Experimental and Numerical Analysis for the Structural Identification of the Dynamical Properties of a Masonry Building Prototype

Fabio De Angelis[1], Donato Cancellara[2]

Department of Structural Engineering, University of Naples Federico II, via Claudio 21, Naples 80125, Italy
[1]fabio.deangelis@unina.it; [2]donato.cancellara@unina.it

***Abstract*- Masonry buildings are known to be characterized by poor performances during seismic events. In fact, their behavior is not optimal when they are loaded by horizontal forces associated to the seismical actions on the structure. In order to characterize the dynamical properties of masonry buildings when subject to horizontal forces, a masonry building prototype has been realized in the laboratory and an experimental investigation campaign has been conducted with the aim of determining a structural identification of the masonry building prototype. Furtherly, the characterization of the structure is also performed via a numerical analysis of the dynamical behavior of the masonry building. Numerical tests are performed and a finite element model of the masonry building prototype is presented in order to achieve the characterization of the dynamical parameters through a comparative analysis of the experimental and the numerical data. Accordingly, in the present paper an experimental campaign is illustrated which has been performed on a masonry building prototype for studying the structural behavior of the masonry building subject to harmonic horizontal forces of different intensity. A physical model is realized in the laboratory by considering a two-storey masonry building. The structure test is subjected to harmonic horizontal force inputs supplied by a vibrodyne. The experimental results characterize the dynamical effects of the masonry building prototype subject to harmonic forces and illustrate the behavior of the building under the predominant actions of a seismic input. Further a finite element modeling of the masonry building prototype is considered and a numerical analysis is performed for describing the dynamical features of the system. The finite element modeling of the structure has the aim to reproduce the experimental testings of the masonry building subject to the harmonic force inputs. For different monitored nodal points of the finite element mesh, the frequency response functions corresponding to the frequency load inputs are determined. Consequently, a comparative analysis is reported in order to perform the characterization of the suitable dynamical parameters of the structure and to finalize the structural identification of the masonry building. Such comparative analysis between the experimental results obtained on the masonry building prototype and the numerical results obtained with the finite element analysis allows assessing the calibration of the material dynamical parameters for characterizing the dynamical behavior of the masonry structure. The proper assessment of the dynamical parameters of the masonry building allows having a refined structural identification of the masonry building for a better and more accurate simulation of the dynamical behavior of the structure.**

Keywords*- Experimental Results; Finite Elements; Masonry Building; Numerical Modeling; Structural Identification

I. INTRODUCTION

In many parts of Italy, especially in the past, buildings were often realized by means of masonry-like materials. However the behavior of masonry buildings is not optimal when they are subject to seismic events, see e.g. Zhuge Thambiratnam and Corderoy [1] and Magenes and Calvi [2]. Consequently for these types of buildings it is of interest to investigate their performance when they are subject to horizontal forces and in addition to characterize their vulnerability in the case of seismic events, see e.g. Vestroni Capecchi Panzeri and Pezzoli [3], Capecchi Vestroni and Antonacci [4], and Genovese and Vestroni [5]. The investigation reported in the present paper has the aim to characterize the experimental behavior of a masonry building prototype when subject to seismic loads, see e.g. Radi Di Tommaso and Viola [6] and Tomaževič Lutman and Petkovic [7], and to implement a numerical modeling of the structural behavior of the masonry building during seismic events, see e.g. Tomaževič and Weiss [8] and Tomaževič [9]. The characterization of some experimental features of the behavior of a masonry building prototype is analyzed when the structure is subject to harmonic forces of different intensity. Subsequently the numerical modeling of the structure is addressed in order to determine a finite element analysis of the behavior of the structure when loaded by harmonic horizontal forces. Consequently, the results of these two parallel research activities are compared for analyzing the structural behavior of the masonry building prototype.

In the first part of the research activity, a two-storey masonry building prototype was built and characterized by a regular floor plan. The masonry building prototype was built in the Laboratory of the Department of Structural Engineering (DIST) at the University of Naples. An initial set of tests was performed in order to characterize the construction masonry material which is assumed to be a tuff, i.e. a soft rock of volcanic origin widely adopted in the construction of ancient masonry buildings in some parts of southern Italy. The masonry structure was realized with a regular floor plan, but with openings which were designed in order to characterize an asymmetrical behavior of the building. A vibrodyne was placed on top of the masonry structure in order to reproduce, depending on the frequency of the action of the vibrodyne, a set of horizontal harmonic forces which may also be intended as representative of the predominant horizontal actions in a seismic event.

Accelerometers were placed on a set of monitored points on the walls of the masonry building prototype in order to measure the corresponding accelerations. Some experimental features of the dynamical behavior of the structure have been determined. The object of this part of the research was to determine experimental parameters which characterize the structural behavior of the masonry building prototype subject to horizontal harmonic forces representative of the predominant actions of a seismic input. The mechanical parameters required for a better definition of the theoretical and numerical modeling of the structure were determined. In fact the knowledge of the physical-mechanical parameters of the materials and of the structure is essential for the verification that the analysis performed with the numerical models corresponds to the real behavior of the structure.

Accordingly, in the second part of the research work a numerical simulation of the dynamical behavior of the masonry building prototype is performed and a finite element analysis of the masonry structure is presented, at this regard see also Page [10], Pande Middleton and Kralj [11], and Lourenco [12]. The evaluation of the physical, dynamical and mechanical properties of the structure is an essential requirement for better defining the simulation of the real behavior of the structure and for the selection and adjustments of the convenient parameters and methods for the design and verification of the masonry structure, see, e.g. Radi Di Tommaso and Viola [6], Tomaževič and Weiss [8], Turnšek and Sheppard [13], Asteris and Tzamtzis [14] and Tzamtzis and Asteris [15]. The finite element analysis is therefore intended to simulate the experimental analysis already performed with the testings on the masonry building prototype. The aim is to develop a comparative study of the two analyses, experimental and numerical, in order to determine the essential parameters that characterize the dynamical behavior of the masonry structure. This comparative study will also provide the adjustments and calibrations for the appropriate mechanical parameters that characterize the dynamical behavior of the structure subject to horizontal harmonic forces and consequently allows performing the proper fitting of the parameters and the corresponding structural identification analysis.

In addition, the importance of the determination of experimentally validated parameters which are characteristic of the dynamical behavior of the masonry building prototype is emphasized since the accurate evaluation of validated parameters is also essential for the identification of experimentally based methods in the verification of the earthquake resistance of masonry buildings, see e.g. Tomaževič Lutman and Petkovic [7], Tomaževič and Weiss [8], Tomaževič [9], and Turnšek and Sheppard [13].

II. MASONRY BUILDING PROTOTYPE

A. The Test Prototype

The masonry building prototype realized in the Laboratory has dimensions reported in Figs. 1-3. It consists of a two-story masonry building with regular floor plans. It is realized with tuff blocks with thickness 25 cm and simple mortar joints. The walls of the test prototype have a constant thickness. The openings in the walls are designed to be asymmetrical as shown in Figs. 1-3. The flooring is realized with a 2 cm thick boarding and a reinforced concrete slab which is also the joining element with the masonry walls. The thickness of the first deck is 15 cm, while for the second deck it is 20 cm.

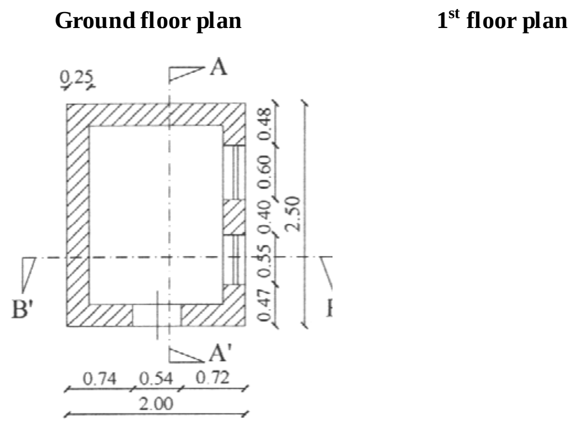

Fig. 1 Plans of the two levels of the masonry prototype (dimensions in m)

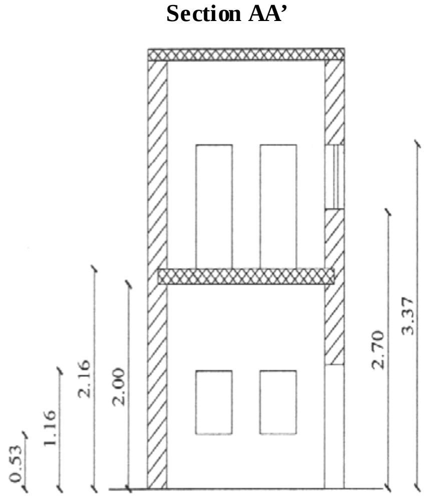

Fig. 2 Cross section A-A' of the masonry prototype (dimensions in m)

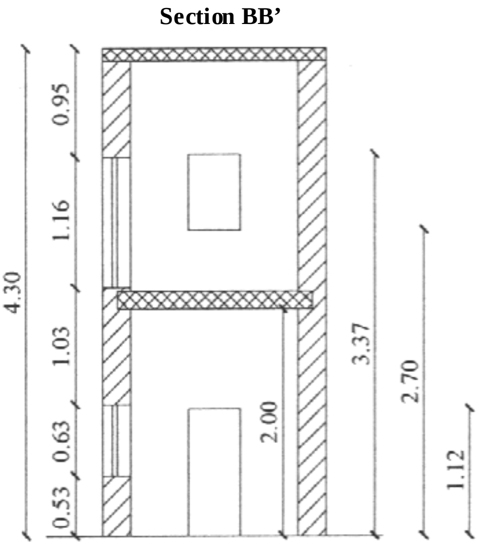

Fig. 3 Cross-section B-B' of the masonry prototype (dimensions in m)

B. *Material Parameters*

A testing procedure has been conducted for characterizing the material properties of the construction. The resulting material parameters for the tuff and for the concrete are illustrated in Table 1.

TABLE I MECHANICAL PARAMETERS OF THE MATERIALS

	Tuff	**Concrete**
specific weight [γ] (Kg/m^3)	1600	2500
Poisson's ratio [ν]	0.15	0.10
elasticity modulus [E] (Kg/cm^2)	20000	300000

C. *The Vibrodyne*

A vibrodyne has been placed on top of the second floor of the building prototype. The vibrodyne is realized by two disks on which cylindrical masses are eccentrically fixed (see Figs. 4-6). The vibrodyne is anchored by pivots to the deck of the second floor by means of a metal frame (see Fig. 7). The maximum amplitude of the horizontal forces associated to the operating frequencies of the vibrodyne is shown in Table 2.

TABLE II FORCE INPUTS ASSOCIATED TO THE OPERATING FREQUENCIES

Frequency [Hz]	1.6	2.0	2.2	2.4	2.6	2.8	3.0
Force [KN]	1.73	2.59	3.13	3.72	4.37	5.07	5.82

Frequency [Hz]	3.2	3.4	3.6	3.8	4.0	4.2	4.4
Force [KN]	6.62	7.47	8.38	9.33	10.34	11.40	12.51

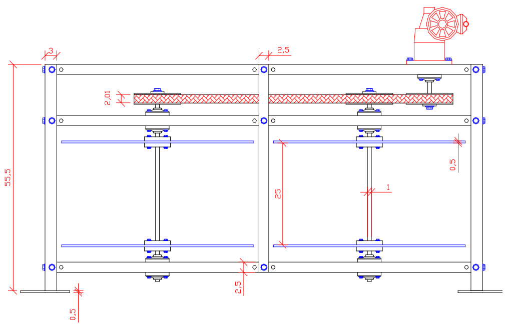

Fig. 4 Scheme of the vibrodyne used for the structural analysis

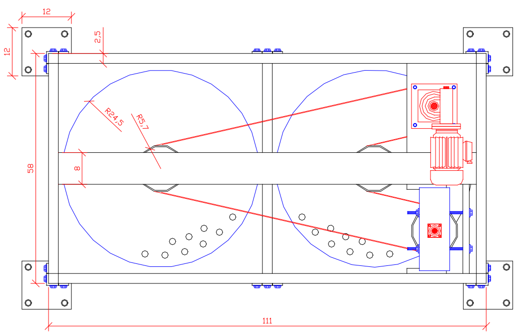

Fig. 5 Scheme of the vibrodyne used for the structural analysis

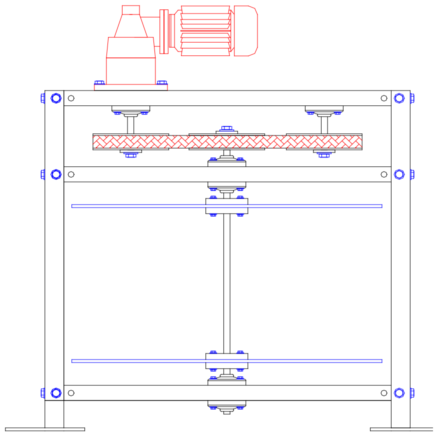

Fig. 6 Scheme of the vibrodyne used for the structural analysis

Fig. 7 Anchoring of the vibrodyne to the deck of the second floor

D. *The Accelerometers and the Measurement Points*

Pictures of the masonry building prototype are shown in Figs. 8-9, where the locations of the points on the walls in which the accelerometers were positioned are also illustrated.

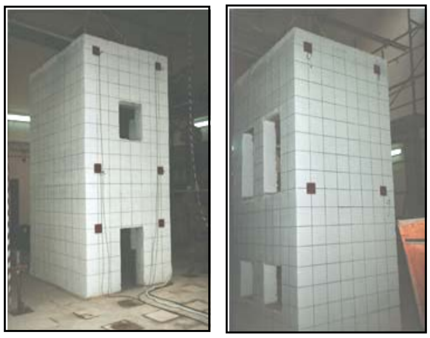

Fig. 8 Test prototype and locations of the accelerometers

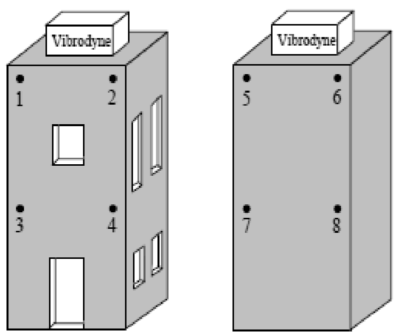

Fig. 9 Location of the accelerometers (measurement points)

Fig. 10 A typical uniaxial accelerometer adopted in the present study

A typical accelerometer adopted in the present experimental study is shown in Fig. 10.

E. Data Acquisition System

In Figs. 11-14 the data acquisition system used in the dynamical analysis is illustrated.

Fig. 11 Data acquisition system

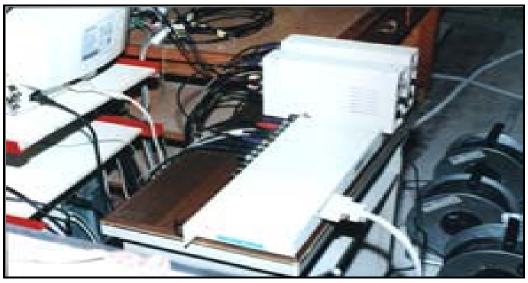

Fig. 12 Data acquisition system

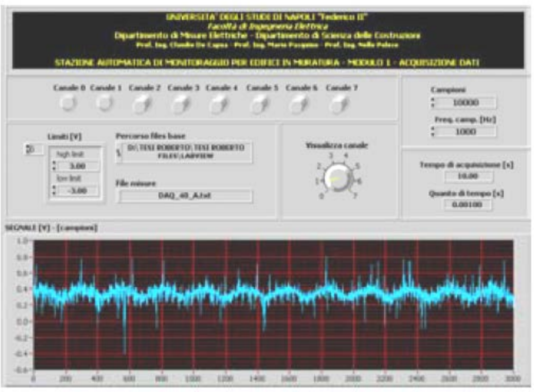

Fig. 13 View of data acquisition

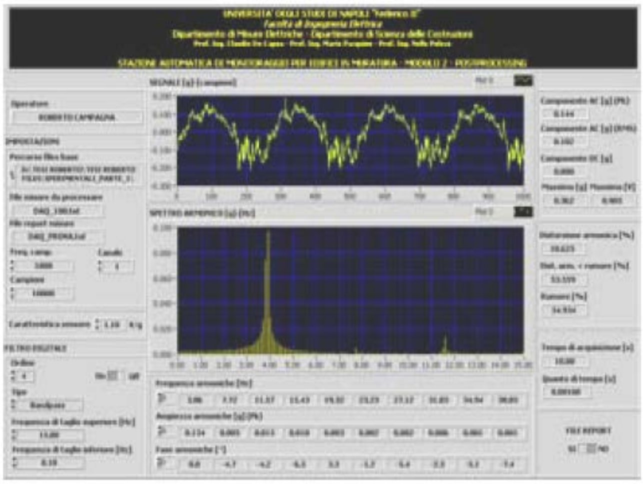

Fig. 14 View of post-processing

III. EXPERIMENTAL RESULTS

The experimental tests have been performed by imposing constant operating frequencies to the vibrodyne and correspondingly by prescribing the associated horizontal force inputs to the masonry building prototype as illustrated in Table 2. The accelerations at the measurement points have been evaluated by the accelerometers and registered by the data acquisition system. In a constant frequency vibration test the applied load and the response are theoretically sinusoidal with the same period. By eliminating the noises from electrical and mechanical sources, the experimental data is thus reduced to the determination of the baseline, period, amplitude and initial phase of the signal.

The characteristic behavior of the system has been evaluated in the frequency domain by the introduction of the frequency response function (FRF). For an assigned input frequency supplied by the vibrodyne, the frequency response function of each sensor is obtained as the ratio of the frequency domain representation of the output and the frequency domain representation of the input. The FRF depends on the prescribed frequency and it provides the response of the structure to the input loading at different frequencies.

For each given frequency input measured on the vibrodyne, the FRF modulus has been evaluated as the ratio of the acceleration measured by the sensor and the acceleration measured on the vibrodyne. The results obtained in the experimental analysis are reported for each location of the accelerometers in Figs. 17-24.

For each measurement point, that is for each location where the accelerometer was positioned, the modulus of the frequency response functions has been plotted for different values of the operating frequencies of the vibrodyne. The experimental results are illustrated in Figs. 17-24 for each measurement point corresponding to the location of the different sensors. These results can be subsequently compared with the results obtained with a finite element analysis in order to perform a parameter identification of the structural behavior of the masonry building prototype.

For a detailed description of the testings and the adopted experimental procedure see e.g. Cancellara De Angelis and Pasquino [16]. For an experimental characterization of the dynamical behavior of other types of building prototypes see also Cancellara De Angelis and Pasquino [17].

IV. BACKGROUND ON THE METHODS IN THE FREQUENCY DOMAIN FOR CHARACTERIZING THE DYNAMIC RESPONSE OF THE STRUCTURE

In the dynamic structural analysis the experimental modal analysis techniques play a significant role since they allow obtaining a model which adequately reflects the dynamic behaviour of the structure. The measurements undertaken on the structure are processed and analysed and the results of the analysis are then used to form a numerical model which reproduces the behaviour in real conditions. This procedure is often called identification process, where the dynamic properties of the structure are evaluated.

If it is possible to determine the excitation (external loading), or to control it, then the ratios between the structural response and each applied force are measured. The frequency response functions (FRFs) are derived if one is working in the frequency domain. The impulse response functions (IRFs) are derived if one is working in the time domain. The IRFs are normally calculated from the FRFs by an inverse Fourier transform. In this paper we analyze the frequency response functions.

For an n-degree of freedom system with viscous damping, the dynamic equilibrium equation is

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=\{f\} \tag{1}$$

where $[M]$, $[C]$, $[K]$ are the mass, damping, stiffness matrices respectively, $\{f\}$ is a vector of external force and $\{x\}$ is a vector of displacements.

In steady state conditions, and for the harmonic excitation case, it is possible to establish the relation between the structural response amplitudes $\{\bar{x}\}$, solutions of equation (1), and the amplitudes of the applied forces, through a matrix $[H]$ called the frequency response function matrix, such that $\{\bar{x}\}=[H]\{f\}$.

Each element $H_{jk}(\omega)$ of the matrix $[H]$ is called frequency response function (FRF), which relates the response at coordinate j to a force at coordinate k. Note that this is a function of the frequency (ω) and provides the ratio of the structural response divided by the input loading at each frequency.

The $H_{jk}(\omega)$ is given by

$$H_{jk}(\omega)=\sum_{r=1}^{N}\left(\frac{A_{jk,r}}{\omega_r\xi_r+i\left(\omega-\omega_r\sqrt{1-\xi_r^2}\right)}\right)+\left(\frac{B_{jk,r}}{\omega_r\xi_r+i\left(\omega+\omega_r\sqrt{1-\xi_r^2}\right)}\right)$$

$$=\sum_{r=1}^{N}\left(\frac{A_{jk,r}}{\omega_r\xi_r+i\left(\omega-\omega_d\right)}\right)+\left(\frac{B_{jk,r}}{\omega_r\xi_r+i\left(\omega+\omega_d\right)}\right) \tag{2}$$

where $A_{jk,r}$ and $B_{jk,r}$, ω_r, ω_d, ξ_r are the constants of mode r, the natural frequency, the damped natural frequency and the equivalent viscous damping ratio of mode r, respectively. An alternative version of the equation (2) is

$$H_{jk}(\omega)=\sum_{r=1}^{N}\frac{A_r+i\omega B_r}{\omega_r^2-\omega^2+i2\xi_r\omega_r\omega} \tag{3}$$

where A_r and B_r are the constants of mode r, determined by the initial condition.

If the hysteretic damping model is used instead, the FRF becomes

$$H_{jk}(\omega)=\sum_{r=1}^{N}\frac{C_{jk,r}}{\omega_r^2-\omega^2+i\eta_r\omega_r^2} \tag{4}$$

where η_r is the hysteretic damping ratio and $C_{jk,r}$ is the constant related to mode r.

The Equations (2) or (4) represent the behaviour of the structure as function of the selected nodal points, and allow working in the frequency domain. Moving from one domain to the other is a matter of applying Fourier transforms.

V. FINITE ELEMENT MODELING OF THE MASONRY BUILDING

The finite element modeling of the masonry building prototype has been performed by adopting a mesh discretization composed of eight-node 3-dimensional finite elements with 5424 total number of nodes. The finite element code used for the analysis is FemLab ver. 3.0. The adopted mesh and the distribution of the nodal points are described in Figs. 15-16 where prospect views are given. For the numerical modelling, the adopted parameters have been calibrated on the values determined from the experimental testing and illustrated in the previous section (Table I).

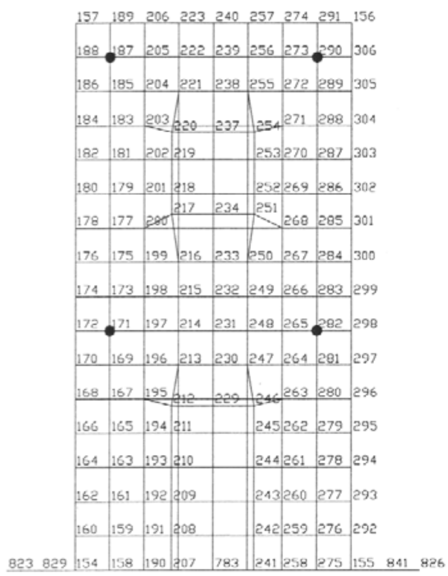

Fig. 15 Finite element modeling of the masonry building prototype: mesh and nodal points. Monitored nodal points (•) corresponding to the locations of the accelerometers n. 1-4 in the experimental prototype (see Figs. 8-9)

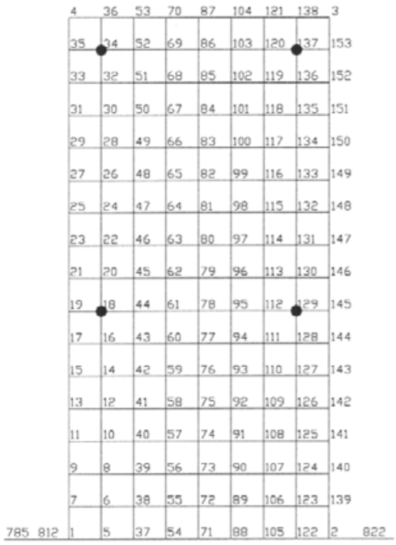

Fig. 16 Finite element modeling of the masonry building prototype: mesh and nodal points. Monitored nodal points (•) corresponding to the locations of the accelerometers n.5-8 in the experimental prototype (see Figs. 8-9)

The loading for the finite element model has been prescribed so to reproduce the actions of the vibrodyne, with force input amplitudes given in Table 2. The positions of the mesh nodal points corresponding to the location of the accelerometers (see Figs. 8-9) have been determined for a comparison of the experimental data with the data resulting from the finite element analysis. For such monitored nodal points, the acceleration has been determined numerically by approximating the structure with a finite element discretization. Another nodal point of interest is the one corresponding to the location of the vibrodyne.

For characterizing the dynamical behavior of the structure, an analysis in terms of frequency response functions (FRFs) has been carried out. The frequency response function has been determined as the ratio of the acceleration of each monitored nodal point divided by the acceleration of the nodal point where the vibrodyne was located. For a detailed account of the performed finite element analysis in the discretization of the masonry building prototype, see also Cancellara De Angelis and Pasquino [18].

VI. EXPERIMENTAL VS. COMPUTATIONAL RESULTS

In this section we summarize the results of the experimental testings performed on the masonry building prototype and the results of the finite element modeling of the structure.

The experimental and numerical frequency response functions (FRFs) characterize the dynamical behavior of the structure and allow a suitable structural identification of the system. In Figs. 17-24 the experimental and numerical frequency response functions are reported as a function of the frequency inputs for the different monitored nodal points of the mesh. The plots illustrated in Figs. 17-24 characterize the essential features of the dynamical response of the structure and allow a comparative analysis between experimental and finite element results for the assessment and the structural identification of the dynamical behavior of the masonry building prototype.

For the experimental testings, in correspondance of the operating frequencies of the vibrodyne, the accelerations at the measurement points are evaluated by the accelerometers and registered by the data acquisition system. The results obtained in the experimental analysis have been reported in Figs. 17-24, where for each measurement point in which an accelerometer was positioned, the modulus of the frequency response functions has been determined for different values of the frequency inputs. Consequently, a comparative analysis between the experimental data and the results of a theoretical or numerical study allows performing a parameter identification for the dynamical behavior of the system.

In the computational testings carried out for analyzing the behavior of the masonry building prototype, the nodal points of the mesh corresponding to the same locations of the accelerometers have been considered. For the monitored nodal points the accelerations were evaluated as the ones resulting from the numerical modeling used in the approximation of the structure with the finite element analysis. In order to characterize the dynamical behavior of the structure, an analysis has been performed in terms of the frequency response functions, evaluated as the ratio of the acceleration of each monitored nodal point divided by the acceleration of the nodal point where the vibrodyne was located.

In Figs. 17-24 the frequency response functions (FRFs) are reported as a function of the frequency inputs for the different monitored nodal points of the mesh. The reported experimental and numerical results illustrate the dynamical response of the structure and can be used for a comparative analysis in order to assess the structural identification of the dynamical behavior of the masonry building prototype.

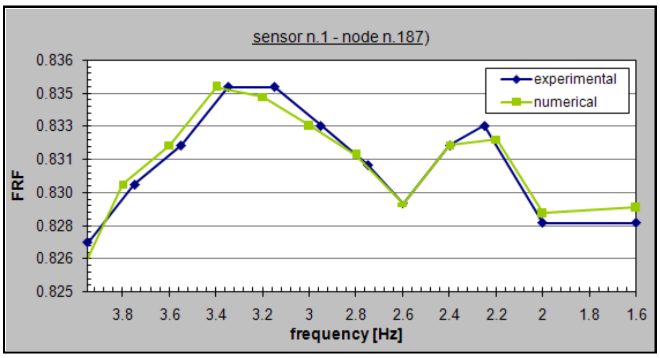

Fig. 17 Experimental vs. Numerical results: sensor n.1 – node n.187

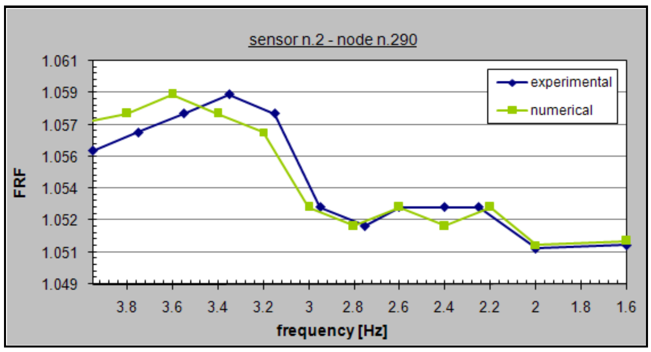

Fig. 18 Experimental vs. Numerical results: sensor n.2 – node n.290

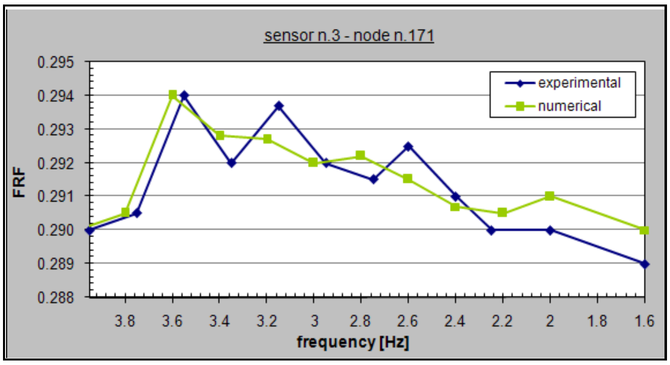

Fig. 19 Experimental vs. Numerical results: sensor n.3 – node n.171

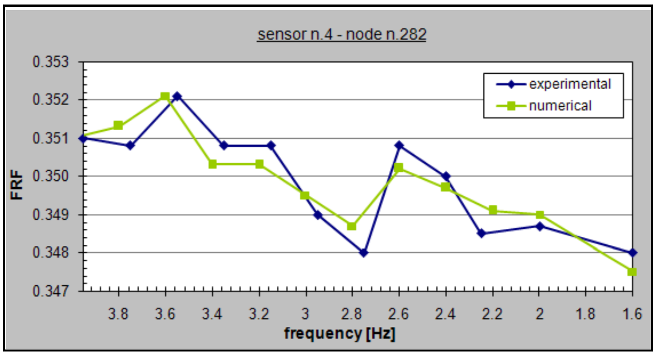

Fig. 20 Experimental vs. Numerical results: sensor n.4 – node n.282

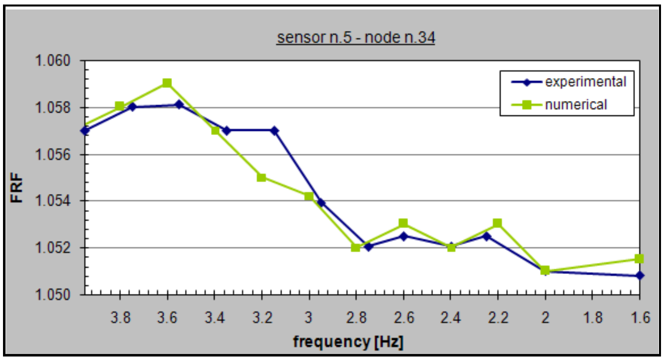

Fig. 21 Experimental vs. Numerical results: sensor n.5 – node n.34

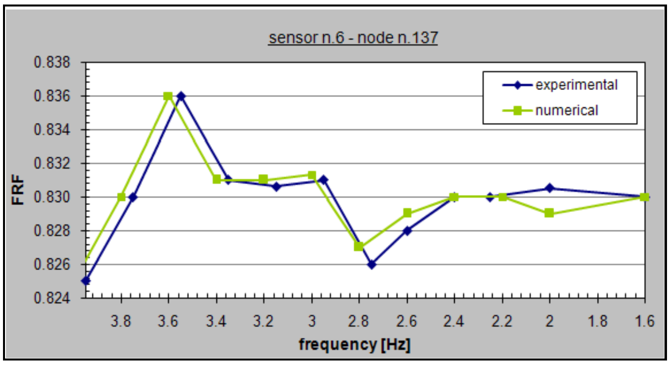

Fig. 22 Experimental vs. Numerical results: sensor n.6 – node n.137

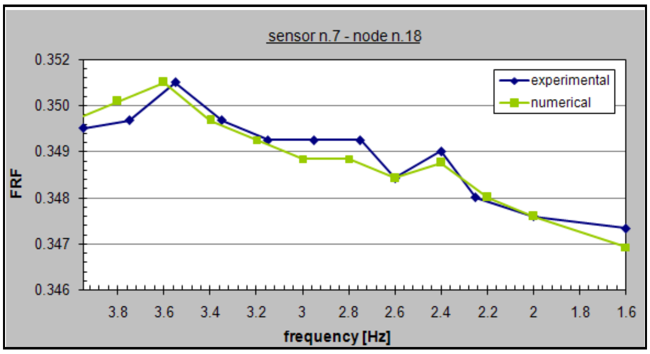

Fig. 23 Experimental vs. Numerical results: sensor n.7 – node n.18

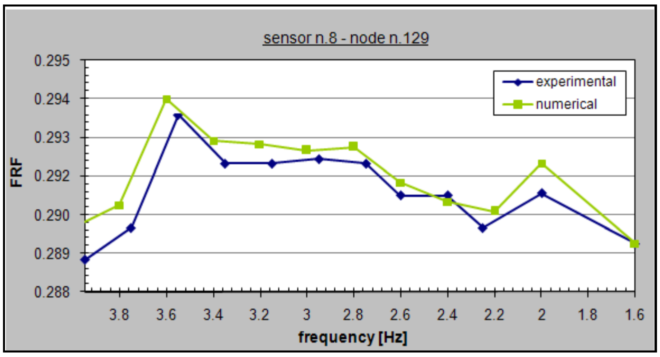

Fig. 24 Experimental vs. Numerical results: sensor n.8 – node n.129

VII. CONCLUSIONS

In the present paper, an experimental testing analysis and a computational finite element analysis have been performed in order to characterize some dynamical properties of a masonry building prototype which was built in the Laboratory of the Department of Structural Engineering (DIST) at the University of Naples.

The masonry building prototype has been realized with a regular floor plan and with openings designed in order to characterize an asymmetrical behavior of the building. Force inputs have been applied to the structure by means of a vibrodyne placed on top of the building. Depending on the operating frequencies of the vibrodyne, a set of horizontal harmonic forces have been applied to the masonry building prototype. A set of measurement points have been located on the walls of the structure and by means of accelerometers, the corresponding accelerations have been measured. In particular it has been of interest to determine the dynamical characteristics of the masonry building prototype subject to horizontal harmonic forces which represent the predominant actions in case of seismic events.

Subsequently, a finite element discretization of the masonry building prototype has been carried out and numerical testings were developed in order to characterize the dynamical effects of horizontal harmonic force inputs on the finite element modeling of the structure. The frequency response functions were determined and reported as a function of the load frequencies for different monitored nodal points of the mesh.

Acceleration frequency response functions have been determined as a function of the frequency spectrum for various measurements points, so that an experimental and numerical characterization of some dynamical properties of the masonry building prototype has been illustrated. The characterization of the structure is thus available through a comparative analysis between the experimental and the numerical modeling of the structure and by means of a suitable calibration of the dynamical parameters.

REFERENCES

[1] Y. Zhuge, D. Thambiratnam, and J. Corderoy, "Nonlinear dynamic analysis of unreinforced masonry", *Journal of Structural Engineering*, ASCE, vol. 124 (3), pp. 270-277, 1996.

[2] G. Magenes and G. M. Calvi, "In-plane seismic response of brick masonry walls", *Earthquake Engineering and Structural Dynamics*, vol. 26, pp. 1091-1112, 1997.

[3] F. Vestroni, D. Capecchi, P. Panzeri, and P. Pezzoli, "Dynamical testings on a masonry building of the 7th century", ("Prove dinamiche su una casa in muratura del '700"), *Proc. IV National Congress of Seismical Engineering in Italy*, 1989.

[4] D. Capecchi, F. Vestroni and E. Antonacci, "Experimental study of dynamic behavior of an old masonry building", *Proc. 9th European Conference on Earthquake Engineering*, Moscow, 1990.

[5] F. Genovese and F. Vestroni, "Identification of dynamic characterisctics of a masonry building", *Proc. 11th European Conference on Earthquake Engineering*, Rotterdam, Balkema, 1998.

[6] E. Radi, A. Di Tommaso and E. Viola, "Modelling and experimental verification of the dynamical behavior of a masonry and concrete building in scale 1:3", ("Modellazione e verifica sperimentale del comportamento dinamico di un edificio in muratura e c.a. in scala 1:3"), *Ingegneria Sismica*, vol. 7 (2), pp. 3-18, 1990.

[7] M. Tomaževič, M. Lutman and L. Petkovic, "Seismic behavior of masonry walls: Experimental simulation", *Journal of Structural Engineering*, ASCE, vol. 122 (9), pp.1040-1047, 1996.

[8] M. Tomaževič and P. Weiss, "A rational, experimentally based method for the verification of earthquake resistance of masonry buildings", *Proc. of the 4th U.S. National Conference on Earthquake Engineering*, Palm Springs, vol. 2, 1990, pp. 349-359.

[9] M. Tomaževič, "Dynamic Modelling of Masonry Building: Storey mechanism model as a simple alternative", *Earthquake Engineering & Structural Dynamics*, vol. 15 (6), pp. 731-749, 1987.

[10] A.W. Page, "Finite Element Model For Masonry Structure", *J. Struct. Division*, ASCE, vol. 104 (8), pp. 1267-1285, 1978.

[11] G. N. Pande, J. Middleton and B. Kralj, "Computer Methods in Structural Masonry", *Proc. 4th International Symposium on Computer Methods in Structural Masonry*, E & FN SPON., London U.K., 1998.

[12] P. B. Lourenco, "Computational strategies for masonry structures", PhD thesis, Delft University, Netherlands, 1996.

[13] V. Turnšek and P. Sheppard, "The shear and flexural resistance of masonry walls", *Proc. of the Intern. Research Conference on Earthquake Engineering*, Skopje, 1980, pp. 517-573.

[14] P. G. Asteris and A. D. Tzamtzis, "Non-linear FE Analysis of Masonry Shear Walls", *Proc. 6th International Masonry Conference*, London, 2002.

[15] A. D. Tzamtzis and P. G. Asteris, "Finite Element Analysis of Masonry Structures: Part II - Proposed 3-D Nonlinear Microscopic Model", *Proc. 9th North American Masonry Conference*, South Carolina (USA), June 2003.

[16] D. Cancellara, F. De Angelis and V. Pasquino, "Preliminary experimental results of a masonry building prototype subject to harmonic forces of different intensity", *Advanced Materials Research*, vols. 446-449, pp. 3405-3411, 2012.

[17] D. Cancellara, F. De Angelis and V. Pasquino, "Characterization of an autoclaved aerated concrete building with respect to a similar unreinforced masonry structure", *Advanced Materials Research*, vols. 476-478, pp. 847-858, 2012.

[18] D. Cancellara, F. De Angelis and V. Pasquino, "Finite element modelling for characterizing some dynamical properties of a masonry building prototype", *Advanced Materials Research*, vols. 446-449, pp. 3745-3752, 2012.