THE SEISMIC PROTECTION OF EXISTING MASONRY BUILDINGS: A ROUTE OF RESEARCH ON COMPOSITE REINFORCED MORTAR

Ingrid Boem, Natalino Gattesco, Allen Dudine, Matija Gams

SUMMARY

Within the last 20 years, Textile Reinforced Mortars (TRM) have gradually spread as innovative strengthening techniques for the seismic protection of existing masonry buildings. They combine an inorganic mortar layer, applied on the masonry surface, with a high tensile resistant, un-corrosive, fiber-based reinforcement. The paper traces the main steps of a deep research route on a specific TRM technique, called Composite Reinforced Mortar, providing an overview on the experimental testing and numerical modeling experiences aimed at achieving an in-depth knowledge on its behavior and on its effectiveness in improving the masonry performances. It is an example of a systematic approach to research, which deals with the complexity and multiplicity of aspects that need to be considered by the professional designer when choosing among the solutions available on the market.

Key words: Seismic vulnerability, Masonry strengthening, Composites, Experimental tests, Numerical modelling.

1. INTRODUCTION

The building heritage in Europe and worldwide consists of many historic masonry buildings that often need refurbishment interventions, due to structural deficiencies related to durability, modifications, fatigue, cyclic stresses, accidental actions… In particular, the experience has shown that these massive structures, traditionally conceived to withstand vertical loads, are particularly vulnerable to seismic actions. This vulnerability is typically influenced by the structural consistency (connections among the walls and between walls and floors), the distribution of the resistant elements (shear walls) and the masonry integrity and resistance. On this latter, the main deficiency is generally related to the poor tensile resistance of masonry, despite its good compressive strength. Thus, the introduction of tensile resistant elements can mitigate the seismic damage in masonry structures.

In this context, within the last 20 years, innovative strengthening systems for the seismic protection of existing masonry buildings, the Textile Reinforced Mortars (TRMs), have gradually spread in the refurbishment sector. They consist in the application, of the masonry surfaces, of mortar coating with a fiber-based reinforcement layer embedded. This is particularly compatible for application on existing masonry, since combines the use of high tensile resistant, un-corrosive material (the fiber-based reinforcement) with an inorganic matrix (the mortar), which is easy to apply on rough surfaces such as masonry and can assure mechanical and chemical compatibility with the substrate and provide fire and UV-ray protection to the fibers. Several materials combinations have been proposed for TRM, differing for the nature and format of the reinforcement (e.g. glass, carbon, basalt, in the form of textiles or meshes) and the type and thickness of mortar matrix.

The development of these modern techniques has actively involved the field of scientific research at different levels: the study of the mechanical and chemical behavior of the compounds, the testing of TRM strengthened masonry elements and structures, the calibration of numerical and analytical methods for the performances estimation.

An overview of recent research achievements in the field is herein presented, focusing on a specific TRM strengthening technique called Composite Reinforced Mortar (CRM). It is an example of a systematic approach to research, which deals with the complexity and multiplicity of aspects that need to be considered by the professional designer when choosing among the solutions available on the market.

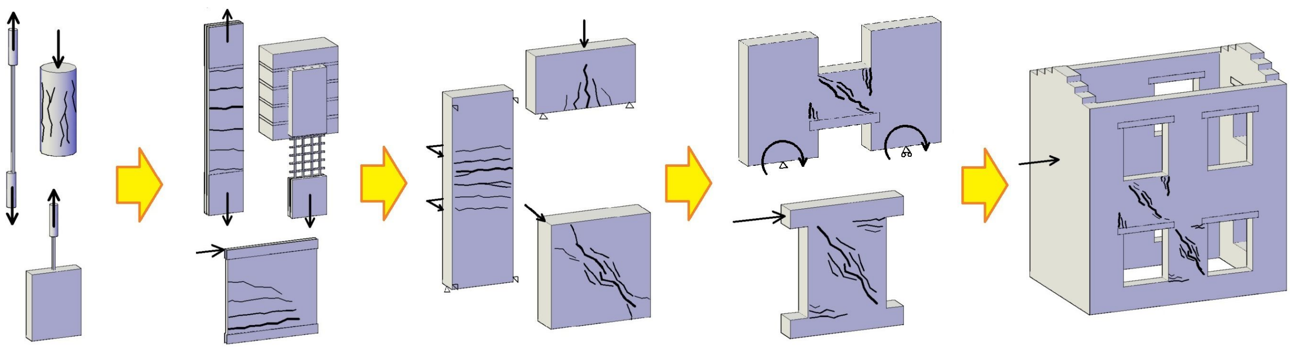
2. THE CRM TECHNIQUE

Composite Reinforced Mortar (CRM) is a TRM strengthening technique based on the application, on the masonry surfaces, of a mortar coating, having a minimum thickness of 30 mm, with embedded a preformed, Fiber-Reinforced Polymer (FRP) grid. FRP passing-through connectors, injected into holes drilled in the masonry, are introduced to improve the collaboration with the masonry. One-side application of CRM is also possible; in this case, artificial diatones should be added to contrast possible leafs separation in case of multiple-wythe masonry.
The mesh of the reinforcement herein considered is composed of orthogonal yarns made of long Alkali-Resistant Glass fibers (Figure 1). During the production process, the fiber yarns are firstly impregnated with a thermosetting polymeric resin (vinylester-epoxy); then, the yarns in the warp direction are twisted and weaved across those in the weft direction. The resin coating is thermo-set and the mesh are stocked in rolls.

Figure 1. Application of CRM on a masonry wall.

3. EXPERIMENTAL INVESTIGATIONS

Experimental tests resulted fundamental to provide evidence of the CRM behavior and its role when applied on masonry elements. To optimize the testing effort, the so called "Building Block Approach" was followed: it is a systematic process consisting in a series of tests of increasing complexity, from single CRM components to entire strengthened buildings (Figure 2). Clearly, as the scale and the complexity of the tests increases, the number reduces, due to the higher effort and expenses.



(a) (b) (c) (d) (e)

Figure 2. The "Building-Block Approach" adopted for the systematic study on the CRM technique for strengthening masonry structures, at the level of (a) single material/interface, (b) CRM coupon, (c) elementary masonry sample, (d) structural element and (e) building.

At the component level (Figure 2a), the experiments concerned tensile tests on the fiber yarns (see example in Figure 3), compression and tensile tests on mortar specimens, shear tests on the mesh intersections and pull-out tests of the yarns from the mortar [Gattesco and Boem, 2017a]. It has thus been possible to understand the mechanical behavior of the different materials and their mutual interaction.
At this level, also durability tests are important to assess the fibers sensitivity e.g. to harsh environmental conditions and fatigue loading. For glass fibers, a particular attention was addressed to the study of the alkaline environment effects (related to the mortar matrix) [Micelli et al., 2017], [Micelli and Aiello, 2019].

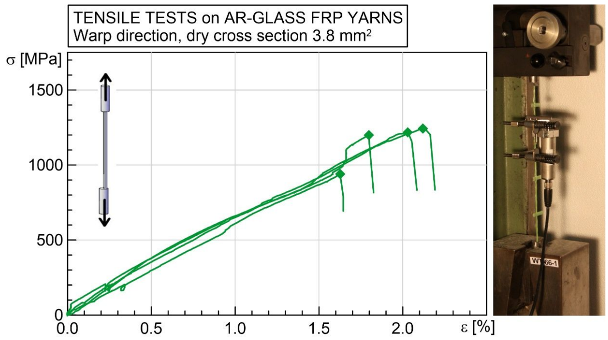


Figure 3. Experimental tensile tests on FRP yarns: stress-strain behavior (the stresses are referred to the fibers dry cross section) and test setup.

At the CRM coupon level (Figure 2b), direct tensile tests, shear-bond tests and in-plane shear tests allowed the evaluation of the equivalent properties of CRM as a composite material [Gattesco and Boem, 2017a], [Sisti et al., 2019]. Examples of direct tensile tests are reported in Figure 4a: the equivalent stress-strain behavior obtained by testing CRM coupons evidences that CRM basically acts in tension as a bi-phasic material. Initially, the mortar governs; then, once it cracks, the stiffness reduces but the mesh yarns crossing the openings continue to carry the tensile stresses and contrast the cracks widening. The final collapse is due, optimally, to the yarns rupture in tension. However, inadequate bond lengths or excessive reinforcement ratios may anticipate the failure, for the occurrence of slip and/or debonding phenomena. This comes clear in the example Figure 4b, in which the results of shear bond tests related to two different bond lengths (180 and 120 mm) are compared. In the former case, with adequate bond length, the yarns failure was attained; in the latter, with inadequate bond length, excessive slips of the yarns from the mortar occurred and the resistance of the yarns was not fully exploited.

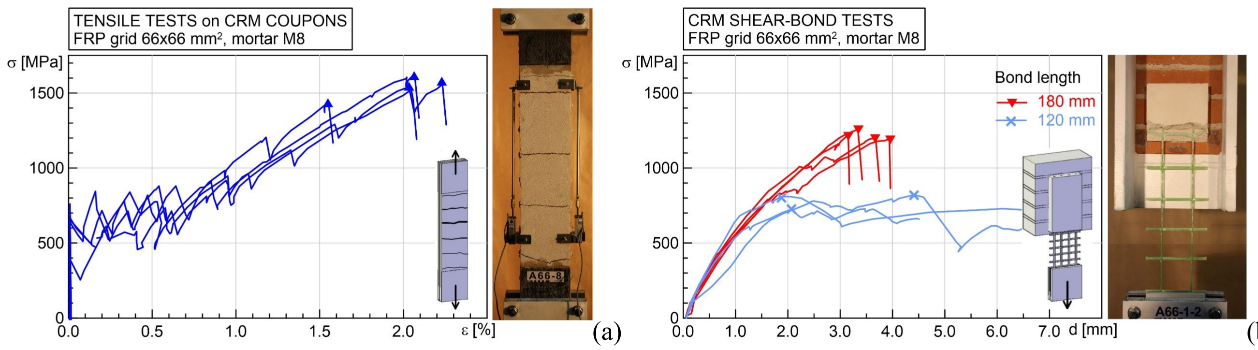


Figure 4. Experimental (a) tensile and (b) shear-bond tests on CRM coupons: equivalent stress-strain (or slip) behavior and typical damage pattern.

The tests at the level of elementary masonry sample (Figure 2c) were aimed at an initial evaluation of the CRM effectiveness against the main failure mechanisms of historic masonry under lateral loads, namely diagonal-cracking, in-plane bending and out-of-plane bending [Gattesco and Boem, 2015] [Gattesco and Boem, 2017b].

The examples in Figure 5a and Figure 5b refer, respectively, to diagonal compression tests performed on solid brick masonry samples (250x1200x1200 mm³) and to out-of-plane, four-point bending tests carried out on rubble stone masonry samples (400x1000x3000 mm³). In the first case, the behavior is described by the trend of the diagonal load varying the shear strain, in the latter, by the out-of-plane load-deflection curve. The comparison between the performances of unstrengthened and strengthened samples evidences the significant performance improvements due to CRM, since the FRP grid intervened in the cracked areas of the mortar coating, allowing the smear of damage and the energy dissipation.

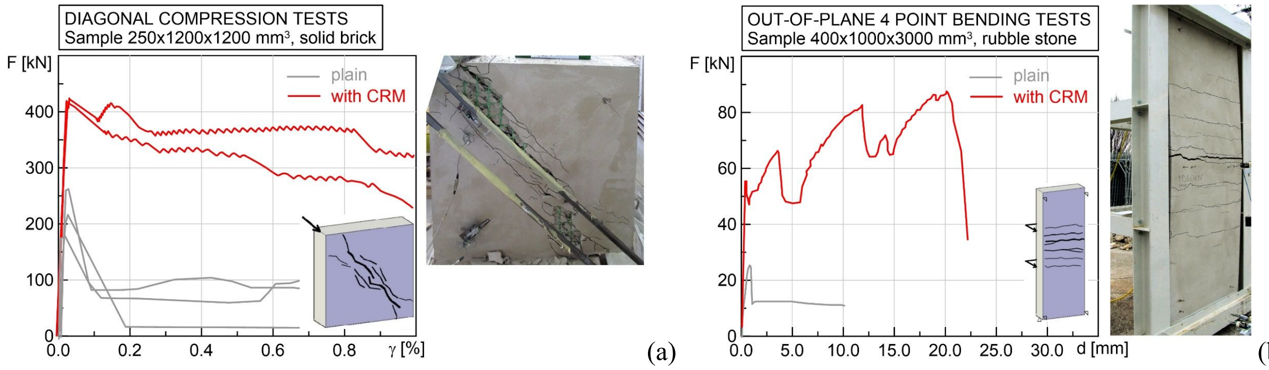


Figure 5. Experimental tests on elementary masonry samples: examples of capacity curves and damage pattern of CRM strengthened samples for (a) diagonal compression tests and (b) out-of-plane bending tests.

Experimental cyclic tests on full-scale structural elements, such as pier and spandrel samples, (Figure 2d) allowed to investigate on the actual behavior of the masonry wall portions between adjacent openings, arranged horizontally or vertically, respectively [Gattesco et al., 2022].
The examples plotted in Figure 6 refer to a 350 mm thick two leaf rubble stone masonry, with the CRM strengthening technique applied on one or both sides. In particular, Figure 6a refers to 1500x1960 mm² pier samples subjected to lateral loading cycles under a constant axial stress level (0,5 MPa) and with rotations at top and bottom avoided (shear-type scheme). The horizontal load varying the horizontal displacement at the top is reported in the graph. The examples plotted in Figure 6b refer to H-shape samples composed of a 1050x1170 mm² spandrel with timber lintel between two 1420x2190 mm² walls. The walls were subjected to identical, cyclic rotations at the bases, so to induce shear actions on the spandrel. The shear load on the spandrel varying its vertical distortion, is represented in the graph.
The comparison with the results of plain masonry samples clearly evidences the CRM contribution in the load bearing, deformation and dissipative capacities of actual resisting elements in buildings, also when diagonal cracking and bending failure modes combine (as evidenced in the damage pattern).

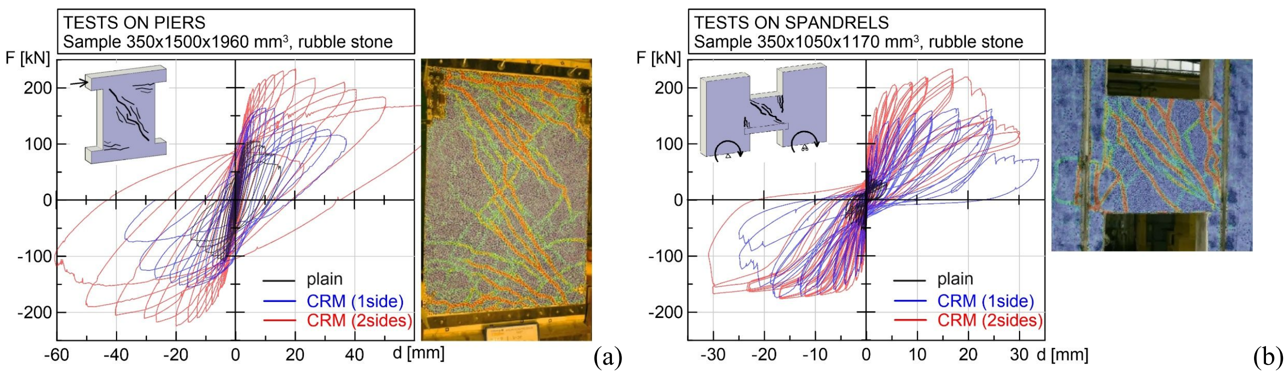


Figure 6. Experimental tests on structural elements: capacity curves and typical damage pattern of CRM strengthened samples for (a) tests on piers and (b) on spandrels.

Pushover cyclic tests on buildings can prove the effectiveness of CRM at the largest, global scale (Figure 2d). The example structure herein considered in Figure 7 was made of two leaf rubble stone masonry walls (350 mm thick) and had plan dimensions of 5750x4350 mm² and a height of 6000 mm [Gattesco et al.. 2022]. It had a unidirectional wooden floor (East-West direction) and a double pitch timber roof; the overall gravity load was 71,5 kN at the 1st floor and 51,7 kN at the roof level. The horizontal cyclic load was applied along the longitudinal direction at the floor and roof levels, accordingly to a prescribed distribution (proportional to the first vibration mode). The building was at first tested unstrengthened, then retrofitted with CRM at the external side only and tested again. To provide the connection with the RC fixed foundation along the perimeter, vertical steel threaded bars were embedded in the mortar coating and fixed through injection into holes drilled in the RC foundation. The effectiveness of CRM at the global scale can clearly be appreciated by comparing the capacity curves of Figure 7b, representing the base shear varying the horizontal displacement at the top. The beneficial crack diffusion effect of the FRP grid visibly emerged in the crack pattern.

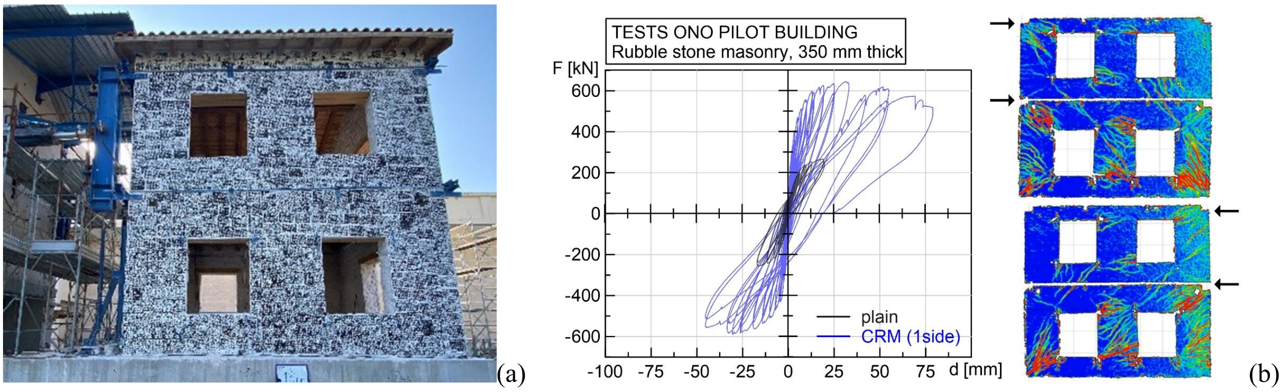


Figure 7. Experimental tests on pilot building: (a) global view and (b) results in terms of capacity curves and damage patterns of the CRM strengthened sample.

4. NUMERICAL MODELLING

The great variability in the material combinations, geometry, stress state and boundary conditions, makes unable to cover experimentally all possible arrangements. The numerical approach is thus fundamental, as permits to investigate on a wider number and more complex configurations, allowing also the optimization of the strengthening intervention.

In this context, a broad numerical study on the structural performances of CRM strengthened masonry was developed in the field of nonlinear-static analysis. According to a "Multi-Level Approach", different modeling strategies were calibrated, varying the scale of investigation (Figure 8): starting with the Detailed-Level Modelling, DLM, for the tests at the small scale level, followed by an optimization procedure to get a more computationally efficient Multi-Layer Model, MLM, based on layered elements, for the tests at the intermediate scale level, until attain to equivalent frame, Lumped Plasticity Model, LPM, for the global analysis of structures.

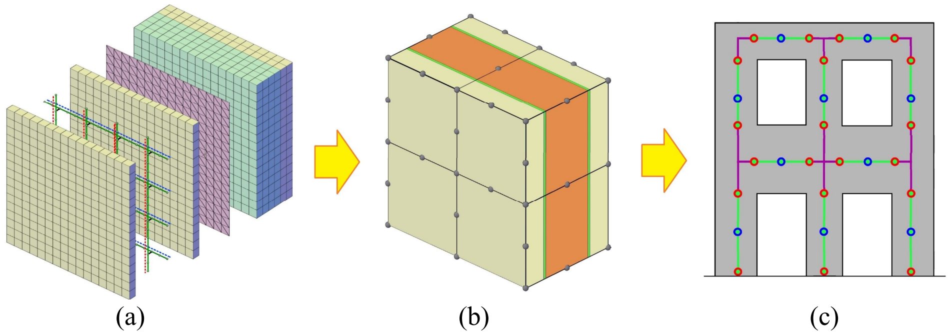


Figure 8. The "Multi-Level Approach" for numerical modelling of CRM strengthened masonry: (a) Detail-Model DLM, (b) intermediate, Multi-Layer Model MLM and (c) simplified, Lumped-Plasticity Model LPM

The Detailed-Level Modelling (Figure 8a) is characterized by a very refined mesh (~15 mm), with 8 nodes brick elements adopted for both the masonry and the mortar coating and truss elements for the mesh yarns. Point-to-point interfaces link orthogonal yarns at the intersections; line interfaces connect the yarns with the mortar coating; surface interfaces couple the mortar with the masonry substrate. The model is able to account for the failure of single materials (e.g. the yarns tensile failure, the mortar cracking and crushing), as well as of their interactions (the debonding of the yarns from the mortar and of the mortar from the masonry substrate).

The model was calibrated on the basis of experimental tests on individual components and interfaces (Figure 2a) and validated through comparison with tests on CRM coupons (Figure 2b) [Boem, 2022a] and elementary samples (Figure 2c) [Boem, 2022b]. As an example, the application of the DLM for the simulation of tensile tests on CRM coupons and diagonal compression tests on elementary samples is reported in Figure 9; the DLM allowed to evaluate detailed aspects such as the cracks diffusion and the stress levels in the yarns.

The DLM was proved to be a useful tool to carry out sensitivity studies aimed at understanding the impact of parameters such as the reinforcement ratio and orientation, the quality of connection between wires, the type of mortar, the rate of adhesion of the grid to the mortar and of the mortar to the masonry… on the performances of CRM and its effectiveness.

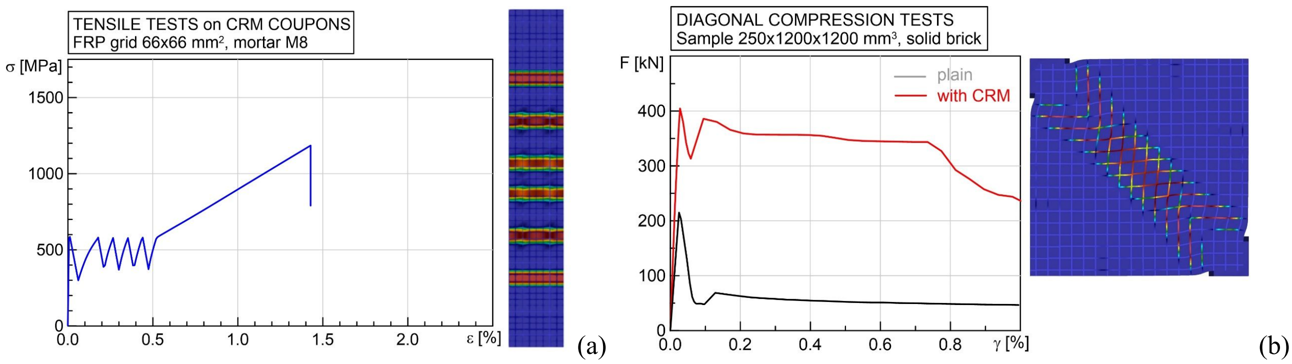


Figure 9. Numerical simulations with the DLM: example of application to (a) tensile tests on CRM coupons and (b) diagonal compression tests on elementary samples.

The intermediate, Multi-Layer Model (Figure 8b) is based on a coarser mesh (~150 mm), composed of multi-layer, 20 nodes solid elements with a through-the-thickness stacking sequence of perfectly bonded plies representing the masonry, the mortar coating and the fiber-based reinforcement. The layers characteristics were calibrated on the basis of experimental tests on individual components and CRM coupons (Figure 2a-b) and the model was validated through comparison with the experimental or DLM outcomes concerning elementary samples. The model was then applied to the simulation of structural elements (Figure 2d) and even entire buildings (Figure 2e) [Boem, 2022c].

The examples reported in Figure 10 and Figure 11 refer to the tests on piers, spandrels and buildings previously described in the experimental section. The numerical capacity curves and the damage pattern can thus be compared to the experimental ones, evidencing the good reliability of the MLM.

Due to the coarse mesh size and the smear plasticization assumption, the MLM is clearly not suitable for the rigorous reproduction of individual cracks, for which more accurate but computationally heavier models, such as the DLM, should be used. However, it represents a good compromise between the goal to grasp the structural performances at the wide scale, including failure modes, and the analysis optimization.

Clearly, the simplified assumption of perfect bond among layers has to be ensured. For example, by respecting the minimum bond lengths and the limits on reinforcement ratio. The calibration of such requirements can be achieved by experimental characterization tests (i.e. direct tensile tests and shear-bond tests) and/or through simulations with the DLM at the coupon level. Alternatively, it is possible to intervene on the MLM by limiting the ultimate deformation of the reinforcement (when the debonding anticipates the reinforcement failure) and/or the compressive strength of the mortar (so to account for its buckling in the most compressed areas).

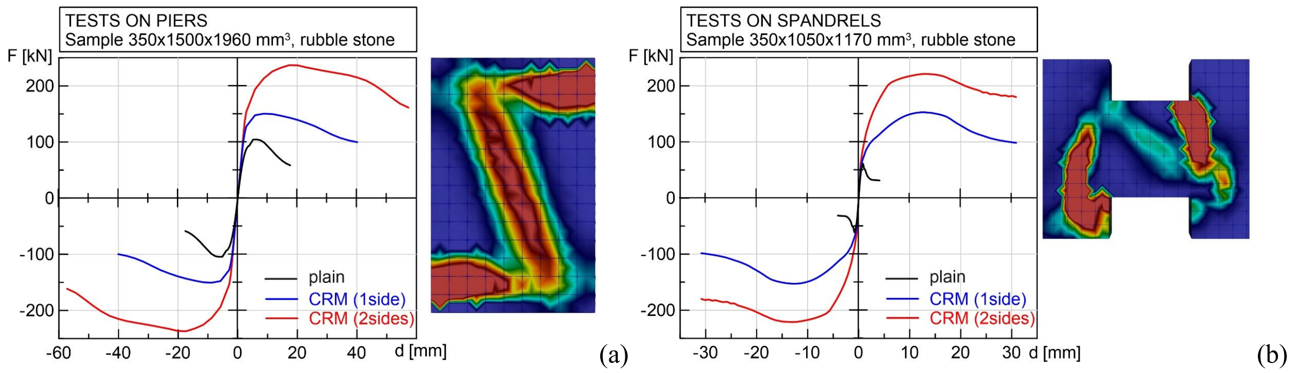


Figure 10. Numerical simulations on structural elements with the MLM: capacity curves and damage pattern of CRM strengthened samples for (a) tests on piers and (b) on spandrels.

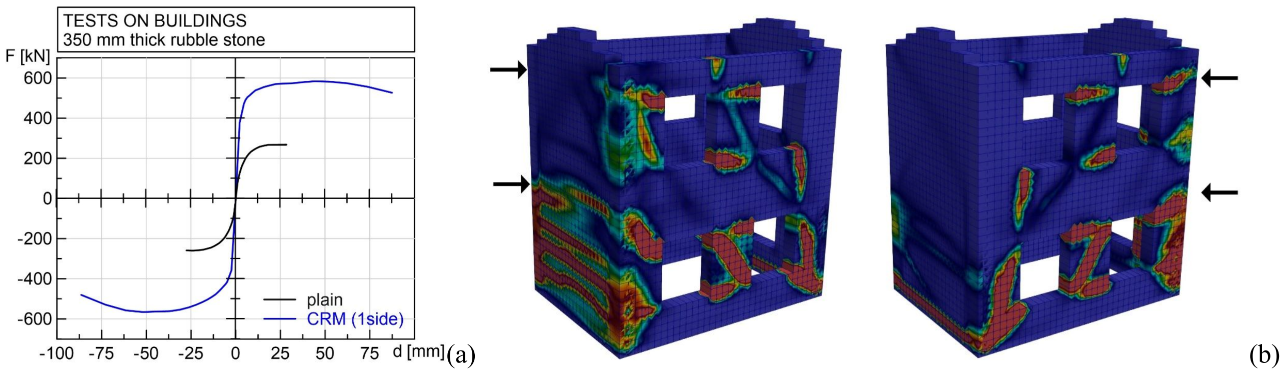


Figure 11. Numerical simulations on pilot building with the MLM: (a) capacity curves and (b) damage pattern of the CRM strengthened sample.

For the evaluation of the global performances of existing masonry buildings in the professional practice, the equivalent frame method with lumped plasticity is typically adopted (Lumped Plasticity Model in Figure 8c). It consists in the schematization of the structure by means of one-dimensional beam elements, with elastic behavior, which represent the resistant macro-elements (piers and spandrels), connected by rigid nodes. The non-linear behavior of the macro-elements is lumped into localized plastic hinges, which take into account the different failure mechanisms (by diagonal cracking or bending).

The MLM allowed sensitivity analyses at the structural element level, permitting the calibration of the characteristics of the equivalent plastic hinges (in terms of resistance and displacement capacities) to be adopted in the LPM of entire CRM strengthened structures (Figure 12). The comparison between the results of the LPM and the MLM models at the building scale allowed the validation of the LPM method for the design of strengthened masonry buildings [Gattesco et al., 2022].

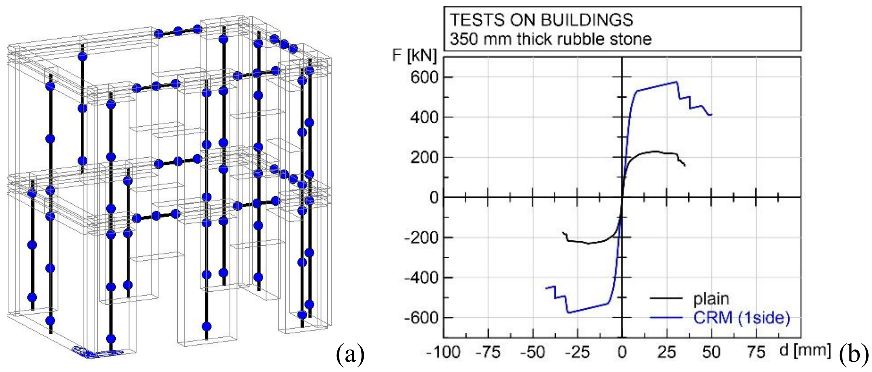


Figure 12. Numerical simulations on pilot building with the LPM: (a) global view of the model and (b) capacity curves.

5. CONCLUSIONS

The twenty-year research experience, combining experimental and numerical investigations, allowed the deepening of knowledge on CRM as a strengthening technique for existing masonry. In particular, the systematic adoption of the "Building-Block Approach", for the experimental testing, and the "Multiple-Level Approach", for the numerical analysis, permitted the effort optimization and was proved very effective in addressing and understanding the various aspects to deal with. Clearly, the research is not exhausted and other aspects should be investigated (e.g. the combination of actions or the effects of the dynamic nature of the seismic action). However, the research experience clearly highlighted that the comprehension of the behavior of TRM strengthened structures is a complex task to be faced, ranging from the scale of materials and single failure mechanism to the behavior of full-scale resisting elements and structures. The existence of proper studies aimed at understanding the various aspects is fundamental in orienting the design choice to reliable solutions to be adopted in practice.

6. ACKNOWLEDGMENTS

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7. REFERENCES

Boem, I., Characterization of textile-reinforced mortar: state of the art and detailed level modelling with a free open-source finite element code. J. Compos. Constr., 26, 04022060, 2022a.
Boem, I. Masonry elements strengthened through Textile-Reinforced Mortar: application of detailed level modelling with a free open-source Finite-Element code. Constr. Build. Mater., 357, 129333, 2022b
Boem, I. Multi-layer modelling of masonry structures strengthened through Textile-Reinforced Mortar [version 1; peer review: awaiting peer review]". Open Res Europe, 2022c, 2, 132.
Gattesco, N., Boem, I., Rizzi, E., Bez, A., Gams, M., Marič, M., Pučnik, V., Dudine, A. The Experimental campaign and numerical simulations of the Constrain project. Interreg Italia-Slovenija standard project co-funded with European Regional Development Fund. Technical Report, 2022.
Gattesco N., Boem I. Experimental and analytical study to evaluate the effectiveness of an in-plane reinforce¬ment for masonry walls using GFRP meshes. Constr. Build. Mater., 88, 94–104, 2015.
Gattesco N., Boem I. Characterization tests of GFRM coating as a strengthening technique for masonry buildings. Compos. Struct., 165, 209–222, 2017a.
Gattesco N., Boem I. Out-of-plane behavior of reinforced masonry walls: Experimental and numerical study. Compos. B Eng., 128, 39–52, 2017b.
Micelli F., Aiello M.A. Residual tensile strength of dry and impregnated reinforcement fibres after exposure to alkaline environments. Compos. B Eng., 159, 490-501, 2019.
Micelli F., Corradi M., Aiello, M.A., Borri A. Properties of Aged GFRP Reinforcement Grids Related to Fatigue Life and Alkaline Environment. Appl. Sci., 7(9), 897, 2019.
Sisti R., Castori G., Dudine A., Borri A. In-plane response of mortar plates strengthened by traditional or innovative reinforcement materials [Comportamento a taglio di lastre di CRM, FRCM o intonaco armato tradizionale - in Italian]. In: Proc XVIII Conference "ANIDIS L'ingegneria Sismica in Italia", Pisa University Press, Ascoli Piceno, I, 2019.