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# ARCHITECTURAL AND ENVIRONMENTAL IMPACT OF RETROFITTING TECHNIQUES TO PREVENT IN-PLANE ≪DOMINO≫ FAILURE MODES OF UNREINFORCED MASONRY BUILDINGS

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**Abstract.** The preservation of heritage buildings is not just about the structural safety, but it is necessarily related to the central themes of restoration, fruition and reuse of ancient buildings. Such topic requires an interdisciplinary design approach that involves, among the others, structural engineering, numerical modelling and architecture to address the challenges of contemporaneity in heritage management also in terms of interests of the stakeholders. In this regard, the opportunities offered by natural F.R.C.M. (Fibre Reinforced Cementitious Matrix) composites, made of basaltic fibres and lime mortar, are analysed. The main objective of the research is to expand the state of the art concerning the influence of such composites' applications on ≪in falso≫ masonries: load bearing walls built without a direct load path to the ground and acting like ≪wall beams≫ in case of collapse of the underlying masonry vaults. On this, an experimental campaign started in order to make a comparative assessment about the influence of composites in the prevention of knock-on collapses due to the aforementioned scenario, with the benefit of avoiding damages to unmovable artistic assets and valuable architectural features (e.g. precious pavings, mosaics, vaulted surfaces etc.). Furthermore, rather than the ≪canon≫ widespread intervention, an innovative application of F.R.C.M. in tapes is proposed, aimed at interventions with reduced quantities of composite material and therefore improving its use in the heritage even more. Finally, a first approach to the 3D Finite Element formulation for the case in question is proposed.

## 1 INTRODUCTION

The Italian architectural heritage has a central and iconic role whose protection is closely linked to a territory that faces a high risk related to natural hazards, such as the seismic events. The knowledge and conservation of buildings through synergies between universities, companies and institutions therefore represent a challenge for society, strategic for its cultural and economic growth. These are the premises for being able to better understand the present manuscript, that deals with the up-to-date requirements of masonry buildings/walls when subjected to seismic actions. Through critical reflections and methodological analyses, especially on most suitable techniques and materials for interventions in contexts of high cultural value, an innovative application criterion for the natural composites – in particular F.R.C.M. - was developed and tested. The project, as an alternative to the "canonical" application of such materials, proposes the use of tapes ("Green Tape") which reinterprets the existing sector know-how devising unprecedented installation schemes for such composite. The originality of this approach consists in limiting the interventions to the most vulnerable masonry areas, thus ensuring safety improvement in the face of a reduced quantity of composites used, with benefits for the architectural quality and eco-sustainability of restoration interventions, especially concerning shortcomings very common in heritage [1, 2, 3, 4, 5, 6, 7]. In the paper, a brief description of the scientific and technical data emerging from the various activities conducted in the years is provided. The project was preceded by an in-depth analytical study conducted with respect to the state of the art and taking into account industry procedures, regulations, guidelines and experimental outcomes produced by numerous authors and research institutions [8, 9, 10, 6, 11, 12, 13]. In particular, several authors have dealt with the complex issue of composite materials, their structural behaviour and their consequent modelling. In this sense, reviews on the state of the art concerning experimental tests aimed at characterizing F.R.C.M. and historical masonries under different profiles have been studied [14, 15, 16, 17, 18, 19, 20, 21, 22]. This phase was followed by the analysis of the current modelling issues for the topic in question [23, 24, 25, 26, 27]. Furthermore, only few authors addressed the topic of "in falso" walls [28, 29, 30] and, for this reason, an innovative experimental setup is proposed, aimed at investigating the features of such masonry elements that in case of seismic action behave like "wall beams". In addition, considering that innovative interventions are presented for high value architectures, different approaches to data acquisition techniques and monitoring were also briefly analysed that are both respectful of the environment and of the heritage [31, 32, 33, 34, 35, 36, 37, 38]. Finally, it is foreseen, as a future development of the ongoing research, that the experimental campaign and its evolution could be the basis for the creation of a proper numerical modelling strategy.

## 2 EXPERIMENTAL CAMPAIGN

The devised experimental set-up is innovative, as well as the protocol defined, since to the knowledge of the authors there is no other similar. The purpose was to simulate the most burdensome scenario, linked to the collapse of the underlying vaults Figure 1: a steel frame constitutes a closed self-balanced system, through which reach the fracture of masonry walls, ordinary and reinforced, suspended for most of their span and constrained only by lateral supports of reduced length. In addition, steel supports were made to have a dual purpose: to build the prototypes on top of them and then move the masonries on the frame and support them – without damages or alterations - until the beginning of the test. It was thus possible to instrument each time the walls before removing the supports and to acquire data from the minutes prior to the loads' application. In particular, linear variable differential transformer transducers (four for each façade) and laser sensors were used and connected, together with a load cell, to a continuously active acquisition system. In addition to their own weight the masonry prototypes, through a hydraulic jack and redistribution elements, were subjected to an increasing distributed load aimed at replicating the actions transmitted in reality by the overlying masonry structures.

**Figure 1**: Starting from the top row: example of an “in falso” wall triggering progressive collapse phenomena. Pics of the elements characterizing the setup, in order temporary steel support and construction on it of one of the prototypes. On the right, beginning of the test with the wall already instrumented (Test 3).

### 2.1 NATURAL COMPOSITES: NEW INTERVENTIONS

The prototypes’ creation was carried with same construction phases and material, in parallel with a characterization of the different. Single-headed walls with regular masonry texture were built using solid bricks and lime mortar, the latter specially made according to the mechanical characteristics of historical masonries. The experimental campaign examined the typology of F.R.C.M. composites made by a bidirectional network in basaltic fiber, with a 20 mm square mesh, and inorganic lime-based matrix M15. In addition to the well-known advantages of this technology (e.g. good mechanical properties, low thickness, compatibility, etc.), it is necessary to underline the feature of the durability, proven in different contexts through severe accelerated aging tests designed to simulate some of the chemical-physical degradation conditions typical of ancient masonries [39]. Moreover, the choice to use basaltic fibers qualifies such composites as natural and guides the intervention towards environmental sustainability: these mineral fibers - although not vegetable - are not synthetic and can be defined natural as the production cycle of the nets consists only in fragmentation, fusion and subsequent spinning of the basaltic rocks.

Commonly, the interventions in F.R.C.M. consist in a widespread application on the entire wall surface, making it difficult to apply in prestigious contexts where openings, niches, frescoes, stuccos etc. are observable. Furthermore, by analysing the structural functioning of such systems it seems clear that they compensate for the lack of tensile strength that is typical of masonry as building material. The definition of the innovative technique was born from this assumption and, through preliminary analytical and numerical studies, proposes an intervention made of “Green

Tape" to be applied only on the most vulnerable areas and, for the case in question, especially on the diagonals subject to lesions due to shear actions. Furthermore, the creation of 20 cm-wide tapes is not casual and, in addition to rely on structural needs, is congenial to installers and producers constituting a precise submultiple of the net's rolls (1 m-wide) manufactured to date. Given this, through applications designed by the Authors, the composite material was applied on both the faces of the masonry prototypes following a precise order of application: first the diagonal tapes subject to traction, then the lower bands of the wall and finally the vertical ones Figure 2.

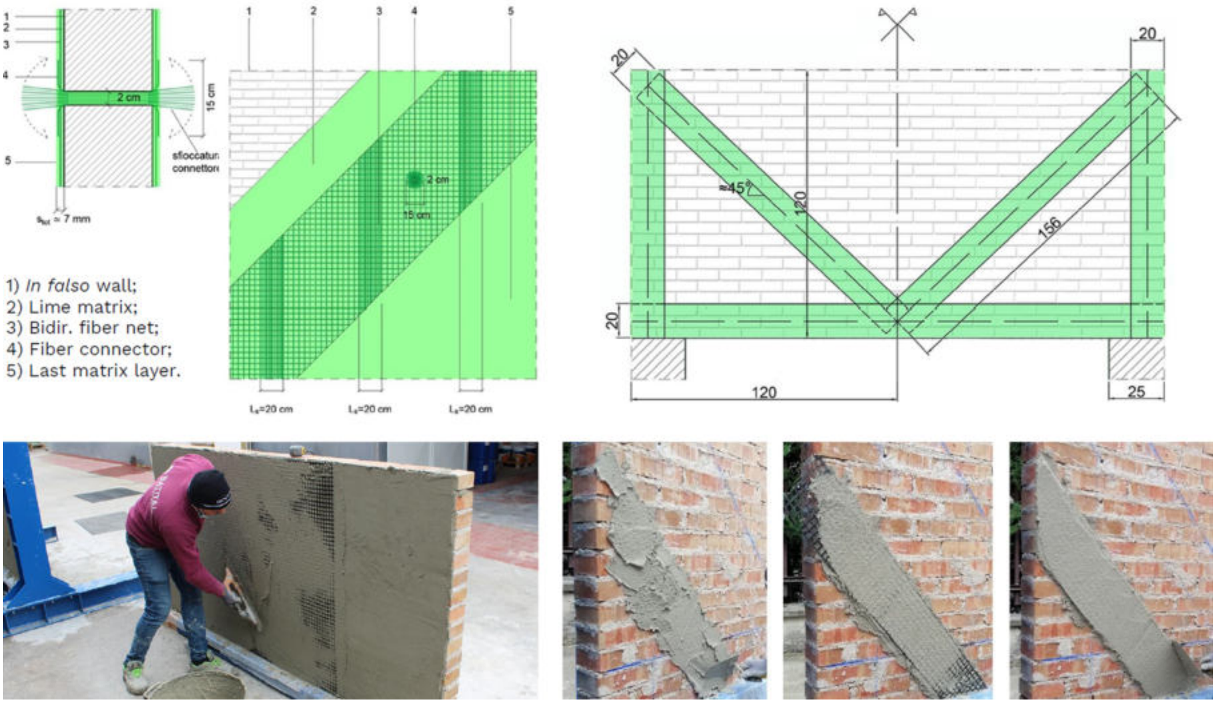


**Figure 2**: On the left row, schematic design - in section and elevation - of the elements making up the classic intervention in F.R.C.M. and below reinforcement of the wall with ordinary approach. On the right, technical detail of one of the configurations designed for the "Green Tape" and their laying for prototype 3.

## 3 RESULTS

To resume, three prototypes have been tested in a first phase: one "ordinary" wall (Test 1) and two walls reinforced through different configurations of "Green Tape" (Tests 2, 3). The goal was to evaluate, in comparative terms (Figure 3), the effectiveness of the proposed applications concerning the increase in resistance (in-plane) and the reduction of risk exposure in case of seismic actions. In Test 1, the collapse of the wall occurred as result of damage and consequent detachment of the mortar joints for a load of about 40 kN. At the end of it, a symmetrical "arching" mechanism, that controls lateral transmission of shear stresses through inclined pressure lines, was observed.

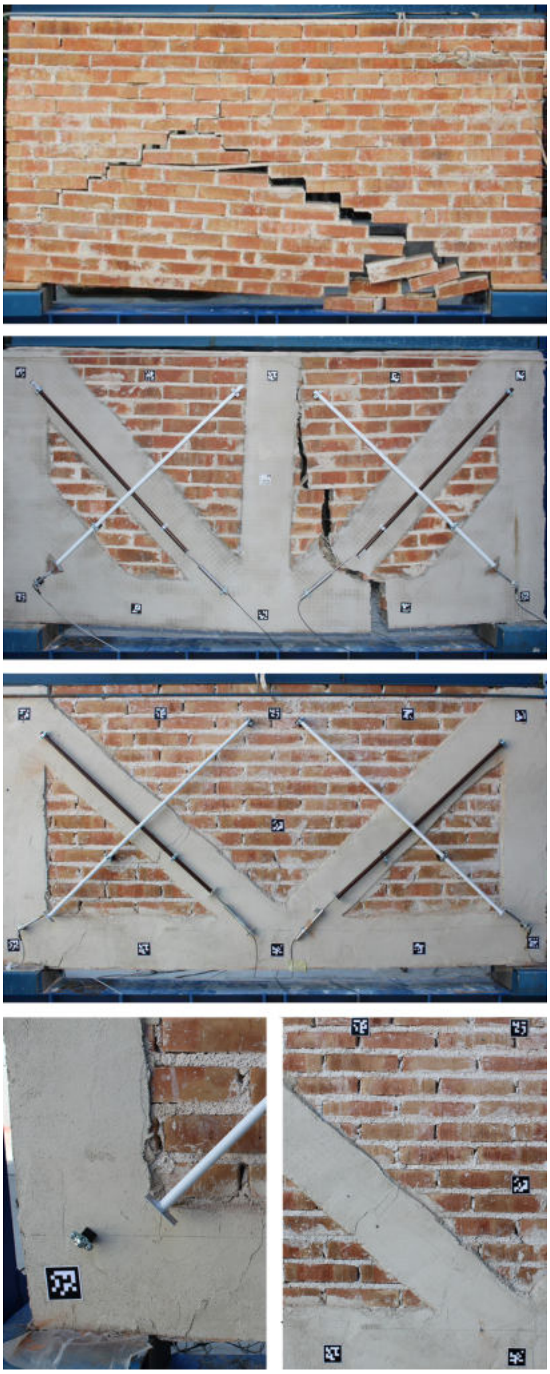

**Figure 3**: Photos of the crack patterns at the end of the three tests. From above, “arched” mechanism of the non-reinforced wall, Test 1; fracture of the wall reinforced with “Green Tape”, Test 2; damage of various masonry elements with superficial lesions on the matrix in Test 3, wall reinforced with a reduced number of “Green Tape” (and close-ups on its damages).

In Test 2, the first lesions on the reinforced wall involved the superficial portions of the composites' matrix and its collapse occurred for a load of about 140 kN, due to the breakage of both composites and bricks with an asymmetrical damage pattern. The Test 3, on the other hand, involved a wall reinforced with a reduced number of "Green Tape". During such test, the prototype has undergone partial damages to bricks, detachment of the mortar joints and lesion of the matrix, which proved to be superficial (on this, samples were taken after the test in the areas of the lesions). The increase in strength was however higher than in the previous test and 160 kN were needed to damage the wall. Furthermore, through the laser sensors, a partially elastic behaviour of the reinforced panel was observed along with a lowering of the midspan of about 3.5 mm, recorded through the use of an optic sensor reading the vertical displacement. By comparing the different instrumental acquisitions (Figure 4). Moreover, it is possible to observe (in addition to differences in the breaking loads) how the displacements recorded during Tests 2 and 3 were lower than in Test 1 - and below 1 mm - until the incipient collapse.

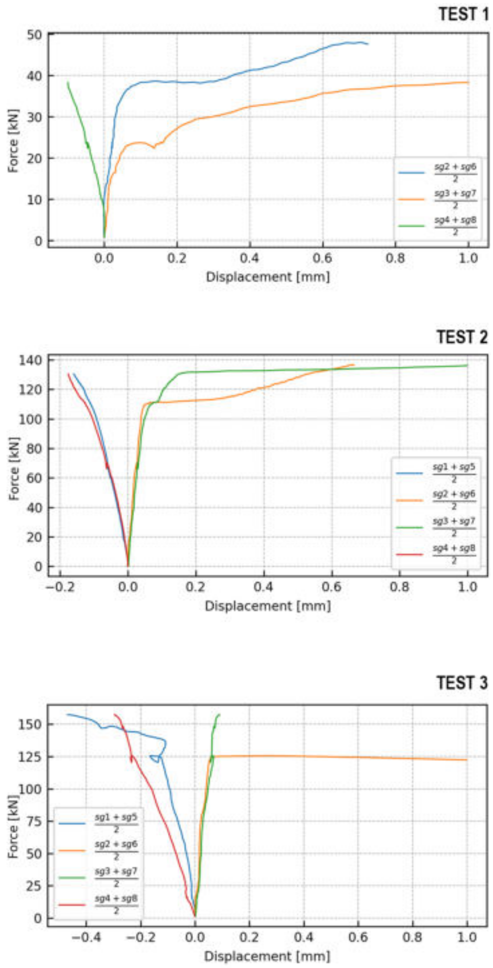


**Figure 4**: Force-displacement graphs elaborated, in each test, from acquisitions' averages of the sensors - correctly functioning - matching on different wall's faces and placed diagonally on the prototypes.

In order to draw the greatest possible conclusions from these data, it was also necessary to relate the innovative applications to the standard ones. On this, during a second phase (still in progress), a new test concerning a widespread and canonical application of F.R.C.M. was done, Figure 5. The collapse of the latter reinforced wall occurred for a lesion at the centreline concerning at the same time bricks, mortar and composites. To resume, the complete breaking of the reinforced walls occurred for a load of about 160kN (Test 3-4) and 140kN (Test 2), compared to the 40kN required for the unreinforced wall (Test 1). The composites have not only contributed to increase the walls' in-plane resistance but also prevented their total disintegration: a passive defence reducing earthquake risks to enhance security.

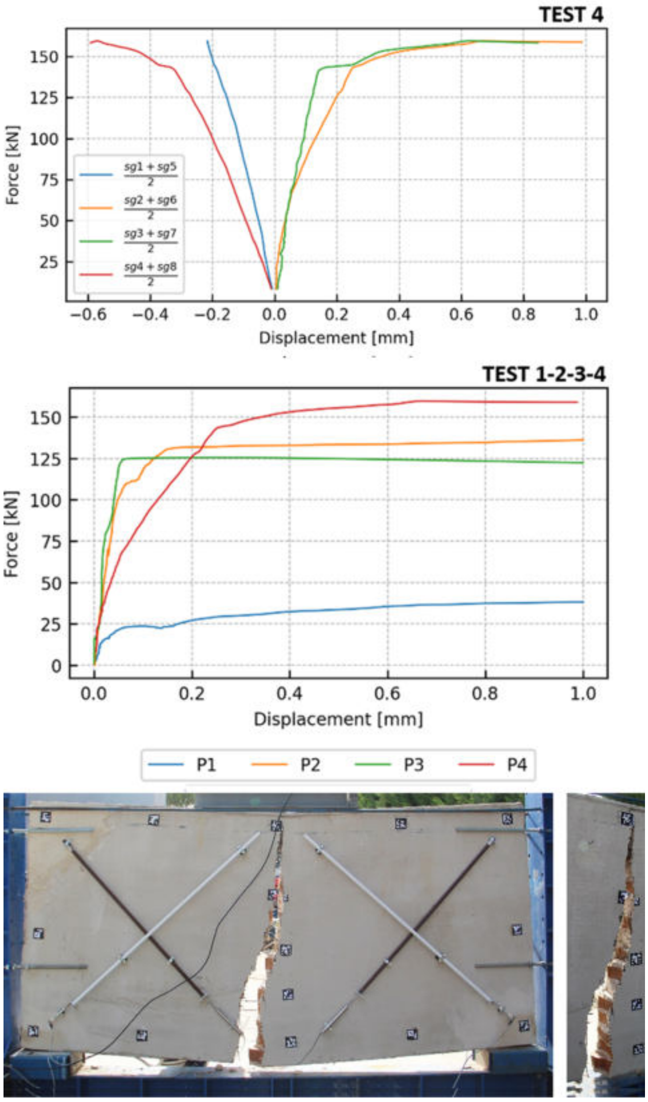


**Figure 5**: Force-displacement graphs (averages) and pics of Test 4. In the middle, tests' comparison - see legend - through the diagonals subject to traction (positive sign). Displacements not exceeding 1 mm and loads' values to the onset of the first lesions are evaluated

### 3.1 PRELIMINARY MODELLING

A preliminary model was created in order to replicate the outcomes of the presented experimental campaign. The masonry walls were discretized by the Simplified Micro-Modelling through the adoption of a homogeneous unit, partitioned in bricks and mortar joints on the boundaries. In particular solid 3D elements with two different cohesive interfaces – in the middle for their tensile failure and on the mortar interfaces for joints – were used. Then, the model foresees the inclusion of the interventions in composites, after a preliminary calibration through strategies that, relying on the experimental data and based on literature, allowed to represent the mechanical feature and the complex behaviour of F.R.C.M. composite materials. On this, for the F.R.C.M., a damageable rebar shell model, using different layers to make the square net, was created and embedded to the masonry support by a concrete model representing the matrix phase. The model proved able to describes the qualitative relations between the damage mechanism and the failure variables observed during the experimental campaign, Figure 6.

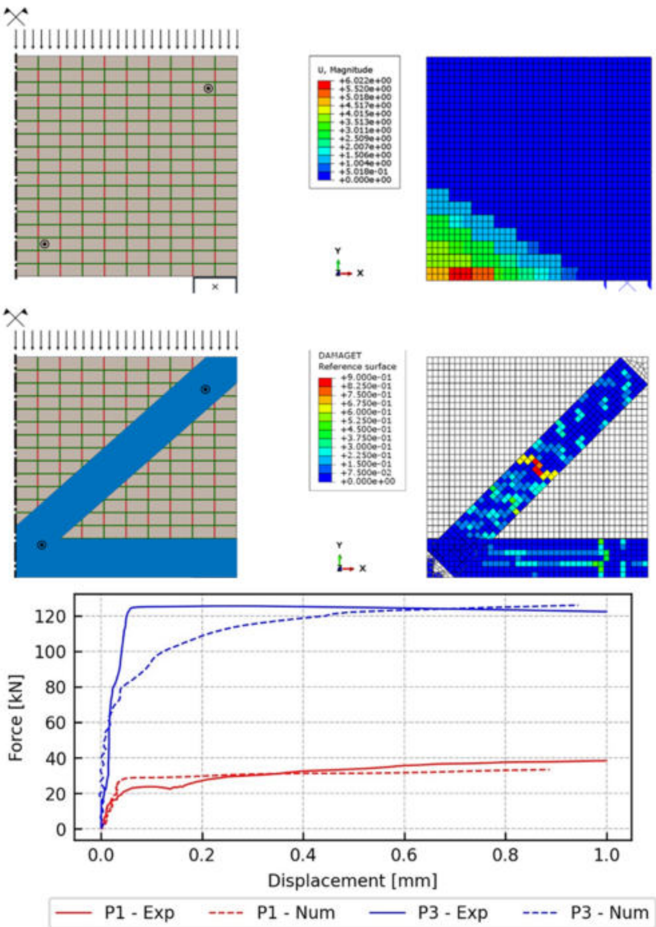


**Figure 6**: Analytic schemes developed and employed for F.E.M. simulations in Abaqus compared to the damage plots. Below, first comparison between the numerical results and the force-displacement graphs related to the tests on the walls unreinforced and reinforced.

Moreover, to allow a preliminary comparison between the experimental data and the numerical outcomes, measurements were taken on the diagonals in traction of the model in analogy with the prototypes; in particular, the displacements of the nodes in object were extracted, then their modules were evaluated and subsequently combined with the linear load trend, Figure 6. So, a behaviour consistent with the experimental data is observable for both the problems under analysis: the "wall beam" and one of the innovative configurations for the reinforcements. For now, the modelling focuses on the proposed "Green Tape" intervention and not on the "canonical" intervention and in this phase does not, considering the experimental outcomes, takes into account the role of delamination of composites. The displacements of QR-code markers, acquired with a high frame rate camera, will be used in a future perspective - coupled to the optic sensors' acquisitions - to track the damage and deformative patterns and to calibrate and refine the numerical model.

## 4 CONCLUSIONS

Experiences deriving from scientific research, prototyping and design are embodied in an innovative strategy for F.R.C.M. materials, easy to apply and scalable for site-specific interventions of architectural restoration. For its testing an innovative experimental set-up was created and four test on full scale prototypes were conducted. As emerged from the results, the "Green Tape" can increase of about four times the in-plane resistance of "in falso" walls and prevent their total disintegration even if damaged. Moreover, the present method proved to be effective in robustness and safety enhancement of ancient buildings, while using a reduced amount of composites compared to standard techniques (65 percentage rollback). Finally, based on the experimental data, a preliminary Finite Element Model is being developed to support the design process in different contexts and taking into account interdisciplinary characteristics, such aspect of the research is ongoing and will be deepened also relying on the execution of new tests.

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