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ASSESSMENT OF THE TRM REINFORCEMENT OF WINDOWED MASONRY WALLS THROUGH OMA IDENTIFICATION

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Abstract. *Masonry constructions compose the majority of the Architectural Heritage worldwide, thus, their preservation is of great importance. Nevertheless, they usually show a great vulnerability to seismic and dynamic loads. Several reinforcement techniques can be used in order to improve their dynamic behaviour. The Textile Reinforced Mortar (TRM) material appears as very suitable, since it meets the requirements of compatibility and reversibility of the retrofitting. Moreover, it avoids some problems related to permeability. And strongly reduces adhesion and debonding issues. In this paper the effectiveness of the TRM reinforcement for dynamic loads for windowed brick masonry walls is evaluated through vibration testing and operational modal analysis. To this aim, two scaled brick masonry walls were built at the "Laboratorio de Grandes Estructuras" of the University of Alicante. Only one of them was reinforced with the TRM. Both were damaged with a cyclic in-plane lateral force for simulating damage due to seismic actions. Structural vibrations of the two walls were measured in the presence of a white noise excitation. Modal parameters were evaluated through Operational Modal Analysis (OMA) before and after the damage. Finally, changes in modal parameters due to damage were compared and investigated in both the unreinforced and reinforced cases. The results suggest that TRM reinforcement can be considered effective for improving the mechanical behaviour of a brick windowed masonry wall.*

1 INTRODUCTION

Masonry buildings represent a relevant part of constructions all around the world. Indeed, the majority of architectural heritage is made of masonry and a lot of new buildings are still built using masonry materials and traditional techniques. However, masonry buildings usually show a great vulnerability to seismic and dynamic loads [1], mainly due to the properties of the materials and to weak connections between horizontal and vertical structural elements [2-3]. Thus, in order to guarantee the stability and the integrity of the construction, it is of great importance to improve its mechanical behaviour through appropriate strengthening interventions. In addition, the reinforcement of masonry construction may be also aimed at repairing damages induced by unexpected static or dynamic loads, in particular earthquakes, that along with other causes can reduce the mechanical properties of masonry structural elements over time [4-6]. In this document, the assessment of the reinforcement of masonry walls in particular is addressed. Among possible reinforcement materials for masonry, in the recent past Fiber-Reinforced Polymer (FRP) composites [7-11] have been widely employed, but these composites show several drawbacks, mostly related to the stress-transfer mechanisms between reinforcement and masonry supports. More recently, another reinforcement material [12-13], the Textile Reinforced Mortar (TRM), has gained interest since it is particularly suitable for masonry constructions. Indeed, due to the presence of a mortar matrix instead of an epoxy one, it meets the requirements of compatibility and reversibility of the retrofitting. Moreover, it avoids some problems related to permeability and, above all, TRM strongly reduces adhesion and debonding issues. Finally, as it is shown in [14], TRM is effective in recovering the pre-damage stiffness of a scaled masonry building.

For the above, a detailed study on the effectiveness of TRM on different types of wall is of great interest. The main purpose of this study is the evaluation of the effectiveness of TRM reinforcement of a windowed brick masonry walls for dynamic loads. For this purpose, two distinct scaled brick masonry walls were built at the “Laboratorio de Grandes Estructuras” of the University of Alicante (Alicante, Spain). The two walls were constructed with the same geometrical features and with the same materials and technique in such a way that they have about the same mechanical characteristics. Only one of the walls was reinforced with the TRM. A vertical load was applied on both the two walls for reproducing real loading conditions of a bearing masonry wall. Both walls were damaged with a cyclic in-plane lateral force in order to simulate damage due to seismic actions. Finally, in order to evaluate the effectiveness of the TRM reinforcement for brick walls in the presence of windows, modal parameters of the two walls were evaluated through Operational Modal Analysis (OMA) before and after the damage by using ARTeMIS Modal commercial software. Indeed, since modal parameters are function of physical features like mass, stiffness and damping, it is well known that these parameters can be employed for structural assessment and damage identification [15-22].

2 MASONRY WALLS, REINFORCEMENT MATERIAL AND DAMAGE

The two windowed brick walls built for this study are shown in Figure 1a-b. The walls were built using clay bricks laid by means of 10 mm thick lime mortar joints adopting an English bond disposition. The geometric and mechanical characteristics of bricks and lime mortar are reported in Table 1. At the base, the walls were constrained through a steel plate and anchors to the strong floor of the laboratory in such a way that the lateral displacement is hindered. In order to simulate real loading conditions of a masonry wall, two vertical loads of 15000 daN were applied on two points (points P_1 and P_2 in Figure 1c). A steel beam allows for an approximately uniform distribution of the total load (30000 daN) applied on the top of the wall (Figure 1).

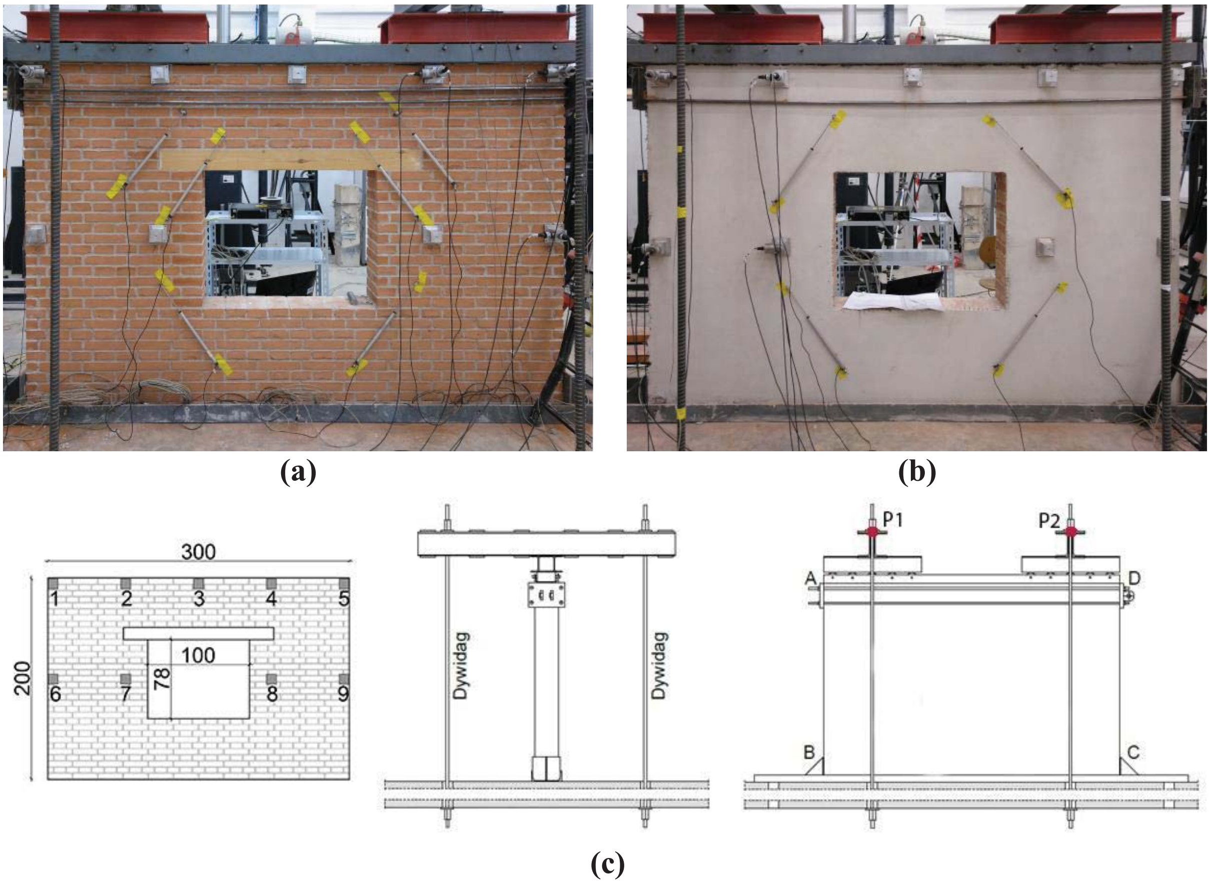

Figure 1: (a) Unreinforced and (b) reinforced windowed masonry walls in the undamaged state; (c) scheme of the experimental setup: preload device and anchorage system.

For the reinforced wall (Figure 1b), a 25x25 mm glass textile mesh embedded into a 10 mm thick cementitious mortar layer was applied on both the two lateral surfaces of the wall. Specifically, the application of the TRM reinforcement occurred in the following steps: (1) a 5 mm thick cementitious mortar layer was applied on the lateral surfaces of the wall; (2) a glass fiber textile grid was located on the cementitious layer; (3) the glass fiber grid was covered with 5 mm thick layer of the cementitious binder. It is worth noting that the first cementitious mortar layer allows for the bond between the masonry support and the glass fiber textile grid. The mechanical properties of the reinforcement are shown in Table 2.

Bricks		Lime mortar	
Dimensions (mm)	230 x 110 x 50	Compression strength at 28 days (MPa)	9.4
Compression strength (MPa)	17.20	Compression strength at 100 days (MPa)	10.1

Table 1: Geometric features and compression strength of bricks and lime mortar.

In order to simulate the effects of a high-intensity seismic action, both the two walls were damaged (Figure 2) by imposing a cyclic in-plane horizontal top displacement with increasing amplitude. Specifically, the horizontal displacement was determined by means of a hydraulic jack with a feedback system capable of producing a displacement control load test.

(a) (b)

Figure 2: (a) Unreinforced and (b) reinforced masonry walls after damage.

Mortar		Textile mesh	
Compression strength at 28 days (MPa)	15	Tensile strength (kN/m)	45
Elastic modulus (MPa)	8000	Elastic modulus (MPa)	7200

Table 2: Mechanical properties of the reinforcing materials.

3 MODAL ANALYSIS

Vibration testing and Operational Modal Analysis (OMA) were carried out on the two walls in order to estimate their modal properties (natural frequencies, mode shapes and modal damping) both in the undamaged and damaged state. Schematically, modal properties were estimated in the following four cases: (1) unreinforced and undamaged wall; (2) unreinforced and damaged wall; (3) reinforced and undamaged wall; (4) reinforced and damaged wall. In each of these four cases, the response of the wall was experimentally monitored through accelerometers with respect to 18 DOF. Specifically, a grid of 9 points (Figure 1c) was defined on each wall and, for each point, the in-plane (x-direction) and out-of-plane (y-direction) vibrations were measured. A white noise excitation was generated through a shaker located in the middle of the top of each wall.

For data acquisition, 8 piezoelectric accelerometers of sensitivity 10 V/g, two signal conditioner model PCB 482A22 and two data acquisition devices model Kyowa PCD-320 were employed. The sampling frequency was set to 2000 Hz. Since only 8 accelerometers were available, the two accelerometers located at point 1 (in the x- and y-direction) were adopted as reference sensors. Consequently, it was possible to measure the response of the wall at the considered 18 DOF by three suitable arrangements of accelerometers, thus resulting in 3 data sets.

Finally, vibration data were processed by using the ARTeMIS Modal commercial software. In particular, the Enhanced Frequency Domain Decomposition (EFDD) method was employed for determining natural frequencies, mode shapes and modal damping.

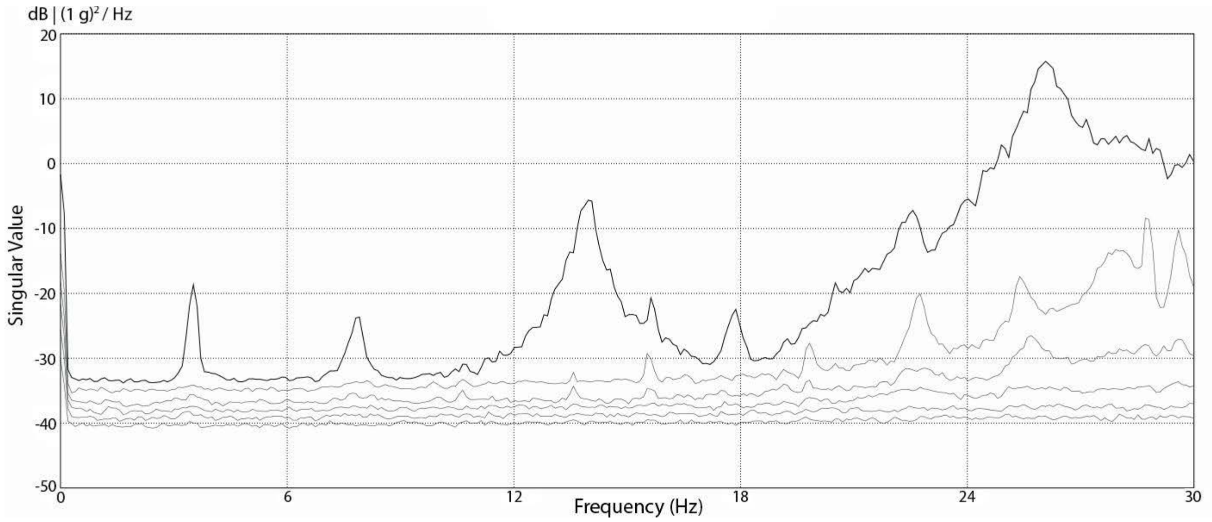

Figure 3: A typical Singular Value Plot obtained by processing acceleration data of the walls through the EFDD technique.

4 RESULTS

Figure 2 shows both the unreinforced and reinforced wall after the damage process. A classical damage pattern with diagonal cracks is visible for the two walls. The horizontal cracks of the reinforced wall are due to the presence of the glass textile grid. In the unreinforced wall, the cracks mainly follow mortar joints, except in some points where they cross one or more bricks. For the unreinforced wall the initial elastic stiffness was 25.2 kN/mm, the ultimate horizontal displacement was 22 mm and the ultimate horizontal load was 143 kN. For the reinforced wall the initial elastic stiffness, the ultimate horizontal displacement and the ultimate horizontal load were 28.7 kN/mm, 33 mm and 351 kN, respectively. Since the two walls were similar to each other, it is evident that the TRM reinforcement improves the stiffness of the wall, its ductility and its ultimate strength to horizontal cyclic loads, and thus to seismic actions.

Regarding operational modal analysis, the first three vibration modes for each wall were identified both in the undamaged and damaged case. Figure 3 shows a typical Singular Value Plot, in the frequency range from 0 to 30 Hz, obtained through the EFDD method. In Table 3, a comparison between natural frequencies estimated in the four cases above listed is reported. Both for the unreinforced and for the reinforced case a noticeable decrease of natural frequencies occurs with damage. In particular, comparing natural frequencies before, f_U, and after, f_D, the damage through the frequency discrepancy parameter $D_f = |(f_D - f_U)/f_U|$, for the unreinforced case a decrease of 24.09 %, 60.00 % and 31.42 % of the natural frequency of the first, second and third vibration mode, respectively, it is observed; the corresponding decreases for the reinforced case are of 44.05 %, 39.20 % and 45.42 %, respectively.

Mode no.	Unreinforced wall			Reinforced wall		
	f_U (Hz)	f_D (Hz)	D_f (%)	f_U (Hz)	f_D (Hz)	D_f (%)
1	5.276	4.005	24.09	6.300	3.525	44.05
2	15.829	6.331	60.00	12.891	7.838	39.20
3	22.415	15.372	31.42	25.551	13.947	45.42

Table 3: Natural frequencies estimated for the unreinforced and reinforced wall both in the undamaged (U) and damaged (D) state.

Since the natural frequency is related to the modal stiffness, a decrease of the natural frequency means that the damage has induced a reduction of the modal stiffness for all the three identified modes. In particular, in the unreinforced wall the damage has mostly affected the second mode, while in the reinforced case it has affected almost uniformly all the three modes. It suggests that the application of TRM reinforcement allows distributing on all vibration modes the negative effects of damage.

Furthermore, it can be observed that, except for the second vibration mode, the reinforced wall has natural frequencies slightly higher than those of the unreinforced wall. Since the two walls are similar to each other, this consideration, together with information about the initial elastic stiffness of the two walls above reported, allows arguing that the TRM reinforcement slightly increase the stiffness of the wall on which it is applied.

Finally, it is worth observing that, even though the ultimate load was much higher for the reinforced wall, the frequency decrease (i.e. the stiffness reduction) due to damage is comparable for the two walls. It means that TRM reinforcement limits the negative effects of the damage on the structural stiffness of the wall.

In Table 4 a comparison between the modal damping ratio estimated for the four considered cases is presented. Both for the unreinforced and for the reinforced case, an increase of modal damping ratio occurs with damage. Comparing modal damping ratio before, ς_U, and after, ς_D, the damage through the discrepancy parameter $D_\varsigma = |(\varsigma_D - \varsigma_U)/\varsigma_U|$, for the unreinforced case an increase of 1.00 %, 227.39 % and 12.16 % of the modal damping of the first, second and third vibration mode, respectively, it is observed. On the other hand, for the reinforced case an increase of 16.18 %, 87.87 % and 51.95 % of the first, second and third vibration mode, respectively, occur. Since the modal damping is related to energy dissipation, an increase in modal damping means that, as a result of the damage, the energy dissipation increase. As for natural frequencies, modal damping ratio values suggest that the application of TRM reinforcement allows distributing on more vibration modes the negative effects of damage. Indeed, considering the discrepancy parameter D_ς, in the unreinforced wall the damage has mostly affected the second mode, while in the reinforced case the effect is distributed on all the three vibration modes.

Mode no.	Unreinforced wall			Reinforced wall		
	ς_U (Hz)	ς_D (Hz)	D_ς (%)	ς_U (Hz)	ς_D (Hz)	D_ς (%)
1	1.608	1.624	1.00	1.922	2.233	16.18
2	0.449	1.470	227.39	0.907	1.704	87.87
3	0.625	0.701	12.16	0.793	1.205	51.95

Table 4: Modal damping ratio estimated for the unreinforced and reinforced wall both in the undamaged (U) and damaged (D) state.

The estimated mode shapes of the reinforced wall in the undamaged state are represented in Figure 4. The mode shapes estimated in the other three cases are similar. In order to quantitatively compare mode shapes, the Modal Assurance Criterion (MAC) values were calculated. In Table 5 and in Table 6 the MAC values respectively for the unreinforced and the reinforced wall are listed. It can be seen that for both walls, the mode shape of the second vibration mode, which is a bending mode, is the most affected by the damage. Considering the cracking pattern for the two wall (Figure 2), it could be explained by observing that, since the second vibration mode involves opposite transverse displacements of the two free vertexes of the wall (Figure 4b-4e), the friction at crack surface is emphasized for that vibration mode. Furthermore, it is worth observing that the MAC values for the unreinforced case are lower than those for the reinforced case. This can suggest that the TRM reinforcement reduces the negative effects of damage in terms of variation of mode shapes.

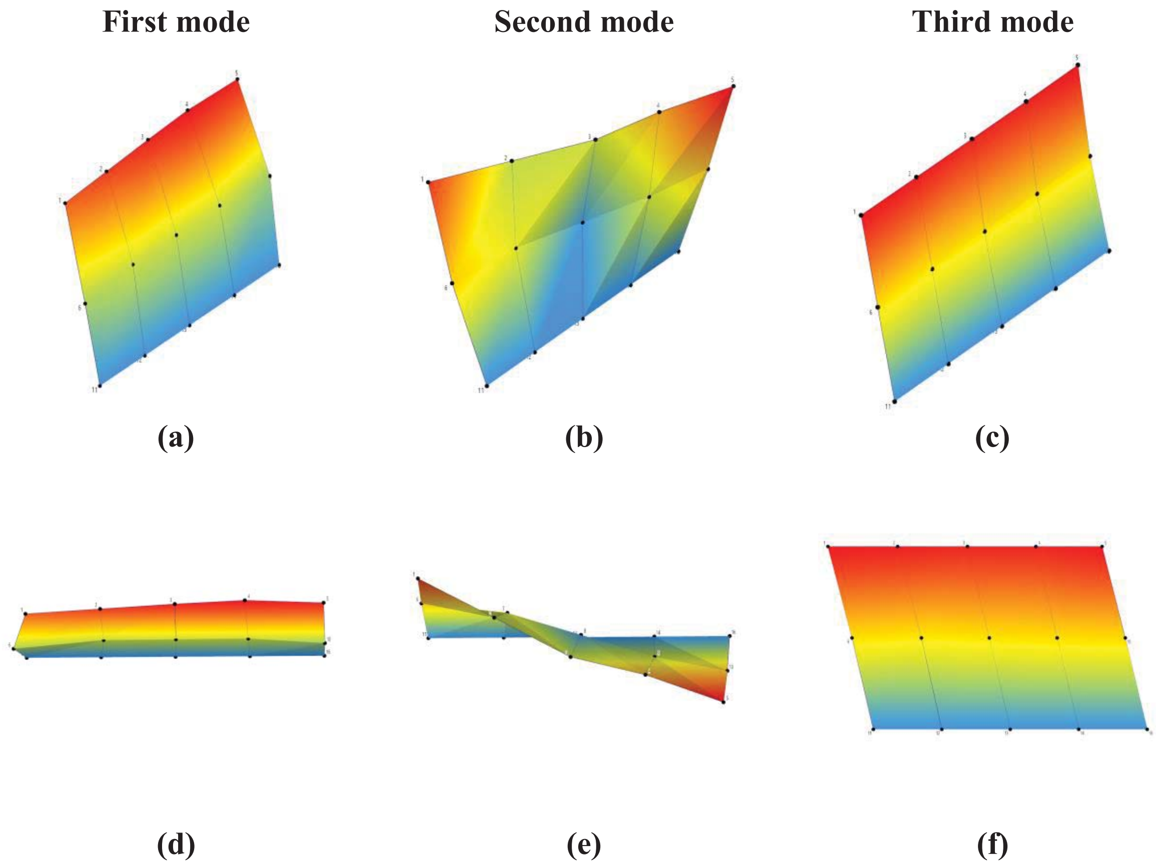

Figure 4: Mode shapes of the unreinforced wall in the undamaged state. General view: (a), (b) and (c). Plan view: (d) and (e). Front view: (f).

Frequency (Hz)	4.005	6.331	15.372
5.276	0.712	0.016	0.017
15.829	0.091	0.531	0.003
22.415	0.001	0.054	0.786

Table 5: MAC values between the mode shapes in the pre and post damage state – unreinforced wall.

Frequency (Hz)	3.525	7.838	13.947
6.300	0.921	0.043	0.001
12.891	0.019	0.842	0.034
25.551	0.001	0.034	0.994

Table 6: MAC values between the mode shapes in the pre and post damage state – reinforced wall.

5 CONCLUSIONS

In this paper, the effectiveness of the TRM reinforcement on scaled windowed brick masonry wall is evaluated through vibration testing and Operational Modal Analysis. In particular, natural frequencies and modal damping are considered as parameters respectively related to the structural stiffness and the energy dissipation. In addition, for both the two walls, mode shapes are investigated through the calculation of the MAC value both in the undamaged and the damaged state. The results show that, both for the unreinforced and for the reinforced case, for all the three identified modes there is a decrease of natural frequency and an increase of the modal damping. This means that after the damage there is a reduction of structural stiffness and an increase of energy dissipation, respectively. Furthermore, it can be seen that the damage affects the mode shapes mainly for the unreinforced case.

More specifically, the results suggest that the application of TRM reinforcement: (1) improves the stiffness of the wall, its ductility and its ultimate strength to horizontal cyclic loads; (2) allows distributing on more vibration modes the negative effects of damage related to both the structural stiffness and the energy dissipation; (3) limits the effects of damage on mode shapes. This last conclusion remarks that the reinforced wall has at the end of the test higher level of structural integrity than the unreinforced specimen. In conclusion, it can be argued that, with respect to horizontal cyclic load, like seismic actions, TRM reinforcement can improve the mechanical behaviour of windowed brick masonry walls.

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