Structural identification from environmental vibration testing of an asymmetric-plan hospital building in Italy.

M. Ferraioli
Department of Civil Engineering, Second University of Naples, Aversa (Caserta), Italy

D. Abruzzese, L. Miccoli, A. Vari
Department of Civil Engineering, University of Rome "Tor Vergata", Rome, Italy

G. Di Lauro
Aires Ingegneria, Caserta, Italy

ABSTRACT: The structural identification from environmental vibration testing of a hospital building in Avezzano (Abruzzo - Italy) was presented. The comparison of the results enables to verify and calibrate numerical predictions on the base of data obtained from modal testing. The response of the structure in the time domain was recorded by highly sensitive sensor network, integrated by a data acquisition system. The identification was performed using techniques of modal extraction in the frequency domain (frequency domain decomposition). During the calibration process of the numerical model the values initially adopted were successively corrected in order to identify a reliable structural model to be used to have an accurate seismic vulnerability assessment of the hospital building.

1 INTRODUCTION

Most of the existing RC buildings are vulnerable to earthquakes because they are gravity load designed or are designed with earlier codes to withstand seismic action of low intensity. Many of these constructions with low lateral load resisting capacity are located in high seismic hazard areas. Some of them play a role in civil protection, and so their functionality is essential during and immediately after an earthquake. However, as an effect of the increase of the seismic design actions, the resistance of these structures has become inadequate even when designed according to old seismic codes, with the consequence that unpredictable damage or failure results when subjected to loads below the new code-prescribed levels. As a consequence, the seismic vulnerability assessment of these buildings is a very actual topic. In this context, the calibration of the mechanical parameters and the definition of reliable models and methods for structural analysis are noteworthy topics. In particular, effective procedures for the identification of the structural parameters from static and dynamic testing are required. In particular, the dynamic test may be very useful for the identification of mechanical properties, the soil restraints and, consequently, for the calibration of advanced numerical finite element models. In this context, the knowledge of dynamic properties, together with site seismicity and stratigraphy, is the starting point for an accurate estimation of seismic safety of these structures. The paper is dedicated to the experimental analysis and subsequent modeling of the hospital building of Avezzano near L'Aquila (Abruzzo, Italy). In particular, the methodology defined to reach the goal consisted of: 1) defining a fem model of the hospital building; 2) defining localization and direction of the measurement points from modal analysis of the fem model; 3) identifying the mode shapes and frequencies, using the environmental vibration; 4) calibrating a refined numerical model.

2 DESCRIPTION OF THE HOSPITAL BUILDING

The hospital is composed of RC wall-frame buildings designed and constructed in 70's. The building is composed of different structures separated by seismic joints (Figures 1,2). The study is carried out on an irregular T" plan shape building (A structure) designed for earthquake action of Italian old seismic code (N.1684 November 25th, 1962).

Figure 1. Aerial view of t\e Hospital of Avezzano (Italy).

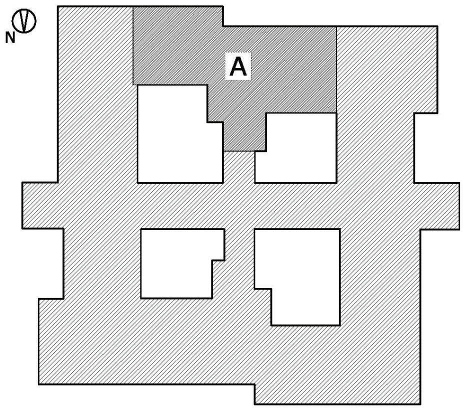

Figure 2. Plan view of the Hospital of Avezzano (Italy).

Both destructive and non-destructive testing methods were used for the building diagnosis-state. In particular, 53 monotonic compressive tests on cylindrical specimens, 24 tensile tests on steel rebars, ultrasonic tests, 40 carbonation depth measurement test, 163 Schmidt rebound hammer tests, 180 radiographic tests. The compressive strength was finally estimated by the combined Sonreb method. The mean value of the compressive strength of concrete on cylindrical specimens is f_{cm}=234 daN/cm^2; the mean value of tensile strength of steel rebars is f_{ym}=4026 daN/cm^2.

2.1 *Material and Soil stratigraphy*

Geological and geotechnical tests were carried out to evaluate the soil profile and to determine the ground type according to Eurocode 8 (2003) and new Italian Code (2008). In particular, the following in-sìtu tests were performed: N.1 soil profile test, N.3 Standard Penetration Tests (SPT) and N.1 Down-hole Test which determines soil stiffness properties by analyzing direct compression and shear waves along a borehole down to about 30 m. The results obtained give the following classification: ground type C, that is $180<V_{S,30}<360$ and $15<N_{SPT}<50$). The building is erected on a flat ground. As a consequence, the topographic amplification factor is S_T=1.00.

Table 1. Soil profile under the hospital building of Avezzano.

No.	Layer	Thickness	Depth
		m	m
1	Organic soil	1.50	0.00
2	Sand gravel soil and pebbles	13.50	1.50
3	Clay	2.00	15.0
4	Silt with clay	5.00	17.0
5	Silt with gravel	8.00	22.0

3 ENVIRONMENTAL VIBRATION TEST

The forced vibrations applied, for instance, by a mechanical vibrodyne, are not suitable to be used on full functional hospital structures, because even small vibration can not be tolerated in such conditions. On the contrary, measurement of environmental vibrations may be carried out without direct excitation on the building using the natural noise and vibration such as wind and traffic loads. An experimental study was developed to evaluate the dynamic behavior of the structure and the dynamic interaction between the natural frequencies of the building and the excitation forces.

The in-situ experimental tests were performed applying the environmental vibration testing method. This method is a relatively simple, and requires equipment easy to be transported and such a test can be conducted even if the structure is in use. This aspect is essential especially in the case of strategic structures (emergency management centers, hospitals and so on) whose function can not be interrupted. This technique allowed, after a careful choice of the positioning of the sensors, to get natural frequencies and vibration modes from the direct measurement.

The response of the structure in time domain was recorded by highly sensitive sensors, accommodated with a data acquisition system. The instrumentation used included (Figure 3): N.16 PCB piezoelectric accelerometers (Piezotronics model 393B04) ; N.1 data acquisition board (National Instruments DAQCard-16XE50); connector block for interfacing I/O (input/output) signals to plug-in data acquisition (DAQ) devices. The accelerometers were appropriately calibrated following the manufacturers' suggested procedures. The environmental vibration testing under wind and traffic vibration was monitored in July 2008. A preliminary model was developed for selecting the location of the devices during vibration testing. The location of the accelerometers and the conditioners is shown in Figure 4 and Table 2. In Table 2 the list of the sensors is shown, as well as the vertical "columns" (No. 4) where the mode shapes have been calculated.

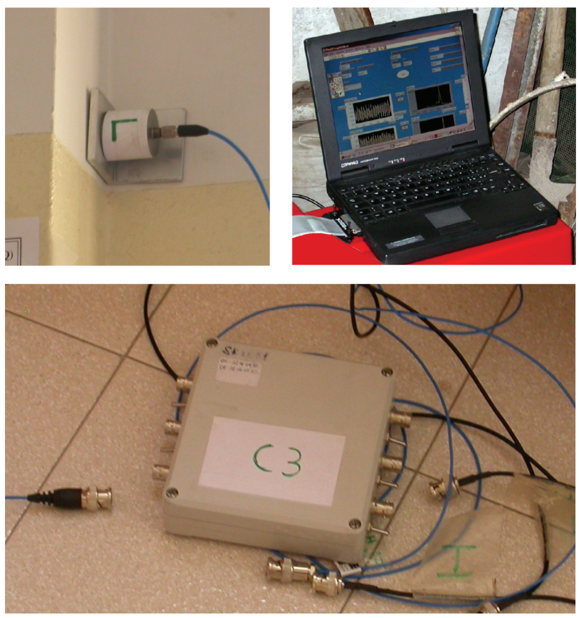

Figure 3. Equipments used for environmental vibration test.

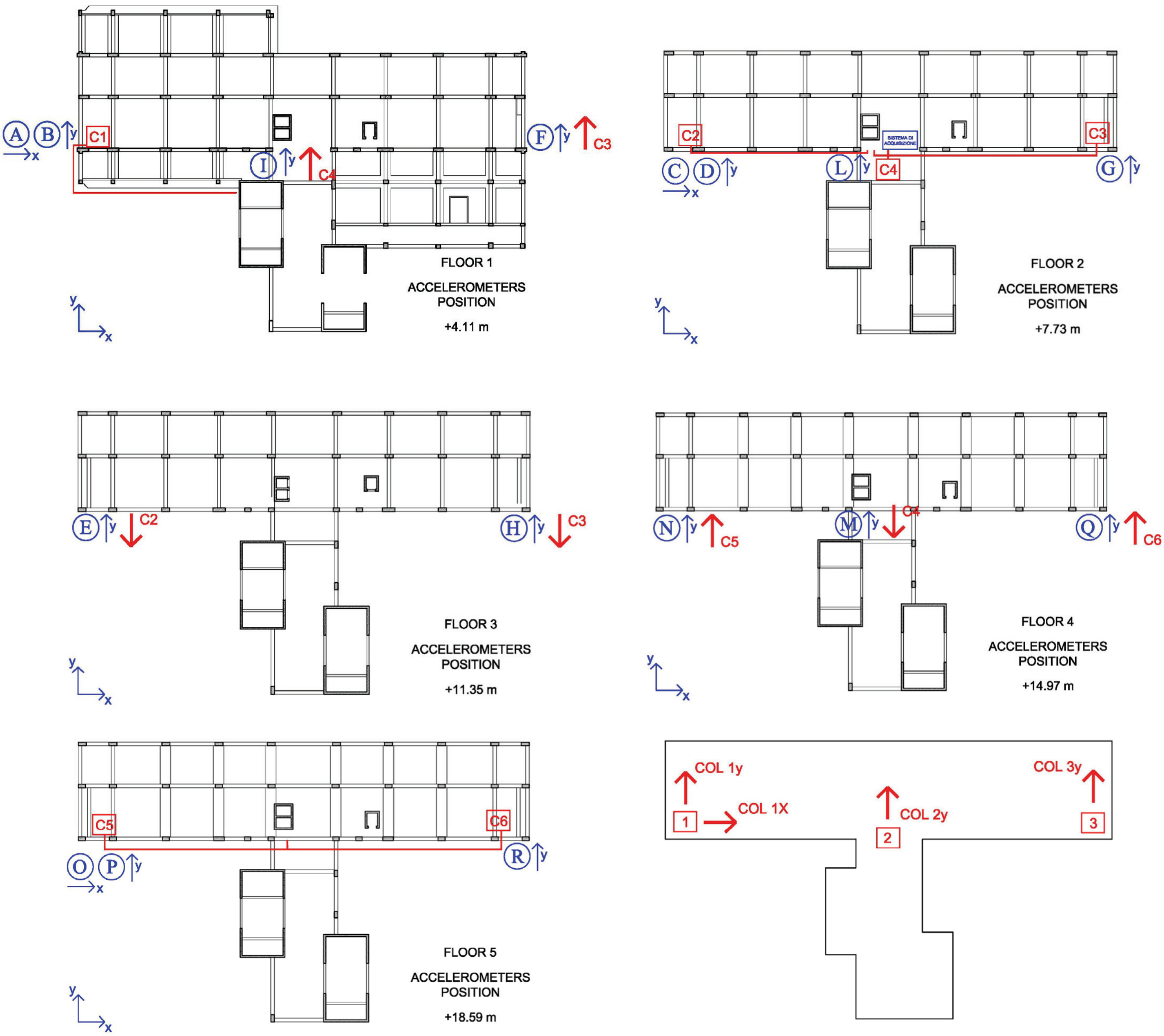

Figure 4. Location of the sensors, at different floors, during environmental vibration test.

Table 2. Location of equipments in vibration.

No.	Accel.	Dir.	Condit.	Height m	Floor	Column
1	A	x	C1	4.11	1	1x
2	B	y	C1	4.11	1	1y
3	C	x	C2	7.73	2	1x
4	D	x	C2	7.73	2	1y
5	E	y	C2	11.35	3	1y
6	F	y	C3	4.11	1	3y
7	G	y	C3	4.11	2	3y
8	H	y	C3	11.35	3	3y
9	I	y	C4	4.11	1	2y
10	L	y	C4	7.73	2	2y
11	M	y	C4	14.97	4	2y
12	N	y	C5	14.97	1	1y
13	O	x	C5	18.57	5	1x
14	P	y	C5	18.57	5	1y
15	Q	y	C6	14.97	4	3y
16	R	y	C6	18.57	5	3y

The spectral analysis of the recorded signals may give the natural frequencies and the corresponding mode shape. Usually, the signal recorded with this technique is very low as well as the signal-to-noise ratio. This means that the recorded signal must be amplified and processed, and the frequencies negligible be filtered (local and partial vibration and phenomenon of the signal transferring with frequencies in the range 0.50-20 Hz).

The data acquisition was realized in Labview 8.0 with sampling frequency of 100 Hz. The Fast Fourier Transform (FFT) was used to determine the frequency spectrum of the signal processed through a 30 Hz low-pass filter. The experimental and theoretical procedure starts from an assumption that the exciting forces are a stationary stochastic process with a relatively flat frequency spectrum.

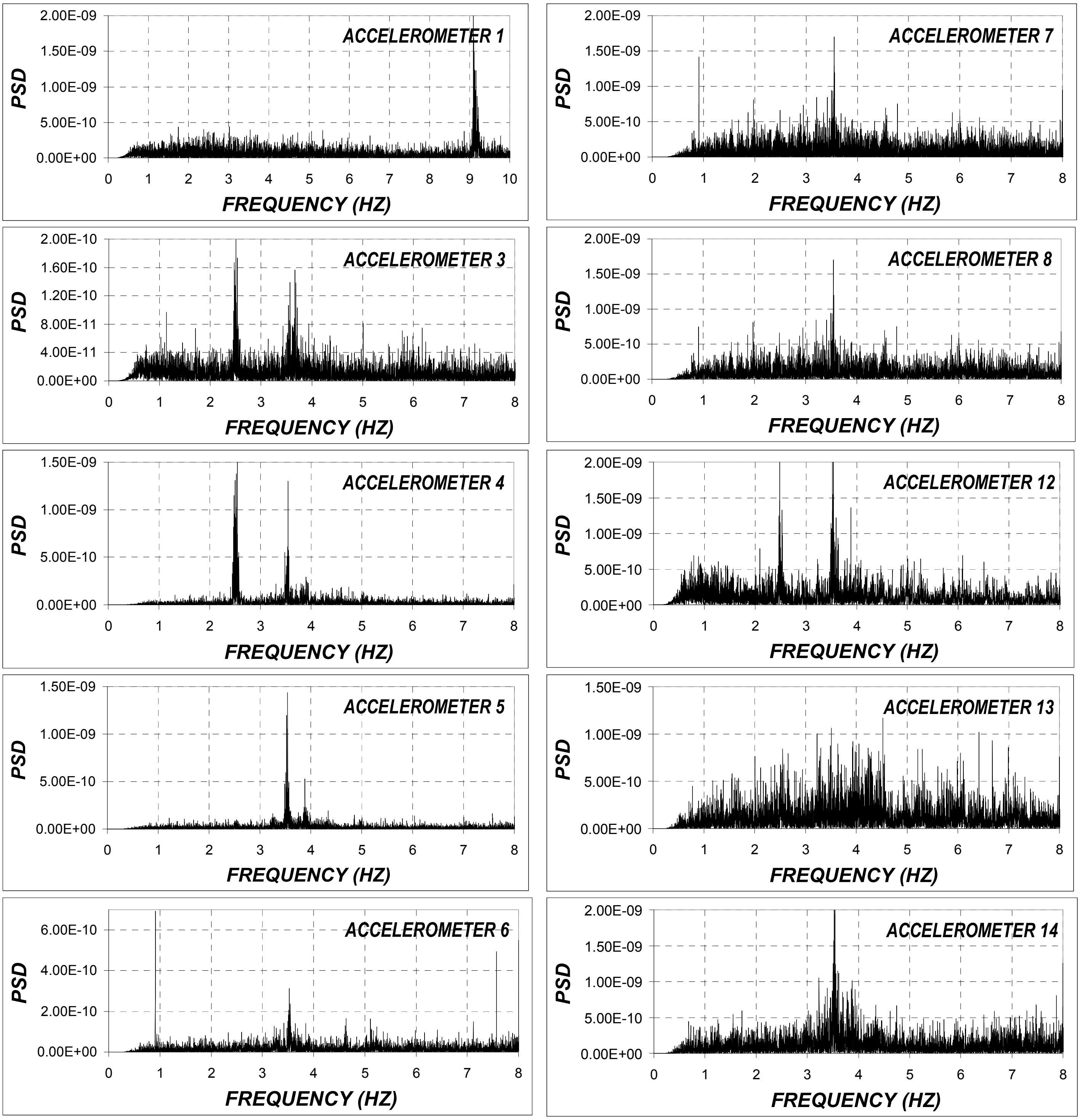

Figure 5. Power spectral density of the accelerometer response.

The identification was performed using techniques of modal extraction in the frequency domain (frequency domain decomposition). These techniques allow the assessment of natural frequencies, modal damping and mode shapes. The Fast Fourier Transform (FFT) was used to determine the frequency spectrum of the signal processed through a 30 Hz low-pass filter. An often more useful alternative is the power spectral density (PSD), which describes how the power of the signal is distributed with frequency. In Figure 5 the resonant frequencies are identified and located at the evident peaks PSD spectrum. In Table 3 the frequencies and periods obtained with this method are reported.

Table 3. Natural frequencies from the test “on site”.

Description	Frequency	Period
	Hz	sec.
1° Flexural Y - Torsional	2.53	0.40
Torsional	3.54	0.28
1° Flexural X	3.67	0.27
2° Flexural Y - Torsional	7.95	0.22
2° Flexural X	9.06	0.11

4 STRUCTURAL IDENTIFICATION

The comparison of data (structural modes obtained by testing) with the analytical model allows for a verification of the adequacy of the model and for its calibration. At first, a preliminary model was developed for selecting the location of the sensors during vibration testing. In particular, a detailed numerical model of wall-frame building was implemented in SAP 2000 computer program. During the calibration process of the numerical model the values initially adopted were successively corrected in order to identify a reliable structural model to be used to have an accurate seismic vulnerability assessment of the hospital building. In particular in the refined model the following aspects are considered: 1) non-structural performance of infill panels modeled as the well-known equivalent diagonal strut model (cross section 40x60; Young's modulus E=5350 daN/cm^2); 2) modeling of the floors as orthotropic shells rather than constraints diaphragms; 3) calibration of the Young's modulus of concrete; 4) introduction of the stiffening RC members that are present at the first, third and sixth floor; 5) calibration of live loads; 6) use of rigid end offsets to model the fact that the ends of a member are not considered to be part of the flexible portion.

In Figure 6 the mode shapes of the fem model are shown. In Table 4 the natural frequencies obtained from the calibrated model are compared with the frequencies derived from the environmental vibration test. A good correlation is found especially for 1st and 2nd flexural Y-torsional mode shape and for 1st flexural X mode shape. Finally, in Figure 7 the comparison between experimental and numerical mode shapes in terms of displacement pattern is carried out. The results are referred to the locations COL 1X and COL 2Y of the sensors (Figure 4) that are close to the center of stiffness of the building. A very good agreement between experimental and numerical patterns is observed. However, it must be noticed that this results is obtained only for the sensors that are close to the center of stiffness of the building (COL 1X and COL 2Y). On the contrary, for the other accelerometers the torsional effects and the higher modes contribution makes more difficult to extract the peaks from the PSD function because there are a great number of very close peaks. Furthermore, in this case the lateral displacement pattern of the mode shapes from numerical model is very sensitive to the value of frequency, and it may be strongly different from the experimental displacement pattern.

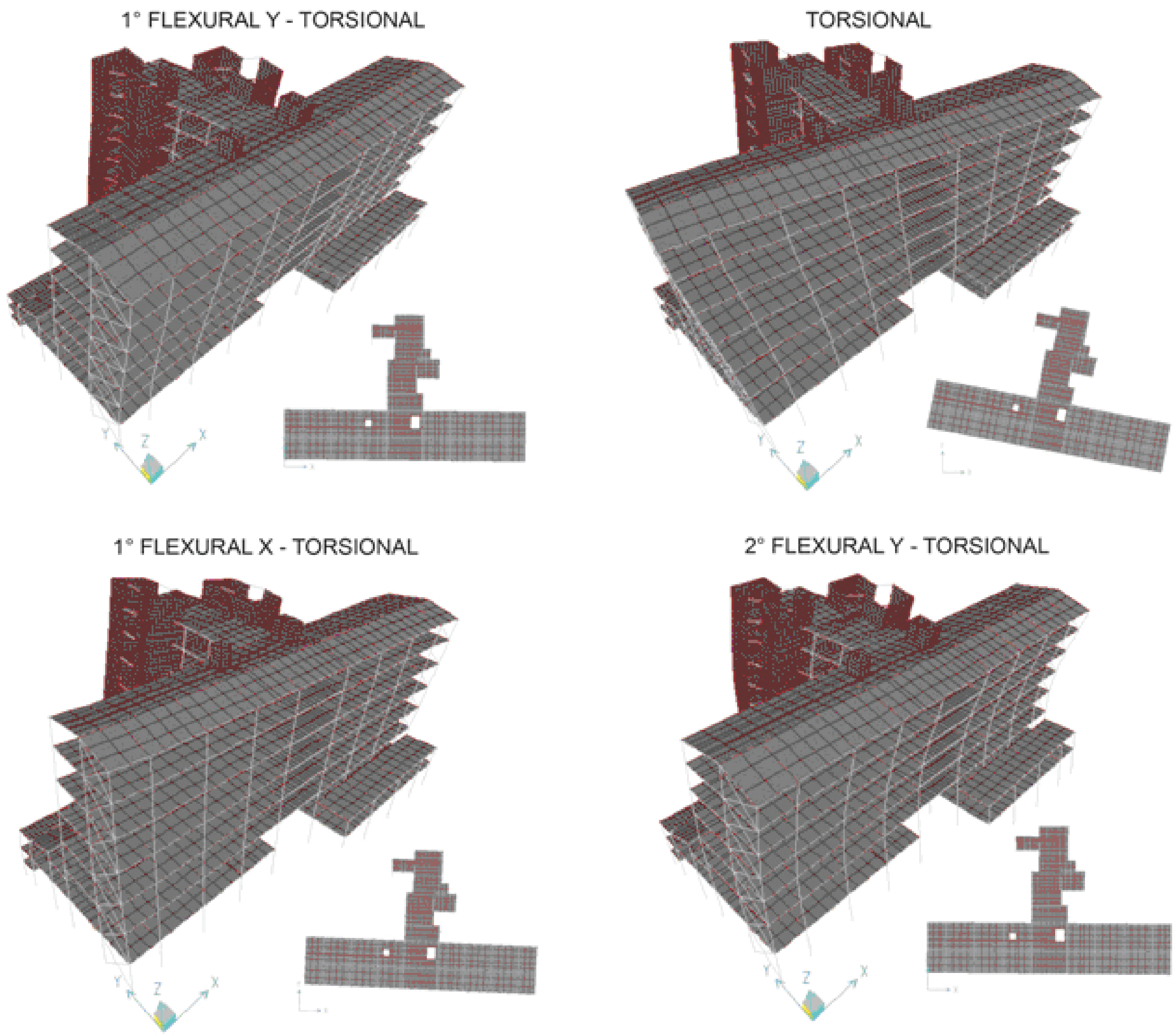

Figure 6. Calibrated mode shapes.

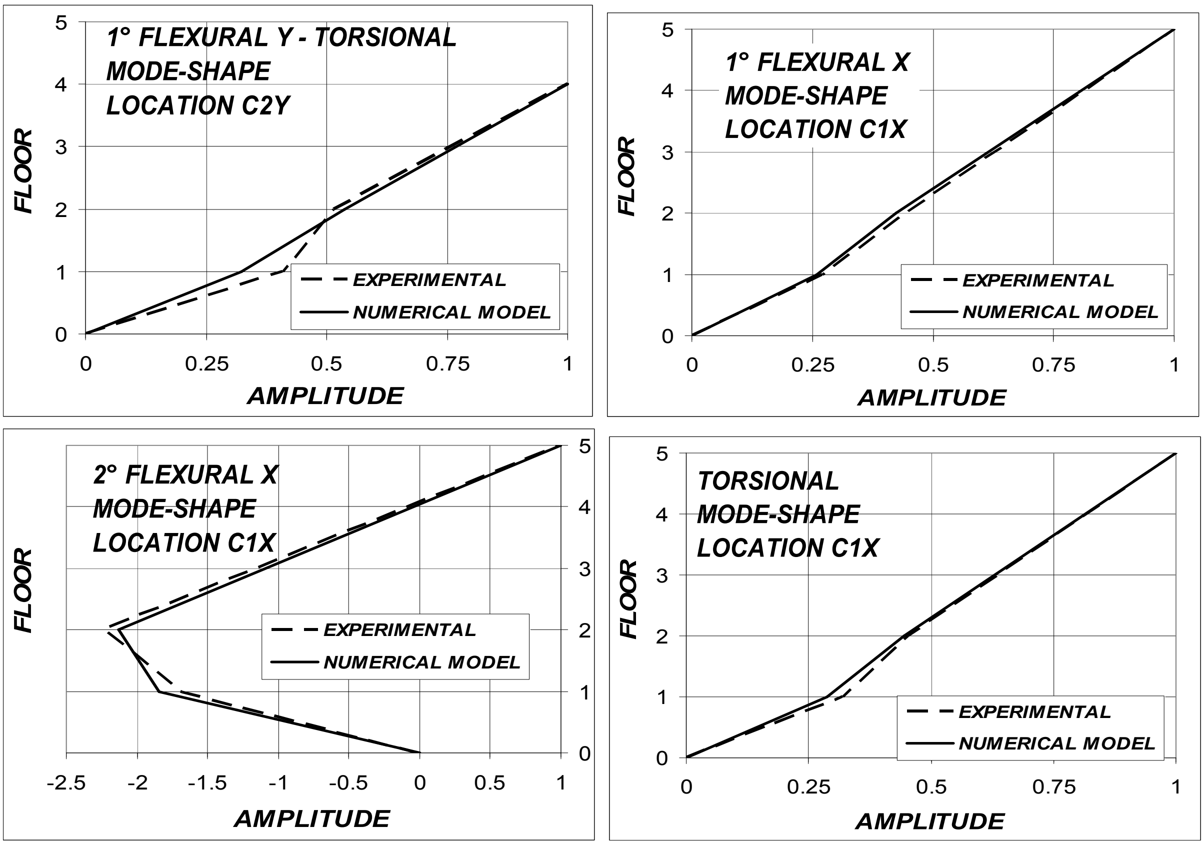

Figure 7. Displacement pattern for experimental and numerical mode shapes.

Table 4. Natural frequencies obtained from the refined numerical model and from the test "on site".

Description	Frequencies from test	Frequencies from model	Variation
	Hz	Hz	%
1° Flexural Y - Torsional	2.53	2.59	-2.27
Torsional	3.54	2.87	22.53
1° Flexural X	3.67	3.52	4.41
2° Flexural Y - Torsional	7.95	8.19	3.02
2° Flexural X	9.06	11.10	22.2

5 CONCLUSIONS

The paper introduces the structural identification from environmental vibration testing of an emblematic case study: the hospital building of Avezzano in Italy. The irregular T" plan shape of the building makes the modal identification from environmental vibration test very sensitive to the location in plan of the accelerometers. In particular, a very good agreement of experimental and numerical modal proprieties was found for the sensors located very to the center of mass of the building. On the contrary, the frequency decomposition may be ineffective for the signals recorded very far from the center of stiffness, especially on the flexible side of the asymmetric in-plane building. In this case, the torsional effects and the higher modes contribution generally produce a great number of very close peaks.

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REFERENCES

Abruzzese, D. & Ferraioli, M. & Mandara, A. & Miccoli, L. & Vari, A. & Froncillo, S. 2009. Dynamic investigations on medieval masonry towers: vibration measurement and structural identification, In F.M. Mazzolani (eds), *Proc. International Conference Prohitech*. Roma.

Bonzi, A. & Pizzigalli, E. & Eusebio, M. & Ravasio, F. 1997. *Dynamics test and monitoring of the Leaning Tower of Pisa*. Methodology and results. ISMES, Italy.

De Sortis, A. & Antonacci, E. & Vestroni, F. 2005. Dynamic identification of a masonry building using forced vibration tests, *Engineering Structures* 27, 155–165.

Júlio, E. & Rebelo, C. & Costa, D. 2008. Structural assessment of the tower of the University of Coimbra by modal identification. *Engineering Structures* 30: 3468-3477.

Krstevska, L. & Tashkov, L. 2006. Ambient vibration testing of historical monuments, *First European Conf. on Earth. Eng.and Seismology*, Geneva, Switzerland.

Zhou, Y. & Yi, W.J. 2008, Ambient vibration measurement and earthquake resistant behavior analysis on a tower tall building with enlarged base, *14th World Conference on Earthquake Engineering*, Beijing, China.