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Procedia Structural Integrity 78 (2026) 702–709

Structural Integrity Procedia

www.elsevier.com/locate/procedia

XX ANIDIS Conference

Diagonal compression testing of FRCM-Strengthened Calcarenite masonry panels: DIC Analysis and Simplified Numerical Modelling

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Abstract

Masonry structures made of calcarenite are common in many historical buildings, especially in Mediterranean regions. These structures often exhibit poor mechanical performance, particularly in resisting lateral loads, due to the inherent weakness of the stone and the aging of mortar joints. Masonry panels are among those elements intended to have load-bearing capacity for vertical loads and subject to horizontal actions resulting from earthquake action. Indeed, recent seismic events have highlighted their vulnerability when it comes to shear stresses acting in the plane of the panel. In recent years, Fabric-Reinforced Cementitious Matrix (FRCM) systems have emerged as a promising solution for the structural strengthening of existing masonry, offering advantages such as compatibility with historical materials, reversibility, and good mechanical performance. However, the wide range of materials available for reinforcement requires a careful assessment to determine the most suitable solution based on the characteristics of the substrate.
This study investigates the structural behaviour of calcarenite masonry panels strengthened with FRCM systems under diagonal compression testing. Two FRCM solutions are compared: one employing glass fibres and the other carbon fibres. A key objective of the study is to highlight the importance of selecting the appropriate strengthening system based on the characteristics of the substrate material. The experimental campaign evaluates the shear performance of the panels, employing Digital Image Correlation (DIC) techniques to obtain full-field strain and displacement data with high spatial resolution. The influence of the different strengthening systems on crack propagation, failure modes, and shear strength is analyzed in detail. Additionally, a

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Peer-review under responsibility of XX ANIDIS Conference organizers
10.1016/j.prostr.2025.12.090

simplified numerical model is developed and calibrated using experimental data to simulate the mechanical response of both unreinforced and FRCM-strengthened specimens.

Keywords: FRCM; masonry; numerical modeling; diagonal compressive test; DIC analysis; retrofitting; in-plane capacity

1. Introduction

The low shear strength of masonry is one of the main causes of its high seismic vulnerability. In recent decades, Fibre Reinforced Polymers (FRPs) have been increasingly applied to retrofit masonry structures due to their limited invasiveness, fast installation, and good mechanical performance at failure (Grande et al. (2008), Ghiassi et al. (2013)). However, concerns have emerged regarding their low vapor permeability, poor behaviour at high temperatures, incompatibility of epoxy resins with certain substrates, high cost, and the limited reversibility of interventions (Triantafillou (2011)). As an alternative, Fabric Reinforced Cementitious Matrix (FRCM) composites have been developed to address these issues (Nanni (2012), D'Ambrisi et al. (2012)). FRCMs, composed of fibre meshes embedded in a cement-based matrix, offer better compatibility with masonry substrates, improved breathability, reversibility, and promising resistance to high temperatures and UV radiation. Despite promising results, research on FRCM systems is still in its early stages. Experimental studies on small-scale specimens and coupon tests have been conducted to better understand the mechanical response of FRCM-reinforced masonry (Carozzi et al. (2014), Bertolesi et al. (2014)), with the aim of developing design guidelines analogous to those already available for FRPs. Modelling the behaviour of full-scale FRCM-strengthened masonry walls presents significant challenges. Accurate simulations would require detailed 3D finite element models that explicitly represent bricks, joints, matrix, and fibres. Moreover, these materials exhibit complex nonlinear behaviour and interact through brittle interfaces whose properties are often difficult to quantify. To address these challenges, homogenization approaches are commonly employed. These methods replace the masonry's heterogeneous structure with a fictitious, homogeneous material with equivalent properties, enabling macro-scale analyses. In macro-modelling, masonry is treated as an orthotropic softening continuum (Lourenço et al. (1997), Pelà et al. (2013)) but model calibration demands extensive experimental data and case-specific validation. Homogenization, instead, offers a less demanding alternative that maintains essential mechanical characteristics by averaging properties over a representative volume element (Cecchi et al. (2005), Drougkas et al (2015), Bertolesi et al. (2016)).

This study presents the results of an experimental campaign carried out at the University of Palermo (Minafò et al. (2024), Di Leto et al. (2025)), aimed at assessing, trough diagonal compressive test, the effectiveness of FRCM reinforcement systems applied to calcarenite stone masonry substrates. The mechanical response of the strengthened specimens was monitored and analysed using the Digital Image Correlation (DIC) technique, which enabled accurate measurement of deformation fields.

The experimental data were subsequently employed to calibrate a numerical model. In particular, a simplified finite element model was developed using the Abaqus software platform, based on a homogenisation approach to represent the masonry and reinforcement interaction. The proposed numerical strategy aims to capture the global behaviour of the strengthened panels while maintaining computational efficiency.

2. Materials and sample characteristics

This study briefly shows the results of an experimental campaign aimed at evaluating the shear behaviour of calcarenite masonry panels subjected to diagonal compression tests, with a focus on the effectiveness of FRCM (Fabric-Reinforced Cementitious Matrix) strengthening systems.

Seven single-leaf masonry panels (1030 × 1045 × 150 mm^3) with a running bond pattern were tested: three unreinforced (URM), two reinforced with carbon-FRCM, two with glass-FRCM. The panels were constructed using calcarenite blocks, commonly found in historic Sicilian buildings, with a compressive strength of approximately

4.09 MPa, and lime-based mortar with strengths equal to 4.12 MPa. The FRCM systems included bi-directional carbon or alkali-resistant glass fibre meshes embedded in a 10 mm thick bi-component mortar matrix on each panel side. Two types of fibre mesh were adopted:

- Glass-FRCM: Alkali-resistant (AR) glass fibre mesh with 12×12 mm openings, thermowelded at intersections, unit weight of 220 g/m², tensile strength of 1400 MPa, elastic modulus of 74 GPa, and ultimate strain of 2.0%;
- Carbon-FRCM: Carbon fibre mesh with 8x8 mm openings, unit weight of 225 g/m², tensile strength of 4100 MPa, elastic modulus of 240 GPa, and ultimate strain of 1.8%.

The matrix for both systems is a bi-component pre-mixed mortar. It is a hydraulic lime and eco-pozzolan mortar containing special admixtures and synthetic polymers in water dispersion. The flexural strength $f_{fl,M1}$ is equal to 4.15 MPa (CoV= 0.076) and the compressive strength f_c is equal to 14.27 MPa (CoV=0.111).

Diagonal compression tests were performed according to ASTM E519 standards to evaluate shear strength and deformation. Load was applied using a hydraulic jack, while deformations were measured via both displacement transducers and Digital Image Correlation (DIC). For this purpose, one side of the specimen was painted creating a high-contrast surface. A white matte paint was used for the background, and a black speckle pattern was created on it. A mirrorless camera with high resolution (6048x4024 pixels) was used for image acquisition, set to capture one photo every 3 seconds. More details regarding material characteristics, test set-up and results of the experimental campaign can be found in Minafò et al. (2024) and in Di Leto et al. (2025).

From the diagonal compression tests, the following results were obtained: the unreinforced masonry panels (URM) reached an average peak load of 110.09 kN; the panels reinforced with carbon fibre (C_FRCM) reached an average peak load of 137.81 kN; and the panels reinforced with glass fibre (G_FRCM) reached an average peak load of 176.12 kN. Figure 1 shows some pictures illustrating the failure modes exhibited by the panels subjected to diagonal compression tests.

a b c

Fig. 1. Failure modes: (a) URM panel; (b) C_FRCM panel; (c) G_FRCM panel

Specifically, the unreinforced panels displayed mixed failure mechanisms, combining diagonal cracking and stepped shear cracking along the mortar joints. In contrast, the reinforced panels exhibited through-thickness cracking and failed due to the attainment of the masonry's compressive strength. The failure was not the expected one, typical of diagonal compression tests, but it was a premature failure. In both the C_FRCM and G_FRCM reinforced panels, no cracking was observed in the mortar matrix, nor were any signs of delamination detected at the interfaces level.

3. Experimental results from DIC analysis

Two-dimensional Digital Image Correlation (DIC) was employed to analyse the strain field on the surface of the specimens. Additionally, an attempt was made to acquire displacement readings using virtual extensometers positioned on the panel surface. The processing of the DIC data was carried out using the CORRELI^{GD} algorithm (Chevalier (2001)). This algorithm computes displacement fields at each loading step by means of a Fast Fourier

Transform (FFT); the displacement value corresponds to the maximum of the cross-correlation product between a reference signal f(x, y) and a deformed signal g(x, y). The algorithm is based on a multi-scale approach, whereby correlation is performed to track the displacements of a macro-area (Region of Interest – ROI) and several sub-areas (Zones of Interest – ZOI), as also described in Caggegi et al. (2015).

Some of the processed results are presented below. Specifically, one unreinforced panel (Fig.2), one panel reinforced with carbon fabric (Fig.3), and one panel reinforced with glass fabric (Fig.4) were considered. Each figure includes the force vs. time graph (Figg.2a,3a,4a), a picture of the panel (Figg.2b,3b,4b), and the corresponding strain field map (Figg.2c,3c,4c).

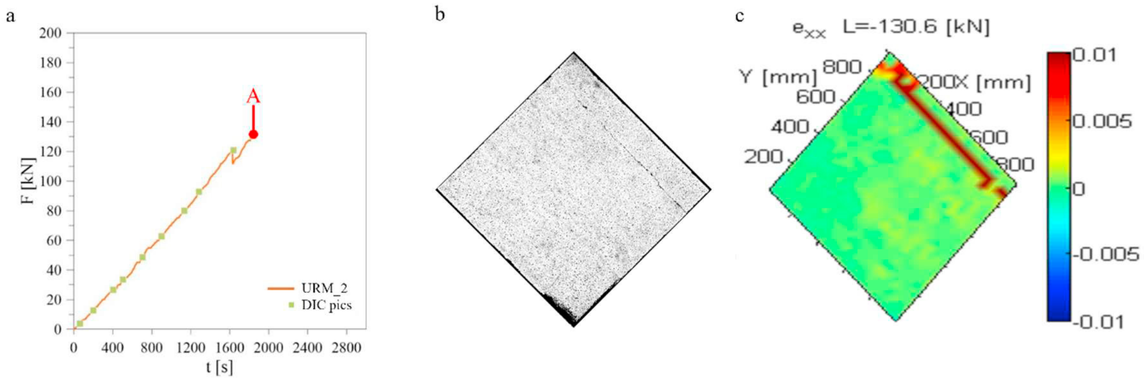

Fig. 2. URM panel: (a) Force vs time graph; (b) real panel picture; (c) strain field map through DIC technique

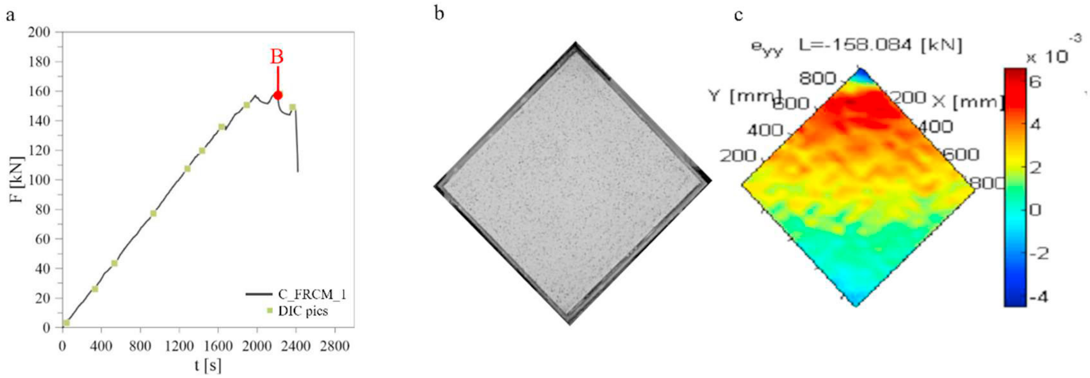

Fig. 3. C_FRCM panel: (a) Force vs time graph; (b) real panel picture; (c) strain field map through DIC technique

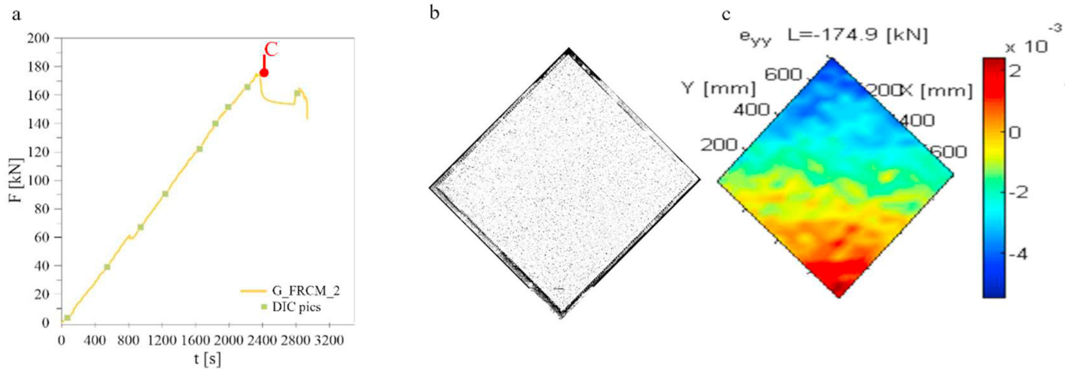

Fig. 4. G_FRCM panel: (a) Force vs time graph; (b) real panel picture; (c) strain field map through DIC technique

From the image analysis, the crack pattern could be clearly identified, particularly in the case of the unreinforced panel. In contrast, for the reinforced panels, which exhibited a toe-crushing failure mode at the interface with the substrate, it was possible to confirm the absence of visible damage to the reinforcing matrix throughout the entire test duration. Furthermore, out-of-plane displacements of the reinforced panels were detected and will be quantified in subsequent analyses.

4. Adopted numerical model

Numerical modelling of diagonal compression tests is essential for understanding the structural behaviour of masonry panels, particularly in the presence of reinforcement. In the present study, numerical simulations were carried out using the ABAQUS CAE software. The masonry panel was modelled using a homogenization approach, in which homogeneous solid (Fig. 5a) elements were adopted for panels along with Concrete Damage Plasticity (CDP) constitutive model to capture the nonlinear behaviour of the materials. Although originally developed for concrete, CDP is widely used for brittle materials by adjusting the main parameters accordingly. The elastic behaviour was defined by specifying the elastic modulus E and Poisson's ratio ν, while the plastic behaviour was characterized by defining the dilation angle Ψ, a correction parameter known as eccentricity ε, the ratio fb0/fc0, which represents the ratio between the initial equibiaxial yield stress and the initial uniaxial compressive yield stress, and the viscosity parameter. The mesh size was set to 20 mm (Fig. 5b). After creating the unreinforced panel model, the reinforcement layer was tied to it. The reinforcement layer composed of a mortar layer, modelled as a continuous solid with nonlinear behaviour using the CDP model, and an embedded fabric reinforcement mesh, which was modelled discretely by assigning an equivalent thickness and mesh size (Fig. 5c).

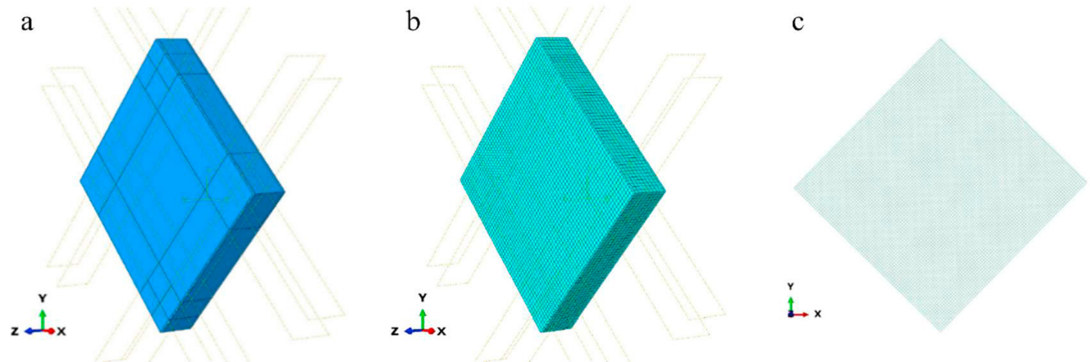

Fig. 5. Numerical modelling: (a) assembled panel; (b) 20 mm mesh definition; (c) fabric modelling

The interaction between fibre and matrix was defined using the embedded command, while the interaction between the matrix and the masonry substrate was defined using the tie command, which simulates perfect bonding. This assumption is consistent with experimental results, as no delamination phenomena were observed at the matrix–substrate interface during the tests. The analysis was displacement-controlled, with the vertical displacement applied through the modelling of loading plates having dimensions equivalent to the steel shoes used during the laboratory tests.

5. Numerical results and comparisons

The mechanical parameter values used to define the constitutive laws for the masonry were derived from the results of material characterization tests. In the absence of experimental data, some parameters were estimated using analytical formulations or sourced from the literature (Eurocode 6 (2005), Lourenco (1997)). For the definition of the elastic behaviour of the masonry, the compressive strength of the calcarenite, as previously defined, was considered. Poisson's ratio was set to 0.15, while the elastic modulus was calculated using the formulation provided in Eurocode 6 (2005), as 1000*f_c, where f_c is the compressive strength. The plastic behaviour was defined using a dilation angle Ψ of 32°, an eccentricity ε of 0.1, a stress ratio f_{b0}/f_{c0} of 1.16, and a viscosity parameter equal to 0. The tensile strength was assumed to be 10% of the compressive strength. The constitutive behaviour for the two reinforcement systems was defined based on the values reported in the technical datasheets, with the elastic modulus and tensile strength assigned according to the material properties described in the previous section. The plastic behaviour of the mortar matrix was defined using the same parameters adopted for the masonry, with an elastic modulus E equal to 9000 MPa and a Poisson's ratio of 0.15. Compressive behaviour was defined using the compressive strength obtained from mortar specimen testing, and the tensile strength was again assumed to be 10% of the compressive strength.

The results obtained from numerical modelling are summarized in the following table (Table 1). The table presents, in the first column, the types of panels considered. The second column indicates the parameters used for comparison: Pmax, corresponding to the maximum load reached; G, the shear modulus, evaluated as the secant modulus between 10% and 30% of the maximum shear stress on the experimental τ-γ curve; and τ, which is calculated according to the formulation provided by ASTM E519 Standards (2022). The table includes these parameters for both experimental tests and numerical modelling. The experimental values shown in Table1 and denoted by Exp. were derived from data registered trough linear displacement transducers. The load values and τ values are also compared with their corresponding estimates derived from the Italian Guidelines (2018) and CNR-DT 215 (2018), denoted in Table 1 as *Analyt.*. The last three columns of the table provide a direct ratio between the three data sets, in order to assess the differences among them. It should be noted that the experimental values of Pmax and τ refer to the average values obtained from each group of specimens, whereas the values of G correspond to a single panel from each group. This is because the elongation values of the horizontal diagonal, which are required for the calculation of the modulus G, were only recorded for one panel per group due to problems in the experimental phase.

By analysing the results in the last three columns, it can be observed that the numerical model is able to accurately capture the experimental outcomes, particularly in the case without reinforcement. In the presence of glass fibre reinforcement, the numerical results are underestimated by approximately 30%; however, they are close to the values estimated using the design code predictive formulas, i.e. *Analyt.* values. The opposite occurs with carbon fibre reinforcement, where the analytical prediction formula overestimates the experimentally obtained result, while the numerical model shows good agreement with the experimental data.

Table 1. Experimental, numerical and analytical results.

		Exp.	Analyt.	Num.	Exp./Analyt.	Exp./Num.	Num./Analyt.
URM	P_{max} [kN]	110.09	93.20	100.74	1.18	1.09	1.08
	G [MPa]	1920	-	2027	-	0.94	-
	τ [MPa]	0.46	0.38	0.45	1.18	1.09	1.08
C_FRCM	P_{max} [kN]	137.81	366.90	135.48	0.38	1.02	0.37
	G [MPa]	2609	-	2339.3		1.11	
	τ [MPa]	0.72	1.67	0.6	0.38	1.02	0.37
G_FRCM	P_{max} [kN]	176.12	135.07	133.7	1.30	1.32	0.99
	G [MPa]	2038	-	2370		0.86	
	τ [MPa]	0.80	0.62	0.59	1.30	1.32	0.99

The same considerations apply to the shear stress τ, as it is directly dependent on the maximum load reached. As for the shear modulus G, the numerical model reproduces the experimental value reasonably well, slightly overestimating it in the presence of glass fibre, and slightly underestimating it in the case of carbon fibre reinforcement. In the unreinforced case, the values are nearly identical. By observing the data in the table, it can also be noted that the analytical formulation overestimates the result obtained in the presence of FRCM with carbon fibre fabric. This can be explained by the fact that the calculations were based on data from technical datasheets, whereas the formulation would require results derived from shear bond tests, which are not always available. Moreover, the discrepancy may be due to the fact that, in the presence of FRCM with carbon fibre, failure occurred prematurely as a result of the masonry reaching its compressive strength. From a numerical standpoint, this behaviour was investigated through the model: a stress concentration was observed at the upper and lower edges of the panel, which can be attributed to the greater stiffness and strength difference of the carbon fibre reinforcement system compared to the case where the system was made with glass fibre.

6. Conclusions

This study highlighted the importance of integrating theoretical, experimental, and numerical analyses to gain a comprehensive understanding of the structural behaviour of masonry panels reinforced with FRCM systems. The work focused on the shear behaviour of seven masonry panels: three unreinforced, two reinforced with a carbon fibre-based FRCM system, and two reinforced with a similar system using glass fibre fabric. Based on the activities carried out, including the prediction of the expected behaviour in terms of shear strength, the analysis of experimental results using the Digital Image Correlation (DIC) technique, and the numerical modelling performed with the ABAQUS CAE software, the following conclusions can be drawn:

- the discrepancies between theoretical and experimental results can be attributed to intrinsic variability among the panels;
- the use of the DIC technique proved valuable for confirming phenomena observed during experimental testing. Specifically, it allowed the correlation between crack pattern development and the corresponding load steps, confirmed the absence of damage in the reinforcement matrix in the reinforced panels, and provided useful data for the eventual estimation of out-of-plane displacements during testing;
- the numerical model produced results consistent with the experimental findings for both unreinforced and reinforced panels. The observed differences between numerical simulations and laboratory diagonal compression tests can be attributed to several factors, including uncertainties in the experimental data, geometric and mechanical variability of the specimens, and simplifications in numerical modelling. Since a macro-modelling approach was adopted, treating the masonry panel as a homogeneous continuum, the actual differences in strength between mortar joints and calcarenite blocks were not accounted for.

Further studies are needed to deepen the understanding of the panels' behaviour, both from experimental and numerical point of view.

Acknowledgements

This paper was produced while Ph.D. student Marielisa Di Leto was attending the Ph.D. program in RETURN project, Spoke 3: VS3 - Earthquake and volcanoes, at the University of Palermo, Cycle XXXVIII, with the support of a scholarship financed by NRRP, funded by the European Union - NextGenerationEU - Mission 4 "Education and Research", Component 2 “From Research to Business” – In-vestment 1.3 “Creation of “enlarged partnerships between universities, research centres, businesses and funding of basic research projects”. This research was also developed among the activity of the project ReLUIS ”Progetto Esecutivo accordo DPC/ReLUIS 2024/2026, WP14-Materiali Strutturali Innovativi per la Sostenibilità delle Costruzioni”. The financial support is gratefully acknowledged.

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