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Natural Fibers for Out-of-Plane Strengthening Interventions of Unreinforced Masonry Buildings in Aggregate Configuration

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Abstract: Most of the Italian historical centers are composed of unreinforced masonry (URM) buildings arranged in aggregate configurations. Past and recent seismic events have underlined the high vulnerability of these buildings especially towards out-of-plane mechanisms. In order to reduce their vulnerability, the use of strengthening interventions based on fiber reinforced composite materials has become widespread in the last years. More recently, strengthening systems using natural fibers have been the object of experimental tests since they represent an innovative environmentally sustainable solution. The aim of this paper is to numerically analyze the feasibility of strengthening systems made of natural fibers embedded into cementitious matrices to prevent the out-of-plane mechanisms of perimeter façades belonging to masonry buildings in aggregate configurations. For this purpose, numerical analyses based on a macro-modeling approach for out-of-plane mechanisms are performed by considering the influence of adjacent structural units and the presence of strengthening systems made of natural fibers. Both aspects have been analyzed in detail and taken into account by introducing in the equation governing the problem both the friction acting between adjacent walls of building units, when in aggregate, and the contribution of the strengthening system. A building case study forming part of an aggregate of an Italian historical center has been considered for the development of the numerical analyses.

Keywords: seismic vulnerability; kinematic analysis; unreinforced masonry buildings; masonry building aggregate; out-of-plane mechanisms; strengthening; sustainable composite materials; NFRCM

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1. Introduction

Recent and past seismic events have highlighted a marked vulnerability of unreinforced masonry (URM) buildings of historical centers arranged in aggregate with particular regard to the occurrence of out-of-plane mechanisms of the perimeter façades [1,2]. The use of externally-bonded composite systems certainly represents a valuable solution to prevent these types of mechanisms thanks to ease of installation, reversibility, high strength-to-weight ratio, suitable mechanical properties, negligible increase of mass, etc.

In the context of the structural reinforcement of existing buildings, in current practice, fiber-reinforced polymer (FRP) composites are widely used as a strengthening system. Nevertheless, FRP composites present poor compatibility with the masonry substrates [3,4] and their organic resins lose most of their mechanical properties when exposed to high temperatures, close to their glass transition temperature. To overcome these drawbacks [5], the use of composite materials made of fabric fibers embedded in inorganic matrices, named fiber reinforced cementitious matrix (FRCM) materials [6], has recently been proposed especially for masonry structures because of their high physical and chemical compatibility with masonry substrates, permeability, and major reversibility with respect to the FRP materials.

A typical FRCM system presents a matrix based on Portland cement and natural hydraulic lime, or geopolymer, and reinforcing grids/fabrics made of synthetic fibers such as carbon, basalt, glass, poly-para-phenylene benzobisoxazole (PBO), and aramid [7,8]. In recent years, in order to further reduce the environmental impact of strengthening interventions, the use of recoverable or biodegradable materials, such as natural fibers, are used in place of synthetic fibers. The new composite materials, named natural fiber reinforced cementitious matrix (NFRCM) materials, are still at a developing phase of study although they represent a promising solution for masonry strengthening as evidenced in some interesting applications reported in [9–13].

Generally, the mechanical behavior and the effectiveness of FRCM systems depend on different aspects such as the mechanical properties of the support and the reinforcement materials, the adherence between the mortar and the support (it is particularly influenced by the modalities of execution), and the interaction between the mortar and the reinforcement at the interface level.

In particular, experimental evidence [14–18] showed that failure in systems with synthetic fibers can occur with different mechanisms such as cohesive failure of the substrate, debonding at the matrix/substrate interface or at the textile/matrix interface, sliding or tensile failure of the textile within the mortar thickness, and tensile failure of the textile in the unbonded portion.

Differently from FRCM, NFRCM systems present failure modes occurring mainly inside the matrix because of lower resistances of natural fibers with respect to the synthetic ones, as evidenced in the experimental tests reported in [10,19]. Indeed, the results presented in [10], obtained from single-lap shear tests on sisal-NFRCM, have evidenced a tensile failure of the textile within the matrix; the double-lap shear bond tests on flax-NFRCM described in [19], have evidenced a progressive failure of the flax fibers characterized by an initial break in the matrix, followed by the breaking/stretching of the single yarns, with a shear stress–displacement curve characterized by a final softening.

In this paper a numerical study devoted to examining both the out-of-plane behavior of masonry façades of buildings in aggregate and the feasibility of strengthening systems made of natural fibers embedded in cementitious matrices for the prevention of out-of-plane mechanisms is presented. To this purpose, the kinematic analysis approach is employed by introducing the constitutive local bond behavior of reinforcement into equations, i.e., the debonding phenomenon, experimentally deduced from literature studies.

Section 2 is initially devoted to analyzing the out-of-plane behavior of perimeter façades of a URM building aggregate by considering the interaction with the contiguous structural units. Subsequently, a finalized numerical study is presented to investigate the contribution provided by FRCM systems made of natural fibers on the 'global' out-of-plane response of masonry façades. Subsequently, Section 3 describes the application of the proposed approach to a real case study of an aggregate building in Borgo San Rocco in Sora, a typical medium town located in Central Italy.

2. Out-of-Plane Behavior of Masonry Walls in URM Aggregate Buildings: The Effect of Strengthening

2.1. Out-of-Plane Behavior of Masonry Walls in URM Aggregate Buildings

One of the peculiarities of URM aggregated buildings is the mutual interaction between adjacent structural units (S.U.) [20–24]. This effect, named the aggregate effect by the authors in [25], could play a relevant role for both in-plane and out-of-plane seismic behaviors.

The seismic safety assessment of masonry buildings towards out-of-plane mechanisms is commonly performed by using the kinematic analysis approach, as also suggested by the current Italian codes and the related guidelines [18,26–28] and international guidelines [29], and employed in several recent scientific literature works [2,30–34]. The approach consists of identifying the possible out-of-plane mechanism [30] and, then, evaluating the horizontal loads multiplier activating the mechanism (linear kinematic analysis) and, in the case of nonlinear kinematic analysis, the capacity curve [26].

Considering the case of a façade wall subjected to a simple global overturning mechanism (Figure 1a), the equation governing the equilibrium in a generic deformed configuration (Figure 1b) can be obtained by applying the principle of virtual work:

$$L_e = L_i \quad (1)$$

where the work done by the external forces, L_e, is given by the contribution of vertical loads and horizontal forces as follows:

$$L_e = \alpha(\theta) \cdot W \cdot \delta_x{}^{w\prime} - W \cdot \delta_y{}^{w\prime} \quad (2)$$

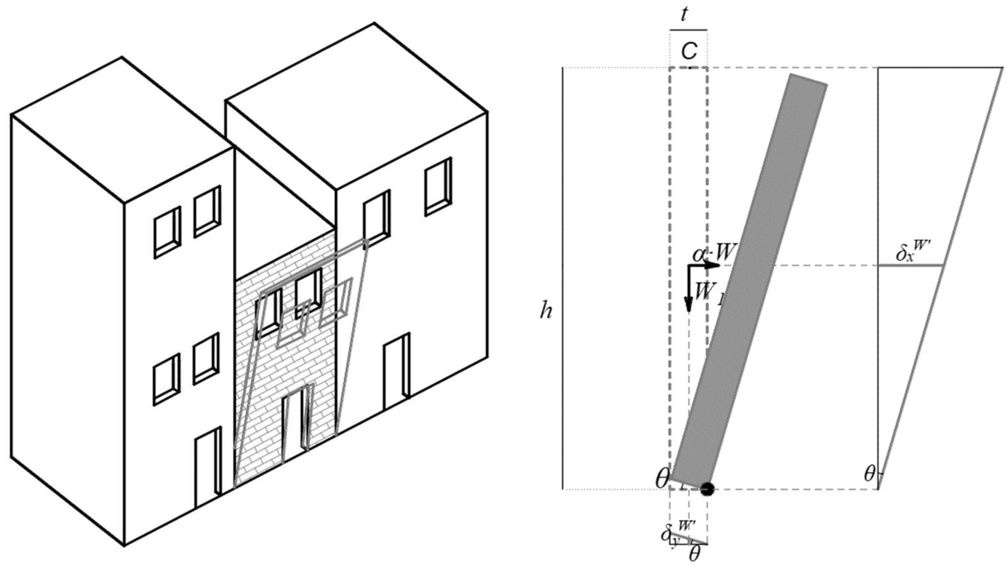
where:

θ is the virtual rotation of the wall;

W is the weight of the wall;

$\alpha(\theta)$ is the horizontal load multiplier;

$\delta_x{}^{w\prime}$ and $\delta_y{}^{w\prime}$ are, respectively, the horizontal and vertical virtual displacements of the point of application of the weight (see Figure 1b).



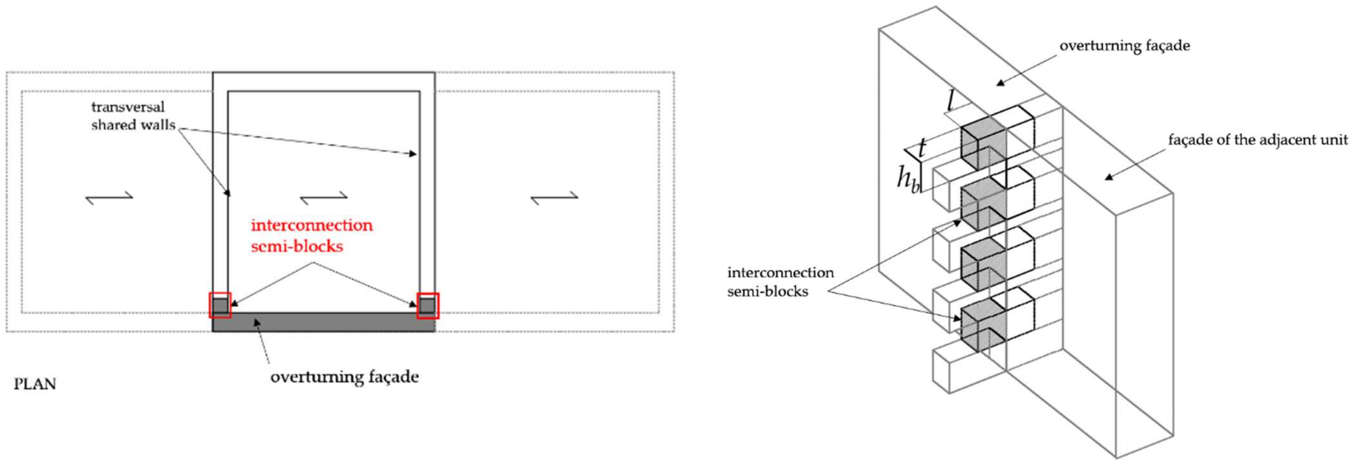
(**a**) (**b**)

Figure 1. (**a**) Façade wall subjected to a global simple overturning; (**b**) overturning façade in the deformed configuration with acting forces and virtual displacement without considering any interaction among the units (no aggregate effect).

On the other hand, in the case of absence of friction between the overturning façade and the adjacent walls (meaning absence of any aggregate effect), the work done by the internal forces, L_i, is zero and, consequently, the horizontal load multiplier as a function of the angle of rotation is provided by the following equation:

$$\alpha(\theta) = [W \cdot 3(-y_W 3\sin\theta + x_W 3\cos\theta)]/[W3(x_W 3\sin\theta + y_W 3\cos\theta)]. \quad (3)$$

However, in the case of aggregate buildings the mutual interaction among adjacent structural units can play an important role, as suggested in recent studies [25] and in the instructions of the Italian code [26]. The effect of interaction can be introduced in terms of frictional forces acting at the interconnection semi-blocks [34–37] when the overturning façade and the transverse walls of the adjacent units are connected as shown in Figure 2a,b.



(**a**) (**b**)

Figure 2. (**a**) Plan view of the structural unit where the interconnection semi-blocks between the overturning façade and the transverse walls shared with the adjacent units are evidenced; (**b**) profile of the interconnection semi-blocks.

The resultant of the friction forces, according to Coulomb's law, depends on the weight acting on the interconnection semi-blocks. Specifically, with reference to an S.U. included between two S.U.s of greater height (Figure 1a), the friction force can be evaluated through the following expression [25]:

$$F = \mu \cdot (W_{uw1} + W_{uw2} + W_{s1} + W_{s2} + 2 \cdot \sum f_i) \tag{4}$$

In Equation (4):

- μ is the friction coefficient [26],
- W_{uw1} and W_{uw2} are the weights of the transversal walls placed above the interconnection semi-blocks, respectively, on the right and on the left side of the façade (Figure 3a),
- W_{s1} and W_{s2} are the loads transmitted to the interconnection semi-blocks by the slabs, in the case of slabs parallel to the façade (Figure 3b).
- f_i is the weight of the *i*-th interconnected semi-blocks given by the expression [35,36]:

$$f_i = \gamma_m \cdot t \cdot h_b \cdot l \cdot i \cdot (i + 1)/2, \tag{5}$$

where:

- i is the *i*-th row of blocks crossed by the vertical crack line (Figure 3a,b),
- γ_m is the specific weight of the masonry,
- t is the thickness of the transversal wall (Figure 2b),
- h_b is the height of the block (Figure 2b),
- l is the length of the contact surface between two overlapped blocks (Figure 2b).

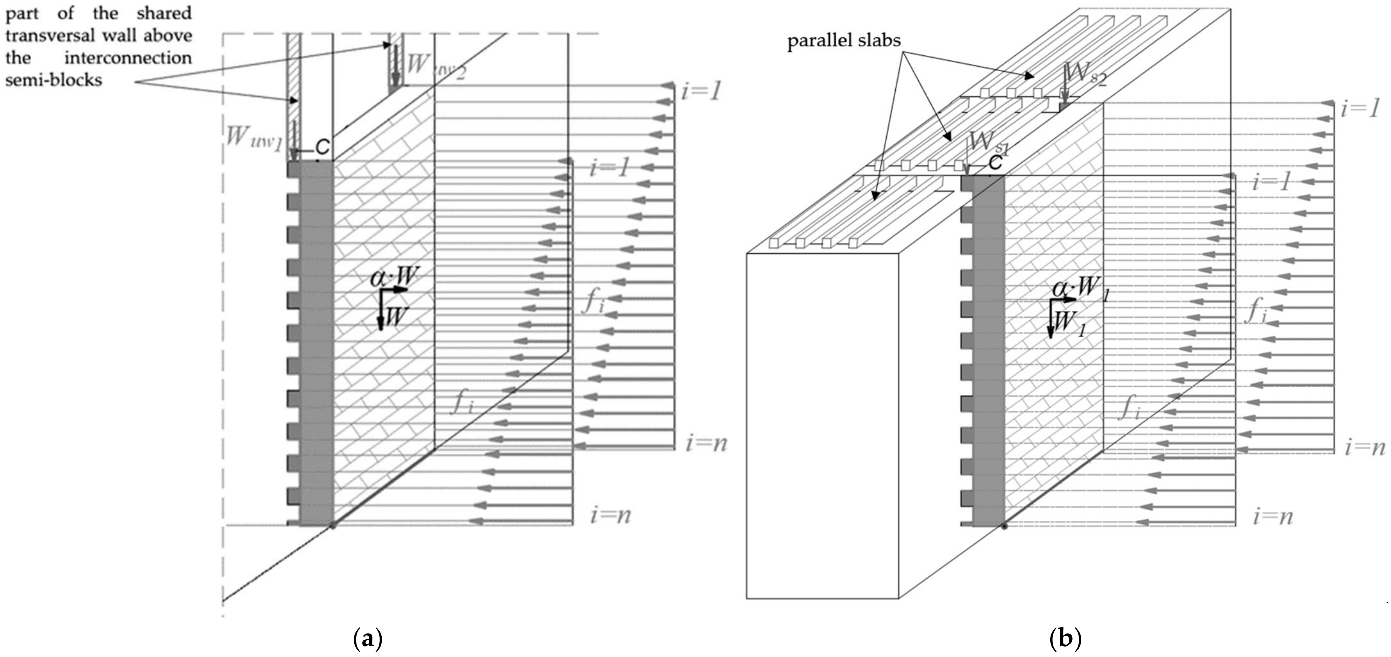


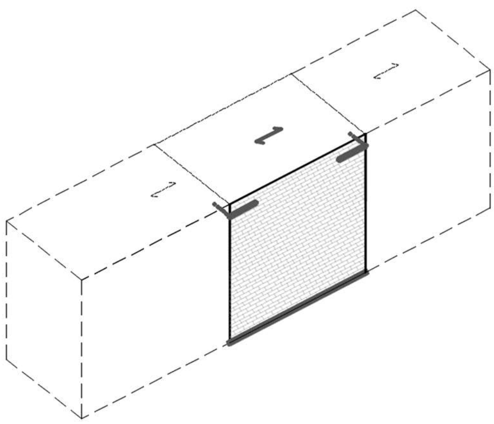
Figure 3. (**a**) Weights of the transversal walls placed above the interconnection semi-blocks; (**b**) loads transmitted to the interconnection semi-blocks by the slabs parallel to the façade.

In the presence of friction forces, the work done by the internal forces, L_i, is no longer zero but equal to:

$$L_i = F \cdot \delta_x^{F\prime} \quad (6)$$

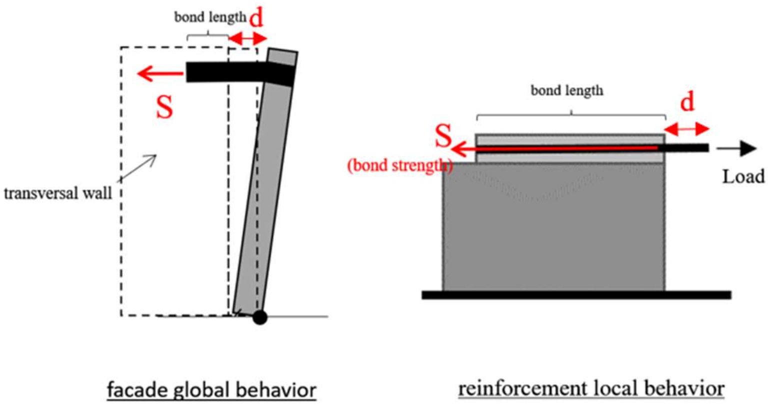
where:

- F is the resultant of the friction forces evaluated through Equation (4);
- $\delta_x^{F\prime}$ is the horizontal virtual displacement of the point of application of force F (Figure 4c).



(**a**)

Figure 4. *Cont.*



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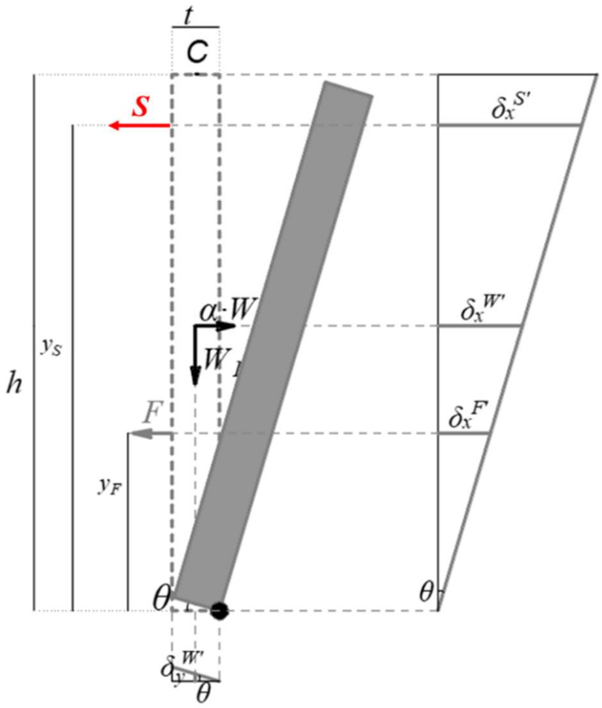


(**c**)

Figure 4. (**a**) FRCM strips arranged along the wall prone to the overturning mechanism and fixed to sidewalls; (**b**) reinforcement contribution depending on the local adhesion behavior; (**c**) overturning façade in the deformed configuration with acting forces and virtual displacement considering the mutual interaction among the units (aggregate effect) and the contribution provided by the FRCM reinforcement.

Then, considering the external work L_e, given by Equation (2), and the internal work L_i, given by Equation (6), the horizontal load multiplier as a function of the angle of rotation in the case of considering the interaction, in terms of friction forces, becomes:

$$\alpha(\theta) = [W\cdot(-y_W \sin\theta + x_W \cos\theta) + F\cdot(x_F \sin\theta + y_F \cos\theta)]/[W\cdot(x_W \sin\theta + y_W \cos\theta)] \quad (7)$$

However, the contribution of the friction is not constant during the evolution of the mechanism: it is maximum at the activation of the mechanism and it progressively decreases during the overturning as the overlapping of the interconnection blocks is lost.

2.2. Strengthening Interventions toward Out-of-Plane Overturning Mechanisms

Although the contribution of the interaction between contiguous S.U. increases the capacity of the façade toward out-of-plane mechanisms, the level of seismic safety of aggregate buildings can often be low. This implies the need to provide suitable interventions aimed at preventing out-of-plane mechanisms.

The use of externally applied fiber reinforced composite materials to masonry buildings represents an efficient and, nowadays, increasingly used solution as already discussed in the introduction of the paper. Generally, in the case of overturning mechanisms of an S.U. façade belonging to an aggregate building, the FRCM material is applied as strips along the wall prone to the mechanisms and fixed to the adjacent orthogonal walls as schematically shown in Figure 4a.

Similarly to friction, the contribution of the strengthening system, activated at the beginning of the out-of-plane mechanism, evolves during the progress of the kinematics of the façade subjected to overturning. Indeed, similarly to what happens during a single-lap shear bond test [17], the reinforcement contribution depends on the displacement at its loaded end which, as shown in Figure 4b, corresponds to the lateral displacement of the façade in its out-of-plane overturning direction. Consequently, the contribution of the reinforcement can be provided by the nonlinear force-displacement law directly deduced from a shear lap test related to the reinforcement/support specimen.

Then, in the presence of the reinforcement, in addition to the friction forces due to the aggregate effect, the work done by the internal forces, L_i, becomes:

$$L_i = F \cdot \delta_x^{F'} + 2 \cdot S \cdot \delta_x^{S'} \quad (8)$$

where:

- S is the contribution provided by the strengthening (Figure 4b,c);
- $\delta_x^{S'}$ is the horizontal virtual displacement of the point of application of the force S (Figure 4c).

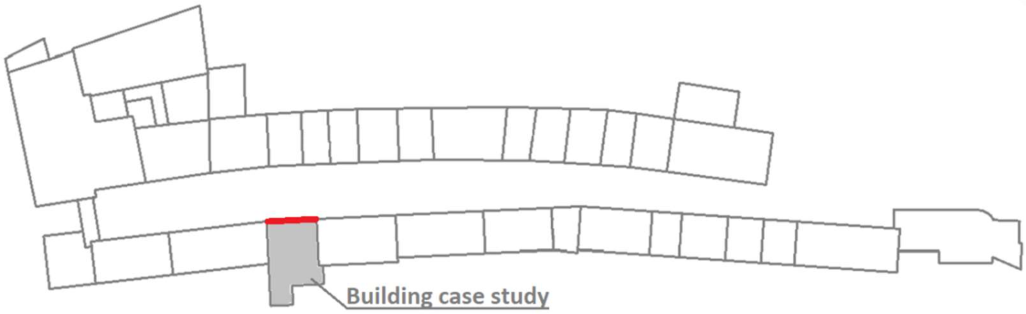
Then, considering the external work L_e, given by Equation (2), and the internal work L_i, given by Equation (8), Equation (1) becomes:

$$\alpha(\theta) = [W \cdot (-y_W \sin\theta + x_W \cos\theta) + F \cdot (x_F \sin\theta + y_F \cos\theta) + 2 \cdot S \cdot (x_S \sin\theta + y_S \cos\theta)] / [W \cdot (x_W \sin\theta + y_W \cos\theta)] \quad (9)$$

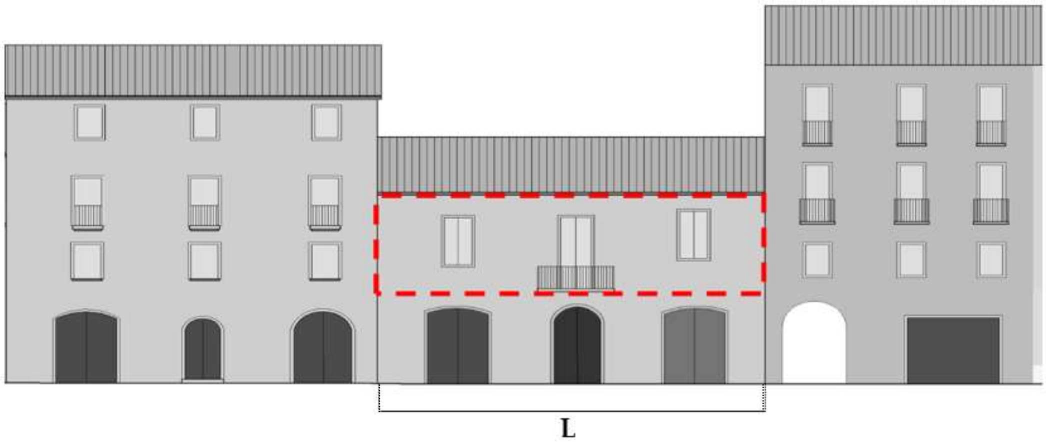
Equation (9) provides the horizontal load multiplier as a function of the angle of rotation in the case of considering the interaction, in terms of friction forces, between the wall subjected to global simple overturning and the adjacent walls, and the contribution of the strengthening system.

3. Case Study

The building examined in this study belongs to one of the building aggregates of Borgo San Rocco (Figure 5a), a case study located in the historic center of Sora (Italy) and analyzed in [30,31]. The building is made of soft stone masonry rubble with slabs and coverage made of wood and parallel to the façade. In particular, the examined building is a two-story unit included between two adjacent four-story units (Figure 5b); on the basis of the previous study presented in [30], the façade of the examined S.U. presents the partial overturning of the second level as the most likely out-of-plane collapse mechanism. With reference to this type of mechanism, the seismic response of the façade wall has been analyzed, as reported in the following subsections.



(**a**)



(**b**)

Figure 5. (**a**) Borgo San Rocco's plan (the analyzed façade is reported in red); (**b**) prospectus of the analyzed S.U. (the portion of the overturning façade is reported in red).

The geometric data of the overturning portion of the façade and of the interconnected blocks are reported in Table 1.

Table 1. Geometric data of the overturning façade and of the interconnection blocks.

Dimension of the Overturning Wall			Dimension of the Interconnection Blocks	
h (m)	L (m)	t (m)	h_b (m)	l (m)
3.9	8	0.70	0.15	0.20

The kinematic analysis of the overturning portion of the façade has been carried out following the procedure illustrated previously in Section 2.1.

In particular, the contribution of the aggregate effect has been evaluated with the actions acting on the wall as shown in Figure 6. The capacity curves obtained by the analysis are reported in Figure 7 where the black curve refers to the case neglecting the aggregate effect and the grey curve to the case of including the aggregate effect. From the figure, the increase of capacity of the façade considering the aggregate effect and, at the same time, the progressive reduction of the contribution due to this effect is evident.

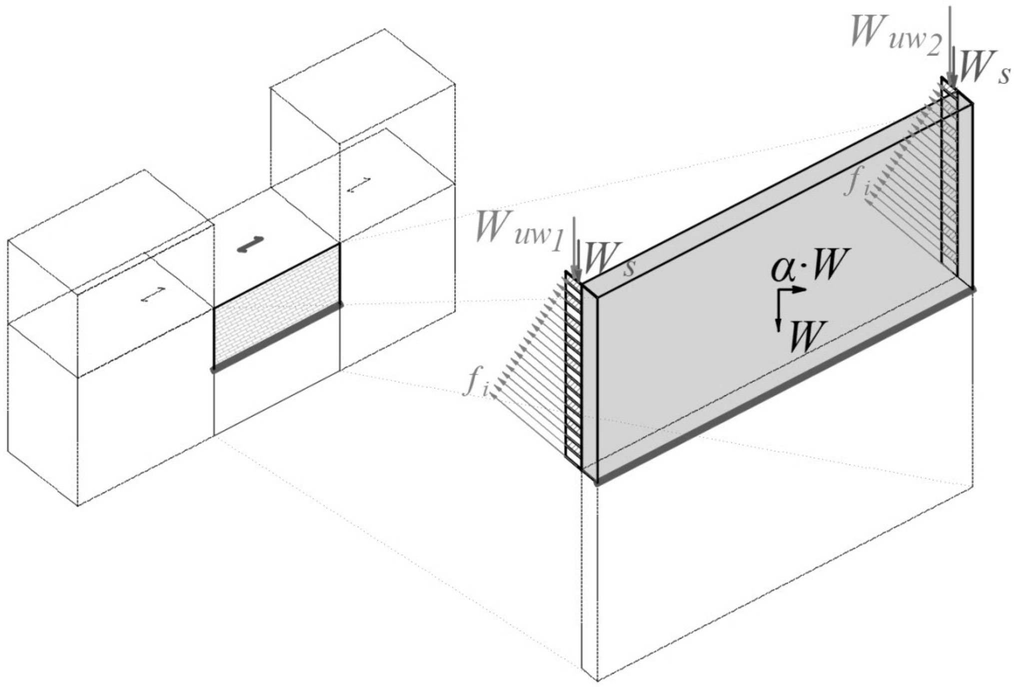


Figure 6. Forces acting on the portion of overturning façade wall of the S.U. due to the mutual interaction between the units (aggregate effect).

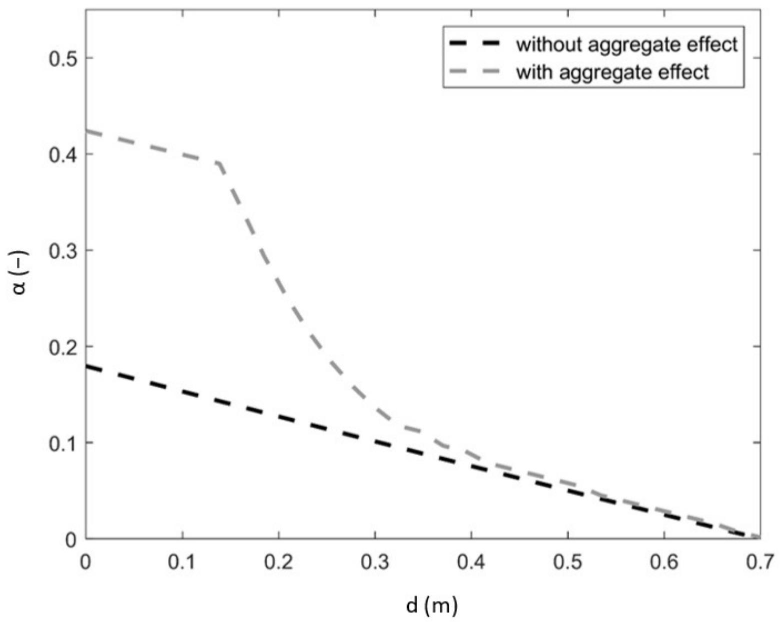


Figure 7. Horizontal loads multiplier α vs. displacement *d* of the overturning wall.

Strengthening Solutions: Natural Fibers vs. Synthetic Fibers

Two different strengthening solutions have been considered, both assumed in the form of strips of width equal to 200 mm at the top of the wall, as shown in Figure 8.

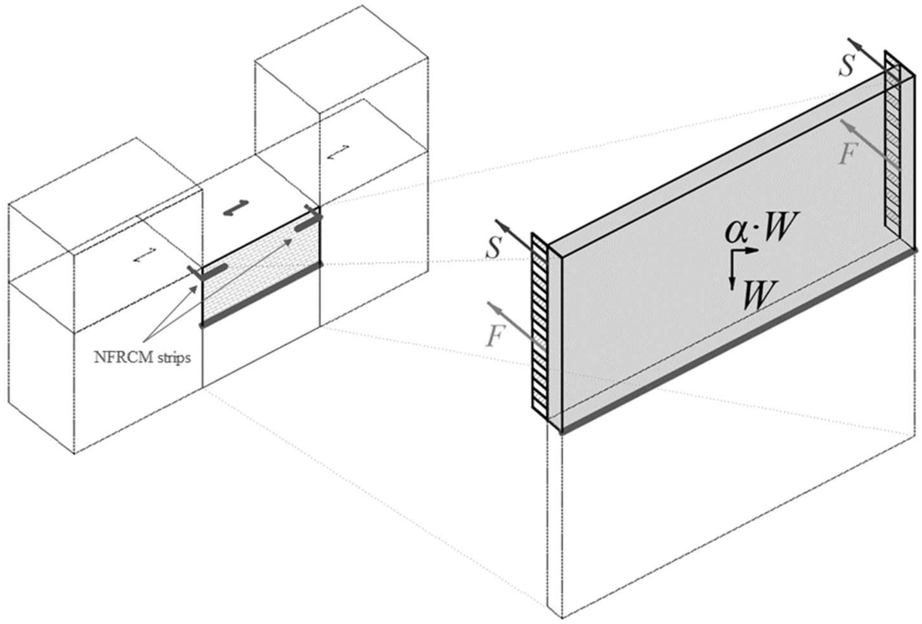


Figure 8. Forces acting on the portion of façade wall prone to the overturning when a strengthening intervention with NFRMC strips is applied.

The first type of reinforcement is made of sisal-FRCM, investigated in [10] through single-lap shear tests in accordance with the RILEM protocol. The second type of strengthening solution is made of FRCM with synthetic fibers in PBO, experimentally investigated through single-lap shear tests in [38].

The main mechanical properties of the accounted strengthening systems are summarized in Table 2.

Table 2. Mechanical characteristics of the FRCM system used in the analysis.

FRCM	Yarns			Mortar	
	$E_{t\,eq}$ (MPa)	ε_u (%)	f_t (MPa)	$E_{t\,eq}$ (MPa)	f_c (MPa)
Sisal [10]	7853	3.04	239.7	700	13
PBO [39]	206,000	1.45	3014	>7000	28.4

The force of the strengthening, S, during the progress of the out-of-plane kinematics to introduce Equation (9), has been directly evaluated, for the two types of strengthening, from the experimental data of shear-lap tests provided in terms of the normal stress s vs. the slip d at the loaded end of the strip, that is:

$$S = \sigma(d)\, A_f \tag{10}$$

where A_f is the cross-section of the reinforcement accounted for in the case study. This datum has been obtained by means of a geometric proportion in terms of the width between the strip used for the accounted shear lap tests in [10,38] and the ones applied to the façade.

The force-displacement curves S–d (where the slip d at the end of the loaded end of the strip during the shear lap tests corresponds to the displacement of the façade at the section where the reinforcement is applied as shown in Figure 4b) obtained for the two types of accounted strengthening systems are reported in Figure 9. From the figure the different local behaviors in terms of stiffness, strength, and post-peak phase (the latter underlines a fragile behavior of natural fibers due to the tensile rupture of fibers during the tests) are evident.

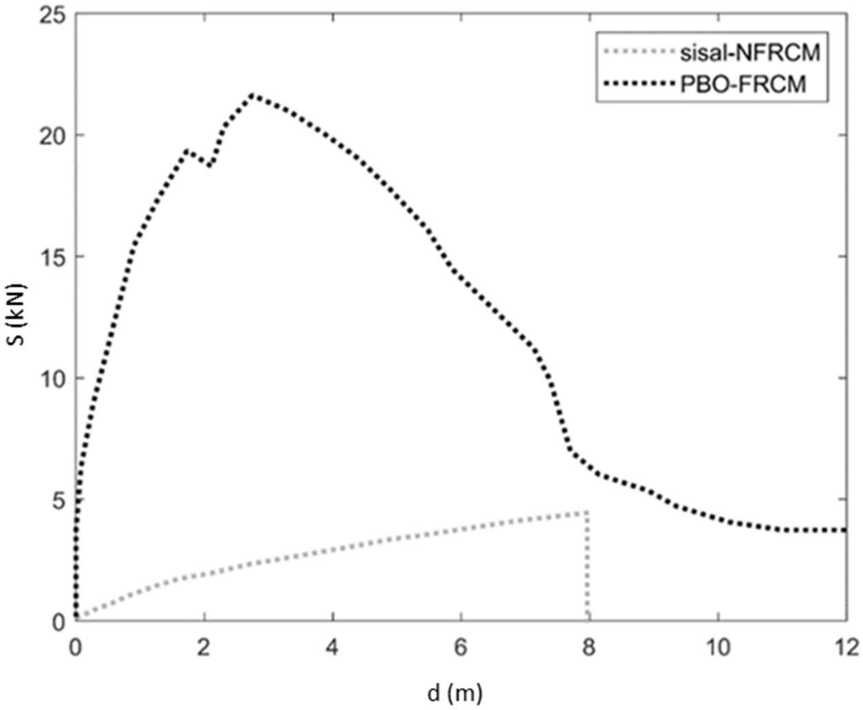


Figure 9. Force–displacement curves obtained for two FRCM systems considered for the comparison.

The kinematic analysis of the overturning portion of the façade with the contribution of the strengthening has been carried out following the procedure illustrated previously in Section 2.2. The obtained capacity curves of the façade are reported in Figures 10 and 11, respectively, for natural fibers and PBO, where the black curve refers to the case without the aggregate effect and the grey curve to the case with the aggregate effect.

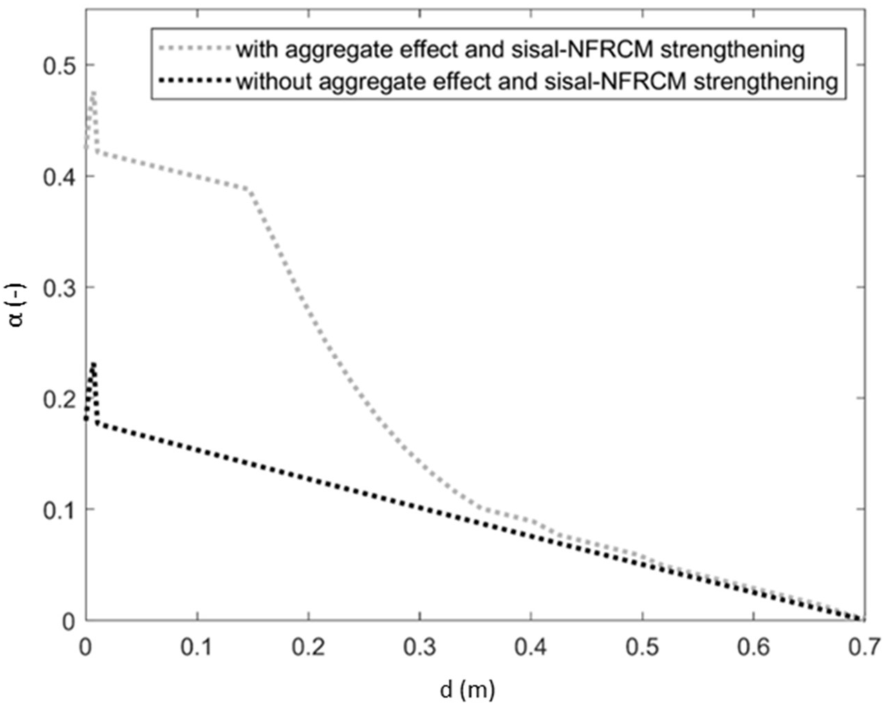


Figure 10. Horizontal loads multiplier α vs. displacement d of the overturning wall strengthened by sisal-FRCM.

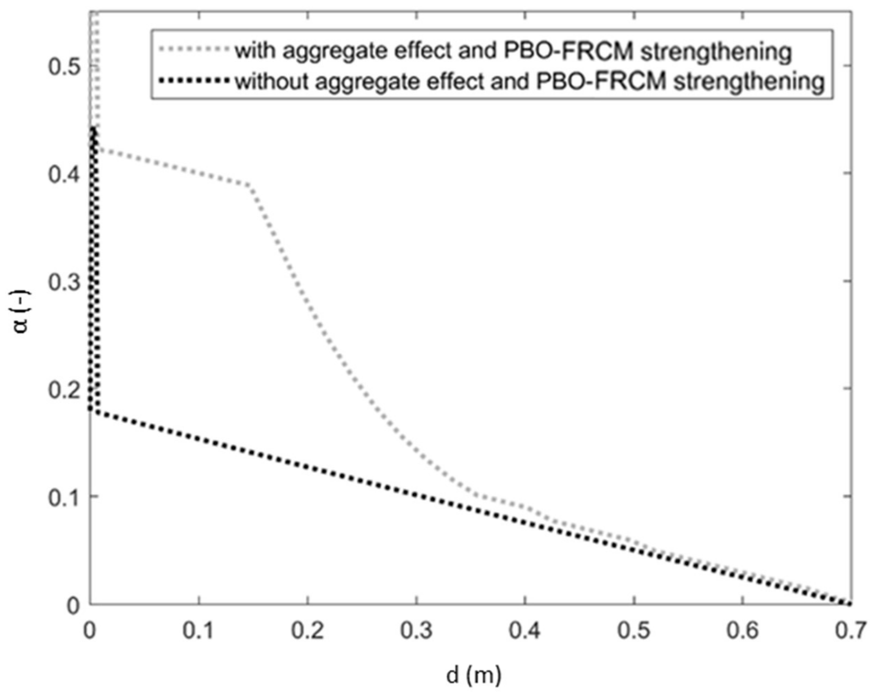


Figure 11. Horizontal loads multiplier α vs. displacement *d* of the overturning wall strengthened by PBO-FRCM.

In Figure 12 the capacity curves of the façades for the two types of accounted strengthening systems are compared. As expected, the local bond behavior influences the global response of the façade. Indeed, PBO provides a greater increase of the horizontal load multiplier with respect to natural fibers. Nevertheless, in both cases, the post-peak behavior underlines a fragile response of the façade after the attainment of the bond strength of reinforcement.

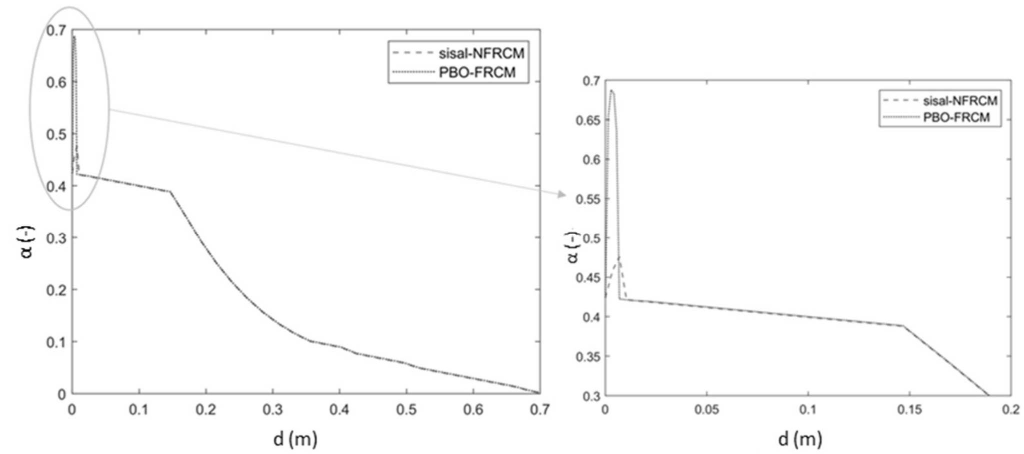


Figure 12. Horizontal loads multiplier α vs. displacement d of the overturning wall strengthened by FRCM with natural and synthetic fibers.

4. Discussion and Final Remarks

The study presented here has been finalized to numerically investigate the influence of the aggregate effect and the contribution of reinforcement systems made of natural fiber-reinforced composite materials on the out-of-plane behavior of perimeter façades of masonry buildings.

Both aggregate effect and reinforcement contribution have been considering by performing nonlinear kinematic analysis. Then, the results deduced in terms of capacity curves have been compared among them in order to appreciate the influence of both aggregate effect and reinforcement contribution on the out-of-plane behavior.

The results deduced from numerical analyses underlined both the influence of the aggregate configuration and the influence of strengthening systems made of natural fibers toward out-of-plane mechanisms induced by seismic actions.

Regarding the aggregate effect, it has been observed that it leads to a significant increase of the horizontal load multiplier, i.e., the capacity of the overturning wall. However, starting from the detachment of the façade from the transversal walls, this beneficial contribution decreases during the evolution of the mechanism.

Regarding the contribution of the strengthening system, it has been observed that, differently from the aggregate effect, its activation requires the activation of the out-of-plane mechanism. Nevertheless, due to the high stiffness of strengthening system (both natural and synthetic) the peak contribution corresponds to a small variation of the wall configuration. Additionally, it was noticed that the behavior of the façade with strengthening is influenced by the fragile local behavior of reinforcing materials, particularly in the case of natural fibers where the tensile rupture of fibers occurs. This leads to the decreased contribution of the strengthening system for values of the out-of-plane displacements being significantly lower than the ones corresponding to the remedial of the aggregate effect.

The above findings have emerged thanks to the approach proposed here by the authors where the contribution of the strengthening system has been correlated to the progress of the kinematics of the façade by directly accounting for the experimental local bond behavior. Indeed, the majority of approaches reported in literature simply consider an approximated rigid-fragile local behavior of the reinforcement: the out-of-plane mechanism of the façade activates when the bond strength of the reinforcement is attained; the subsequent kinematics do not account for the presence of the reinforcement. This type of approach does not allow considering of the influence of neither the pre- nor the post-peak local behavior of the reinforcement on the kinematics of the façade.

The goal of the present paper has consisted of presenting the proposed methodology aimed at accounting for both the friction and reinforcement contributions on the evolution of the kinematics of the façade. To this end, it has been supposed that the local bond behavior of FRCM systems deduced from shear lap tests carried out on a different type of masonry support, is the same for the masonry material composing the accounted façade. As underlined in the paper, since the tests deduced from literature underlined failure modes occurring inside the matrix, it seems reasonable to assume that the accounted law for the development of numerical analyses of the façade is not particularly influenced by the type of masonry support.

Nevertheless, it is also important to underline that, before applying the selected reinforcement system on the specific type of masonry composing the façade, it is necessary to perform specific tests finalized to assess the effective bond behavior of the selected type of reinforcement system. Indeed, in the particular case of historical masonry supports, incompatibilities between the material composing the matrix and those composing the masonry could lead to inefficient solutions characterized by mechanisms occurring at the interface between the masonry and the matrix instead of inside the matrix, with a consequently different local bond behavior.

Finally, it is also important to underline that the application of the proposed approach is closely related to the knowledge of the experimental constitutive bond behavior of the reinforcement. Nevertheless, future development of formulas for deriving simplified constitutive laws for this type of strengthening (nowadays available for FRP only) will allow for the use of the proposed approach as a practical design tool.

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