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DEFENCE OF ARCHITECTURAL HERITAGE: EXPERIMENTAL CAMPAIGN ON MASONRIES REINFORCED WITH NATURAL FRCM COMPOSITE MATERIALS

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Abstract. *In this contribution are reported the first results of an experimental campaign conceived to evaluate the performance of FRCM (Fiber Reinforced Cementitious Matrix) composite materials for the recovery and restoration field of heritage buildings. With reference to the risks of seismic collapse concerning ancient masonry buildings, the peculiar structural behaviour of "in falso" walls, a typology of load-bearing masonries built without a direct load path to the foundations, has been examined. The tests have been conducted, through an experimental set-up specially designed, on two rectangular walls characterized by the same basic traits: the first one in unreinforced masonry, the second presenting a non-canonical "truss-like" application of bands of composites. Alongside the progression of the experimental campaign - delayed due to the COVID outbreak - that in the near future will engage other two masonry panels enhanced by different applications of the FRCM, the creation of a FEM will be achieved gathering data from the new tests in order to replicate the complex mechanical behaviour of the FRCM composites with reference to the skills and time required for different installation modalities.*

Keywords: Heritage, FRCM, Retrofit, Composite Materials, Masonry.

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1 INTRODUCTION

For any country, the conservation of heritage buildings is a primary goal: it is a reflection of the society and a basic tool to transfer its cultural and educational values. These purposes require an inclusive and interdisciplinary approach to masonry structures'reinforcement that involves, among the others, structural engineering, non-destructive techniques of survey, numerical modelling and architectural design [1, 3, 4]. In this regard, as part of an ongoing research, a peculiar focus is dedicated to the study of the mechanical behaviour of natural FRCM composite materials in the field of the innovative strengthening techniques, since they are compatible with the architectural value of historic surfaces and are, to a large extent, reversible, biodegradable and eco-friendly; however, their numerical modelling represents a complex task, due to the interactions between fibers, matrix and masonry. Moreover, a previous experience, that covered the seismic assessment and the restoration plan of an architectural complex designed by Luigi Vanvitelli, pointed out a recurrent feature affecting the structural safety of Italian heritage architectures: the presence of "in falso" walls, consisting of load bearing walls built without a direct load path to the ground and standing on top of masonry vaults [2, 5]. That occurrence, in case of seismic action, could trigger a "domino effect", due to the possible collapse of underlying masonry vaults, then compromising the safety of the entire heritage structure. However, it should be noted that the investigation for the mechanical behaviour of the such walls, that struggle to perform like masonry beam structures, is not adequately investigated by the scientific literature. In order to improve the knowledge about such topic and to investigate new applications of FRCM technology, an experimental campaign has been started in partnership with a company, the Kimia S.p.a., to evaluate the effectiveness of composites regarding the prevention of in-plane collapses described above.

2 THE EXPERIMENTAL CAMPAIGN

2.1 The setup implementation: an experimental test designed "ad hoc"

The FRCM systems represent an innovative class of fiber-reinforced composites, which are becoming broadly used concerning heritage constructions. The key feature of this emergent technology is the replacement of the classical polymeric matrix with an inorganic one, making them particularly effective in retrofitting of historical masonries given their chemical, physical, and mechanical compatibility to the ancient substrates. Such new-gen. methodologies allow to fulfil the strengthening and the architectural reconfiguration of historical masonry buildings in compliance with the cultural and social context. On this, the benefits of FRCM materials are the following:

- Good mechanical properties in the face of low thickness and little weight;
- Easy installation modalities ensuring the continuity of the building's activities;
- Use of inorganic mortar (less aggressive than the epoxy resins) that is useful in order to apply first aid enhancements whilst and at the same time permits a better transpiration to masonry;
- Chance to recycle, considering the natural origin of nets and the matrix characteristics.

Several experimental investigations have been carried out so far - during previous experiences - both at the scale of the composite material and of the single components, reaching an adequate level of experimental mechanical characterization of the materials used for the campaign in question; for further details refer to such data [6]. Even so, in this contribution the beneficial effects of composites on walls subjected to gravity loads and earthquake actions in peculiar conditions are highlighted, also with reference to the installation modalities. Indeed, the outcomes deriving from an experimental test on an ordinary masonry wall and another one retrofitted according to non-canonical criteria are compared. In order to evaluate the influence of FRCM in the prevention of knock-on collapses a specific experimental set-up has been conceived, and realized, to engage life-sized masonry walls with action similar to the ones ascribed in case of collapse of the below vaults on which they rest: masonry panels inferiorly suspended, except for lateral supports of reduced length, Figure 1. Therefore, with the aim of bringing a single brick wall to failure, a steel contrast portal has been designed - and realized - to make a self-balanced closed system.

2.2 Preparation of the specimens

The masonry specimens are walls of the dimensions 2.4m wide for 1.2m high, made of a single wythe of solid bricks, of dimensions 12x24x5.5 (respectively thickness, width and height), and recalling the wall's dimensions provided by the Italian Building Code for the shear verification [7]. Concerning the materials'features of the walls, solid bricks and lime mortar were used and with reference to the latter a "shoddy" lime inorganic mortar (M 2.5) with poor mechanical properties was created from the company in order to simulate the structural behaviour of a historical masonry.

Concerning the composite materials, the fiber net *Kimitech BS ST 200* and the matrix *MALTA M15/F* have been used. In particular, has been used a bidirectional basaltic fiber net characterized by a size of the square knitting interaxle spacing of 20mm between the strands (of 4mm wide). The matrix is a lime inorganic mortar with maximum 1.20 mm particle size distribution. The samples'preparation, concerning the application of the composites, required:

- the cleaning of the surface of the masonry substrate and its saturation and wetting (condition s.s.a.);
- application of a first layer of mortar Basic MALTA M15/F;
- positioning of the fiber net Kimitech BS ST 200;
- application of a second layer of mortar Basic MALTA M15/F.

As mentioned so far regarding the reinforced wall, for this non-conventional reinforcement a specific intervention was designed - since generally this type of composite material is applied evenly on the wall's surface - devising the application of FRCM bands each 20cm wide, a measure that represents a multiple of one meter, the dimension with which the meshes in basaltic fiber are produced [8].

The goal was to reinforce the weakest areas of the wall thus using less composite material than ins the classic applications: the diagonals subject to traction, two shorter diagonals parallel to the main ones but placed below, the lower band of the masonry panel and, moreover, three vertical bands useful for maintaining adhered to the wall the ends of the other strips of composite material. The reinforcement intervention was applied with the same criteria on both sides of the wall. After the curing period exceeding 56 days - 28 days for the walls plus the same duration for the FRCM - the experimental tests were performed. All the material's mechanical features are available in the aforementioned contribution [6].

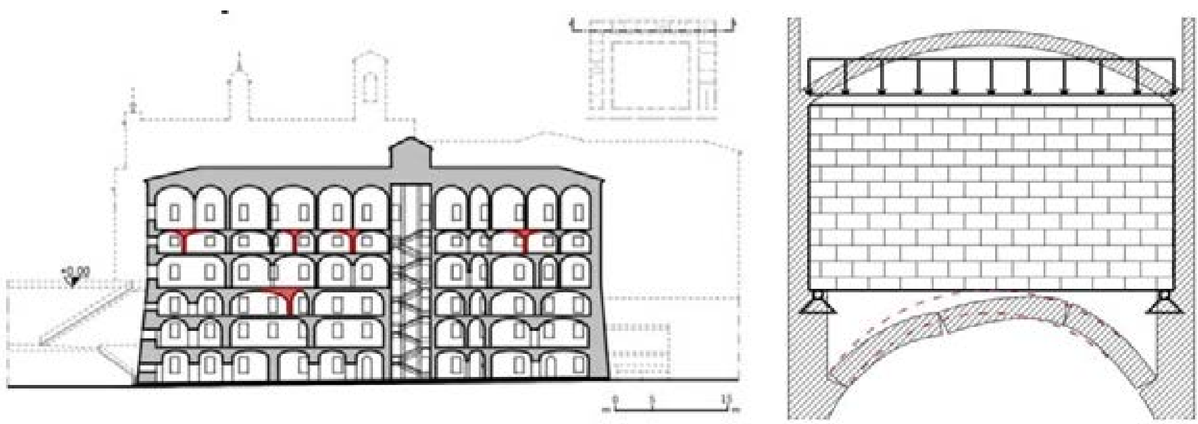

Figure 1: On the right, the “in falso” walls of Palazzo Murena. On the left, a schematization of the walls in the vault’s collapse scenario.

2.3 Boundary conditions and acquisition systems

In the scientific literature there are several references to experimental tests, both codified and innovative ones for these materials, but there is no one similar to the one presented in such contribution [9, 10]. The specimens were built directly on top of steel temporary supports, designed with a dual function: the first reason to facilitate their movement on the portal-shaped steel frame, the other to prop-up the walls themselves until the beginning of the test; in both cases without causing damages or deformations to the samples. Thanks to a forklift it was possible to remove the support - separated from the rest thanks to plastic sheets - and begin the test with the walls, already equipped with sensors, resting only on the remaining permanent lateral supports (Figures 2 and 3); such constraint condition is addressing the described above damage scenario (Figure 1). Concerning the load conditions, the load was applied gradually by means of a hydraulic jack placed on the top of a load cell. About the modalities, force distribution steel beams were used to create a load concentrated in two points, by means of two steel plates, similar to an equivalent distributed load. Moreover, an active sensor system has been implemented. A total of 8 Linear Variable Displacement Transducer (LVDT) sensors was installed on the wall - 4 for each side - as indicated in Figure 4. The measured lengths waere extended by means of diagonal support rods anchored to the specimens through rocker like constraints. Those sensors along with the load cell, aimed at measure the applied load, were connected to an acquisition system.

3 THE TWO EXPERIMENTAL TESTS

In this Section will be discussed, and finally compared, the results of the aforementioned first two tests, in the order: ordinary masonry and masonry reinforced on both faces with a truss-like application of FRCM designed to reinforce the diagonals subjected to tension and other significant parts [11].

3.1 Experimental test on the ordinary wall

Both tests lasted less than 15 minutes. The breakage, as can be seen in Figure 3, occurred due to the separation and breakage of the mortar joints. In test led to breaking the masonry sample with the damages starting at a load of about 40KN.

As far as possible, the load was applied gradually with the hydraulic jack by controlling the load cell connected to the acquisition system.

Due to the structural relaxation, even before the removal of the sensor's support rods, a further collapse and the effective damage pattern came forward. From the critical interpretation of this latter, a "arched" stress redistribution mechanism is observable, comparable to the one to which are subject the weakly reinforced concrete beams, Figure 3. Moreover, concerning the data acquisitions, it is observable that the sensors sg2 with sg6 and sg3 with sg7 record consistently even if, however they mate on opposite faces, not all manifest the same trend. For example, it is noted that, possibly due to a manufacturing defects on the wall, the sensors sg1 and sg4 were in traction (negative sign on the acquisitions), Figures 4 and 5, perhaps implies a flexural behaviour out of plane of the wall. Considering that is an innovative and non-codified type of test, such results have been used as a basis for the subsequent test which, except for the application of the composite materials, in every part has been analogous to this one. The purpose is to evaluate, by comparison, the influence of FRCM on the structural behaviour due to seismic damages to the vaulted underlying masonry elements. Therefore, the same procedure will always be respected also in the future tests, also in terms of points of view for the photos.

Figure 2: On the right starting with the top row, the ordinary wall ready to be moved, handling of the same and the subsequent removal of the steel support, zoom on one of the two remaining supports. On the left, masonry wall reinforced with truss-like application of FRCM at the start of the test, all components of the setup.

3.2 Experimental test on the wall reinforced with FRCM

In this case it was possible to witness a peculiar collapse phenomenon which manifested itself first with partial lesions on the composite reinforcements and then led to the collapse through the breaking of bricks (and not by the separation of the courses, as seen in the first test). Moreover, were necessary about 140KN to break this wall, compared to the 40KN needed to breach the unreinforced one in the very first test.

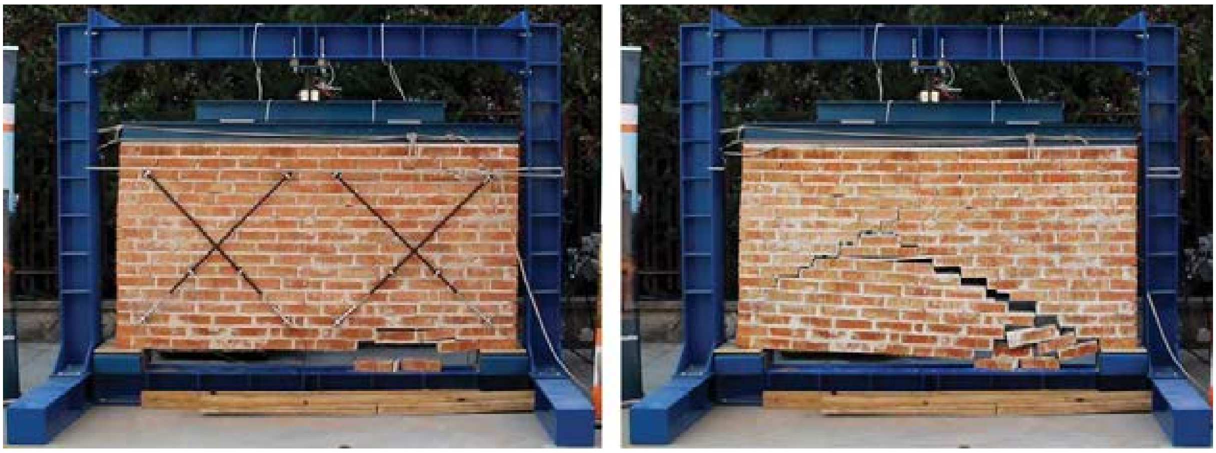

Figure 3: On the right, tearing of the wall at the end of the test. On the left, photo of the experimental setup at few minutes later the completion of the test.

Although the beginning of a fracture in the lower left reinforcement band has been observed during the test, the presence of the vertical strip in composite probably led to an asymmetry in the damage pattern of the wall that has collapsed because of a large crack located on the right side of the wall, that evidently was weaker (Figure 6). It is observed how the instruments that match each other on the opposite faces of the reinforced wall (sg1-sg5, sg2-sg6, sg3-sg7, sg4-sg8) seem to acquire data consistently and in parallel. In particular the diagonals with sensors sg1, sg4, sg5 and sg8 worked at traction, Figure 7. From the previous and further data processing (Figure 8) it is clear that during such test the expected behaviour of the diagonals, in terms of displacements related to compressive and tensile deformations, was confirmed. Among the readings of the instruments, the one of inferior quality this time concerned only that of the sensor marked as sg1. For purposes of comparison, the averages of the sensor readings with positions sg3 and sg7 (Figures 5 and 8) were plotted in relation to the applied load path, which in the authors'opinion represent reliable measurements in both the experimental tests, Figure 9.

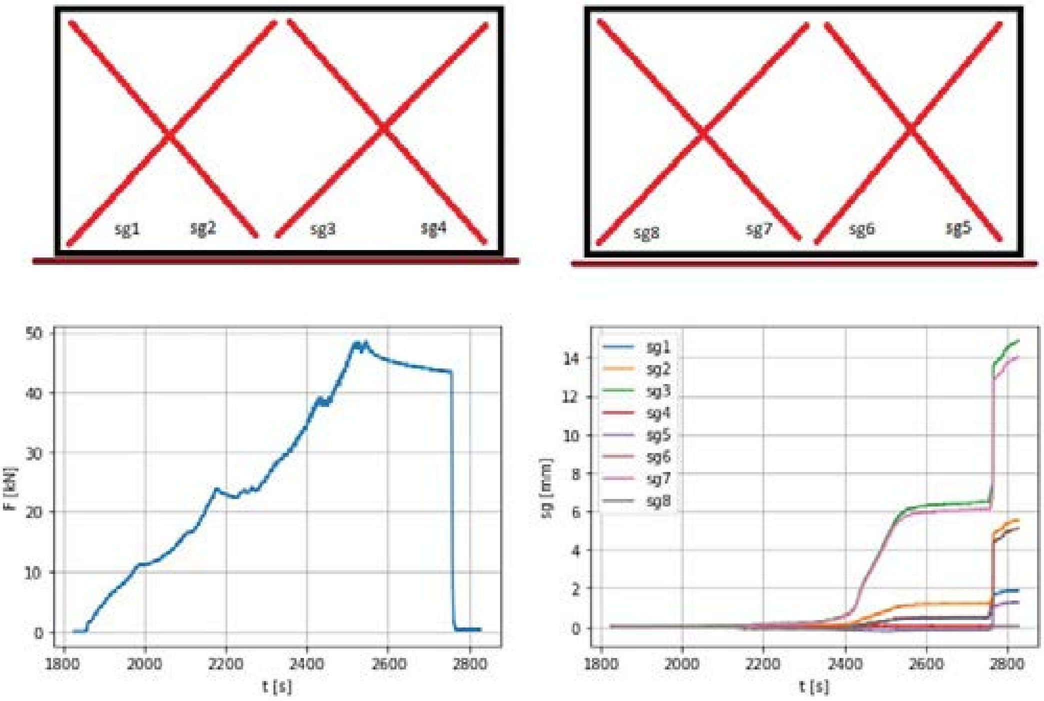

Figure 4: On the top the positions of the sensors on the wall (the picture on the right presents the same point of view of the photos reported in Figure 3). Below, respectively the force and displacement diagrams against time.

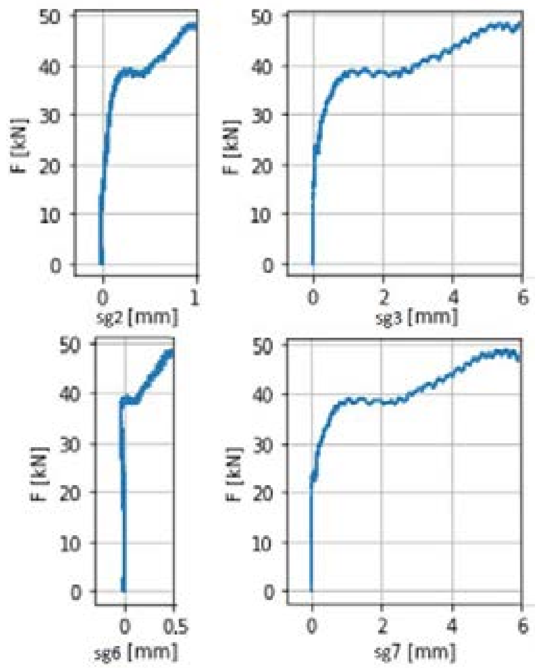

Figure 5: For the sensors subjected to tension, force-displacement graphs for collapse incipient.

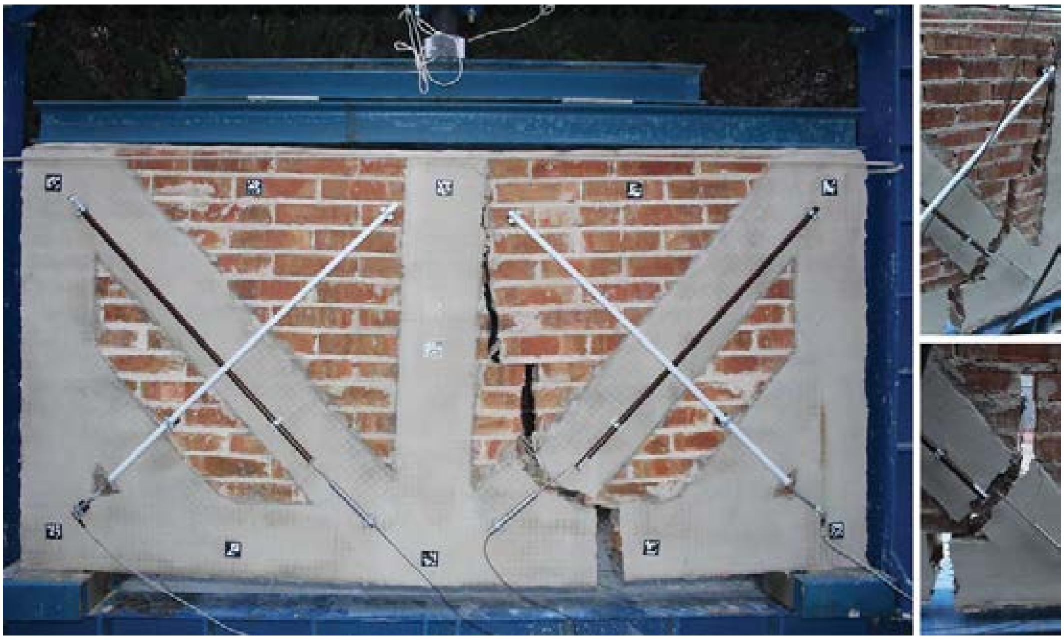

Figure 6: On the right, tearing of the wall at the end of the test. On the left, two closer photos of the crack taken on the opposite face than the previous photo.

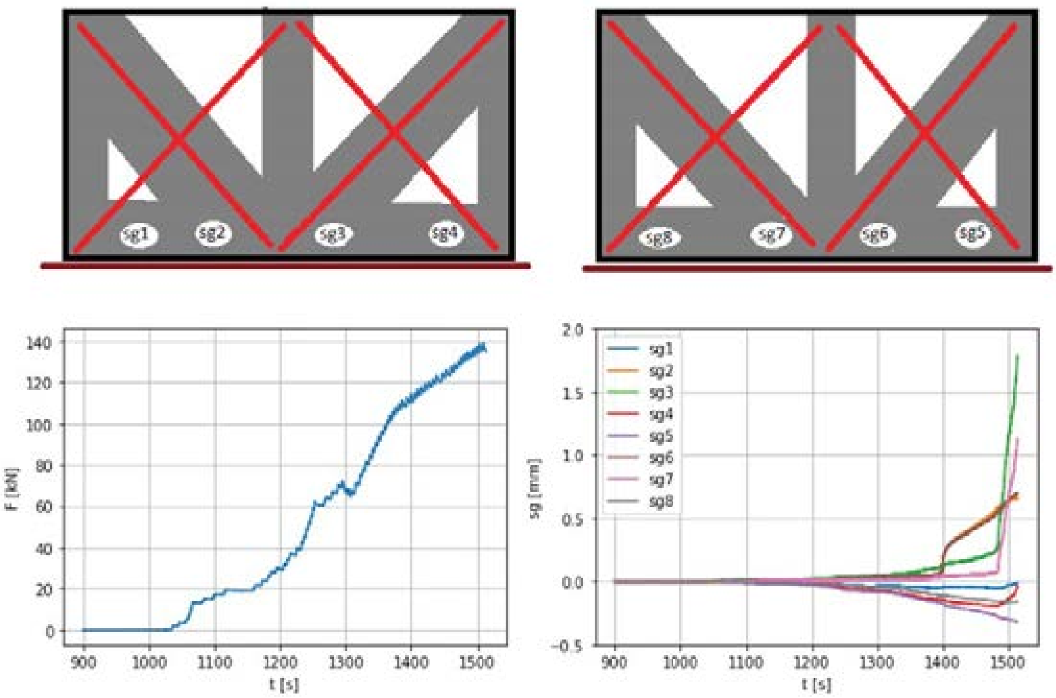

Figure 7: On the top the positions of the sensors on the reinforced wall (the picture on the right presents the same point of view of the photos in Figures 4). Below, respectively the force and displacement diagrams against time.

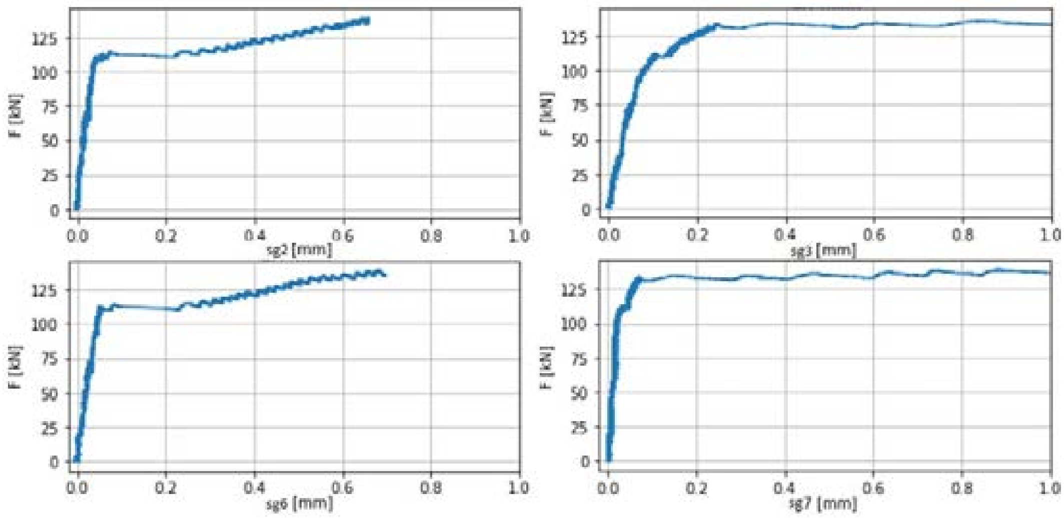

Figure 8: For the sensors subjected to tension, force-displacement graphs.

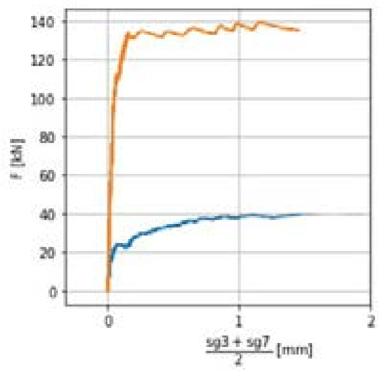

Figure 9: A comparison diagram between the two tests: unreinforced masonry in blue lines, the reinforced wall in organge lines.

4 CONCLUSIONS

- A focus on the study of the mechanical behaviour of natural FRCM composite materials was carried out in the field of the innovative strengthening techniques on masonry structures, since they are more compatible with the architectural value and specificities of heritage buildings;
- A experimental setup has been designed and realized in order to evaluate the influence of FRCM in the prevention of knock-on collapses in heritage buildings and to, in a future perspective, achieve the creation of a Finite Element Model gathering data from the tests;
- The first two tests have been made, involving an unreinforced masonry panel and a reinforced one, whose allowed to analyse the good functioning of the experimental setup designed and to evaluate the loads necessary to break the prototype and observe the stress redistribution mechanism due to the peculiar constraint conditions.

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