patterns for as-built and strengthened panels](image)

Figure 6. Crack Pattern. Numerical prediction of masonry panels under diagonal compression test
CONCLUSIONS

The repair and retrofit of existing masonry structures is traditionally accomplished using conventional materials and construction techniques. This research work demonstrates the potential of CMG for enhancing the strength and ductility of tuff masonry structures which are a significant part of the Mediterranean area building inventory. Further implementation and acceptance of this technology basically depend on the development of appropriate guidelines and standards (including the development of design equations), and demonstration of strengthening effectiveness.

The main purpose of our numerical modeling was to validate the experimental outcomes in terms of shear strength, elastic stiffness, cracked behavior of tuff masonry walls under diagonal loads, considering different mechanical properties (parametric analyses) of the constituent materials both to simulate the natural variability and workmanship-induced variability of material properties. All the numerical analyses showed that the performance of as-built panel was sensitive mostly to the mortar’s compressive strength and partly to the Young Modulus, whereas, in the case of strengthened panels, the shear strength was mainly governed by the amount of reinforcement, and does not appear to be sensitive to the mechanical properties of the mortar.

FEM results were compared to experimental data and were found to be in good agreement. Significant improvements in panel strength and ductility were achieved by installing different layouts of the CMG grid. A negligible influence on the initial stiffness of the strengthened walls, that is reduced impact of the intervention on the existing structure, was observed. Failure modes were also checked: the CMG system led to a better redistribution of the stresses in the panel, and a more uniform and diffused crack pattern.

Further numerical investigations on calibrated FEM models are in progress in order to assess the effectiveness of the proposed strengthening solution when applied to different brickworks and structural layouts.

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