TRADITIONAL AND INNOVATIVE TECHNIQUES FOR THE SEISMIC RETROFITTING OF MASONRY BUILDINGS

Stefano DE SANTIS[1] and Gianmarco DE FELICE[2]

Abstract: The effectiveness of innovative mortar-based composites for the seismic retrofitting of masonry structures was investigated through shake table tests. The experimental study was carried out on a natural scale wall assemblage under natural accelerograms, applied with increasing intensity up to failure. The proposed strengthening system comprises connectors and horizontal strips of Ultra High Tensile Strength Steel (UHTSS) cords externally bonded to the masonry with hydraulic lime mortar, within the thickness of a plaster layer. Test results proved the effectiveness of SRG as a promising solution, to integrate or substitute traditional steel tie-bars, for improving the out-of-plane seismic capacity of masonry walls.

Introduction

The out-of-plane capacity of front walls is one of the crucial issues in the seismic vulnerability of masonry structures, especially in historical centres. Examples have been observed after recent earthquakes on masonry buildings, aggregates, and churches (Lagomarsino, 2012; Sorrentino et al., 2013). Therefore, improved retrofitting solutions are needed that combine structural effectiveness, economic and environmental sustainability, and possibility of being integrated with maintenance works. Traditional steel tie bars, which have been being installed since centuries, proved to effectively avoid the out-of-plane overturning. However, the localized constrain provided by the end-plates cannot always prevent the failure by out-of-plane bending, especially for slender masonry walls. Reinforced concrete bond beams have been used in the last decades to provide a box-type behaviour and a higher bending capacity to the walls, but in some cases the stiffness discontinuity and the lack of proper connection have even caused the collapse of the masonry below the beam.

Aiming at overcoming these drawbacks, innovative solutions with externally bonded composites have been developed in the last two decades. Composite materials offer significant strength improvement with minimum thickness, nor variation of original structural geometry, with no mass increase and limited stiffness modification. Beside well-established Fibre Reinforced Polymers (FRPs) (see, amongst others: Willis et al., 2009), a new generation of composites with inorganic matrices are currently under development. Despite a lower bond strength than FRPs (de Felice et al., 2014), mortar-based reinforcements ensure better vapour permeability and material compatibility, cheaper and faster installation on uneven surfaces, and higher fire resistance, providing remarkable advantages, especially for applications to masonry (Papanicolaou et al., 2008; Valluzzi et al., 2014). Recent studies on medium-scale specimens have shown the potential use of mortar-based composites for the retrofitting of masonry walls under out-of-plane loads (Papanicolaou et al., 2008). Nevertheless, a deeper understanding still needs to be gained on the actual response of strengthened structures to earthquake motion, the importance of connections between façade and lateral walls, as well as between floors and walls (Mendes et al., 2014), the size of the reinforcement necessary to provide a significant increase of the seismic capacity, and the importance of proper installation procedures. The development of an improved knowledge on these issues may have important implications on current design practice and maintenance activities.

This paper presents a shake table study carried out on a full-scale masonry wall, retrofitted with either traditional steel tie-bars or Steel Reinforced Grout (SRG). This latter consists of

[1] Research Assistant, Roma Tre University, Dept. of Engineering, Rome, Italy, sdesantis@uniroma3.it
[2] Professor, Roma Tre University, Dept. of Engineering, Rome, Italy, gianmarco.defelice@uniroma3.it

Ultra High Tensile Strength Steel (UHTSS) textiles applied with hydraulic lime mortar to the surface of the masonry. Among all the available composites (including carbon, basalt, glass, PBO, aramid and natural fibres), steel-based reinforcements offer particularly good mechanical performance thanks to the high tensile strength of the textile and the effective cord-to-mortar interlocking (Ascione et al., 2015; De Santis and de Felice, 2015), at relatively low costs. The seismic responses exhibited after strengthening with tie-bars and after retrofitting with SRG are compared in terms of seismic capacity, damage development and dynamic properties to investigate the effectiveness of the proposed solution with steel-based composites.

Description of the specimen and test setup

The specimen was a full-scale U-shaped tuff masonry wall, consisting of a façade and two transverse walls (Fig. 1). The façade was 3.30m long, 3.44m high and 0.25m thick; the transverse walls had the same thickness and height of the façade and were 2.30m long. To to simulate the poor connection between front and side walls, which is one of the main causes of the seismic vulnerability of historic masonry buildings, the specimen was realized without block interlocking; the walls were built next to each other and a mortar joint was laid between them at the corners. The specimen was initially subjected to a shake table session without reinforcement (AlShawa et al., 2011), which caused the detachment of the façade from the transverse walls and out-of-plane overturning. Then, the specimen was reinforced with steel tie-bars and tested again. Finally, it was repaired and retrofitted with SRG and subjected to a final shake table session.

Tests were carried out at ENEA Casaccia Research Centre, in Rome, Italy, equipped with a 4m×4m shake table. The seismic inputs were based on six natural records of Italian strong earthquakes: three signals were recorded during the 1980 Irpinia earthquake, one during the 1997 Umbria-Marche earthquake, one during the 2009 L'Aquila earthquake, and one during the 2012 Emilia earthquake (Table 1). The order of the input signals was established on the base of both the Velocity Spectrum Intensity (VSI) and the average spectral acceleration in the 8-16Hz frequency range (S_a). Signals were applied with increasing scaling factor (SF) from 0.1 to 2.5 in direction normal to the front wall (tests were unidirectional).

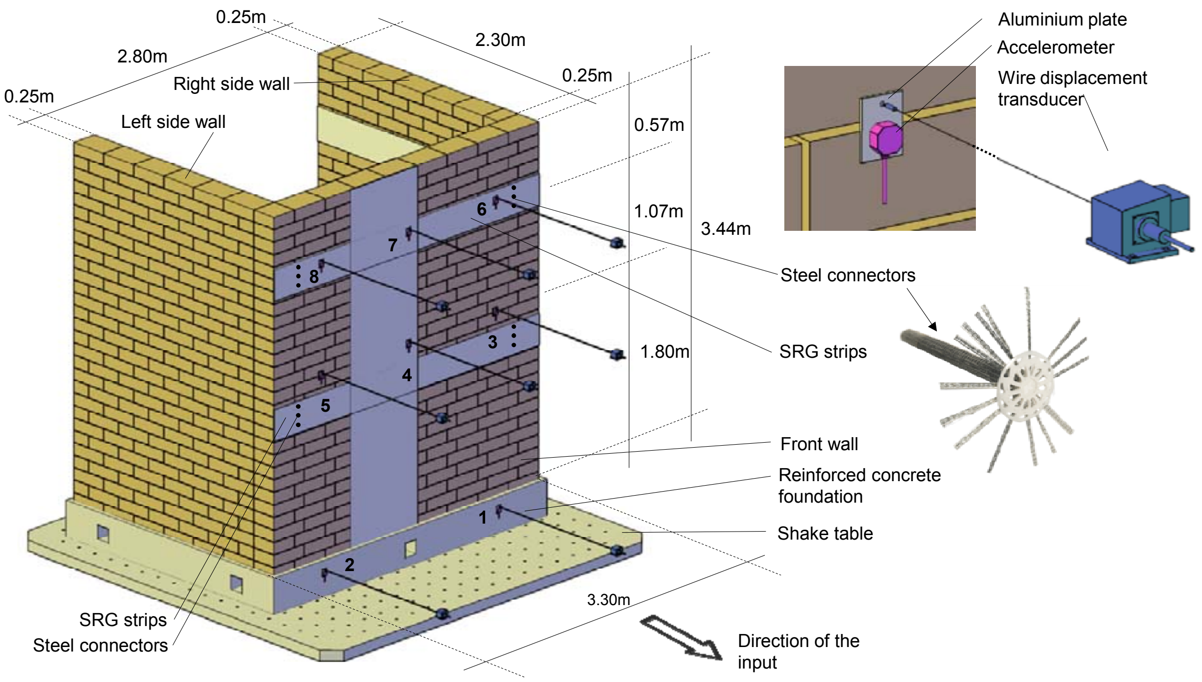

Figure 1. Specimen under study and test setup.

Table 1. Accelerograms selected to perform shake table tests.

#	Earthquake	Date	M_W	Record	PGA	PGV	PGD	VSI (8-16Hz)	S_a (8-16Hz)
					[g]	[mm/s]	[mm]	[mm]	[g]
1	Irpinia	23/11/1980	6.9	CalitWE	0.181	281	90	0.246	0.209
2	Irpinia	23/11/1980	6.9	BagnirWE	0.167	374	135	0.397	0.350
3	Emilia	20/05/2012	5.9	MrnWE	0.261	298	90	0.519	0.456
4	Irpinia	23/11/1980	6.9	SturWE	0.313	705	309	0.597	0.526
5	Aquila	06/04/2009	6.3	AQGNS	0.451	372	39	0.877	0.756
6	Umbria-Marche	26/09/1997	6.1	R1168EW	0.438	288	42	1.170	0.905

M_W: Moment magnitude; PGA: Peak Ground Acceleration; PGV: Peak Ground Velocity; PGD: Peak Ground Displacement; VSI: Velocity Spectrum Intensity; S_a: average spectral acceleration.

A high-resolution 3D motion capture system was also installed, which makes use of near infrared cameras to record the displacement of retro-reflecting markers glued on the specimen. Such system allowed for 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 conventional accelerometers and displacement transducers.

In order to measure the out-of-plane behaviour of the façade, 6 accelerometers and 6 wire potentiometers were installed as show in Fig. 2. Two additional measurement points were placed on the foundation to record seismic base motion. Finally, the strains in the steel textiles were recorded through four strain gauges. Test data were acquired at 100Hz sampling frequency. A third-order baseline correction and a fourth-order Butterworth band-pass filter in the 0.35-25Hz range were used to process acceleration recordings. A third-order band-stop filter at 2.1Hz was also necessary to remove errors due to sampling and background noise.

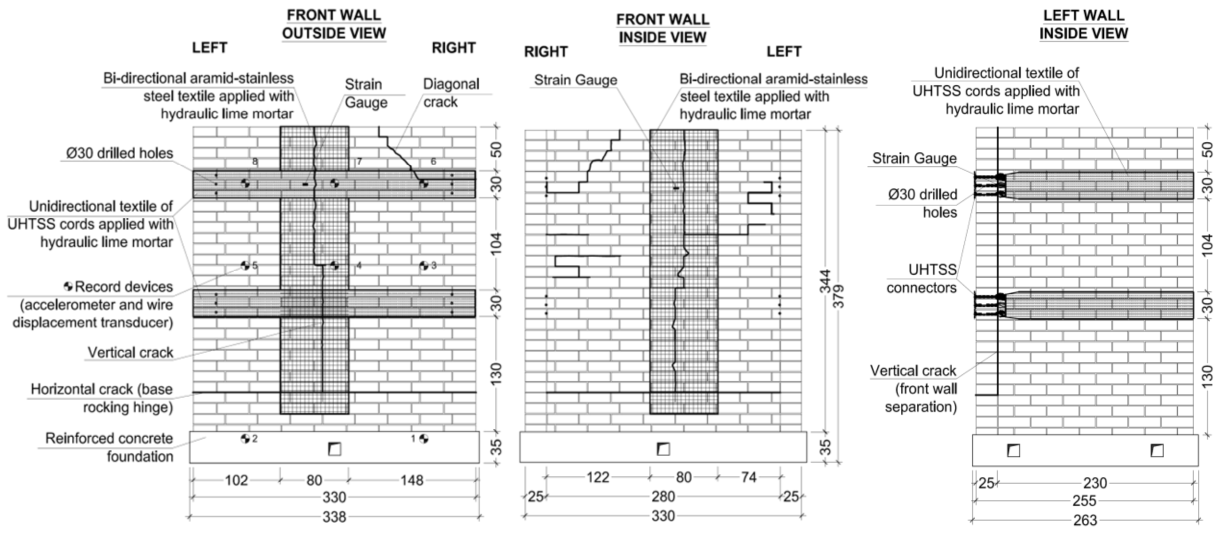

Figure 2. Position of instruments on the façade and strengthening design.

Strengthening with tie-bars and with Steel Reinforced Grout

After the test series on the unreinforced specimen, two ∅20mm steel rods were installed at a distance of about 0.85m from the top of the wall. Two 600mm long UPN100 steel bars, placed at 45°, were used as end-plates to anchor the rods to the façade. A further test series was carried out. The tie-bars impeded the collapse of the façade, but didn't prevent the development of severe damage, as it will be shown afterwards.

Finally, the wall was repaired and retrofitted with SRG. The textile is a unidirectional mesh of UHTSS cords, spaced 6.35mm (4 cords/inch) and coated with zinc to ensure protection against rusting. It has 3208N/mm^2 tensile strength (corresponding to 269kN/m per unit width) and 183.9kN/mm^2 Young's modulus.

The NHL mortar used to bond the textiles to the masonry has 20.6N/mm^2 compressive strength, 11400N/mm^2 Young's modulus, and 5.4N/mm^2 tensile strength. The composite strengthening system was tested under tension, revealing a strength of 3254N/mm^2 and a tensile modulus of elasticity (after cracking) of 183kN/mm^2 (De Santis and de Felice, 2015). Finally, the bond strength (per unit width) on tuff was 53kN/m (De Santis et al., 2014).
The SRG retrofitting system comprised 12 steel connectors and two horizontal strips (Fig. 2). The steel connectors crossed the front wall and were anchored to the internal surface of the side walls by adhesion, and were responsible for retaining the out-of-plane overturning of the façade (playing the same role of tie-bars). Four horizontal SRG strips were applied to the side walls to transfer the load from the connectors to the masonry. The horizontal SRG strips were applied to the front wall at the same height of the previous ones, to transfer the retaining effect (in a more distributed way than steel end-plates) of the connectors and provide an increase of the bending resistance of the wall. Despite in this case the specimen could have been strengthened by external bandages, the work was intentionally designed so as to be feasible in the more general field conditions of a long façade, which needs to be connected to all the transverse walls. In the proposed solution, this role is entrusted to the steel connectors crossing the front wall.

Test results and comparisons: damage development and seismic capacity
In order to develop a deeper understanding of the effectiveness of the proposed strengthening solution with composites, the seismic performances of the specimen with no reinforcement, with traditional tie-bars and with SRG are compared in terms of seismic capacity, bending response, and dynamic properties. The former (comparison of seismic capacity) is shown in Fig. 3, having the recorded PGA on the y-axis, and either the vertical bending (T_6-T_1, Fig. 3a) or the horizontal bending (T_7-T_6, Fig. 3) on the x-axis. The vertical bending was measured by the relative displacement (δu) between two points vertically aligned (T_6-T_1), while the horizontal bending was measured by the relative displacement between two points horizontally aligned (T_7-T_6). In the former, the wall behaved as a vertical cantilever fixed at the base, rotating/bending in a vertical plane (around a horizontal axis), as a result of both the nearly elastic deformation of the whole specimen and the detachment from the side walls. In the latter, the façade bent in a horizontal plane (around a vertical axis) due to the constrains provided by the side walls and the steel connectors at the corners.

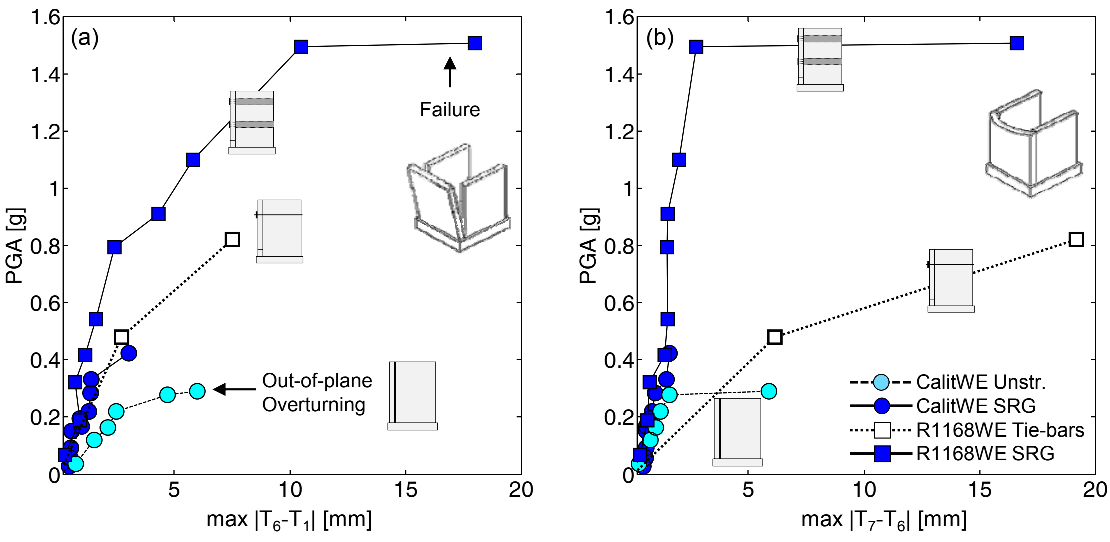

Figure 3. Seismic capacity of the wall without any reinforcements, with steel tie-bars and with SRG: PGA vs. vertical bending (T_6-T_1, a) and horizontal bending (T_7-T_6, b).

The out-of-plane overturning of the unreinforced wall occurred under CalitWE signal with a PGA of 0.29g. Apart from the last test (in which overturning occurred), the maximum relative displacement was nearly 5mm for PGA=0.28g. The damage pattern after the test series on the unreinforced wall comprised two vertical cracks, one per side, dividing the façade from the transverse walls (Fig. 4a) and a horizontal crack at the fourth mortar bed joint (at about 0.44m from above the foundation, and all along specimen width), which constituted the overturning hinge of the façade.
R1168WE signal applied with PGA=0.82g on the wall with the steel tie-bars caused a severe damage, though not a proper failure. A vertical crack developed in the middle section of the façade (Fig. 4b), due to the out-of-plane bending and to the impacts occurring at the corners during motion. In addition, some diagonal cracks formed at the top and mid-height of the front wall, probably related to the punching effect of the end-plates (Fig. 4c).

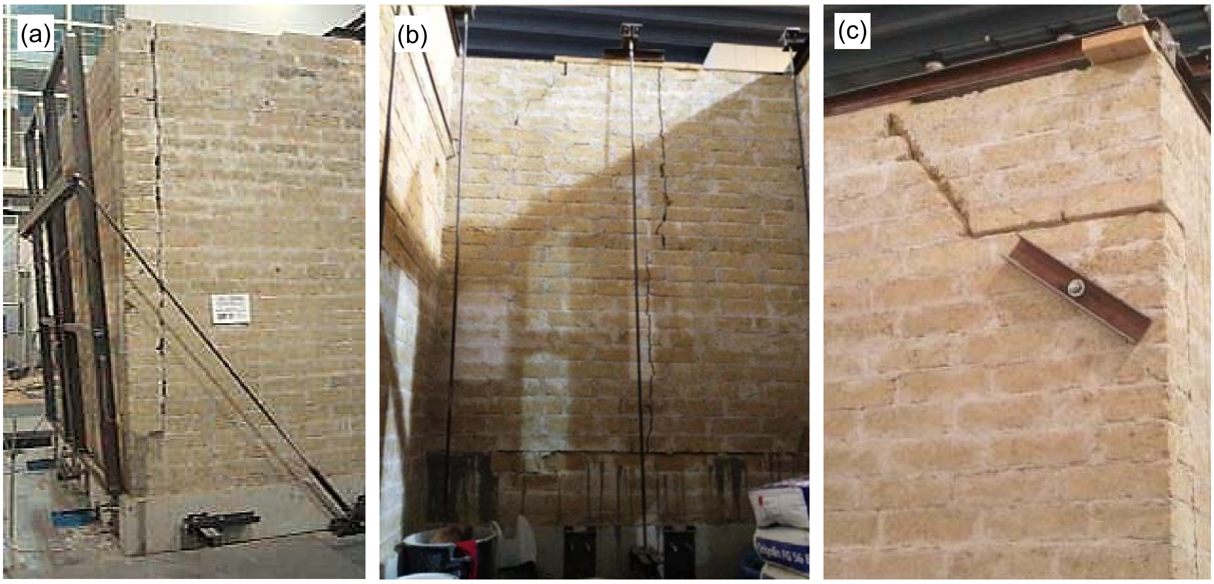

Figure 4. Damage pattern induced by shake table tests on the specimen strengthened with steel tie-bars: vertical crack at the corner separating the façade from the side walls (originated during tests on the unreinforced wall, a), vertical crack in the middle of the front wall (b), and diagonal cracks in the vicinity of the steel end-plates (c).

The specimen retrofitted with SRG, if compared to the previous ones, showed higher stiffness and strength. Itfailed under a PGA of 1.51g. Both the unreinforced wall and that retrofitted with SRG displayed a strong increase in the relative displacement only at failure, while in the specimen strengthened with tie-bars large displacements occurred also well before failure, due to the development of the vertical crack in the middle of the façade.
In conclusion, assuming the PGA as a reliable indicator of the input intensity, the improvement of the seismic capacity provided by the reinforcement with steel-tie bars and with SRG was, in the present case, in the order of 3 and 5 times, respectively.
Furthermore, damage remained extremely limited along the entire test session, consisting of 57 shake table tests. The strongest input was L'Aquila record amplified by a scale factor of 2.5 with a PGA of 1.49g. Such a high intensity proved the full effectiveness of the proposed reinforcement system with SRG.
The last test was carried out under Nocera-Umbra record amplified by a factor of 2.5, and the acceleration recorded on the foundation had 1.51g PGA. After this test, the specimen was considered failed due to the severity of damage (shown in Fig. 5). Though the masonry of the façade was completely separated from the transverse walls (Fig. 5a), the steel connectors did not fail nor were pulled out from the front wall, and the horizontal reinforcements on the side walls did not detach, so no out-of-plane overturning occurred. Despite the severe vertical bending experienced by the façade, outwards failure was prevented by the horizontal

SRG strips installed on the external side of the wall. On the contrary, the absence of horizontal SRG strips in the internal side led to the development of a vertical crack dividing the wall into two portions, which rotated inwards around the connectors (Fig. 5b). The load on the connectors retaining the façade was effectively transferred by adhesion from the four SRG strips to the side walls, where an in-plane mechanism activated due to the combined effect of bending and shear stresses, as it is expected when the masonry structure exhibits a box-type behaviour. A diagonal crack formed on both the side walls, from the connectors at 1.50m of height down to the opposite back corner (Fig. 5c) as a consequence of the impact at the corners of the front wall moving inwards. Immediately after, with the inversion of earthquake motion, a horizontal crack developed all along the base of both side walls, completely separating them from the foundation. Despite the overall severe damage, no portions of relevant size felt down.

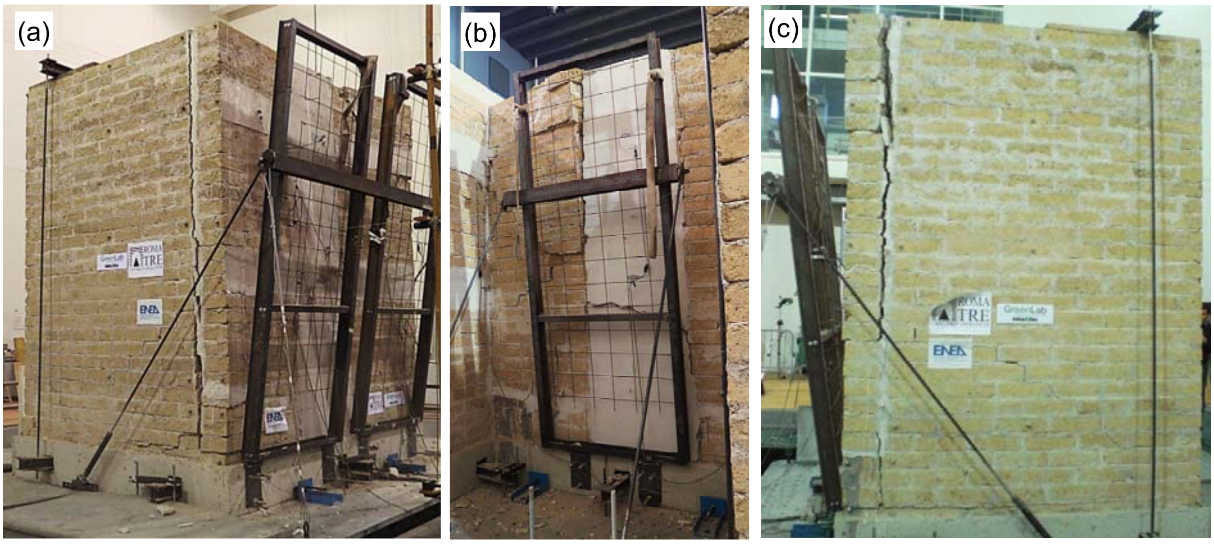

Figure 5. Damage pattern induced by shake table tests on the specimen strengthened with SRG: vertical cracks at the corner separating the façade from the side walls (a), damage in the internal side of the front wall (b), and damage in the side walls (c).

Test results and comparisons: out-of-plane bending responses

The seismic response of the wall without any reinforcements, after the installation of tie-bars, and after retrofitting with SRG are shown in Fig. 6 under CalitWE record with SF=1.50 and PGA=0.27g (recorded on the foundation during the test on the retrofitted wall, Fig. 6a).

The unreinforced wall displayed the largest displacements, especially in terms of vertical bending, while the installation of the tie-bars prevented this out-of-plane rotation of the façade (Fig. 6b). At the same time, despite the significant capacity increase, tie-bars didn't provide a reduction of horizontal bending, such that T_7-T_6 displacements of the unreinforced specimen were comparable to those of the wall with tie-bars. In this latter, the development of the vertical crack in the middle of the front wall, due to the bending force and to the impacts at the corners during inward motion, were responsible for relatively large displacements (Fig. 6c). Finally, the wall retrofitted with SRG showed the smallest displacements in terms of both vertical and horizontal bending (Figs. 6b-c), thanks to the constrain of the connectors and the distributed effect of the horizontal SRG strips, which prevented crack development in the middle of the façade and increased its bending strength.

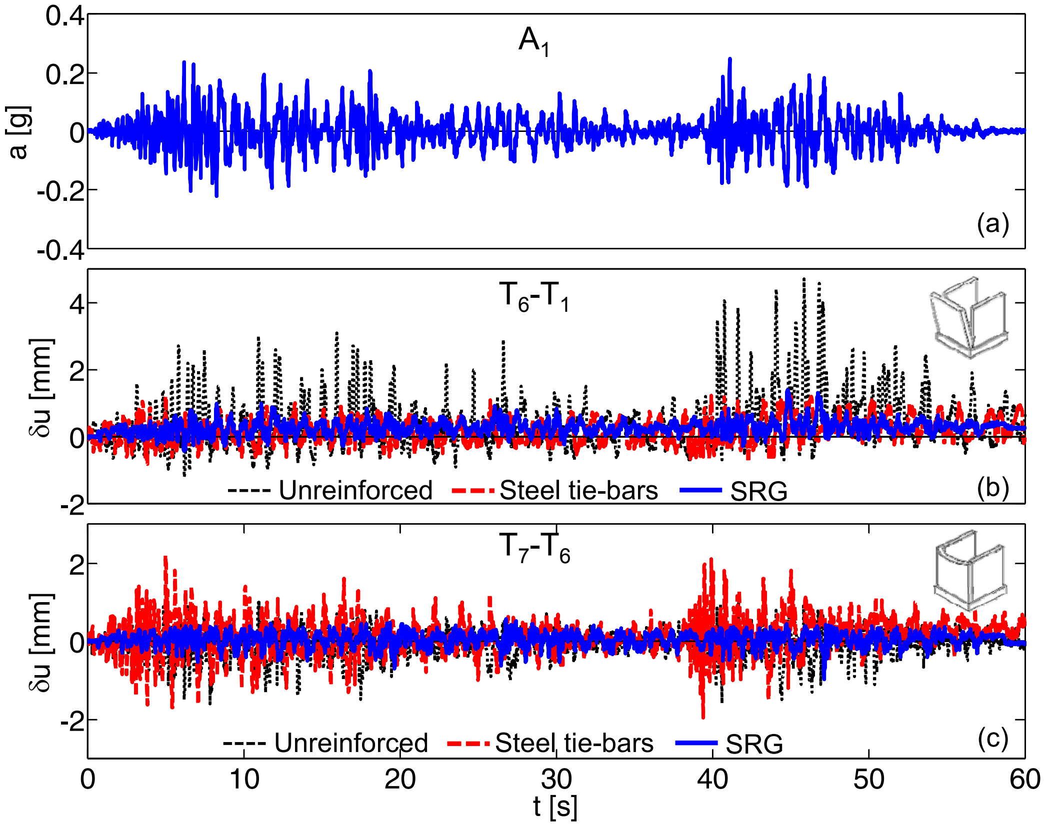

Figure 6. Seismic behaviour under CalitWE record with SF=1.50 of the specimen without reinforcements, with tie-bars and with SRG: time histories of earthquake base acceleration (a), vertical bending (T_6-T_1, b), and horizontal bending (T_7-T_6, c).

Test results and comparisons: dynamic properties

The dynamic properties of the specimen without any reinforcements, with tie-bars and with SRG are illustrated in Fig. 7 for some sample tests and in Fig. 8 for the entire test series. The fundamental frequency was derived from the transfer function (T_{xy}), which represents the filtering effect of the structure through the comparison of the output signal (*y*) and the input signal (*x*). In the present work, the time histories recorded by accelerometer #1 was assumed as input signal and that by #7 as output signal. $T_{xy}(f)$ is defined as the ratio between the cross power spectral density of *x* and *y* and the power spectral density of *x*. It is a complex function, and its modulus is depicted on the y-axis of the graphs. Before the beginning of the test series, the fundamental frequency of the unreinforced specimen (detected under a white-noise input with 0.05g PGA) was 12.1Hz (Fig. 7a). The wall steadily accumulated damage, decreasing its fundamental frequency to 6.6Hz (Fig. 8). After the installation of the tie-bars, the fundamental frequency was 7.8Hz (measured under R1168WE record with SF=1.0, Fig. 7b) and decreased to 5-6Hz after 9 tests with comparable intensity (Fig. 8). Finally, the specimen retrofitted with SRG displayed a frequency of 16.2Hz under white noise before test beginning (Fig. 6a), of 14.3Hz under R1168WE record with SF=1.0 (Fig. 7b), and of 10-11Hz during the most severe tests at the end of the shake table session, before collapse (Fig. 8), indicating that the accumulation of damage developed more slowly than in the other configurations (i.e., no reinforcement and tie-bars).

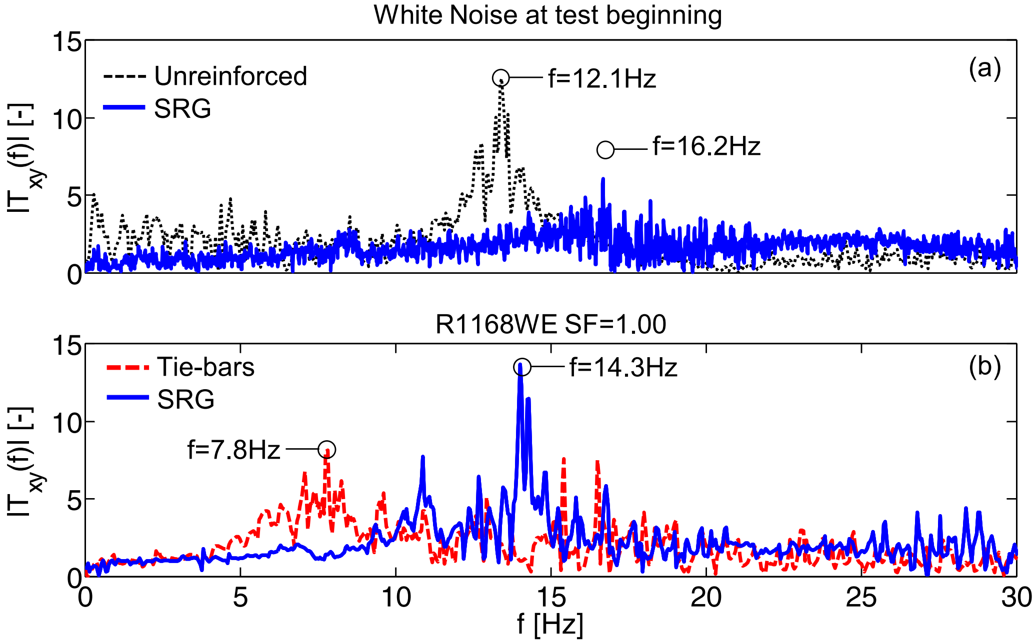

Figure 7. Modulus of the transfer function of the specimen without any reinforcements and with SRG under white noise at test beginning (a) and of the specimen with tie-bars and with SRG under R1168WE record with SF=1.0 (b).

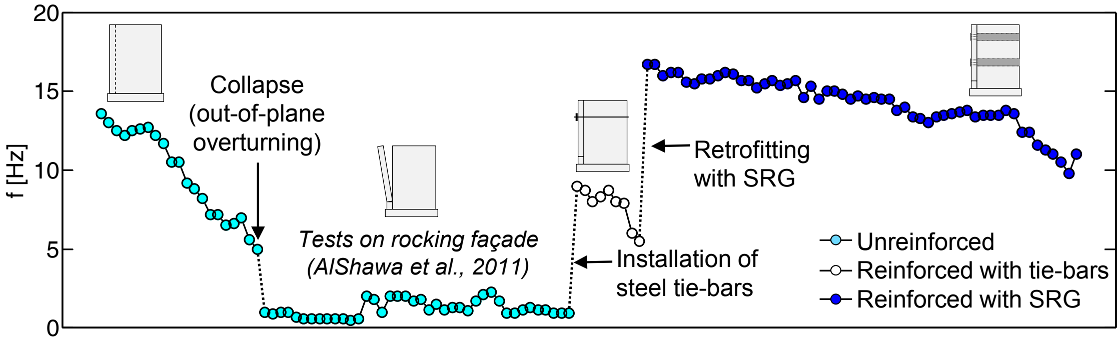

Figure 8. Variation of the predominant frequency during whole test sequence.

Conclusions

A shake table investigation was carried out on a natural scale masonry specimen strengthened with either steel tie-bars or Steel Reinforced Grout (SRG). Tests were carried out under natural accelerograms with increasing intensity up to failure, to investigate the effectiveness of the proposed solution with SRG in comparison with traditional devices. The following results were achieved:

- The maximum Peak Ground Acceleration was 0.29g for the unstrengthened wall (failure by overturning), 0.82g for the wall reinforced with steel tie-bars (extremely severe damage without collapse), and 1.51g for the wall retrofitted with SRG (damage without collapse).
- Externally bonded reinforcement with SRG provided a significant improvement of the out-of-plane seismic capacity, proving to be an effective alternative to traditional strengthening devices.
- The SRG connectors provided an good connection between the transverse walls and the façade, preventing the out-of-plane overturning of this latter. The SRG strips applied to the front wall also improved its bending strength and provided a distributed retaining effect, avoiding the local damage due to the punching effect of the end-plates of tie-bars.

- SRG entailed a relatively small modification of the initial dynamic properties of the specimen and limited damage development induced by earthquake loading.

The retrofitting system with SRG proposed and investigated in the present work appears promising for safeguarding the cultural heritage, as it ensures the mechanical effectiveness, is time and cost efficient, and, thanks to the use of inorganic matrices, allows for the fulfillment of preservation requirements for applications to historic substrates. Moreover, thanks to its small thickness, it can be installed within the existing layer of plaster, and, therefore, can be integrated in the maintenance/cleaning works of the façades, allowing for the preservation of the appearance and of the architectural value of the construction.

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