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SHAKE TABLE TESTS ON MASONRY WALLS STRENGTHENED WITH MORTAR-BASED COMPOSITES

Stefano De Santis[1], Gianmarco de Felice[1], Paolo Casadei[2], Gerardo De Canio[3], Marialuisa Mongelli[3], and Ivan Roselli[3]

[1] Roma Tre University, Department of Engineering
Via Vito Volterra 62, 00146 Rome, Italy
e-mail: stefano.desantis@uniroma3.it; gianmarco-defelice@uniroma3.it

[2] Kerakoll S.p.A.
Via dell'Artigianato 9, 41049 Sassuolo (MO), Italy
e-mail: paolo.casadei@kerakoll.com

[3] ENEA, Casaccia Research Centre
Via Anguillarese 301, 00123 Rome, Italy
e-mail: gerardo.decanio@enea.it; marialuisa.mongelli@enea.it; ivan.roselli@enea.it

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Abstract. *The paper presents the preliminary results of a shake table test carried out on a tuff masonry, natural scale, U-shaped assemblage (façade adjacent to transverse walls). The specimen has been subjected to scaled natural accelerograms with increasing intensity, inducing the detachment of the façade from the transverse walls and the activation of its rocking motion up to the out-of-plane overturning. The structure has been then repaired and strengthened with externally bonded reinforcement systems (SRG) comprising steel and slate textiles embedded in a hydraulic lime mortar matrix. Test results before and after the strengthening are compared in order to investigate the effectiveness of the SRG reinforcement in improving the seismic capacity of the structure, in the perspective of applying mortar-based composites for the seismic retrofitting of historic structures and the safeguarding of cultural heritage.*

1 INTRODUCTION

Past earthquakes have shown that the out-of-plane capacity of front walls is one of the crucial issues in the vulnerability of masonry structures. Due to the discontinuous nature of masonry, the perimeter walls tend to separate from internal structures, such as transverse walls and ground floors, and overturn. Numerous examples have been collected during recent strong earthquakes, ranging from civil constructions and aggregates [1] to large span buildings and churches [2].

Beyond traditional reinforcement techniques, such as tie bars, steel slabs, horizontal diaphragms, injections, and transverse connectors [3], innovative solutions have been developed that make use of externally bonded composites, which offer significant strength improvement without modifying the original structural geometry and masses. Mortar-based composites have been recently proposed, that provide remarkable advantages with respect to the more established Fibre Reinforced Polymers (FRPs) for application to historical substrates: better vapor permeability and material compatibility, cheaper and faster installation on uneven surfaces, and higher fire resistance. Furthermore, mortar based composites appear preferable for the retrofitting of historic buildings, which requires the fulfilment of specific preservation criteria [4]. New reinforcement systems are currently under development and proposed in the market for field applications. A deeper knowledge, however, still needs to be gained and, as a consequence, comprehensive instructions to practitioners concerning design parameters, dimensioning criteria, and installation methods are still lacking. Recent research on reinforcements with inorganic matrix has been mainly focused on their mechanical characterization in terms of tensile behaviour [5] and substrate-to-composite bond performance [6,7]. Some experimental investigations have been carried out on medium scale specimens [8,9], while large-scale dynamic testing have not been performed to prove their actual effectiveness for the protection against earthquakes.

This paper presents a shake table campaign carried out on a full-scale U-shaped masonry specimen (façade and two transverse walls), retrofitted with mortar-based composites. The wall has been tested without any reinforcements [10], and then repaired and retrofitted by means of galvanized steel textile and slate-stainless steel fabric, applied with hydraulic lime mortar. The systems is generally named as Steel Reinforced Grout (SRG). The specimen has been tested under scaled natural accelerograms, recorded during the most important Italian earthquakes of the last 35 years, applied with increasing scaling factor up to failure. The results are compared to show the effectiveness of the proposed strengthening solution.

2 DESCRIPTION OF THE SPECIMEN AND TEST SETUP

2.1 Specimen under investigation and pre-existent damage

The specimen is a full scale U-shaped masonry wall (Figure 1), consisting in a façade and two transverse walls. The façade is 3.30m long, 3.44m high and 0.5m thick; the transverse walls have the same thickness and height and are 2.30m long. The wall is made out of 350mm×370mm×110mm tuff units and hydraulic lime mortar and is built on a reinforced concrete foundation. The tuff has the following mean properties: 12.06kN/m^3 unit weight, 5.98N/mm^2 compressive strength and 1575N/mm^2 Young's modulus. The mortar has a mean compressive strength of 4.08N/mm^2, a Young's modulus of 2030N/mm^2 and a tensile strength (from three point bending tests) of 0.84N/mm^2.

The specimen has been subjected to a shake table campaign without any reinforcements [10], which caused the detachment of the façade from the transverse walls and its out-of-plane overturning. The resulting damage pattern comprised two vertical cracks, one per side, dividing the façade from the transverse walls (Figure 2a) and a horizontal crack at the fourth mortar bed joint, which constituted the overturning hinge. A vertical crack developed in the middle section of the façade induced by the impacts at the corners during motion (Figure 2b). Finally, some diagonal cracks formed at the top and mid-height of the front wall (Figure 2c).

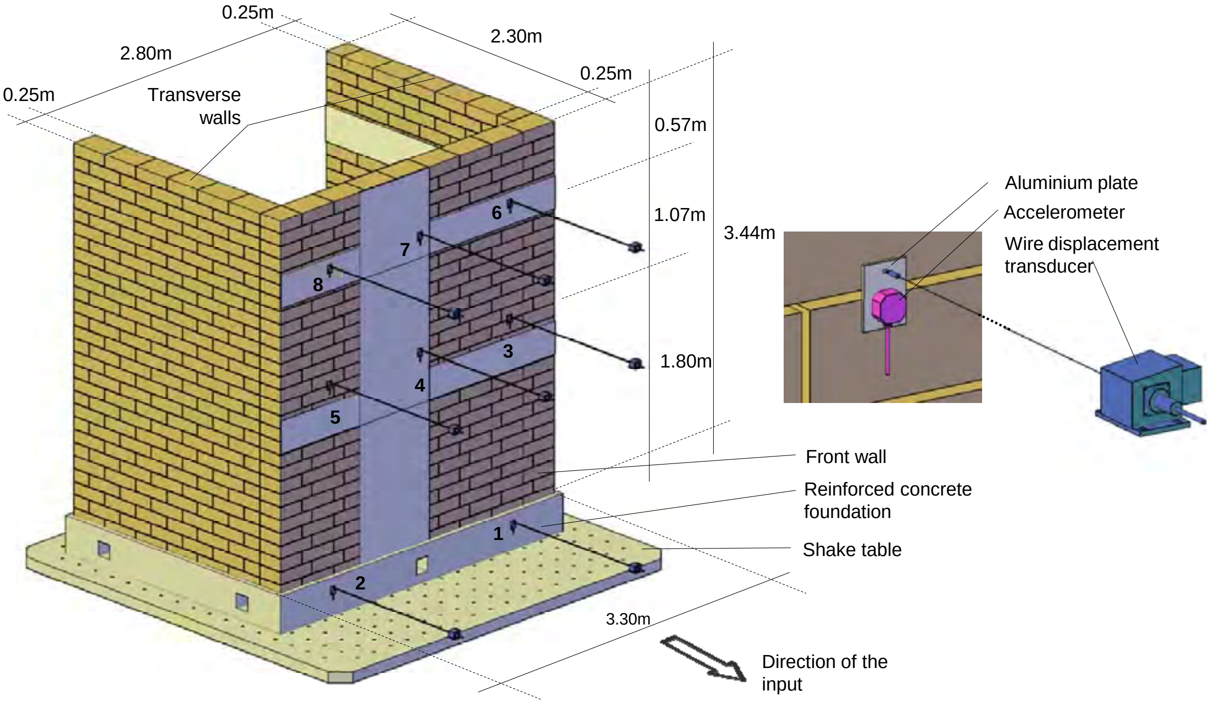

Figure 1. Specimen under study and test setup.

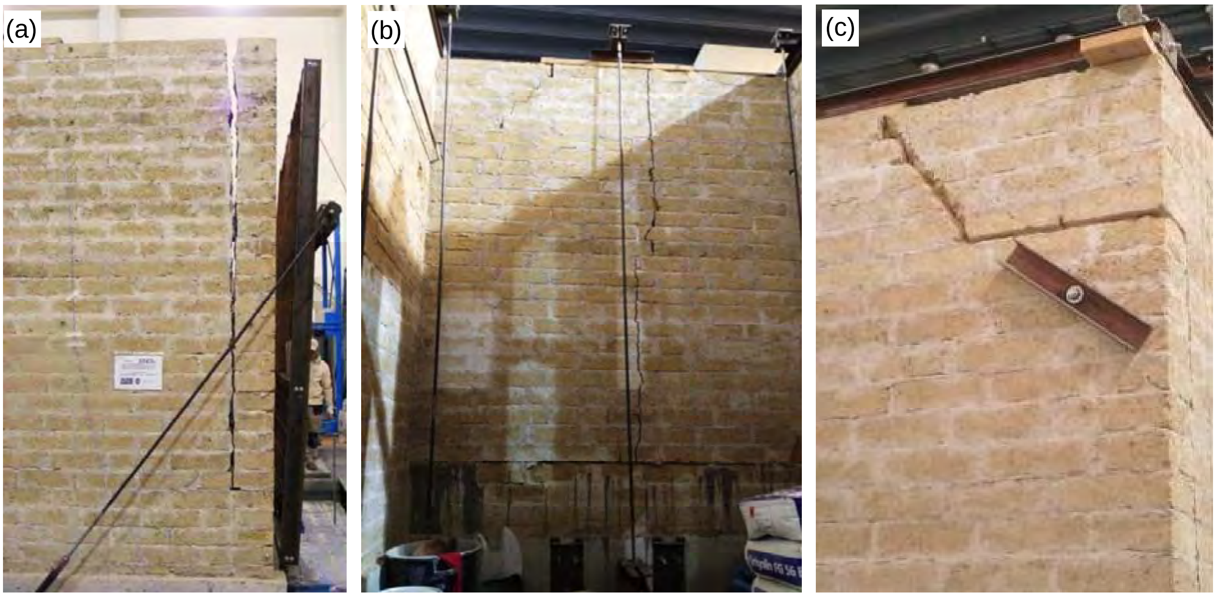

Figure 2. Pre-existent damage pattern induced by the tests series on the unreinforced specimen [10].

2.2 Test set up and instrumentation for data recording

Tests were carried out at ENEA Casaccia Research Centre, in Rome, Italy, equipped with a 4m×4m shake table, which is able to apply displacement or acceleration time histories within a frequency range of 0-50Hz with a maximum acceleration of ±3g. The instrumentation installed on the specimen to record test data is shown in Figure 1. One accelerometer and one wire linear potentiometer were installed by means of steel pivots drilled into the masonry in six measurement points on the front wall, three at 1.80m and three at 2.87m, and two on the foundation. The transducers were anchored to a steel frame placed out of the reaction mass of the shake table, in order to prevent measurements from being affected by floor vibrations. In order to record strains in the reinforcements, four resistive strain gauges were glued directly on the textiles and embedded into the mortar matrix, to prevent the measurements from being influenced by mortar cracking [11].

Test data were acquired at 100Hz frequency by means of a National Instruments system, the acquisition software was developed in LabView environment. A third-order baseline correction and a fourth-order Butterworth band-pass filter in the 0.35Hz-25Hz range have been used to process acceleration recordings; moreover a third-order band-stop filter was necessary in the 2.1-2.2 Hz range to remove errors related to sampling and background noise introduced by the shake table. Filtering parameters have been chosen by comparing the displacement time-histories derived by the double integration of accelerations against those measured by wire displacement transducers.

In addition, a high-resolution 3D motion capture system was installed which makes use of 9 near infrared cameras to record the displacement of a number of retro-reflecting markers glued on the specimen. The system allowed the measurement of the relative displacement between the two sides of the vertical cracks at the corners, and the in-plane deformation of the side walls, which were not monitored by accelerometers and displacement transducers [12].

2.3 Input signals

Records from the main Italian earthquakes of the last 35 years (all related to normal faulting events) were used in the tests. Input signals are collected in Table 1, also listing the year, the magnitude (M), the record name, the peak ground acceleration (PGA), velocity (PGV), and displacement (PGD). Signals were applied with increasing scaling factor (SF) ranging from 0.10 to 2.50, in direction normal to the front wall (unidirectional tests).

Table 1. Italian accelerograms selected to perform shake table tests.

#	Earthquake	Year	M	Record	PGA [g]	PGV [mm/s]	PGD [mm]
1	Irpinia	1980	6.9	CalitWE	0.181	281	90
2	Irpinia	1980	6.9	BagnirWE	0.167	374	135
3	Emilia	2012	5.9	MrnWE	0.261	298	90
4	Irpinia	1980	6.9	SturWE	0.313	705	309
5	Aquila	2009	6.3	AQGNS	0.451	372	39
6	Umbria-Marche	1997	6.0	R1168EW	0.438	288	42

3 SEISMIC RETROFITTING

Two reinforcement textiles were used in the retrofitting intervention: an unidirectional mesh of galvanized Ultra High Tensile Strength Steel (UHTSS) cords (Figure 3a), spaced 6.35mm (4 cords/inch, Figure 3b), having 3207N/mm^2 tensile strength and 183.9kN/mm^2 Young’s modulus [5]; and a balanced bidirectional fabric made out of slate yarns and stainless steel wires (Figure 3c), having 1447N/mm^2 tensile strength and 275.1kN/mm^2 Young’s modulus (from direct tensile tests). A mineral NHL mortar was used to apply the reinforcement textiles. It comprises natural kaolin, bauxite and hydraulic lime (NHL) binders and has

20.6N/mm^2 compressive strength, 5.4N/mm^2 tensile strength (from three point bending tests) and 11400N/mm^2 Young’s modulus.

The retrofitting intervention (shown in Figure 4) comprises 12 steel connectors retaining the façade towards out-of-plane overturning, two horizontal SRG strips applied to the front wall to increase its bending resistance and transfer the retaining effect of the connectors, and, finally, two strips of bidirectional slate-stainless steel textile applied to both the external and internal surfaces of the façade to repair existing damage and contribute to its bending capacity. The installation required two working days of two specialised workmen. First, existing cracks were filled with hydraulic lime mortar to restore continuity and prevent impacts during motion. In order to consolidate the tuff substrate and remove dust, an aqueous solution of potassium silicate was applied prior to the laying of the first mortar layer (Figure 5a). Then, the slate-stainless steel net and the two SRG strips were installed on the façade. Two 300mm wide strips of UHTSS cord textile were applied to the internal surfaces of each transverse wall, for its whole length and at the same height of the external SRG bands (Figure 5b). The textiles were pressed slightly into the fresh mortar, which protruded through all the perforations between fibre rovings. Finally, a second layer of mortar was applied, for an overall thickness of about 5-6mm (Figure 5c). In the vicinity of the façade, each strip was divided into three portions to obtain the connectors, which were then placed into ∅30mm holes drilled through the front wall (Figure 6a). Each of the 12 connectors was made out of a 100mm wide band of steel textile. On the outer side, the connectors were unfold for a length of about 100mm, out of the SRG horizontal band (Figure 6b), and fixed by means of resin wedges (Figure 6c), while the mortar was still fresh. Finally, the holes were injected with a fluid NHL mortar (Figure 6d). The specimen was stored in laboratory conditions for about 40 days before testing.

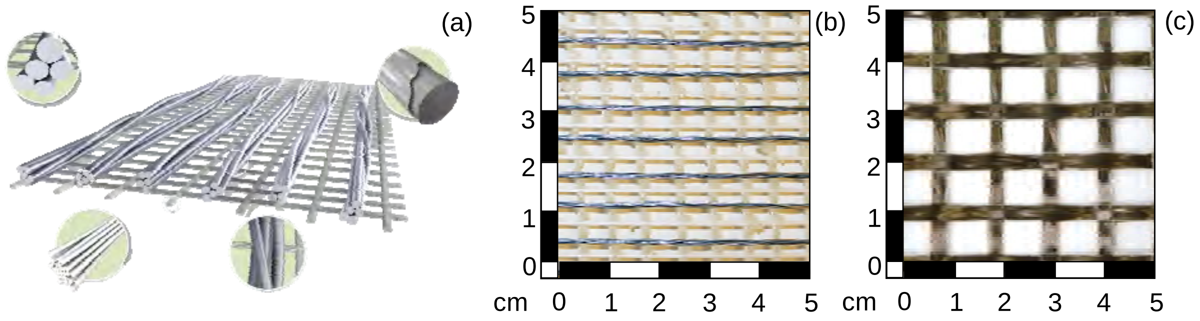

Figure 3. Reinforcement textiles applied for the seismic retrofitting: galvanized ultra-high tensile strength steel (UHTSS) cord detail (a) and unidirectional textile (b); slate-stainless steel bidirectional mesh (c).

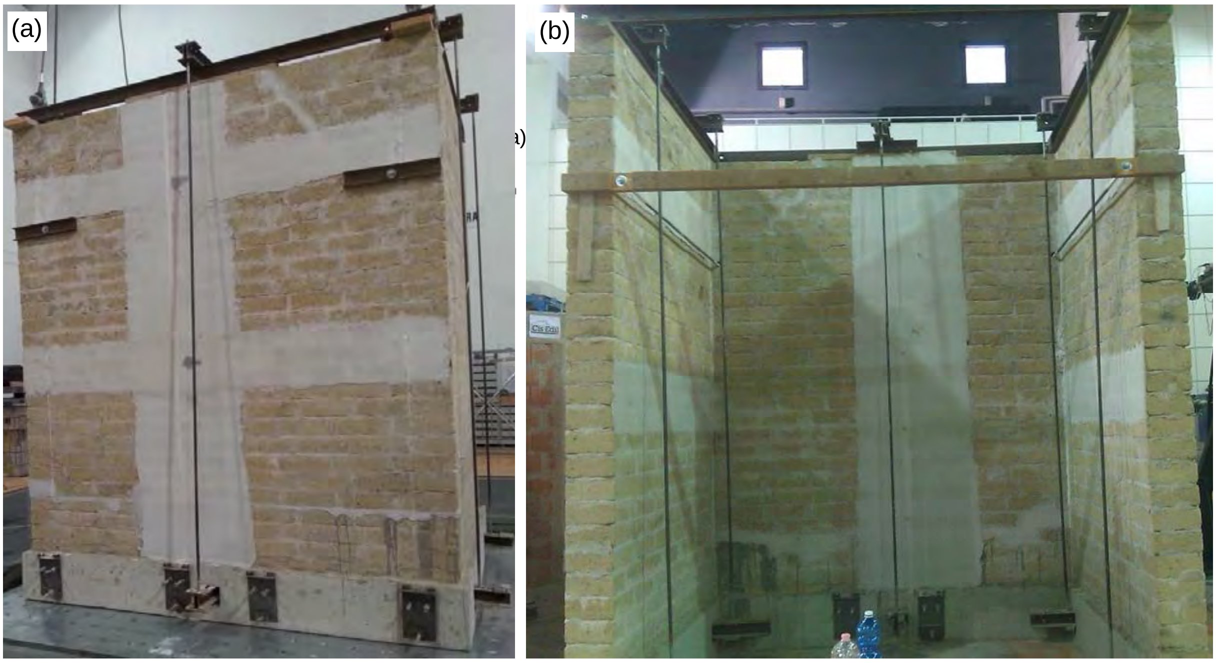

Figure 4. Specimen after the installation of the mortar-based reinforcement: external (a) and internal (b) views.

Figure 5. Installation of the mortar-based reinforcement: laying of the first layer of hydraulic lime mortar on the consolidated substrate (a), application of the steel textile (b), and laying of the covering mortar layer (c).

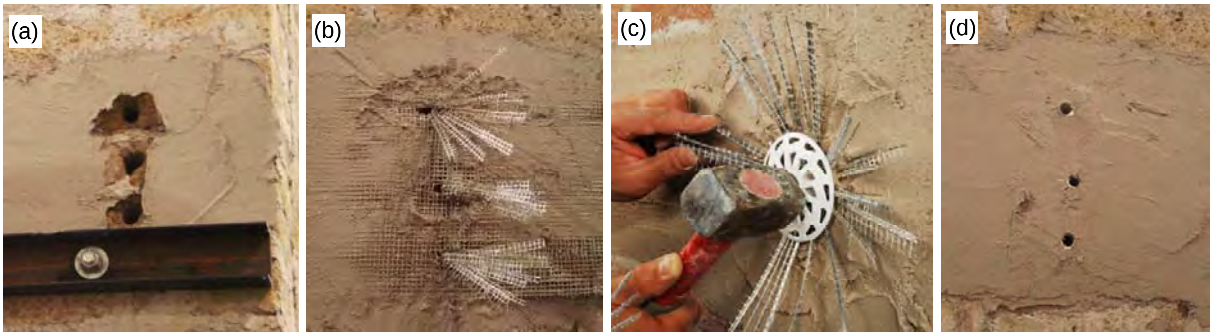

Figure 6. Installation of the steel connectors on the façade: drilled holes through the wall and the horizontal SRG strip (a), unfolding of the connectors (b), installation of the wedges (c), mortar finishing prior to injecting (d).

4 TEST RESULTS AND COMPARISONS

Totally, 57 shake table tests have been carried out on the retrofitted specimen, starting from 0.10 scaling factor, up to failure. The first damage was detected after MrnWE record with SF=1.0. A narrow crack appeared in the vertical joint between façade and left wall. The strain gauge glued on the left connector indicated that wall separation with small relative movements occurred. During the SF=2.0 test series a vertical crack between façade and right wall developed. Damage remained extremely limited until the application of R1168WE input amplified by a factor of 2.50. The acceleration recorded on the foundation had 1.507g PGA and 583.8mm/s PGV. The façade completely separated from the transverse walls (Figure 7a). Nevertheless, the steel connectors didn't fail nor were pulled off from the front wall, and the horizontal reinforcements on the side walls did not detach. The façade experienced a severe vertical bending, such that a vertical crack divided the wall into two portions, which rotated inwards around the connectors (Figure 7b). The tensile load on the connectors retaining the façade was transferred by adhesion of the SRG strips to the side walls. A diagonal crack developed on both of them, from the bottom connectors to the opposite corner; moreover, an horizontal crack developed for the whole length of the traverse walls, separating them from the foundation (Figure 7c). Sliding of 10mm and 25mm were measured on the right wall and on the left wall, respectively. Despite the severe damage, no portions of masonry felt down.

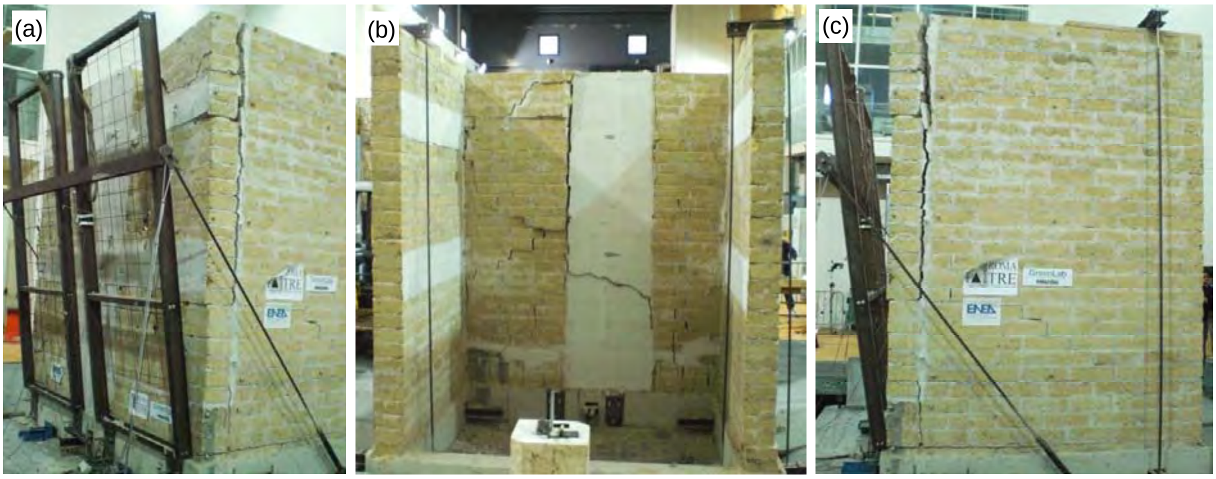

Figure 7. Specimen after collapse: front wall from outside (a) and inside (b), and right side wall (c).

The results derived for the instruments installed on the specimen (Figure 1) are represented in terms of vertical and horizontal bending, the former being expressed as the relative displacement (δu) between two measurement points vertical aligned (e.g., T_6-T_1 or T_8-T_2), and the latter being the relative displacement between two measurement points horizontally aligned (e.g., T_7-T_6 or T_7-T_8). Finally, the record of the seismic input assigned to the specimen is provided by the time histories acquired in the measurement points 1 and 2. Figure 8 shows the response to 2009 L'Aquila earthquake (M=6.3), amplified with a scale facto of 2.0, corresponding to a peak ground acceleration of 1.089g (Figure 8a). The horizontal bending is induced by a relative displacement of about 70mm (over a height of about 3m) (Figure 8b), while the vertical bending is related to a relative displacement of the centre of the façade of nearly 2mm with respect to the corners (Figure 8c). The two time histories plotted in both these graphs are in good agreement, thus indicating that the behaviour of the specimen is practically symmetric. Moreover, despite the high intensity of the input, the residual displacement is negligible in all cases.

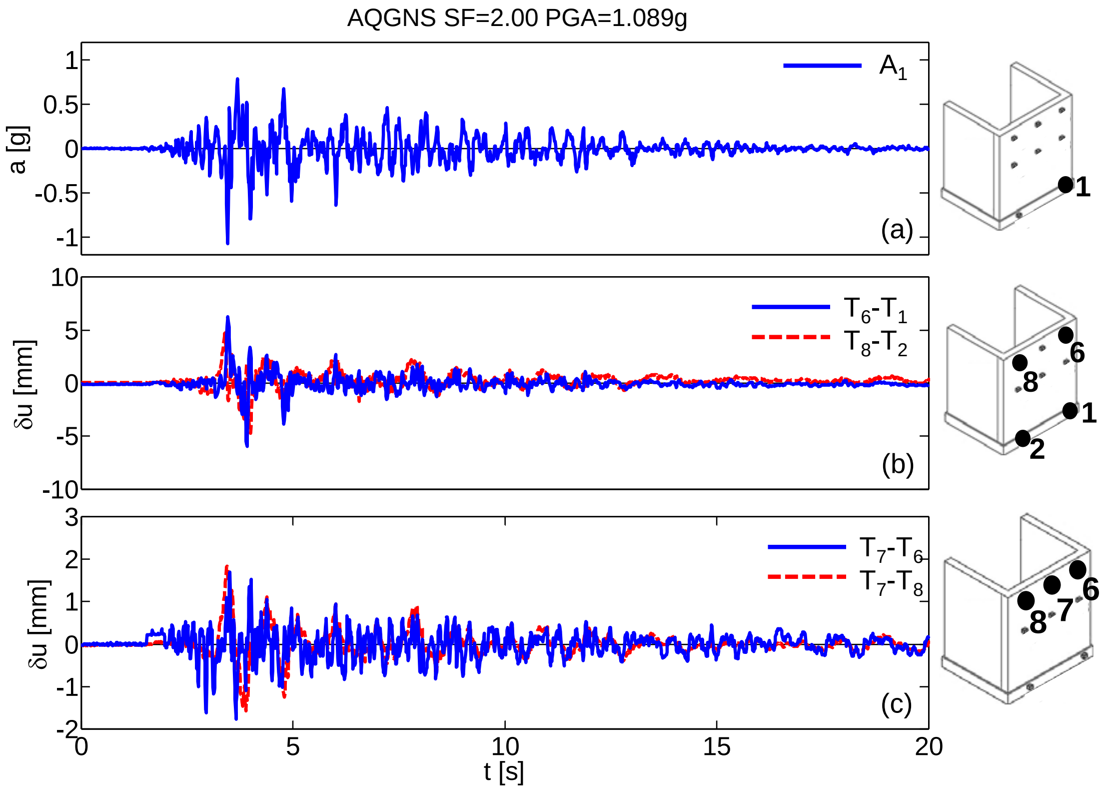

Figure 8. Time histories recorded during tests under AQGNS, SF=2.00 signal: base acceleration (a); horizontal bending (T_6-T_1 and T_8-T_2, b); vertical bending (T_7-T_6 and T_7-T_8, c).

The behaviour before and after strengthening during the entire test series is shown in Figure 9, in which the recorded PGA and the horizontal bending are on the y-axis and on the x-axes, respectively. The retrofitted specimen, as already said, collapsed after R1169WE record at 1.5g PGA, while the out-of-plane overturning of the unreinforced specimen occurred under CalitWE record at 0.29g PGA (1980 Irpinia earthquake, SF=1.75). From this moment on, tests were carried out on the detached wall behaving approximately as a rigid body undergoing a rocking motion.

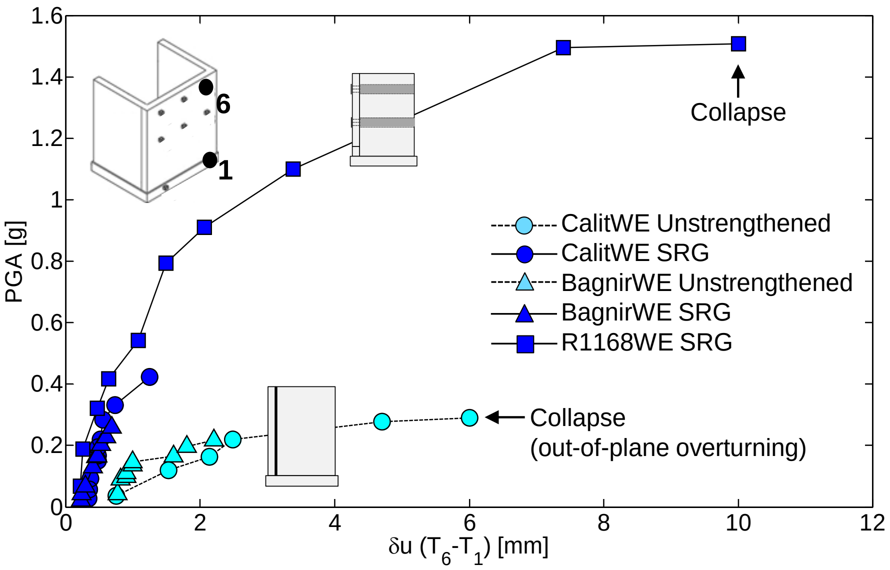

Figure 9. Seismic capacity of unstrengthened and retrofitted specimens.

The seismic response of the specimen can be studied with reference to a total of four different configurations (Figure 10), such as undamaged (unreinforced, before crack development, a), damaged (façade detached from the side walls, before collapse, b), rocking (façade overturned out-of-plane, and behaving as a rigid body under rocking motion, c), and, finally, SRG (retrofitted with mortar-based composites, d). Figures 11 and 12 show the time histories recorded during the same input (same signal with same scale factor) on different configurations to allow comparisons. Under BagnirWE record with SF=0.50 (PGA=0.083g, Figure 11a), the response of the undamaged and of the retrofitted specimens are similar, especially in terms of vertical bending (Figure 11b), while the SRG reinforcements entails smaller relative displacements between points horizontally aligned (Figure 11c), which is related to the horizontal bending. Conversely, the comparison under CalitWE SF=1.50 signal (PGA=0.271g, Figure 12a) shows that occurrence of damage entails much larger displacements for both horizontal and vertical bending (Figures 12b and 12c), as well as a slower damping of oscillations.

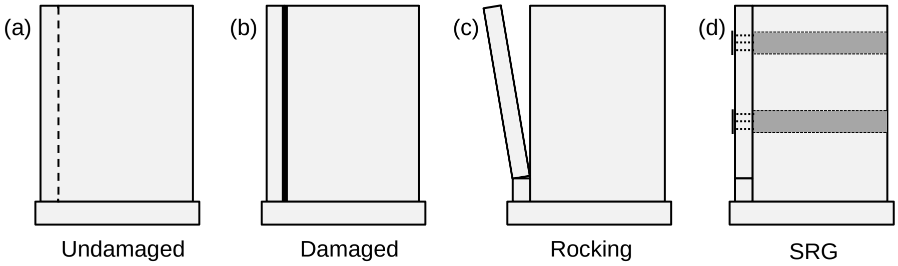

Figure 10. Specimen configurations: undamaged (a), damaged (cracked without front wall separation, b), rocking (detached façade, c), and retrofitted with SRG (d).

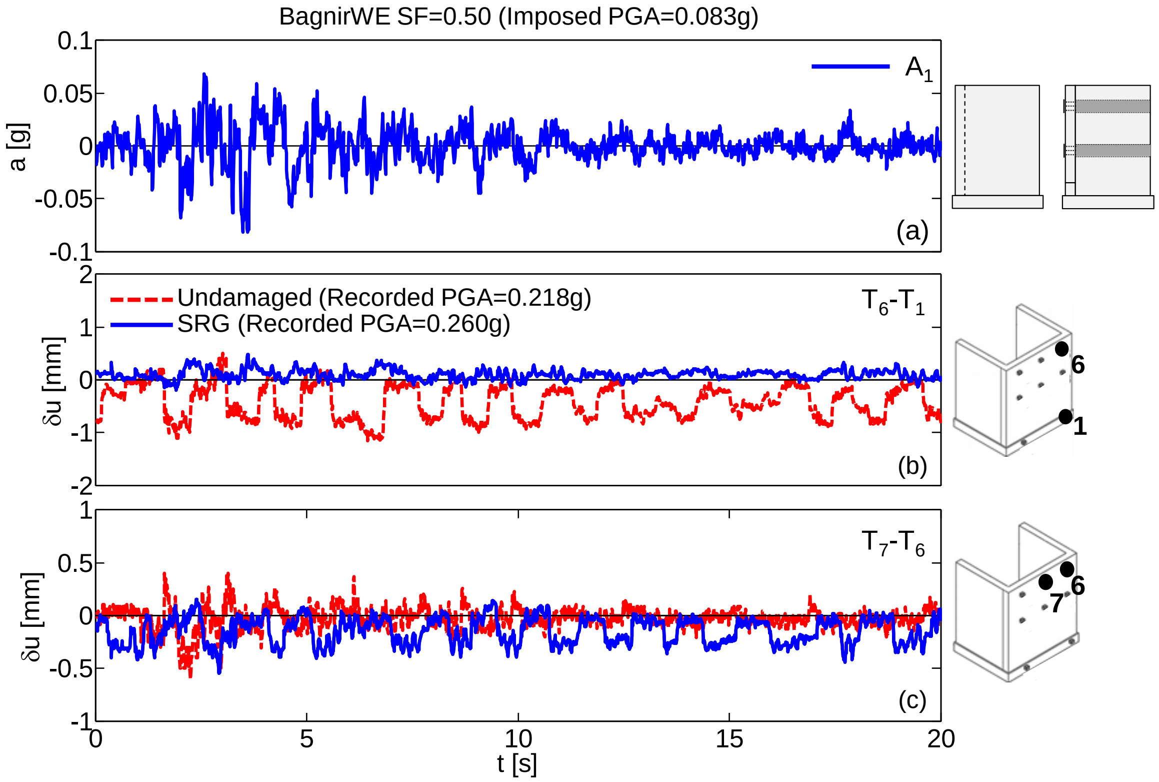

Figure 11. Time histories recorded during tests under BagnirWE, SF=0.50 signal on undamaged and retrofitted specimens: base acceleration (a); horizontal bending (T_6-T_1, b); vertical bending (T_7-T_6, c).

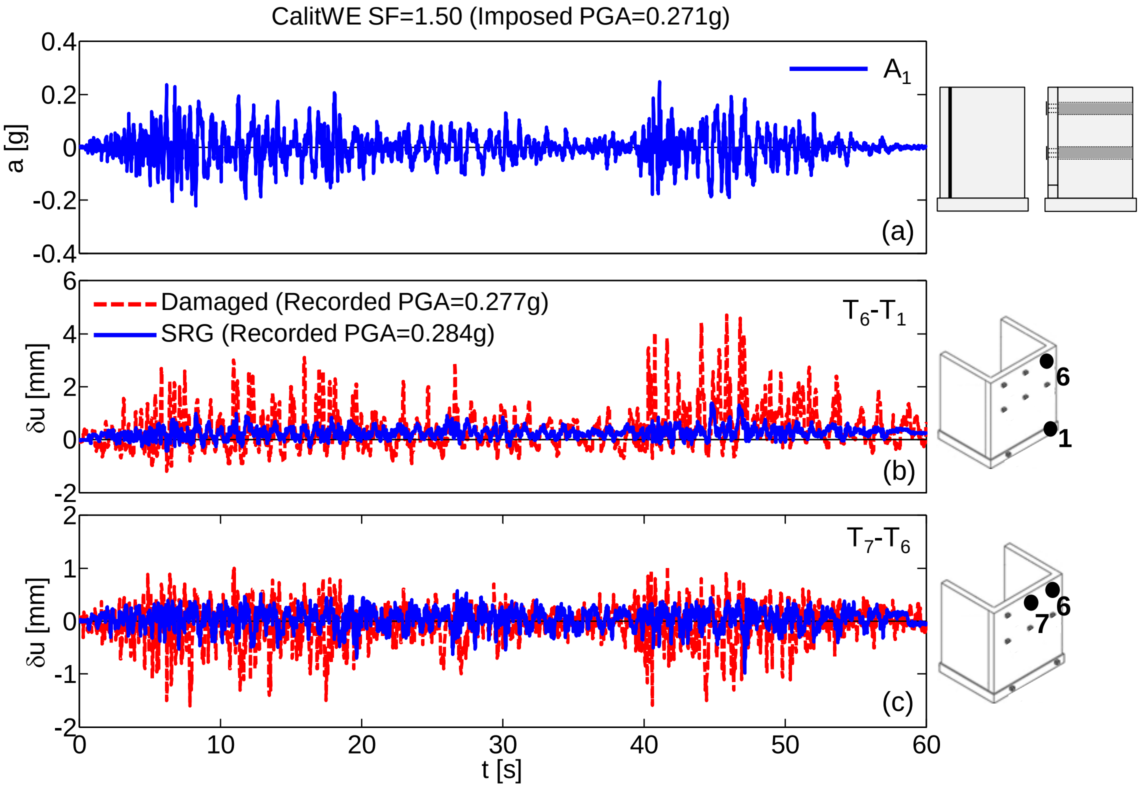

Figure 12. Time histories recorded during tests under CalitWE, SF=1.50 signal on damaged and retrofitted specimens: base acceleration (a); horizontal bending (T_6-T_1, b); vertical bending (T_7-T_{6}, c).

The four configurations are compared in Figure 13 in terms of dynamic properties. The fundamental frequency of the specimen is derived on the base of the transfer function (T_{xy}), which represents the filter effect of the structure by comparing the input signal (x) and the output signal (y). $T_{xy}(f)$ is defined as the ratio between the cross power spectral density (P_{yx}) of x and y and the power spectral density (P_{xx}) of x. It is a complex function depending on the frequency f, and its modulus is represented on the y-axis of the graphs. The fundamental frequency of the undamaged specimen and the retrofitted one are 12.1Hz and 16.2Hz, respectively, as detected before the beginning of the test series, assigning a white noise with PGA=0.01g to the shake table (Figure 13a). The occurrence of damage causes a significant stiffness reduction, as indicated by the decrease of the frequency to 6.6Hz. The application of inputs with equivalent intensity up to CalitWE with SF=1.0 caused a much smaller deterioration on the retrofitted specimen, displaying a frequency of 14.8Hz (Figure 13b). Finally, the frequency of the rocking façade is one order of magnitude lower than that of the reinforced wall (1.1Hz versus 14.6Hz, Figure 13c).

5 CONCLUSIONS

The shake table test series described in this paper proved the effectiveness of mortar-based reinforcements in improving the out-of-plane seismic capacity of masonry walls. More specifically, the detachment of the façade and its out-of-plane overturning are prevented by steel connectors. Reinforcement textiles applied to the façade ensure a distributed retaining effect and, at the same time, contribute to bending strength of the wall. A significant increase can be achieved. Within the present study, the façade of the unreinforced specimen overturned under a PGA of 0.29g, while after the seismic retrofitting with mortar-based composites failure occurred under a PGA of 1.5g. At the same time, the reinforcement entails a slower deterioration due to damage development (after several tests with increasing input intensity) and a limited modification of initial dynamic properties.

The proposed retrofitting system appears promising for safeguarding the cultural heritage, as it ensures the mechanical effectiveness, is time and cost efficient, and can be integrated in the maintenance/cleaning works of the façade. Thanks to their small thickness, the SRG reinforcements can be applied within the existing layer of plaster, thus preserving appearance of the façade and the architectural value of the construction. Moreover, the use of inorganic matrices ensures material compatibility and vapor permeability, as needed in applications to historic substrates.

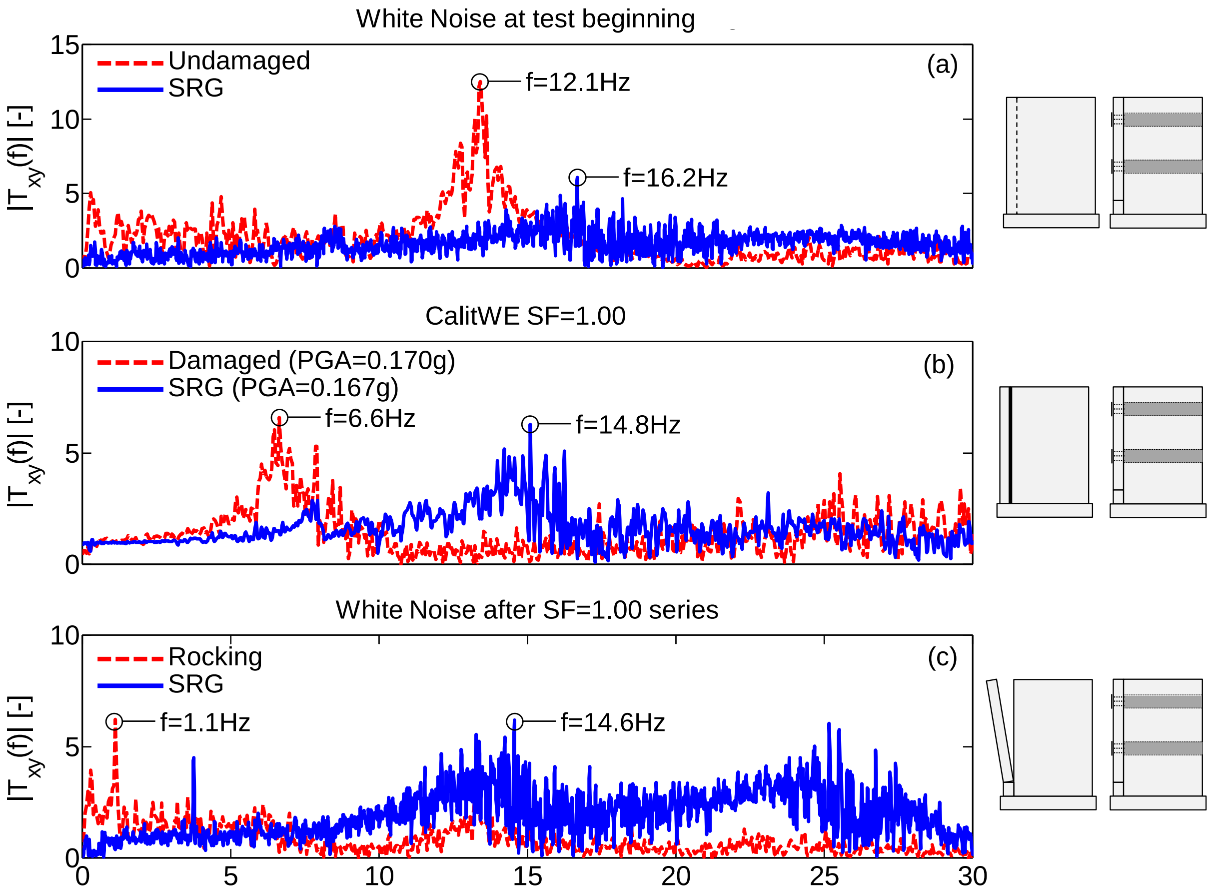

Figure 13. Fundamental frequencies of undamaged (a), damaged (b), rocking (c) and SRG (a,b,c) specimen configurations.

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