

## PRELIMINARY RESULTS OF EXPERIMENTAL STUDY ON THE DIAGONAL COMPRESSION BEHAVIOUR OF MASONRY PANELS RETROFITTED WITH FRCM

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**Abstract:** *The use of composite fibre grids embedded in an organic matrix, namely Fabric Reinforced Cementitious Matrix (FRCM) and fibre mesh in a mortar plaster, e.g., Composite Reinforced Mortar (CRM), were increasingly applied in structural retrofitting applications and already known by the scientific community. Both systems have promising results in improving the structural performances of masonry members, such as walls, arches, and vaults. This is due to their load-carrying capacity and their great compatibility with masonry substrates, compared to other types of organic matrix composite materials. However, the literature on these strengthening systems is still quite limited, and limited research is available regarding their mechanical properties and the behaviour of strengthened masonry members.*

*In this work, preliminary results and considerations of the experimental campaign are presented, with the goal of examining the effectiveness of various strengthening options for increasing the in-plane shear behaviour of masonry. Single-leaf masonry panels reinforced with FRCM and CRM systems using various fibre typologies and arrangements are tested under diagonal compression tests. Masonry panels are made of calcarenite stone units, a material typically used in historic Sicilian (in the South of Italy) constructions. The mortar used as a matrix is a fibre-reinforced lime-based mortar which is medium-grained and suitable for structural work on stone and brick masonry, even where there are historical and architectural constraints. Concerning the type of fibre, a glass grid and a carbon grid are used for the FRCM system, while a Glass-FRP grid is used for the CRM system.*

*The planned experimental campaign involves the construction of masonry panels with different retrofitting systems, including control specimens, panel retrofitted with FRCM, and panels reinforced with the CRM system. The main objective is to evaluate the gains in shear strength and ductility of retrofitted masonry panels and to compare the results for different system types and configurations, also in terms of failure.*

### 1 Introduction

The need to design efficient strengthening interventions to improve the structural behaviour of existing buildings has directed research toward the study of new retrofitting systems. As demonstrated by major seismic worldwide events, masonry buildings are particularly susceptible to horizontal actions (Ceci et al., 2010, Lagomarsino, 2006, Valluzzi, 2007, Colajanni, 2023, Greco et al., 2020), mainly because of inappropriate construction rules resulting from the design and poor-quality materials and their degradation over time. Hence, reinforcement materials must be used to improve the in-plane and out-of-plane behaviours of the structure, ensuring strength, compatibility, and durability. To satisfy these requirements, the use of fibre-reinforced composite materials (Valluzzi, 2016) is becoming increasingly popular. Unlike traditional reinforcement techniques, e.g., welded steel meshes embedded in cementitious mortar layers, it is possible to increase the

structural capacity without determining significant changes in the distribution of mass and stiffness of the structure. Among the most widely used materials, e.g. Fabric-reinforced cementitious matrix (FRCM) and composite-reinforced mortar (CRM) are reasonable alternatives to fibre-reinforced polymers (FRP) (Incerti et al., 2015, Ferretti et al., 2023). The advantage of their use is derived from the presence of an inorganic matrix, which provides good durability and breathability, and above all, greater compatibility in presence of masonry support (Tilocca et al., 2019). The mechanical behaviour of the two systems depends on the type of reinforcement used. FRCMs consist of fabric, which is made of different types of fibre materials and put in place according to different configurations. Within CRMs, the reinforcement is in the form of an FRP or a resin-impregnated mesh. Different solutions can be used at the design stage of the intervention in terms of both the material combination and spatial configuration. The choice is dictated by the compatibility of the resisting layer with the matrix, and that of the matrix with the support. The study on compatibility, which is reflected in numerous works in the literature (Bellini et al. 2019, 2020), aims to assess the phenomena generated at the interface between the various layers of material, on which the effectiveness of the intervention depends. Numerous studies have been conducted on the mechanical characterization of these materials and evaluation of the effectiveness of reinforcement systems. Many studies have been conducted on the characterization of historic Sicilian buildings, especially concerning the definition of the construction materials used. The work presented in this paper focuses on the use of calcarenite stones extracted from quarries in Marsala. The variability of the mechanical characteristics depending on the nature of the material and the area of extraction makes it necessary to characterize the material. This specific type has never been characterized and has never been used for these purposes. For this reason, an experimental campaign was organized to characterize the masonry through diagonal compression tests, both on the bare support and with different types of retrofitting systems. Analytical models were used to estimate the shear strength of the panel to predict the behaviour of different material combinations.

## 2 Existing design provisions for FRCM strengthened masonry panels

To design strengthening interventions for masonry walls using composite systems, national and international standards or guidelines have only recently been developed. This is because the relevance and spread of these materials have increased in recent times. Within the frameworks of the United States and Europe, particular design guidelines for FRCM and CRM systems have been developed and included in worldwide technical guidelines, e.g. ACI 549.6R-20 (2020), RILEM, and CNR-DT 2015 (2018) Guidelines in Italian. Regarding the retrofitting of masonry walls exposed to in-plane loads, a comparable design strategy is proposed by every referenced document. The in-plane shear capacity of an FRCM/CRM-strengthened masonry panel  $V_{t,R}$  in the case of a shear-controlled failure mode was calculated using the following equation:

$$V_{t,R} = V_t + V_{t,f} \quad (1)$$

where  $V_t$  is the in-plane masonry shear contribution and  $V_{t,f}$  is the fibres shear contribution. The former must be assessed in light of the masonry panel's minimum shear capacity and potential shear failure mechanisms for an unreinforced masonry wall. Equations (2–4) can be used to determine the latter.

Equation 2 was derived from ACI guidelines:

$$V_{t,f} = \phi_s \cdot n_f \cdot A_f \cdot E_f \cdot \varepsilon_{fd} \quad (2)$$

where  $\phi_s$  is a shear strength reduction factor equal to 0.8 and  $E_f$  is the elastic modulus of the cracked FRCM system.

Equation (3) is proposed according to the RILEM Guidelines:

$$V_{t,f} = \gamma_k \cdot n_f \cdot A_f \cdot E_f \cdot \varepsilon_{fd} \quad (3)$$

in which  $\gamma_k$  is a safety factor equal to 0.5 and  $E_f$  is the dry fibre elastic modulus.

Equation (4) is proposed by CRN Italian Guidelines:

$$V_{t,f} = \frac{1}{\gamma_{Rd}} \cdot n_f \cdot A_f \cdot \alpha_t \cdot E_f \cdot \varepsilon_{fd} \quad (4)$$

where  $\gamma_{Rd}$  is a safety factor equal to 2,  $\alpha_t$  is a coefficient, equal to 0.8, accounting for a reduced tensile strength for fibres subjected to shear, and  $E_f$  is the dry fibre elastic modulus.

In all three Equations (2-4)  $n_f$  is the number of layers,  $A_f$  is the area of the fibre grid, and  $\varepsilon_{fd}$  is the design strain of the composite system. Specific indications for evaluating the design strain  $\varepsilon_{fd}$  are included in all the guidelines, and they should be evaluated by taking into account some peculiarity: the outcomes of bond and tensile tests carried out to characterise the mechanical properties of the composite systems, the anticipated mechanism of failure, such as end or intermediate delamination, design safety factors.

Because the maximum load that the fibres can support is always determined by multiplying the area of the fibre reinforcement effective in shear by the maximum design strength, the expressions reported in Equations (2–4) are conceptually equivalent. The only variation consists of the values attributed to the safety factors or strength reduction factors. Furthermore, if the strengthening system is applied asymmetrically, for example, only on one side of a panel, the effects of eccentricity should be sufficiently considered by lowering the reinforcement shear contribution  $V_{t,f}$  by at least 30%. It is worth noting that in all three proposed formulations, the shear strength contribution provided by the system considers only the characteristics of the fibre and does not consider the influence of the mechanical properties of the mortar on the global response.

### 3 Mechanical characterization of the materials

The experimental campaign presented in this paper consists of diagonal compression tests performed on strengthened masonry panels using composite systems. The experimental campaign involves 12 samples, constructed from the same type of stone units and mortar mix. The objective is to analyse the efficiency of different types of strengthening systems in increasing the shear capacity of existing masonry walls. The samples were designed to reproduce what is observed in historic Sicilian construction, and for the sake of simplicity, a running bond pattern was used, in which each unit is staggered a  $\frac{1}{2}$  unit further than the adjacent course, resulting in a one-over-two pattern.

#### 3.1 Stone units

The stone units adopted for the construction of the specimens are made of calcarenite stone and as previously mentioned, the choice of this type of material stems from its extensive use in historic Sicilian construction. Calcarenite stone is a rock of sedimentary origin, formed by limestone particles. Due to its nature, this type of stone has rather variable morphological and mechanical characteristics, which depend on the place of extraction as well as the depth of sedimentation. Calcarenite stone is characterized by high variability in their deformability, strength, and permeability characteristics, as a function of the zone. For example, the value of the uniaxial compressive strength ranges from 2.5 to 4.5 MPa for the Marsala calcarenite, and from 8 to 15 MPa for Palermo calcarenite (Zimbaro *et al.*, 2011). For this reason, the material characterization plays a key role in this work. The calcarenite stone used comes from the Marsala area in Sicily. Regarding the properties, it is not possible to find much information in the literature, as this type had never been used within an experimental campaign aimed at its characterization. For this reason, a preliminary mechanical characterization was carried out to identify the main mechanical properties. Specifically, four series of materials, shown in Figure 1, were tested. Considering the macroscopic aspect, material samples were similar two by two, and they are different in point of extraction and, consequently, in composition.



Figure 1. Four series of material. From left to right: Serie G, Serie GS, Serie FC, Serie FS.

The first two series, identified in the following as “G” and “GS”, exhibited a lighter colour, tending toward yellow, and appeared to be more compact. The other two series, named in the sequel with “FC” and “FS”, exhibited a more intense colour, tending toward orange and the presence of more fossils. Figure 2 shows two graphs containing curves obtained from compression tests on cubes with a side of 110 mm. For the G, GS, and FC

series, 6 samples were tested, while for the FS series, 3 samples were tested. The tests were conducted under displacement control with a Universal Testing Machine (UTM), with a loading rate of 0.5 mm/min. Results are shown in Figure 2. It should be specified that the deformation values were evaluated from the displacements measured by the machine. The average values obtained are shown in Table 1, which indicates the number of samples tested for each series, the unit weight, the maximum stress value reached during the test, and the estimated elastic modulus.

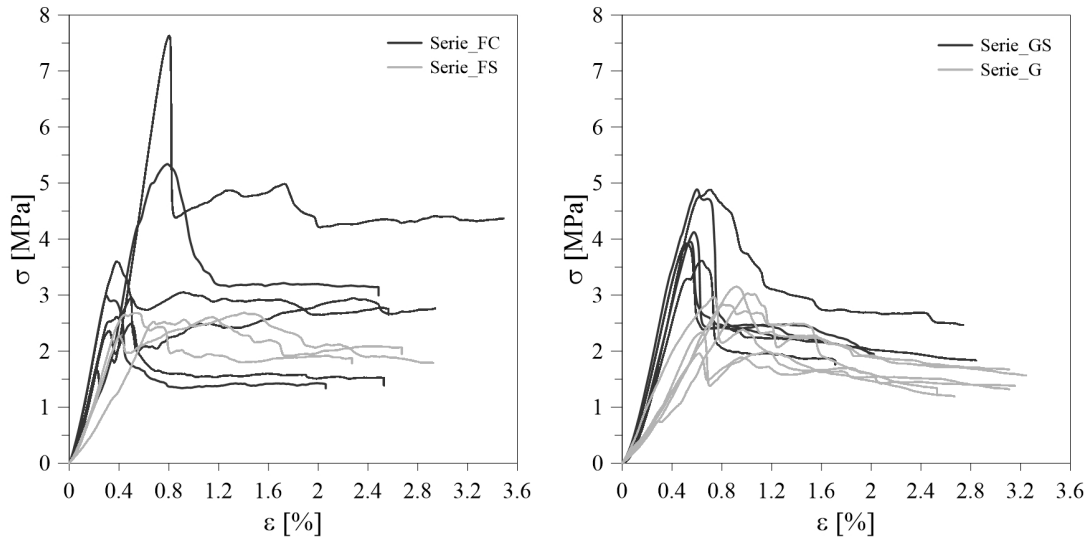


Figure 2. Compression tests results of series FC, FS (on left) and of series GS, G (on right).

Table 1. Stone unit's mechanical properties: average values.

SERIE ID	Number of samples	Unit weight [kN/m <sup>3</sup> ]	Compressive strength [MPa]	Elastic Modulus [MPa]
G	6	16.2 (CoV=0.02)	2.97 (CoV=0.17)	316 (CoV=0.63)
GS	6	17.1 (CoV=0.02)	4.47 (CoV=0.13)	1029 (CoV=0.25)
FC	6	17.5 (CoV=0.04)	4.6 (CoV=0.4)	1115 (CoV=0.38)
FS	3	16.2 (CoV=0.05)	2.9 (CoV=0.03)	352 (CoV=0.17)

Looking at the graphs in Figure 2 and Table 1, the FC and GS series exhibit better mechanical properties, but at the same time, the GS series shows greater variability of results. While lower values of compressive strength were exhibited by the G and FS series. Therefore, for this work, a stone similar to the G and GS series was chosen, also taking into account the fact that it seems to be the most representative type of what can be found in historical construction. Considering the great variability of the material properties, the chosen type was tested again by making cubic specimens from the material that was then actually used to build the masonry panels. The series is referred to in the following as C, to differentiate the results from preliminary tests. The tests were carried out on cubic specimens of 100 mm side, according to UNI EN Standards (UNI EN 772-1, 2011). The results obtained are summarised in Table 2. which indicates the unit weight, the maximum tension value reached during the test, and the estimated porosity. As expected, different results were obtained from the tests than in previous cases. The considered stone units seem to exhibit mechanical characteristics intermediate between the G and GS series.

Table 2. Stone unit's mechanical properties: average values.

SERIE ID	Unit weight [kN/m <sup>3</sup> ]	Compressive strength [MPa]	Porosity [%]
C	14.6	4.09	46
	(CoV=0.03)	(CoV=0.36)	(CoV=0.045)

The porosity value was high compared to the average value usually attributed to calcarenite stone, e.g. for that extracted from the Sabbucina quarry the estimated porosity value is about 20 percent. The porosity evaluation was of fundamental importance for the choice of the treatment to be carried out for the installation of the stone units. It was indeed necessary to wet the contact surfaces, to prevent the mortar mix water from being absorbed, hindering the chemical reactions necessary for the curing phase.

### 3.2 Mortars

In the experimental program, three different types of mortar were considered. One type, hereafter referred to as M, was used for the construction of the masonry panels, while the other two types, called M\_FRCM and M\_CRM, were used as the matrix for the two reinforcement systems considered. They are all pre-mixed natural hydraulic lime-based mortars and were chosen taking into account the stiffness and compressive strength of the stone units. The M type is a Certified, eco-friendly natural mortar of pure natural lime NHL 3.5. M\_CRM is a ready-mixed, fibre-reinforced, light-coloured, two-component mortars composed of natural hydraulic lime (NHL) and Eco-Pozzolan, natural sands, special additives, and synthetic polymers in water dispersion. The respective characteristics are shown in the following table, which shows the compressive strength and elastic modulus.

Table 3. Mechanical properties of mortar matrix provided by the manufacturer.

ID SAMPLE	Compressive strength [MPa]	Elastic Modulus [GPa]
M	5	-
M_FRCM	> 15	8
M_CRM	> 15	8

Type M mortar has also been laboratory tested, by UNI EN Standards (UNI EN 1015-11, 2006). Two sets of specimens were tested: the first set derived from a specially made mixture for preliminary characterisation of the material, and the second set consisted of specimens made from the same mixture used to make the panels. Specifically, 19 specimens were made, one for each casting, taking into account the fact that more than one pack of mortar was needed for each panel, and the mix was made using one pack at a time. The first set, tested after 28 days of curing, exhibited a compressive strength of 4.12 MPa (CoV=0.072) and a flexural strength of 1.59 MPa (CoV=0.022). The second set, tested after 29 days of curing, exhibited a compressive strength of 6.2 MPa, and a flexural strength of 1.8 MPa. Figure 3 shows the set-up of the bending and compression tests on the mortar. The 3 pictures on the right in the same figure show the failure surfaces of the samples. In particular, the typical "hourglass shape" fracture can be seen in the figures on the right.



Figure 3. Tests set-up and samples after flexural and compressive tests on mortar pieces.

### 3.3 Fibres

The type of strengthening system chosen for the three series of panels includes a bidirectional fibreglass mesh, a bidirectional carbon fibre mesh, and a bidirectional G-FRP mesh. For GFRCM strengthening systems, an Alkali Resistant (AR) dry glass fibre mesh is used. At the intersection of the longitudinal and transversal threads, the mesh grid is termowelded along the weft direction. Its dimensions are 12 x 12 mm, with a unit weight of 220 g/m<sup>2</sup>, a density of 2.5 g/cm<sup>3</sup>, and an equivalent fibre thickness of  $t_f = 0.02$  mm. For CFRCM strengthening systems, a carbon fibre mesh is used. Its dimensions are 12 x 12 mm, with a unit weight of 225 g/m<sup>2</sup>, a density of 2.25 g/cm<sup>3</sup>, and an equivalent fibre thickness of  $t_f = 0.056$  mm. For G-FRP strengthening systems, a carbon fibre mesh is used. Its dimensions are 12 x 12 mm, with a unit weight of 420 g/m<sup>2</sup>, a density of 2.5 g/cm<sup>3</sup>, and an equivalent fibre thickness of  $t_f = 0.19$  mm.

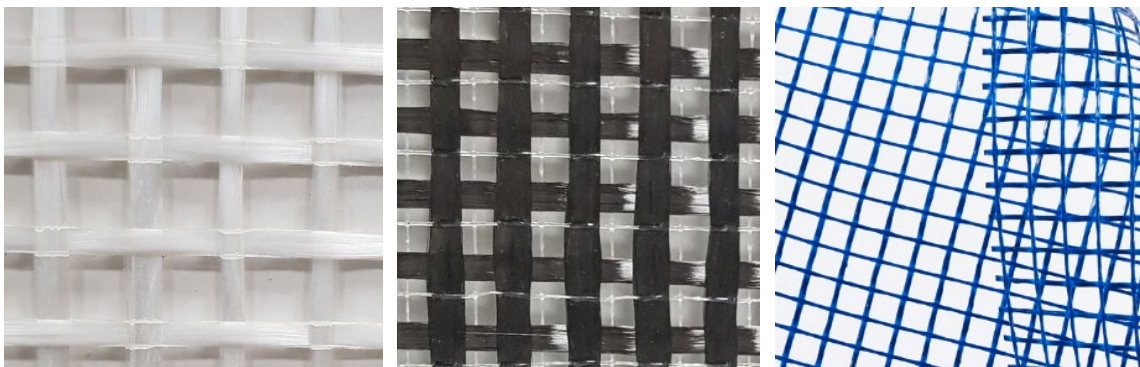


Figure 3. Fibre mesh. From left to right: Glass, Carbon, and G-FRP.

The mechanical properties from the data sheet, referred to glass fibre are: tensile strength  $f_{tu}=56$  kN/m, ultimate strain  $\epsilon_{fu}=2.0\%$ , and elastic modulus  $E_f=74$  GPa. Mechanical properties of the carbon grid reported in the technical data sheet are tensile strength  $f_{tu}=60$  kN/m, ultimate strain  $\epsilon_{fu}=1.8\%$ , and elastic modulus  $E_f=240$  GPa. Mechanical properties of G-FRP reported in the technical data sheet are: tensile strength  $f_{tu} = 106$  kN/m, ultimate strain  $\epsilon_{fu}=4\%$ , and elastic modulus  $E_f=33$  GPa.

### 3.4 Masonry panels

The samples are single-leaf panels, having a size 103 x 104.5 x 15 cm<sup>3</sup>, as shown in Figure 4.



Figure 4. Masonry pattern and strengthening layout.

The 12 specimens were built over 10 days and characterized by a running bond pattern with mortar joints thickness of about 10/15 mm. They were cured in the laboratory, planning to wet the surfaces daily throughout the curing period, followed by the application of the reinforcements. The number of panels was chosen according to the type of reinforcement: 3 panels with G-FRCM reinforcement, 3 with C-FRCM, and 3 with CRM reinforcement, while three panels were left without reinforcement to assess the strength of the unreinforced masonry and, consequently, the effectiveness of the reinforcement. The strengthened system is applied on each masonry panel adopting a continuous layout on both sides. In the case of the FRCM system total matrix thickness of 10 mm per side was used; in the case of the CRM system, the FRP grid was embedded within the mortar matrix obtaining an overall thickness equal to 30 mm. To avoid applying direct force to the reinforcing layer, which might cause early debonding events, the FRCM composites were placed on the brickwork surface at an offset of around 20 mm from the edges. The chosen strengthening systems are anchored to the masonry support using mechanical anchors, transversally applied on the surface. The recommended number of anchors is five per square metre. Considering the size of the real panels, the application of five connectors per side is foreseen, for a total of 10 connectors per panel. Two different types of connectors were used. For the FRCM system, connectors were made in the laboratory from a high-strength unidirectional glass fibre rope, with a 10 mm diameter. The portion of the connector that fits inside the masonry is impregnated with epoxy resin, whereas the filaments of the outer part are expanded and laid on the surface until a circular area around the hole is covered. For the CRM system, preformed 'L' connectors were used. They are made of glass fibre impregnated with thermosetting resin and have a 7 mm diameter. Both types of connectors were inserted into the masonry using vinyl ester-resin-based chemical fixing.

#### 4 Diagonal compression test

The panels will be tested between 28 and 40 days after application of the strengthening system. The results will be captured through the application of two dial gauges on the diagonals to measure the displacements along them to obtain the shear vs. sliding behaviour of the panels.

##### 4.1 Setup

Diagonal compression tests will be conducted in accordance with ASTM E519 (2019) Standards. To correctly estimate both pre-peak and post-peak behaviour, the test was conducted under displacement control.

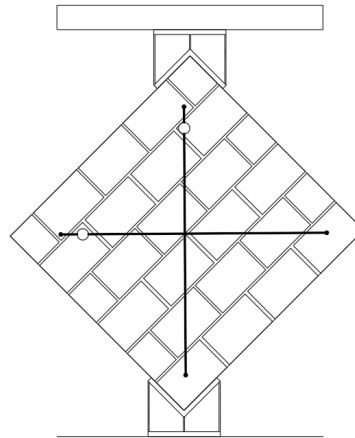


Figure 4. Diagonal compression test set-up.

The test set up is represented in Figure 4. The measurements of shortening and elongation along the two diagonals of the panel were made through dial gauges. A couple of displacement transducer is applied on both faces of the tested specimen, in the case of unreinforced masonry panels. In the case of the strengthened panels, a couple of displacement transducer is applied on a single face of the tested specimen. The other one was prepared for the use of the Digital Image Correlation (DIC) technique. This makes it possible to compare the results obtained with the two measurement methodologies. The use of DIC was not envisaged for unreinforced panels due to the irregularity of the surface. The use of white paint on the very porous surface would have implied surface defects that could cause problems during image acquisition. Whereas the use of plaster could contribute to the homogeneity of the surface, the use of which, without the fibre, is planned for later experimentation.

#### 4.2 Analytical prediction of shear capacity of strengthened masonry panels

As experimentally observed (Del Zoppo, 2019), many variables influence the overall response of a panel subjected to a diagonal compression test. An unreinforced masonry panel, after an initial linear elastic branch to peak, usually exhibits brittle or quasi-brittle failure. On the other hand, the curves obtained for a reinforced panel generally show an initial linear elastic branch to peak, followed by a drop in the load-bearing capacity. Subsequently, a second or multiple peaks are recorded, the presence of which depends on the reinforcement technique used. As experimentally observed (Ferretti *et al.*, 2021) the first peak load corresponds to the appearance of the first macroscopic crack in the mortar, when the panel is strengthened with a continuous layer. While the post-peak phase is governed by the cracking progress, also influenced by the type of fibre used. On this depends the failure mode and deformation capacity of the specimen. What is expected from the results on the specimens of the present work, is a post-peak phase characterised by a second peak load followed by a softening branch (Del Zoppo, 2019). Comparison of experimental results from tests on unreinforced and reinforced specimens in the literature shows that the contribution of the reinforcement system is limited during the first phase of the test. While the contribution becomes significant in the second phase, during the masonry cracking process. Once the cracking phase of the masonry is complete, the response depends only on the strengthening system, until the fibre failure load or the detachment of the reinforcement from the substrate is reached. According to the previous remarks, the first peak load corresponds to matrix cracking, while the second peak corresponds to the load value associated with fibre rupture or delamination at the fibre-to-matrix interface. Therefore, in estimating the panel shear strength, it is not sufficient to take into account only fibre contribution, according to Equations 2-4.

In the absence of the experimental results, in the present work, an estimation of the shear strength value of the panels was produced using analytical formulations. The masonry shear strength was calculated according to the formulation proposed by the Italian standard NTC (2018). The equation used is:

$$V_t = L \cdot t \cdot \frac{f_t}{b} \cdot \sqrt{1 + \frac{\sigma_n}{f_t}} \quad (5)$$

where  $L$  is the length of the panel,  $t$  is the thickness of the masonry,  $f_t$  is the tensile strength of the masonry,  $b$  correction factor is evaluated as the ratio of the height to the length of the panel, and  $\sigma_n$  is the compressive stress on the panel. Considering the geometry of the panels and the mechanical properties of the materials, a tensile strength value of 27.9 kN is estimated. To evaluate the strengthening system contribution, Equation 4 was used. Considering two layers of reinforcement for each panel, one for each face, and using the same formulation in the case of CRM, the following values were estimated: 29.6 kN with G-FRCM, 193.5 kN with C-FRCM, and 59.1 kN with CRM. The equation proposed by the guidelines estimates the contribution of the reinforcement system taking into account the contribution of the fibre. Instead, as highlighted earlier, the matrix also intervenes in the overall response of the panel. There are no formulations proposed by the guidelines that take this contribution into account, but they can be found in the literature. In the present work, the analytical formulation proposed by Ferretti et al. (2021) is used. Specifically, the study takes into account the two contributions of masonry and matrix, and allows to estimate of the peak load according to the following equation:

$$P_1 = P_M + P_{mx} \quad (6)$$

where  $P_M$  is the contribution of the unreinforced masonry panel and  $P_{mx}$  is the contribution of the strengthening system matrix. The expressions for their evaluation are as follows:

$$P_M = \frac{f_{t,M} \cdot A_n}{0.5} \quad (7)$$

$$P_{mx} = \frac{f_{fl,m} \cdot A_{mx}}{0.5} \quad (8)$$

where  $f_{t,M}$  is the tensile strength of the masonry and  $f_{fl,m}$  is the flexural strength of the mortar.  $A_n$  is the cross-sectional area of the masonry panel, while  $A_{mx}$  is the cross-sectional area of the matrix calculated by multiplying the total thickness of the matrix by the width of the reinforcement surface. The two quantities, evaluated using Equations 7 and 8, allow to assess the contributions of the unreinforced masonry panel and reinforcing mortar to shear strength. The first contribution, evaluated using Equation 7, is estimated by considering the shear capacity offered by the URM panel when subjected to the diagonal compression test, which is a function of the estimated tensile strength of the masonry. Equation 8, on the other hand, estimates the contribution of the strengthening system's mortar, taking into account the cracking phenomenon and the fact that the tensile strength of the mortar is usually indirectly evaluated as 50% of the flexural strength. In the case of using the CRM system, the tensile strength value of the mortar was used in Equation 8 (D'Antino, 2019). The results obtained were reported in Table 4, together with the values estimated with the previous formulation and the values for unreinforced masonry panels. The table shows in the first column, the fibre contribution calculated by using Equation 4, in the second the panel strength calculated by using Equation 2, in the third the matrix contribution calculated by using Equation 8, and in the fourth the panel strength estimated by using Equation 6.

Table 4. Shear strength prediction for strengthened panels with an analytical approach.

SAMPLE	$V_{t,f}$ [kN]	$V_{t,R}$ [kN]	$P_{mx}$ [kN]	$P_1$ [kN]	Error $V_{t,R}$ [%]
G_FRCM	29.6	57.5	18.0	156.0	+173.6
C_FRCM	193.5	221.4	18.0	156.0	-29.5
G_CRM	59.1	87.0	27.0	165.0	+89.6

Looking at the table, the values obtained with the two analytical formulations are different from each other. In all cases, a higher contribution is obtained with respect to the shear capacity of the unreinforced panel. In particular, the minimum estimated increase is obtained with the first formulation, in the case of G\_FRCM, with a shear resistance value that doubles. The maximum increase in resistance is obtained in the case of C\_FRCM, estimated with the first formulation. Comparing, on the other hand, the results obtained with the two analytical formulations, it is possible to note the difference in the estimation of the shear resistance value. The last column of the table shows the percentage error evaluated with respect to  $V_{t,R}$  and it can be seen that the

difference is more than 25 %. Further considerations are postponed to a later elaboration, taking into account the experimental results obtained from the diagonal compression tests.

## 5 Conclusions

In the present work, the behaviour of reinforced masonry panels was investigated from an analytical point of view, and preliminary results of the planned experimental investigation were presented. The aim was to evaluate the effectiveness of different reinforcement systems and subsequently compare the analytical predictions with the experimental result. An experimental campaign involving 12 panels was planned, 9 of which were to be reinforced with FRCM and CRM. The masonry type was chosen to be representative of typical Sicilian historical buildings. For this reason, wide space was dedicated to the characterisation of the material during the experimental campaign. The results obtained allow the following conclusions to be drawn:

- The mechanical properties of calcarenite are widely variable, both for units taken from the same quarry and for units taken from different points of the Sicilian territory;
- The type of calcarenite stone taken into consideration is representative of historical masonry and, based on the analytical forecasts, allows for lower shear strength values than the average of the types of calcarenite present on the Sicilian territory;
- The reinforcement intervention could be effective in the consolidation of elements made with this type of calcarenite, as shear resistance contributions have been estimated that allow for a much greater capacity of the panel;
- Taking into account the equations used to estimate the capacity of the panels, it is possible to conclude that the most effective intervention could be the use of C\_FRCM or G\_CRM;

Further tests are necessary to express an opinion on the real effectiveness of the reinforcement system. Please refer to the conclusion of the laboratory tests for further comments and comparisons with the analytical prediction models.

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## 7 References

- ACI (2020). ACI- 549.6R. *Design and construction of externally bonded Fabric-Reinforced Cementitious Matrix (FRCM) systems for repair and strengthening concrete and masonry Structures*. American Concrete Institute.
- Bellini A., Bovo M., Mazzotti C. (2019). Experimental and numerical evaluation of fiber-matrix interface behaviour of different FRCM systems, *Composites Part B Eng.* 161: 411–426.
- Bellini A., Mazzotti C. (2020). Bond Behavior of FRCM Composites Applied on Concrete and Masonry, p. 347–59.
- Bellini A., Shahreza S.K., Mazzotti C. (2019). Cyclic bond behavior of FRCM composites applied on masonry substrate, *Composites Part B Eng.* 169: 189–199.
- Ceci A.M., Contento A., Fanale L., Galeota D., Gattulli V., Lepidi M. (2010). Structural performance of the historic and modern buildings of the University of L'Aquila during the seismic events of April 2009, *Engineering Structure*, 32:1899–1924.
- CNR. CNR-DT 215 (2018). *Istruzioni per la Progettazione, l'Esecuzione ed il Controllo di Interventi di Consolidamento Statico mediante l'utilizzo di Compositi Fibrorinforzati a Matrice Inorganica (in Italian)*. National Research Council
- Colajanni P., Cucchiara C., D'Anna J., Pennisi S., Pagnotta S. (2023). Vulnerability and Seismic Exposure of Residential Building Stock in the Historic Center of Alcamo. *Applied Science*, 13:7092.
- D'Antino T., Carozzi F.G., Poggi, C. (2019). Diagonal shear behavior of historic walls strengthened with composite reinforced mortar (CRM). *Materials and Structures*, 52:114.

- Del Zoppo M., Di Ludovico M., Prota A. (2019), Analysis of FRCM and CRM parameters for the in-plane shear strengthening of different URM types, *Composites Part B: Engineering*, Volume 171, 2019, Pages 20-33,
- UNI (2011) EN 772-1. *Methods of test for masonry units - Part 1: Determination of compressive strength*.
- UNI (2006) EN 1015-11:1999/A1. *Methods of test for mortar for masonry - Part 11: Determination of flexural and compressive strength of hardened mortar*.
- Ferretti F., Khatiwada S., Incerti A., Giacomini G., Tomaro F., De Martino V., Mazzotti C. (2023). Structural strengthening of masonry elements by reinforced repointing combined with FRCM and CRM, *Procedia Structural Integrity*, Volume 44, Pages 2254-2261.
- Ferretti F., Mazzotti C. (2021), FRCM/SRG strengthened masonry in diagonal compression: experimental results and analytical approach proposal, *Construction and Building Materials*, Volume 283, 122766.
- Greco A., Lombardo G., Pantò B., Famà A. (2020). Seismic Vulnerability of Historical Masonry Aggregate Buildings in Oriental Sicily, *International Journal of Architectural Heritage*, 14:4, 517-540.
- Incerti A., Vasiliu A., Ferracuti B., Mazzotti C. (2015), Uni-Axial compressive tests on masonry columns confined by FRP and FRCM, *Proceedings of the 12th FRPRCS and 5th APFIS Conference*, Nanjing, China.
- Lagomarsino S. (2006), On the vulnerability assessment of monumental buildings, *Bulletin Earthquake Engineering*, 4 :445–463.
- CSLLPP (2019). *Linea Guida per la identificazione, la qualificazione e il controllo di accettazione dei sistemi a rete preformata in materiali compositi fibrorinforzati a matrice polimerica da utilizzarsi per il consolidamento strutturale di costruzioni esistenti con la tecnica dell'intonaco armato CRM (Composite Reinforced Mortar)* (in Italian).
- NTC (2018), D.M. 17 gennaio 2018, *Aggiornamento delle Norme tecniche per le costruzioni, ministro delle infrastrutture e dei trasporti*.
- Tilocca A.R., Incerti A., Bellini A., Savoia M. (2019). Influence of Matrix Properties on FRCM-CRM Strengthening Systems. KEM
- Valluzzi, M.R. (2007). On the vulnerability of historical masonry structures: analysis and mitigation. *Material Structure*, 40: 723–743.
- Valluzzi, M.R. (2016). *Challenges and perspectives for the protection of masonry structures in historic centers: the role of innovative materials and techniques*, RILEM Tech Lett 1 45.
- Zimbaro M., Nocilla N., Evangelista A., Ramondini M., Scotto di Santolo A.(2011). Destructuration of typical Sicilian calcarenites, *Bulletin of Engineering Geology and the Environment*, 70 (3):507–515.