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DYNAMIC IDENTIFICATION OF MASONRY PARTITION WALLS BY AMBIENT VIBRATION DATA

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Abstract

Masonry infill walls and partitions are commonly used in r.c. building and seismic events showed that out-of-plane collapse can be one of the predominant mode of failure for masonry infill walls and partitions leading to life-safety hazard. This type of mechanism is related to the geometrical and mechanical features of the masonry but it is substantially affected by the constraints along the structural frame; however, these actual boundary conditions are very difficult to be defined, especially in the case of an existing building, for which information are lack and deterioration can be occurred respect to the design conditions. Moreover, in order to conduct a more accurate seismic analysis or damage assessment of these components, it is necessary to establish reliable numerical models.
In this paper the results of experimental ambient vibration tests carried out on two masonry partition walls with different constraints along the structural frame are reported. The dynamic properties extracted using Operational Modal Analysis (OMA) techniques have been used to update a preliminary finite element model implemented by SAP2000 software. The implemented procedure, including the in-situ test and the updating of the numerical model confirmed its effectiveness in defining the mechanical characteristics of the masonry and the out-of-plane constraints along the perimeter.

Keywords: out of-plane; ambient vibration test; dynamic parameters; Operational Modal Analysis; finite element method; model updating.

1 INTRODUCTION

In Italy, as in all the world, infill panels and masonry partition are used in RC framed buildings to ensure an adequate thermal and sound insulation. They are usually considered non-structural elements due to their modest bearing capacity, thus, neglected in the seismic modelling of building structures. Nevertheless, the behavior of the framed buildings with in-

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fill walls during earthquakes have highlighted their influence on the global response of the structures [1]. Mechanical properties and detailing aspects, such as the relative stiffness and strength between the frames and the masonry walls or the type of connection between masonry and surrounding elements, can influence the seismic performance of buildings [2].
The out-of-plane movement of masonry infill walls and partitions is very common and it is a threat to human safety since it is characterized by brittle behaviour [3]. The out-of-plane failure mechanisms and associated cracking patterns of infills walls are influenced by several aspects [4], but more potentially by (i) the connection efficiency to orthogonal infill walls and inner leaf panels; (ii) the connection efficiency to upper and lower RC beams, as well as columns; (iii) the wall support conditions over concrete slab or beam.
However, the boundary conditions are very difficult to be defined, especially in the case of an existing building, for which there is no sufficient information and also a visual screening can't be efficient.
An innovative procedure based on experimental dynamic test in situ and a consequent process of updating to calibrate the actual boundary conditions has been proposed by De Angelis and Pecce [5].
More recently, vibration-based tests have been also adopted to investigate the influence of the non-structural elements on the dynamic behaviour of buildings, with the advantage that this kind of tests can be performed both on laboratory specimens and on in-situ buildings [6]. However, only few works are available in the literature dealing with the application of this test typology to infill masonry walls. Arslan and Durmus [7] performed AVTs on a full-scale one-bay one-storey laboratory RC frame without and with the infill wall. Varum et al. [8] carried out, in Nepal after the 25th April earthquake, some ambient vibration tests on damaged and undamaged infill masonry walls with the aim of characterize their OOP dynamic properties and understand the influence of the damage and opening on their OOP frequencies. In situ tests were recently carried out also by Furtado et al. [9] on infill masonry walls with the main goal of characterize the dynamic properties such as the in-plane and OOP frequencies of the panel with different characteristics. Further, these type of tests have been also used to estimate the infill stiffness that can be adopted to model the infill walls within FE models of buildings in order [10].
Therefore, vibration-based tests are relevant to the identification of the infill out-of-plane dynamic behavior and can be simple performed since they only require the recording of the wall vibrations in the orthogonal direction of the wall plane.
The aim of this paper is to verify the effectiveness of a local structural identification technique for the infill panels or partition walls that allows to establish its out-of-plane response, especially in terms of constraints to the RC frame.
Therefore, first of all the results of experimental ambient vibration tests carried out on two masonry partition walls with different constraints along the structural frame are reported. Then the dynamic properties extracted using Operational Modal Analysis (OMA) techniques are used to update a preliminary finite element model implemented by SAP2000 software.
The overall procedure, including the in-situ test and the updating of the numerical model confirmed its effectiveness in defining the mechanical characteristics of the masonry and the out-of-plane constraints along the perimeter.

2 DYNAMIC IDENTIFICATION OF MASONRY PARTITION WALLS

The basis of the modal identification tests is that the relation between the input force(s) exerted on a structure and the resulting linear responses is a reflection of the structure's modal properties [11]. Modal identification method are classified as input-output approach or input-only approach. The Hammer Impact Modal Testing (HIMT) is a typical input-output approach and it requires to apply an impact force to the tested object by an instrumented hammer with a built-in force transducer. The input signals are measured by the built-in force transducer, and the output signals are measured by external vibration sensors. The recorded input-force and output signals are then processed to extract the fundamental frequency and damping of the selected element.

Instead, in case of output-only approach only the response vibration can be measured. The most common application of an output-only method is the Ambient Vibration Testing (AVT) approach, that consists of real time recording of the vibrations and processing of the records; it is based on measuring the small structural vibrations caused by the ambient forces, that may be caused by the wind, the traffic noise or some other micro-tremor. An advantage of the ambient vibration over the forced vibration surveys is that usually light equipment is required. Further it requires only relatively short and simple field measurements, and the measuring instruments can be installed and operated by a smaller number of operators. The method is very fast and relatively simple procedure can be performed on an element in use without disturbing its normal functioning [12].

Dynamic identification of both structural and non-structural components requires the experimental determination of the main modal parameters (frequencies, damping and modal shapes) and the development of a numerical model for predicting the dynamic behavior of the investigated element. Due to numerous uncertainties including actual geometry, material properties and boundary conditions, there is a need to bridge the differences between finite element model and reality through model updating techniques. Figure 1 summarizes the procedure adopted to provide the calibrated model of the selected infill wall or partition able to detect the actual in-situ out-of-plane constraints between the infill wall and the surrounding structure. Therefore, the AVT tests carried out on the selected case studies are described and discussed.

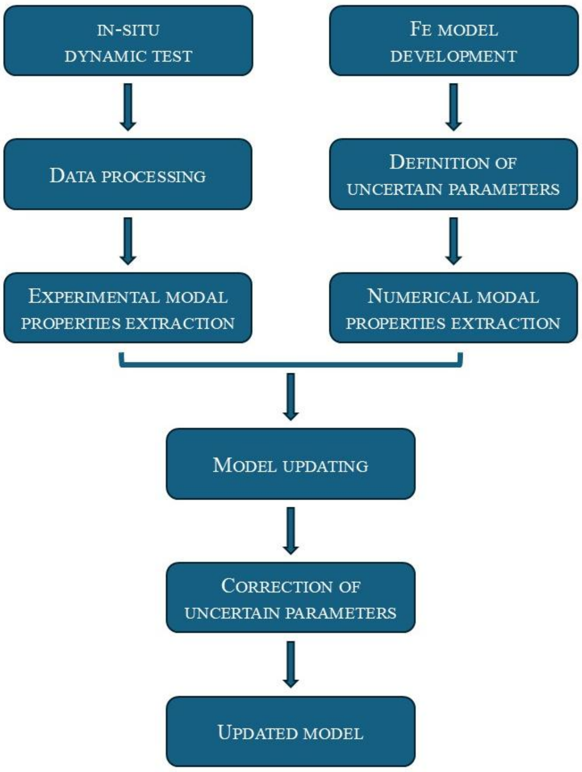


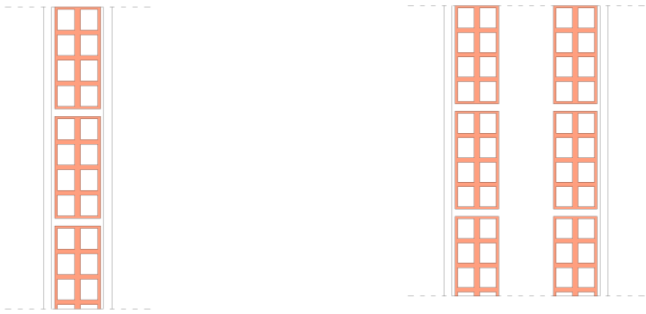
Figure 1 – Flow-chart of the adopted procedure

2.1 The selected partition walls

Two masonry internal partition wall are selected for the application of the previous described identification procedure. The first masonry partition (Figure 2a), with a total thickness, $t_{tot,}$ of 0.15 m, is a single leaf wall made by hollow clay brick with a thickness of 0.12m and finished by a 15 mm thick plaster layer at both sides. The dimensions are 3.8 m x 4.0 m (b x h = width x height). The second wall (Figure 2b) is 5.00m x 3.50 m (b x h) with a total thickness t_{tot} = 0.37 m obtained by coupling two hollow clay bricks independent layers with t = 0.10m , with an internal gap of 0.14m and a 15 mm thick plaster layer at both sides.

The first wall is located at the first floor of a mixed masonry-RC building while the second one is located at the first floor of a RC framed building in a seismic area of the South of Italy.

Note that the second masonry partition walls has been further studied in [13] applying two different damage detection procedures, i.e., operational modal analyses (OMA) and an innovative machine learning techniques such as artificial neural networks.



(a) (b)

Figure 2 –Wall cross section of a single leaf (a) and double leaves (b) masonry partition

2.2 Ambient vibration tests

Two ambient vibration tests (AVTs) have been carried out to obtain the dynamic response (natural frequencies, damping ratios, mode shapes) of the masonry partition walls under operating conditions. As stated above the second partition wall is constituted by two leaves that are not connected, namely independent. Therefore, the investigations have been performed exclusively on one leaf.

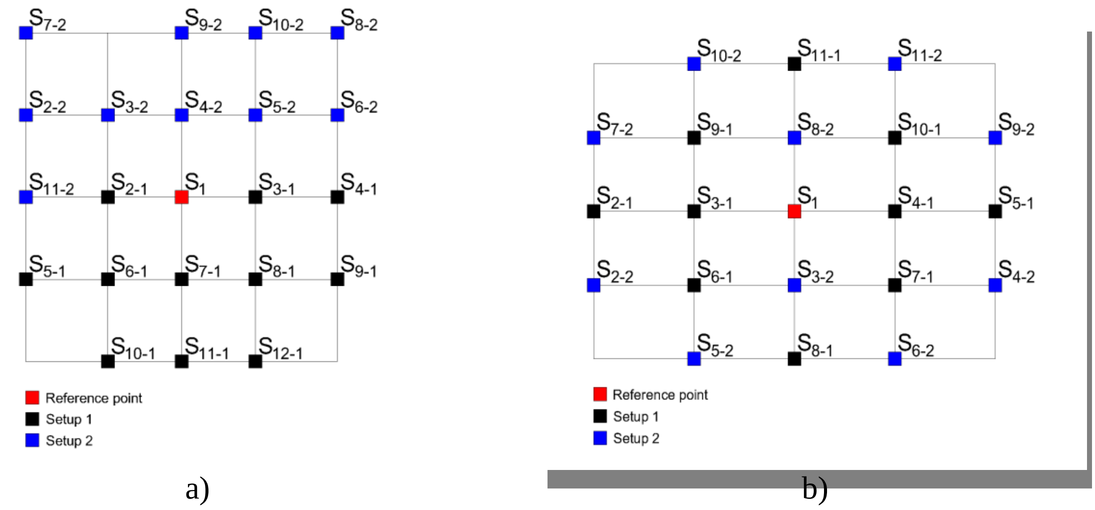


Figure 1 – Layout of the sensors placement: (a) single leaf partition wall and (b) two leaves partition wall.

The best sensor location has been planned according to the results of a modal analysis carried out on a preliminary FE model as described in the following section. To get mode shapes of high accuracy, the measurement grid needs to be as dense as possible; thus, the monoaxial sensors were located on the infill wall to measure the out-of-plane acceleration in 22 points for the first partition wall and 21 points for the second one. In particular, it is possible to note a primary crosswise disposition, which identifies four quadrants on the wall, and a network of secondary sensors, mostly arranged in the center line of each quadrant. Moreover, since the objective of the test is also to detect the degree of constraint between the infill wall and the surrounding structural frame, other sensors have been arranged on each sides near to the structural frame elements.

a)

b)

Figure 2 - Pictures of the sensors layout in each setup for a single leaf (a) and double leaves (b) partition walls.

A multi-setup (or roving sensors) measurements strategy has been applied because the number of wanted measurement DOFs exceeds the number of available sensors. This measurement strategy is based on selection of a number of reference DOFs that are fixed during the measurements and the remaining available sensors are then roved over the structure until all DOFs have been measured [14].

The available accelerometers (twelve) were used in two separate tests (black and blue squares in Figure 3 for test 1 and test 2, respectively). One accelerometer (red square in **Errore. L'origine riferimento non è stata trovata.**) has been used as reference to merge the data obtained by the two acquisitions.

The measurement equipment for the AVT consisted of uniaxial Integrated Circuit Piezoelectric (ICP) accelerometers with a bandwidth ranging from 0.04 to 400 Hz and a sensitivity of

10 V/g. These accelerometers were connected via cables to a twelve-channel data acquisition system with a 24-bit ADC, provided with anti-alias filters (Figure 4). The parameters set for the dynamic tests were a sampling frequency of 200 Hz and 3600 s time duration for each test. These assumptions assure that frequencies from 1 to 80 Hz would be properly measured.

2.3 Data processing for the dynamic identification

The data processing to extract the modal properties has been carried out with the software Artemis Modal Pro [15] working both in the frequency domain both in the time domain. In the frequency domain, the power spectral densities matrices have been obtained using the frequency domain decomposition (FDD) [16] that decomposes the spectral density matrix of the system response into a set of single degree of freedom (SDOF) systems using the singular value decomposition (SVD). Indeed, the singular values estimate the spectral density of the SDOF systems, and the singular vectors estimate the mode shapes. In the time domain, the SSI-UPC merged test setups algorithm available in the software based on the data driven Stocastic Sub space Identification (SSI) method has been used. For a detail description of the method the reader is referred to [17, 18]. In this procedure the data is merged and normalized prior to the identification step. In particular, first subspace matrices (or hankel matrices) from each setup are separated into a reference sensor part and a roving sensor part, then the moving part matrices are re-scaled with a common Kalman filter state of one setup and finally merge the together with the reference matrix of with the re-scaling was performed. The outcome is a merged subspace matrix that contains all measured setups, hence the SSI method only has to be performed once [19].
Table 1 lists frequencies and damping factors of four modes identified through these methods (FDD and SSI). The methods are in excellent agreement being characterized by a frequency difference ε lower than 2% and modal assurance criteria (MAC) values greater than 0.9. Figure 5 shows the modal displacements for the identified mode shapes.

		FDD	SSI		Comparison	
Partition wall	Mode	f_{exp} [Hz]	f_{exp} [Hz]	ξ [%]	ε [%]	MAC [-]
Single leaf	1	*20.02*	*20.33*	*1.44*	*1.5*	*1.00*
	2	*39.55*	*40.16*	*2.70*	*1.5*	*0.99*
	3	*43.95*	*43.89*	*1.84*	*-0.1*	*0.95*
	4	*66.31*	*65.22*	*1.57*	*-1.6*	*0.90*
Double leaves	1	*19.04*	*19.12*	*2.09*	*0.4*	*1.00*
	2	*30.86*	*30.79*	*0.84*	*-0.2*	*0.99*
	3	*41.50*	*41.55*	*0.89*	*0.1*	*0.91*
	4	*52.44*	*52.58*	*0.64*	*0.3*	*0.96*

Table 1 - Identified frequencies and damping factors

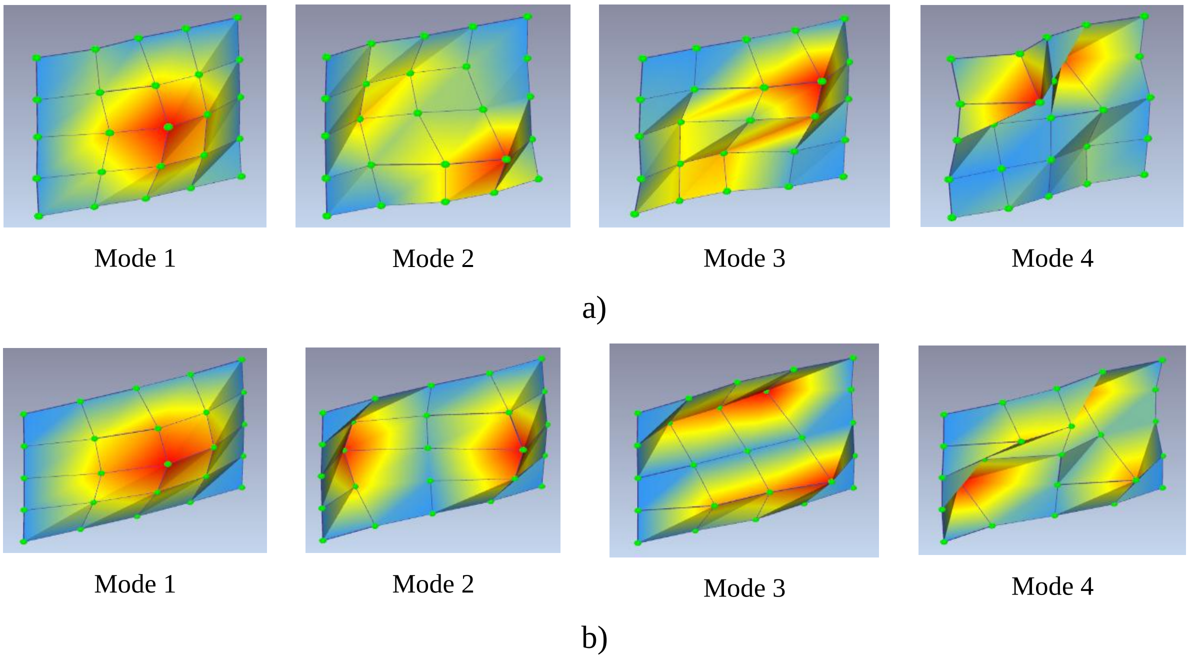


Figure 3 – Identified modal shapes for the single leaf (a) and the double leaves (b) partition walls.

3 MODEL UPDATING

In general FE models can be created using technical design data, as-built drawings and engineering judgment; however, the actual behavior is affected by many geometrical and mechanical uncertainties. A possible practice to fill the lack between the real object and the models is to update the FE model by a suitable technique by means the target of the results of a dynamic test in-situ. The updating of FE models emerged in the 1990s as a subject of paramount importance for the design, construction and maintenance of structures [21].

In model updating process, the target is a good correlation between numerical and experimental results but maintaining physical significance of updated parameters; thus, setting up of an objective function and selecting parameters are the crucial starting steps of the procedure. They require deep physical insight and trial-and-error approaches. The success of the FE model updating is depending on the use/quality of experimental data, the selection of the updating variables and the correct application of an optimization method [22].

If the experimental behavior is obtained by dynamic tests with ambient vibration, as in this case, the experimental data are natural frequencies and mode shapes, considering that the response includes resonant frequencies and mode shape ordinates that are strongly dissimilar for FEA and OMA. The reliability of the dynamic test data is of paramount importance [23], furthermore it has to be considered that higher modes are not so accurate partly due to spatial resolution of mode shapes, and updating does not work as well for these modes.

The comparison between the dynamic experimental behavior and the numerical simulation can be developed by simple tabulation or plotting of the eigenvalues to evaluate the scatter between the measured and predicted results, but a stricter correlation technique is the use of the so-called “Modal Assurance Criterion” (MAC), that was proposed by Allemang and Brown [24]. It uniquely identifies a real scalar between zero and one, and is defined between mode “i” and mode “j” by eqn. (1):

$$MAC_{ij} = \frac{\left(\{\phi_A\}_i^T \cdot \{\phi_X\}_j\right)^2}{\left(\{\phi_A\}_i^T \{\phi_A\}_i\right)\left(\{\phi_X\}_j^T \{\phi_A\}_j\right)} \tag{1}$$

Values close to unity indicate good correlation between the experimental mode shape, $\{\phi_X\}$, and the predicted eigenvector, $\{\phi_A\}$.

3.1 Preliminary numerical model

A 2D linear elastic model of one leaf of the wall was developed using the software SAP2000 **Errore. L'origine riferimento non è stata trovata.**. Homogeneous and orthotropic material was adopted since the masonry wall is constituted by horizontally hollowed clay units, with mass per unit volume ρ = 700 kg/m3. The hollow clay brick wall was modelled using 10 cm x10 cm shell elements with the thickness 15 cm for the first partition wall and 13 cm ((i.e., the brick and the plaster layer) for the second wall. This mesh allowed also having joints at the same position of the sensors used during the experimental test. The elastic modulus E1=900 MPa and E2 = 1800 MPa of the hollowed clay brick infill in the two directions parallel and orthogonal to the holes, respectively were assumed, according to the technical literature for masonry infill similar to the case study [26]. Moreover, the model of the wall was restrained along the perimeter by linear springs that have to be calibrated using the experimental results. At this initial stage very high values of stiffness are assigned to the springs to reproduce a fully restrained condition along the four sides.

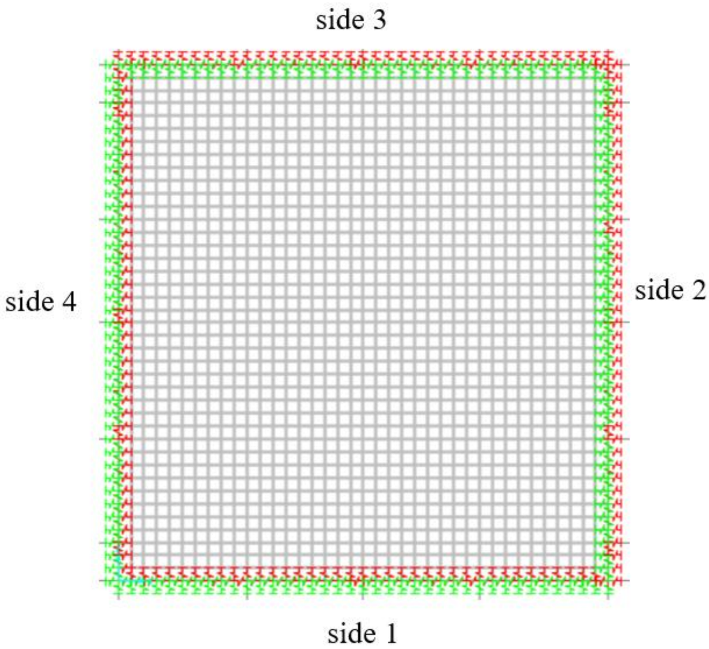


Figure 6 – Preliminary FE model of the partition walls

3.2 Correlation analysis

Therefore, a modal analysis was performed with this model in order to obtain the numerical modal properties (i.e., frequencies, damping ratios and mode shapes). The numerical mode shapes are reported in Figure 7. The correlation between the dynamic experimental behaviour and the numerical one was developed using the frequency difference, ε, in percentage and the "Modal Assurance Criterion" (MAC). For each i-th mode, Table 2 lists the values of the experimental and numerical frequencies, f_i, and MAC_i values.

For the first partition wall, i.e., the single leaf one, the numerical frequencies are higher than the experimental ones with differences up to 12%. The MAC values show a really bad correlation for all the modes (values lower than 0.60) except for the first one (with a value of 0.79). It means that the actual boundary conditions are different from those adopted in the numerical model and they should be updated. Moreover, the fifth numerical mode was not experimentally detected.

Instead, for the second partition wall, the numerical frequencies are lower than the experimental ones for the first two modes and higher for the other modes, with differences up to 13%. The MAC values show good correlation for all the modes except the last one (with a value of 0.76). Moreover, the third numerical mode has been not detected experimentally.

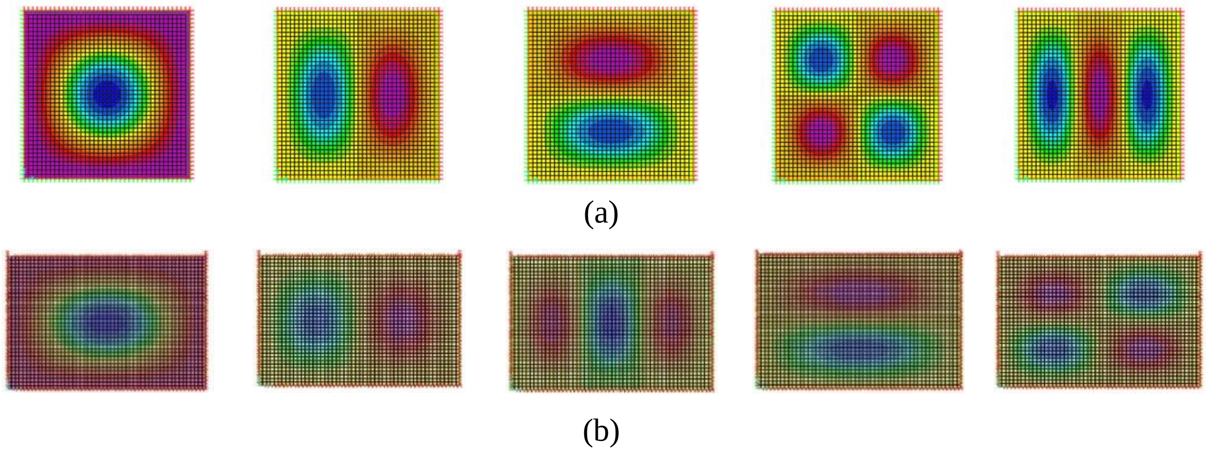


Figure 7 – Numerical mode shapes obtained by preliminary FE models: (a) single leaf and (b) double leaves walls

Partition wall	Numerical frequency	Experimental frequency	ε [%]	MAC
Single leaf	f_1= 22.49	f_1= 20.02	12.3	0.79
	f_2= 42.28	f_2= 39.551	6.9	0.45
	f_3= 48.72	f_3= 43.945	10.9	0.39
	f_4= 67.23	f_4= 64.063	4.9	0.32
	f_5= 73.38	not detected	-	-
Double leaves	f_1= 18.72	f_1 = 19.04	-1.7	0.97
	f_2= 26.71	f_2 = 30.86	-13.45	0.96
	f_3= 40.36	not detected	-	-
	f_4= 46.93	f_3 = 41.50	13.07	0.87
	f_5= 54.57	f_4 = 52.44	4.06	0.76

Table 2 – Frequencies (in Hz) provided by numerical model and experimental identification, and MAC values before the model updating

3.3 Modal tuning

Hence, it is necessary a calibration of the model to improve the correlation with the experimental results. Indeed, through the model updating the differences between the numerical and experimental modal properties can be minimized by changing some uncertainty parameters, such as material properties and boundary conditions.

To update the model, it was manually adjusted the Young's modulus in the two directions (E_1 parallel and E_2 orthogonal to the holes) and the stiffness of the translational springs along the vertical y-axis (K_y) and the rotational springs around the horizontal in-plane x-axis (K_{rx}) for the two horizontal sides and the horizontal z-axis (K_{rz}) for the two vertical sides. Table 3 lists the parameter before and after the tuning.

For the first partition wall, i.e., the single leaf one, the numerical mode shapes are different from the numerical ones except for the first mode. Therefore, in this case, through a trial and error procedure it was found that along the top side (side 3) there is a variable degree of constraint, due to the presence of a false ceiling, that has to be updated. The numerical mode shapes after the updating procedure are reported in Figure 8.

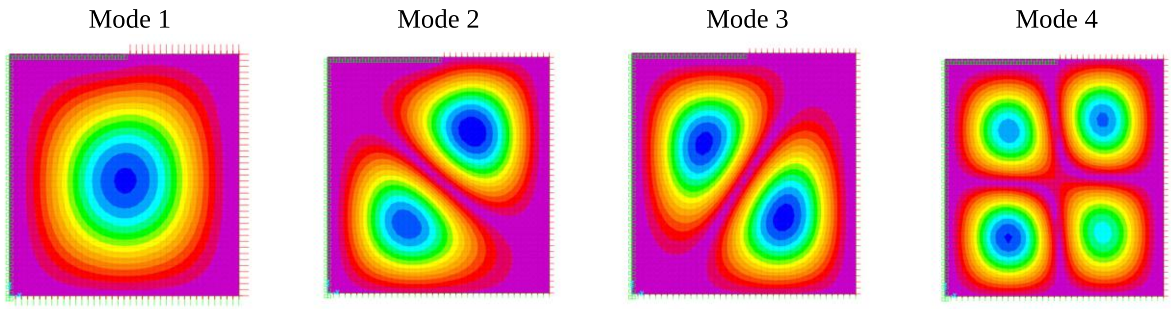


Figure 8 – Numerical mode shapes obtained by the updated FE models for the single leaf wall.

For the second partition wall, i.e., the double leaves one, there is already a good match between the experimental and numerical mode shapes but the stiffness of the springs along the perimeter has to be updated to improve the MAC values. After the updating it is possible to see that the degree of constraint of the horizontal sides is lower than the vertical sides.

		Double leaves wall		Single leaf wall	
Updated parameters		Initial Value	Updated Value	Initial Value	Updated Value
E_1	[MPa]	900	1480	900	900
E_2	[MPa]	1800	2150	1800	1500
K_{y1}	[kN/m/m]	10^7	10^4	10^8	10^2
K_{y2}	[kN/m/m]		10^6		10^5
$K_{y3,left}$	[kN/m/m]		10^4		10^8
$K_{y3,right}$	[kN/m/m]				10^2
K_{y4}	[kN/m/m]		10^6		10^8
K_{rx1}	[kNm/mrad]	10^7	10^2	10^8	10^2
K_{rz1}	[kNm/mrad]	-	-		10^5

K_{rz2}	[kNm/mrad]	10^7	10^4		10^5
$K_{rx3,left}$	[kNm/mrad]	10^7	10^2		10^8
$K_{rz3,left}$	[kNm/mrad]	-	-		10^8
$K_{rx3,right}$	[kNm/mrad]	10^7	10^2		10^2
$K_{rz3,right}$	[kNm/mrad]	-	-		10^5
K_{rz4}	[kNm/mrad]	10^7	10^4		10^8

Table 3 - Values of the updated parameters

Errore. L'autoriferimento non è valido per un segnalibro. shows the correlation after the updating process. It is possible to see that for the first partition wall the frequencies' differences are lower than 10% for the first two modes and slightly higher for the third and fourth modes. Now there is a good match between the modal shapes except for the fourth mode. It is also due to the fact that it is not correctly detected from the experimental test.
Instead, for the second partition wall the frequencies' differences are lower than 10% for all the modes. The MAC values show a good correlation for the first three mode shape and an acceptable correlation for the last higher mode.

Partition wall	Numerical frequency	Experimental frequency	ε [%]	MAC
Single leaf	$f_1 = 18.83$	$f_1 = 20.02$	-5.9	0.98
	$f_3 = 39.13$	$f_2 = 39.355$	-3.8	0.83
	$f_2 = 37.85$	$f_3 = 44.043$	-11.1	0.82
	$f_4 = 55.84$	$f_4 = 64.063$	-12.8	0.30
Double leaves	$f_1 = 17.99$	$f_1 = 19.04$	-5.5	0.98
	$f_2 = 29.69$	$f_2 = 30.86$	-3.8	0.99
	$f_3 = 43.56$	$f_3 = 41.50$	5.0	0.90
	$f_4 = 55.07$	$f_4 = 52.44$	5.0	0.79

Table 4 - Frequencies (in Hz) provided by numerical model and experimental identification, and MAC values after the model updating

4 CONCLUSIONS

The out-of-plane response of masonry infill walls and partitions is very common and it is a threat to human safety since it is characterized by brittle behavior. The out-of-plane failure mechanisms are influenced by several aspects but more potentially by the connection efficiency to orthogonal infill walls and inner leaf panels, the connection efficiency to upper and lower RC beams, as well as columns. However, the boundary conditions are very difficult to be defined, especially in the case of an existing building, for which there is no sufficient information and also a visual screening can't be efficient.
In this paper, a procedure based on experimental dynamic test in situ and a consequent process of updating to calibrate the actual boundary conditions has been applied to two masonry partition walls.
At first, the results of experimental ambient vibration tests carried out on two masonry partition walls with different constraints along the structural frame are reported. The dynamic

properties extracted using Operational Modal Analysis (OMA) techniques have been used to update a preliminary finite element model implemented by SAP2000 software.
The overall procedure, including the in-situ test and the updating of the numerical model confirmed its effectiveness in defining the mechanical characteristics of the masonry and the out-of-plane constraints along the perimeter

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