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IN-PLANE SHEAR RESPONSE OF FRCM-STRENGHTENED MASONRY WALLS

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Abstract. This paper aims at investigating the in-plane shear response of FRCM-strengthened masonry walls. To this end, available results of experimental tests are collected, accounting for the masonry substrate made with bricks and mortar joints and several FRCM materials applied with different strengthening configurations. The contribution of the composite material to the masonry wall shear capacity is evaluated. The influence of some geometrical and mechanical parameters on the shear strength of the retrofitted walls is assessed. Available analytical design formulations are implemented to the database and commented.

1 INTRODUCTION

Within the framework of seismic risk mitigation of existing masonry structures, the beneficial feasibility of the strengthening system is a key topic. In the last decades, the use of fiber-reinforced composites has gained attention from the scientific community as the most innovative technique for the structural rehabilitation. In particular, this work focus on the inorganic mortar-based materials, named with 'FRCM' acronym (Fiber Reinforced Cementitious Matrix), where the fibrous reinforcement is fully embedded in the matrix [1].

Advantageous and drawbacks have been deeply discussed in literature. The ease of application represents one of the most attractive positive aspect, only based on laying mortar layers and textile grid alternatively [2]. Although made with a small thickness attested around 10 mm, this FRCM system can guarantee both good mechanical performances and compatibility with masonry surfaces, without modifying the original geometry, stiffness and mass. Indeed, the load-carrying capacity of structural members is improved clearly, also preserving the existing masonry substrate thanks to the good vapor permeability of the mortar, its applicability on wet surfaces and its reversibility. The textile grids under investigation could comprise steel, polyparaphenyle benzobisoxazole (PBO), carbon, AR-Glass, basalt, aramid, or natural fibers. Thus, these reinforcements are combined with inorganic mortar lime or cement-based matrices.

The typical tensile response of FRCM coupons is influenced by different mechanical mechanisms. During the tension loading, the mortar cracking and the slippage of the fibrous grid within the matrix occur in the composite. These nonlinear mechanisms determine, in their turns, a nonlinear constitutive law in tension, characterized by three specific stages: the cracking of the mortar, the slippage of the fibers and the last stage wherein the tensile load is carried out only by the internal reinforcement. As explained in [3] the tensile response is governed by the tension stiffening phenomenon that leads to the stress redistribution along the members after the first cracking stage, due to the propagation of the crack along the FRCM material and the consequent stress transmission between the mortar and the reinforcement trough the shear stress. Many efforts have been done by different authors in order to suggest numerical modeling approaches for reproducing the tensile response of FRCMs, both at the micro-scale [4,5] or macro-scale [6]. Regarding the application on masonry surfaces, the FRCM-to-substrate bond analysis represents a crucial point to discuss. Experimental evidence shows that, differently from the most known polymeric composites, such as FRPs, the most common typical failure mode concerns the slippage of the textile grid within the mortar, with or without the cracking or the detachment of the outer mortar layer, and the breakage of the fibers in tension. The cohesive failure that involves the substrate generally does not happen [7–9].

Analytical theoretical design formulations for evaluating the in-plane shear capacity of FRCM-strengthened walls have been proposed [10,11]. Nevertheless, more refined and accurate models based on numerical approaches can be found in literature. The most of the suggested models are based on macro-modelling approaches and different FEM codes are utilized. The masonry element is modeled in different ways. For instance, in [12] the masonry is simulated to behave as an equivalent homogenized non-linear orthotropic softening material. In [13–15] the smeared crack approach for the homogenized masonry element is used. A discrete element approach that foresees the simulation of the blocks and mortar joints is taken into account in [16–18]. The FRCM material is modeled as a homogenized material [15,17], or by simulating the single constituents with specific constitutive laws [12–14,16,18]. In all the models, the perfect bond between the textile and the mortar is assumed, except in [18], where an interface element is inserted between the constituents. In order to take into account the shear-bond failure mode that occurs within the composite, in [14] the mortar tensile strength is reduced to the axial bond strength. Finally, all the models simulate the perfect bond between the substrate and the composite by means of homogenized elements or mortar elements. Only in [17] an interface element is considered.

The shear response of FRCM-masonry walls and the reliability of the suggested numerical models need to be studied and validated through experimental campaigns on real-scale specimens. In this context, several experimental tests have been carried out in order to assess the effective shear response improving the retrofitted masonry walls, in terms of both strength and ductility. Nevertheless, the variability of the experimental data and results depending on different test set-ups and different specimen typology appears rather large [19]. Thus, final goal of this paper is to assess the influence of the mechanical and geometrical properties of the FRCM and masonry materials on the in-plane shear capacity of retrofitted walls. Therefore, a large database of 157 experimental tests on FRCM-masonry systems is collected and critically analyzed.

2 EXPERIMENTAL DATABASE

In order to assess the response of FRCM-strengthened masonry walls subjected to in-plane actions, a wide database of available experimental results is collected. The database refers to 157 experimental data reported and described into 25 works published between 2011 and 2022, taking into account only the specimens made with clay brick masonry substrate. The data concern specimens tested under different set-up typology, designed with several geometry and made with different combination of constituents. The specimens are strengthened on only one surface or on both the surfaces, and the FRCM strengthening configuration could be continuous or discrete on the wall surfaces (Fig. 1). The performed test set-ups adopted to reproduce the shear response of masonry walls are the diagonal compression test (Fig. 2,a-b) and the shear-compression test (Fig. 2,c). The first one foresees the application of an increasing compression load parallel to the diagonal of the wall, imposing a pure shear stress condition at the center of the specimen. The second test-set up is based on the application of a constant compression load on the top side of the wall combining with an increasing lateral force. This latter set-up simulates better the effective in-plane behavior due to the seismic action, on the other hand this kind of test is more difficult to realize with respect to the diagonal compression test. For this reason, most of the results refer to the diagonal compression test set-up.

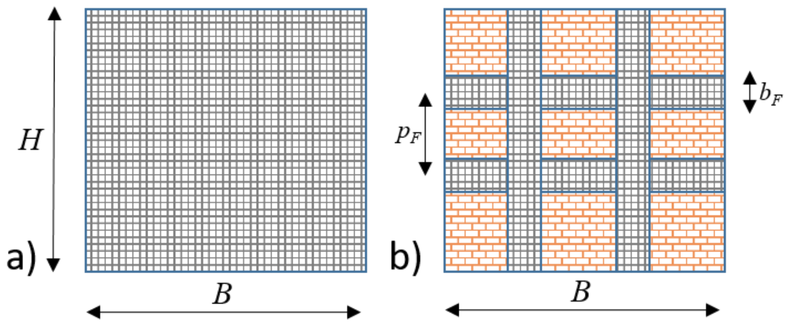

Figure 1: Geometrical features of the walls strengthened with a) continuous configuration, b) discrete configuration.

The database is divided into homogeneous families, labelled with a specific name AXB-C. The first subdivision concerns the adopted test set-up, with A=D and A=S for diagonal compression test [14,16,20–37] or shear-compression test [38–42], respectively. Furthermore, each data family is subdivided depending on the FRCM configuration: X=1 or X=2 depending on the number of the strengthened surfaces, B=C and B=D for continuous retrofitting on the wall surfaces and for discrete configuration with FRCM strips, respectively. The letter C is set equal to the letter A if the anchorages are present.

For each data family the occurrence of the different fibrous type inside the composite is assessed. In Fig. 3 each pie chart refers to a single data family and the corresponding numerosity within brackets is reported. Along the first row the walls retrofitted only in one side and along the second row the walls retrofitted in both sides are reported, respectively. While the first three columns refer to walls tested by diagonal compression tests and the last two columns represent the amount of walls tested by shear-compression tests. The 86% of walls are tested with diagonal compression set-up. Regarding the type of fibers, the specimens made with continuous

FRCM configuration, both tested with diagonal compression test (D1C, D2C) or shear-compression test (S2C), are mainly made with carbon, AR-glass or basalt fibers, while the steel grid is used for the strengthening with strip composite configuration (D1D, D2D, S1D, S2D). Nevertheless, very few are the data of specimens tested with the shear-compression test made with the discrete FRCM configuration (S1D and S2D).

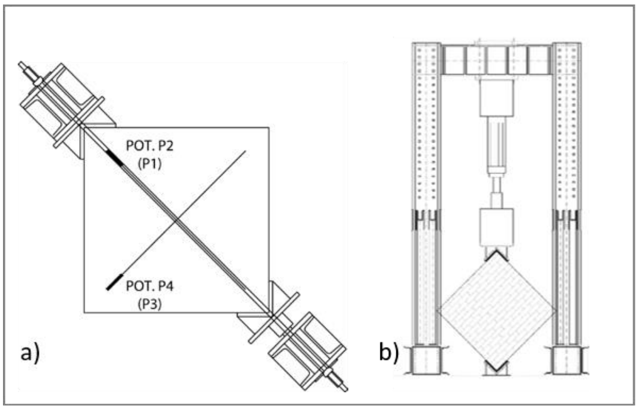

Figure 2: Sketch of a)-b) diagonal compression test set-up; c) shear-compression test set-up.

The geometrical parameters of the FRCM-masonry specimens as represented in Fig. 2 and the range of their variability in the database for each family is listed in Table 1. The specimen dimensions *B* and *H* and the slenderness ratio *H/B* are specified. As it emerges from the data, the specimens subjected to diagonal compression tests are squared according to the standard ASTM E519-07 [43], while different geometries are taken into account for the S2C class. The FRCM thickness is about 6-10 mm for the most of the specimens.

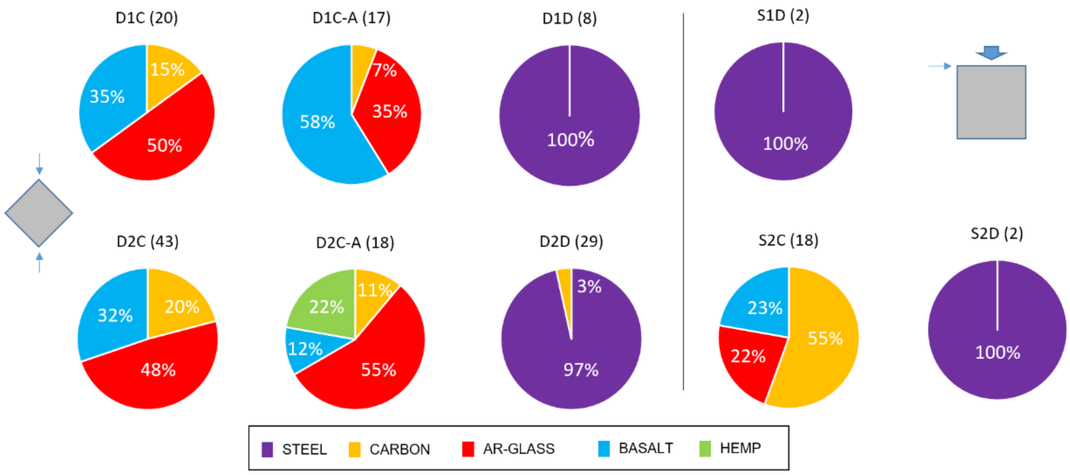

Figure 3: Occurrence of the fibrous material type for each data family.

Table 1: Variability of the geometrical parameters for each data family.

	B [mm]	H [mm]	H/B [-]	b_F [mm]	p_F [mm]
D1C (20)	520-1200	530-1280	1-1.02	-	-
D1C-A (17)	650-1280	650-1280	1	-	-
D2C (43)	520-1280	530-1280	1-1.02	-	-
D2C-A (18)	650-1200	650-1200	0.97-1	-	-
D1D (8)	515-1205	510-1210	0.98-1	50-150	180-500
D2D (29)	515-1270	510-1270	0.98-1	25-100	180-300
S2C (18)	400-3000	400-2000	0.3-3.33	-	-
S1D (2)	1270	1270	1	150	250
S2D (2)	1270	1270	1	150	250

2.1 Experimental Shear Capacity

The results in terms of shear capacity (i.e. the maximum achieved shear load) of the strengthened walls are herein commented. In detail, the experimental results for each datum include the shear capacity of the retrofitted wall $V_{t,R}$ and the corresponding shear capacity of the unstrengthen masonry wall V_t. In Fig. 4, the comparison between these quantities are reported in order to evaluate the enhancement of the FRCM retrofit on the wall shear capacity. As it emerges in Figure 4, considering the specimens made with the continuous FRCM configuration and tested with the diagonal compression set-up (D1C, D1C-A, D2C and D2C-A) the tendency line is almost parallel to the bisector line. This it means that the increase of the shear capacity is almost the same for all the data independently from the shear capacity of the corresponding control wall. This remark is not true for the specimens made with the discrete FRCM configuration and tested with the diagonal compression set-up (D1D and D2D) or for the walls retrofitted with a discrete FRCM configuration and tested with the shear-compression set-up (S2C). In these last cases, indeed, higher the shear strength of the unstrengthen wall, greater the shear capacity of the retrofitted walls. Nevertheless, it is worth to underline that for the D1D and D2D families, this effect could depend by the textile constituent made with steel fibers. Because of the exiguity of the results for the S1D and S2D families, the data are not reported. Comparing the results of the specimens with or without the anchorages presence, the graphs in Fig. 4 show that the anchorages do not provide a great enhancement of the shear capacity. As general result, the FRCM composite determines an average shear capacity increasing about 66.4% for both the D1C and D1C-A classes, about 127% and 115% if the strengthened surfaces are doubled (D2C and D2C-A classes, respectively). The discrete strengthening configuration leads to a lower increasing, about 51% and 75% for the D1D and D2D classes, respectively and about 92% for the S2C family.

The contribution of the FRCM composite on the shear capacity of the strengthened wall is computed as the difference between the shear capacity of the strengthened wall $V_{t,R}$ and that of the unstrengthen wall V_t, as:

$$V_{t,f} = V_{t,R} - V_t \tag{1}$$

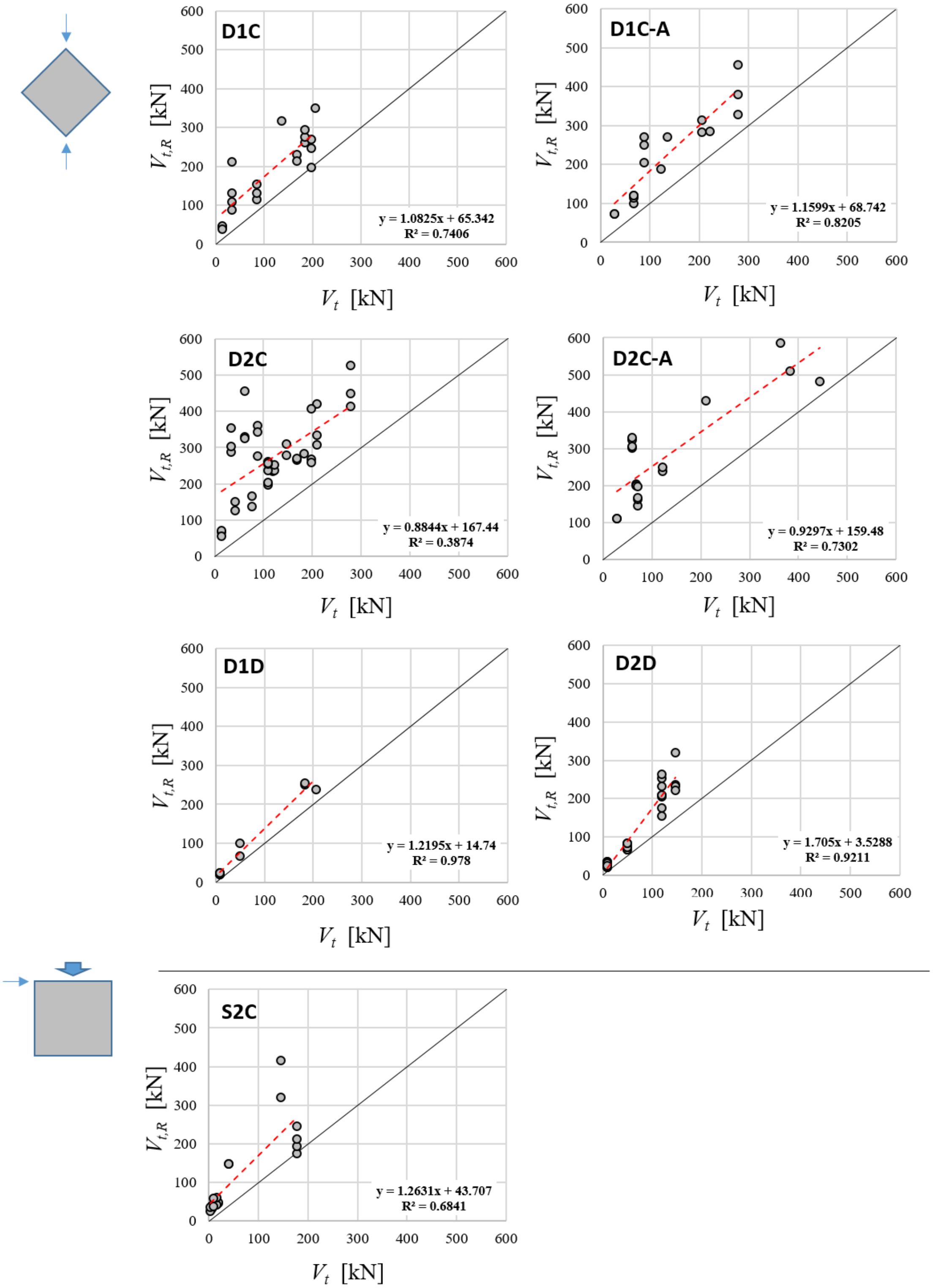

Figure 4: Comparisons between the experimental shear capacity of the strengthened walls and the unstrengthen walls, for each data family.

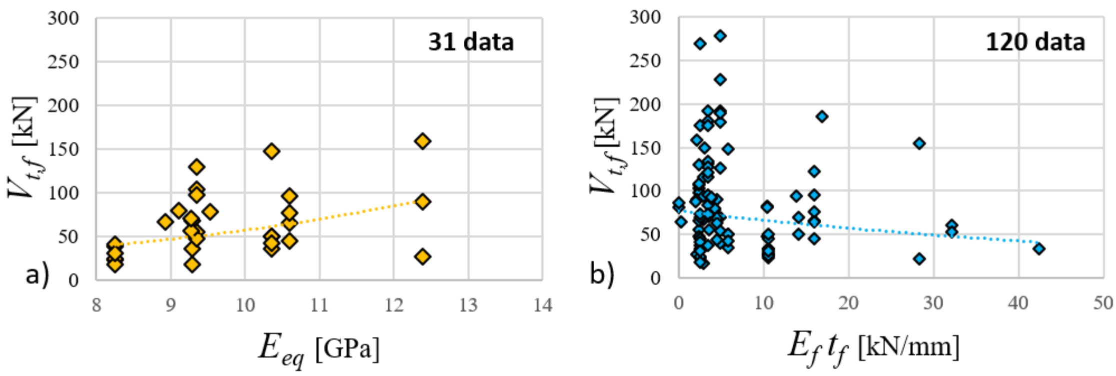

Figure 5: Correlation between the shear strength contribution of the FRCM with mechanical parameters: a) equivalent FRCM stiffness, b) fiber elastic modulus, c) mortar elastic stiffness.

In order to analyze the relationship between FRCM shear contribution and mechanical properties of FRCM, two mechanical properties have been considered: i) equivalent stiffness E_{eq}, ii) textile axial stiffness $E_f\, t_f$. The equivalent stiffness E_{eq} is calculated as:

$$E_{eq} = \frac{E_m \cdot t_m + E_f \cdot t_f}{t_m} \tag{2}$$

where E_m and E_f are the elastic moduli of the mortar and of the fibers, respectively, t_m and t_f are the mortar thickness and the textile equivalent thickness, respectively.
The FRCM shear contribution versus the equivalent stiffness of the strengthening material is reported in Fig. 5,a, while in Fig. 5,b the dependence of the FRCM strength contribution on the textile axial stiffness is also evaluated. Unfortunately, not many authors report the mortar Young modulus, therefore only 30 data are considered. Instead, the great part of the collected experimental data contains information about the fiber mechanical and geometrical properties (120 data).
The contribution of the shear capacity is proportional to the equivalent composite stiffness, while it decreases with the fiber axial stiffness.

2.2 Analytical formulations

Predictive design formulations for evaluating the shear capacity of the FRCM-strengthened walls are available, such as those proposed in ACI549.4R [10] and in the Italian guidelines CNR-DT215 [11]. In both the analytical approaches, the shear strength of the retrofitted wall is entrusted to the shear capacity of the unstrengthen masonry wall added to the contribution of the composite material (see eq. (1)). This latter is analytically computed as:

$$V_{t,f} = A_{f,v} \cdot E_f \cdot \bar{\varepsilon} \tag{3}$$

with $A_{f,v}$ the area of the mesh reinforcement effective in shear ($A_{f,v} = \alpha \cdot n_s \cdot n_l \cdot L$, with α=0.75 [10] or 0.8 [11], n_s the number of reinforced wall surfaces, n_l the number of textile layers for each side, L is the FRCM width) and $\bar{\varepsilon}$ a conventional strain. In [10] this latter coincides with the ultimate tensile strain of the textile, limited by 0.004. In [11] it derives from the shear-bond tests performed on FRCM-masonry systems. In detail, this is the tensile strain corresponding to a textile stress level identified with the maximum stress achieved during the shear-bond test, as schematically represented in Fig. 6,a. However its value is limited with the ultimate tensile strain. The theoretical value of the shear strength is reduced of the 30% if the specimen is strengthened on only one side. Of course, for applying such design formulation, the suppliers must provide the results of shear-bond tests.

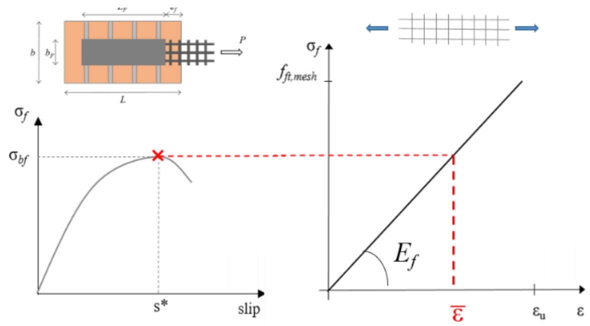

Figure 6: Definition of the conventional strain according to the guideline CNR-DT215.

The evaluation of the reliability of the provisional formulation by comparing the CNR-DT 215 theoretical results with the collected experimental data is only partially possible because of the lack of information about the conventional strain for FRCM used in diagonal compression test or shear compression test. For the sake of consistency, it is important to underline that the authors have taken into account only the data for which the bond stress level was experimentally evaluated, published and included in the same document, decreasing the numerosity just to 23 data. On the contrary, considering the ACI549.4R formulation, the numerosity of the available textile ultimate tensile strain is higher, increasing the data to take into account to 99 data. It is worth underlining that, in this latter case, the tensile strain is for all the cases lower than the threshold value equal to $\bar{\varepsilon}$=0.004.

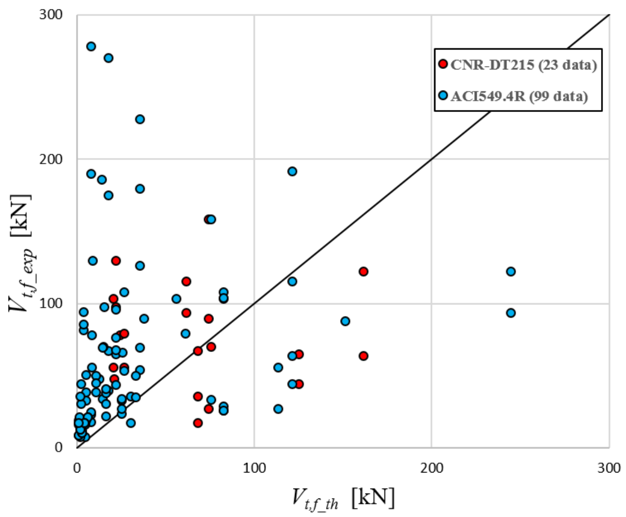

Figure 7: Comparison between the theoretical and experimental shear strength due to the FRCM contribution.

A first comparison between the experimental results V_{t,f_exp} and the theoretical ones V_{t,f_th} obtained with both the methods is reported in Fig. 7. From the comparison, it emerges that it is necessary to increase the number of data in order to better estimate how the mechanical response of the FRCM material influences the shear capacity of the strengthened walls and to suggest a more reliable theoretical formulation. Analytical approaches can be considered such as that illustrated in [3], where a tensile uniaxial constitutive law for the FRCM material, based on the mechanical and geometrical parameters of the composite, is drawn along with numerical models.

4 CONCLUSIONS

- In this paper a large database (157 data) of available results of in-plane shear tests on FRCM-masonry walls is collected, referring to different test set-ups and several FRCM materials. Homogeneous classes are defined from the database analysis.
- The contribution of the FRCM composite on the shear capacity of the strengthened walls is investigated. The application of the FRCM material on both the wall surfaces doubles the average shear capacity in case of specimens with continuous FRCM configuration. In case of FRCM applied in the way of strips (discrete configuration), the recorded increase of the shear capacity is lower and does not appear proportional to the number of the retrofitted wall surfaces.
- Two available design formulations are commented and applied to the database, comparing the theoretical with the numerical results, in terms of the shear strength due to the FRCM reinforcement. The lack of data concerning the bond stress deriving from shear-bond tests on FRCM-masonry systems leads to a not effective study of the reliability of the CNR-DT 215 formulation. The theoretical-experimental comparison, performed with the limited available data, showed a great difference between experimental and theoretical formulations. Hence it is clear the need to determine novel efficient approach for assessing the FRCM contribution by means of analytical and numerical approaches.

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