Research and Applications in Structural Engineering, Mechanics and Computation – Zingoni (Ed.)

Dynamic identification of Palazzo Marchesale in S. Giuliano di Puglia

G. Bongiovanni, G. Buffarini, P. Clemente, D. Rinaldis & F. Saitta
ENEA, Centro Ricerche Casaccia, Roma, Italy

M. Nicoletti & A. De Sortis
Italian Civil Protection Dept., Roma, Italy

G. Rossi
Office for the reconstruction of San Giuliano di Puglia, Italy

ABSTRACT: Palazzo Marchesale in San Giuliano di Puglia (Italy) is an old masonry structure hosting the new City Hall. It is quite complex and is characterized by several parts with different height and foundation levels, and includes an internal court. After the earthquake of October 31st ($M_L = 5.4$) and November 1st, 2002, ($M_L = 5.3$), the building was retrofitted and seismic joints were realized between the different buildings, in order to regularize the dynamic behaviour. The structure has been considered for seismic monitoring in the framework of a research project funded by the Office for the reconstruction of San Giuliano di Puglia. Therefore a permanent accelerometric array has been designed and installed. It was tested by deploying also a temporary array in different configurations and recording ambient vibrations and weak motion effects. The experimental results were compared with those obtained by means of a finite element model. Thus, linear and nonlinear analysis allowed to evaluate the seismic safety of the structure. Modal identification and model updating are shown in the paper.

1 INTRODUCTION

Identification of dynamic characteristics of historical buildings is an important step that is necessary for two basic reasons: to assess possible dynamic behaviour of such complex structures during strong events and to gain experience on the dynamic behavior of historical buildings such that the experience and data base can be used in future design and analyses.

Past efforts in determination of dynamic behaviour of historical buildings allowed the development of data bases, which in turn have been used in design codes. Actually, data on dynamic behaviour of complex structures such as historical buildings are scarce.

The data bases are in general obtained from dynamic testing of structures (forced vibration, ambient vibration, etc.), and from analyses of data from instrumented structures. With this purpose, ENEA, the Italian Civil Protection and the Municipality of San Giuliano di Puglia organized a research project for seismic monitoring of relevant structures in the framework of the reconstruction of San Giuliano di Puglia, Italy. A permanent accelerometric array was designed and installed as part of the Seismic Observatory of Structures (OSS) of the Italian Civil Protection. The OSS (Spina et al., 2011) is the Italian State permanent network that monitors the seismic response of public structures, including 133 buildings (schools, city halls, hospitals, etc.), 7 bridges and 1 dam. The array was designed after a detailed study of the expected dynamic behavior of the structure and then installed and tested by recording ambient vibrations and weak motion effects also using a temporary array. The experimental results were compared with those obtained by means of a finite element model. Thus, linear and nonlinear analysis allowed to evaluate the seismic safety of the structure. All the steps of the modal identification, the model updating and the seismic analysis are summarized in the paper.

2 THE BUILDING

The Palace, located in the historical center of San Giuliano di Puglia, is composed of a series of masonry buildings, arranged around a central courtyard. They spreads over several levels, two completely above the ground emerging from the courtyard (level 0 and level 1), two below (level −1 and level −2) and then partially buried by the presence of a slope, which affects the site. In more detail four buildings can be distinguished, which are structurally separated (Fig. 1). For the seismic monitoring the following buildings have been considered:

- building A, developed from level −1 to level 1; a little room on level −2 is present in the left corner in Fig. 1;
- building B, which includes levels 0 and 1 but also levels −1 and −2 in some parts;
- the tower T, which starts from level 0 and presents levels 1, 2 and 3.

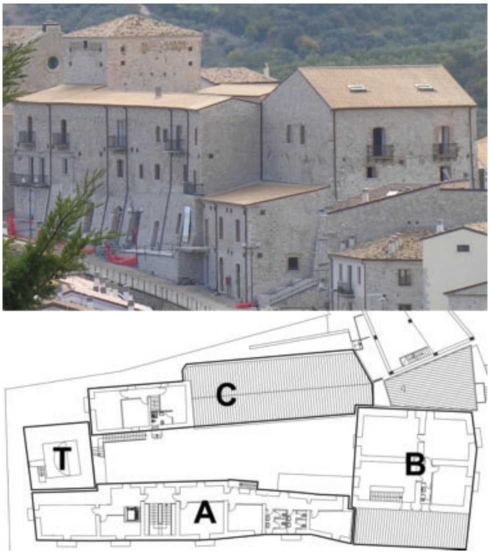

Figure 1. View and plan of Palazzo Marchesale.

Seismic improving interventions have recently been done. These consisted in mortar injections in masonry, substitution of some floors with new ones having laminated wood structure, and retrofit of vaulted roofs by means of FRP. Furthermore, the Palace was divided into buildings of regular shape (T, A, B and C), with seismic joints between them. Therefore, the tower, at the entrance of the courtyard is separated structurally and so are the buildings A and B, where the municipal offices are placed. In these buildings, which belong to the local municipality, an accelerometric network has been installed.

3 ACCELEROMETRIC NETWORK

The accelerometric network was designed on the basis of previous dynamic tests carried out on Palazzo Marchesale (Fig. 2). It is composed by 26 sensors, 4 of them are triaxial, 8 are biaxial sensors and 14 are uniaxial accelerometers. The total number of channel is 48. In more details, in building A three sensor (A1) were deployed on the floor and two sensor (A4) under the ceiling at level −1. Three other sensor (A9) were put on level 0 as well as two sensor respectively on the floor (A6) and under the ceiling (A7). On level 1, five accelerometers are on the floor and six under the ceiling. This deployment should be able to record both longitudinal and transversal movements of building A, in which one size is much higher than the other.

In building B three accelerometers (A2) were put on level −1, three (A10) on level 0 and three (A16 and A17) on level 1. The latest should be able to analyze both the translational and torsional modes of building B. The tower was instrumented by means of four accelerometers (A21, A22, A23 and A24) on level 2, four on the floor of level 3 (A8 and A19) and four under the ceiling of level 3 (A24, A25, A26 and A27).

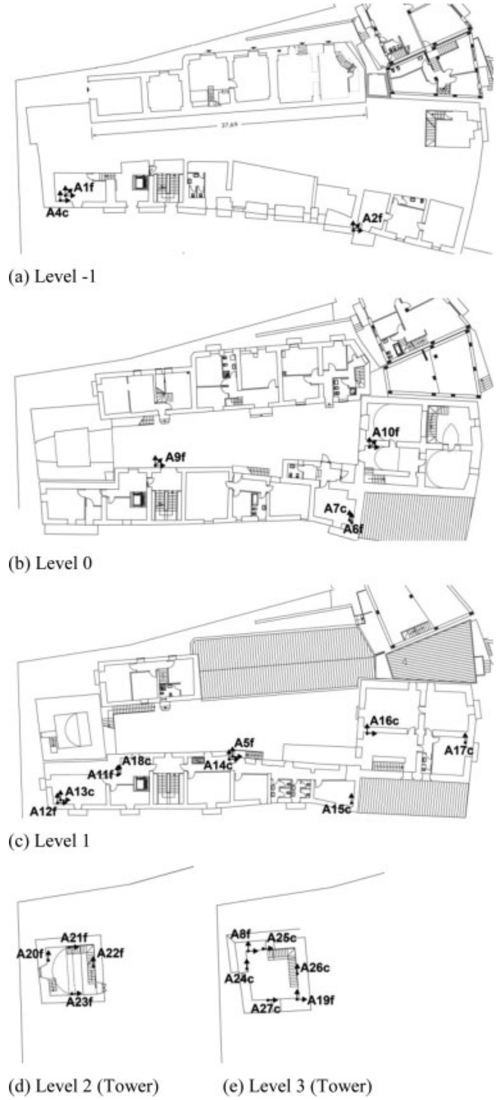

Figure 2. Accelerometric network (f = floor, c = ceiling).

Another triaxial accelerometer is in the courtyard, about 10 m below the ground level. This should record the seismic input to the building.

4 AMBIENT VIBRATION ANALYSIS

The ambient vibration analysis were carried out by using a Granite acquisition system and seismometers SS-1. Sensors were deployed in 2 configurations. In the first one 15 seismometers were deployed in the tower T (Fig. 3), in the second 17 seismometers were positioned in buildings A and B (Fig. 4). In both cases sensors positions were very close to the accelerometers of the fixed network. In the case of accelerometers placed at the top of the level, seismometers were positioned on the above floor. In Tab. 1 each seismometer in

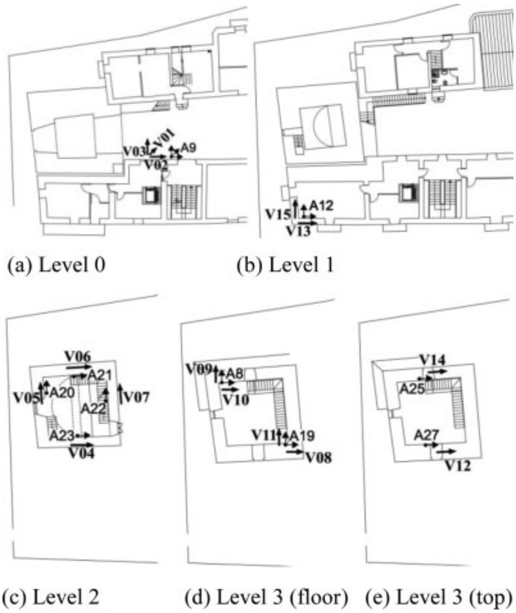

Figure 3. Configuration 1 – Tower.

the two configuratons is associated to the corresponding accelerometer in the tower T and in buildings A and B. Also the direction is associated to each sensor, x being the longitudinal, y the transversal and z the vertical one.

Several test for each configurations were carried out, each lasting 5 minutes, with the sampling rate of 250 samples/sec ($\Delta t = 0.004$ sec) in analogy to the sampling rate of the fixed accelerometric network (Clemente et al., 2012).

For all recordings the analysis was performed in the time and frequency domains. The velocimetric data were first derived in order to obtain accelerations. Then the corresponding auto- and the cross-spectral densities were compared with those of the accelerometric recordings. All recordings gave similar results. So only one test for each configuration was reported here in detail.

4.1 *Ambient vibration of the tower*

The resonance frequencies and the dynamic behavior of the tower, which is taller than the other portion, are apparent from the first configuration.

The main peak in the X direction is at 6.59 Hz, while in the Y direction the main peak is at 5.73 Hz. A resonance frequency is also at 10.10 Hz, apparent in all sensors, which is associated to a torsional mode, as demonstrated by the phase factors.

To assess the degree of connection of the tower T with building A, sensors V13x and V15y were placed just beyond the joint. The transversal sensor V15y followed the behavior of the sensors in the tower, while the longitudinal sensor V13x recorded the presence of the tower but also other peaks typical of building A, which will be analyzed later. For low levels of excitation the links with non-structural elements across the joint form a continuous link in the direction perpendicular to the joint (V15y).

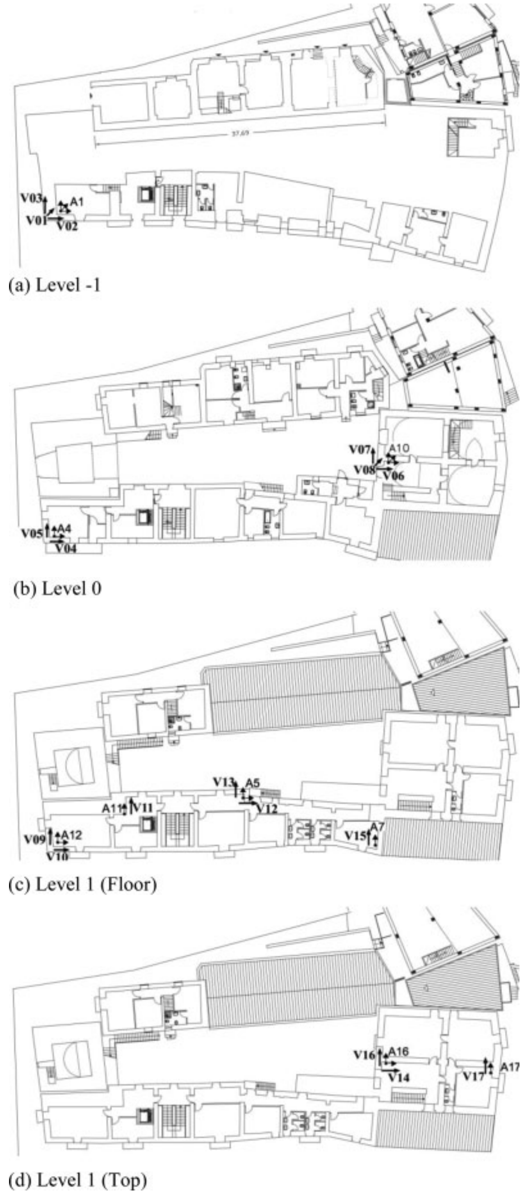

Figure 4. Configuration 2 – Buildings A and B.

Other resonance frequencies apparent in the spectra can be attributed to the local modes present in such complex structure. These make difficult the interpretation of the global behavior but have less importance in the interpretation of the general dynamics of this part of the building. The frequencies recorded by seismometers in the tower are shown in Table 2, while the first and second modal shapes obtained with accelerometric recordings are in Figs. 5a and 5b with the associated frequencies.

Table 1. Correspondence between seismometers and accelerometers in the tower and in buildings A and B (configuration 1 and 2, respectively).

Seismometers	Accelerometers in Tower	Accelerometers in buildings A and B
V01z	A9z	A1z
V02x	A9x	A1x
V03y	A9y	A1y
V04x	A23x	A4x
V05y	A20y	A4y
V06x	A21x	A10x
V07y	A22y	A10y
V08x	A19x	A10z
V09y	A8y	A12y
V10x	A8x	A12x
V11y	A19y	A11y
V12x	A27x	A5x
V13x	A12x	A5y
V14x	A25x	A16x
V15y	A12y	A7y
V16y	–	A16y
V17y	–	A17y

Table 2. Experimental frequencies of the tower.

Freq. (Hz)	Modal shape
5.73	Transversal Traslation Y
6.59	Longitudinal Translation X
10.10	Torsional

4.2 *Comparison with the accelerometric recordings*

To perform the comparison the operation of derivation of the velocity recordings was performed, in order to make the data consistent to accelerations recorded from the fixed network. For these comparisons the frequency range was expanded up to 30 Hz. Then the comparison was performed in the frequency domain, through the auto-spectra and cross-spectra and the difference between the auto-spectra of the corresponding sensors.

The analysis of the diagrams showed significant values of the coherence function in the studied frequency range, while the phase factor assumes almost everywhere values around $\pi/2$, consistent with the derivation operation performed in the frequency domain.

Particularly significant is also the difference between the auto-spectra of the two measuring systems. Actually, the spectral shapes of the velocimeter recordings are always in agreement with the accelerometer ones while the amplitudes of velocimeters at the foundation level are not very similar to the corresponding accelerometric recordings (A9x, A9y, A9z). Proceeding to the positions at the upper levels of the structure a good compliance between the amplitudes is apparent. The presence of a low frequency component in the recording of A20y is apparent, which does not influence the spectrum but could affect the peak in the time domain.

Table 3. Experimental frequencies of buildings A and B.

Freq. (Hz)	Building	Modal shape
8.17	A	Transversal Y
9.88	A	Longitudinal X
6.22	B	Transversal Y
8.54	B	Longitudinal X

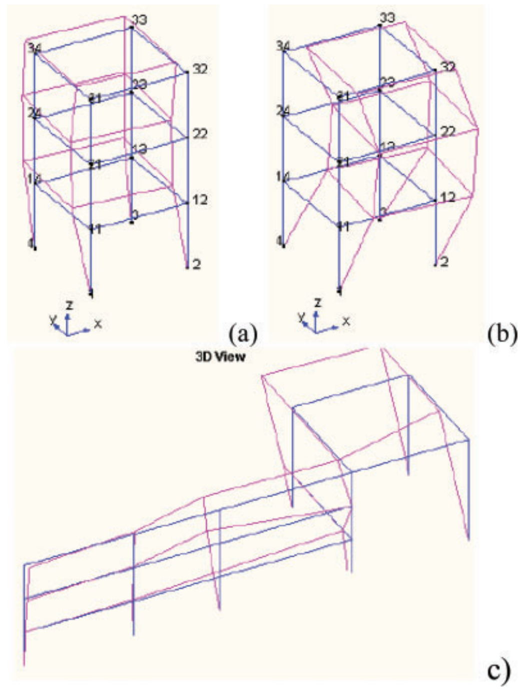

Figure 5. Experimental modal shapes with accelerometric data: (a) f = 5.6 Hz (Translational Y Tower), (b) $f = 6.7$ Hz (Translational X Tower), (c) $f = 6.2$ Hz (Translational Y building B).

4.3 *Ambient vibration of buildings A and B*

In the second configuration seismometers were deployed in buildings A and B. The complexity of the structures made the interpretation of the dynamic behaviour very hard. In the records of sensors in the transversal direction in the central portion of building A (V13y) the prevalent resonance frequency is at 8.17 Hz. This is associated to a bending modal shape with maximum amplitude in the central portion. In the records of sensors close to the tower (V05, V09) the same resonance of the tower, 5.73 Hz, was found. In the longitudinal direction (V04, V10 and V12) the main resonance is at 9.88 Hz.

With reference to building B, records of sensors in transversal direction (V16 and V17) showed an apparent peak at 6.22 Hz. Only V16 presents peaks at higher frequencies, between 10 and 11 Hz. In the longitudinal direction the record of sensor V14 has the main peak at 8.54 Hz. Both 6.22 Hz in the transversal direction and 8.54 Hz in the longitudinal one, can

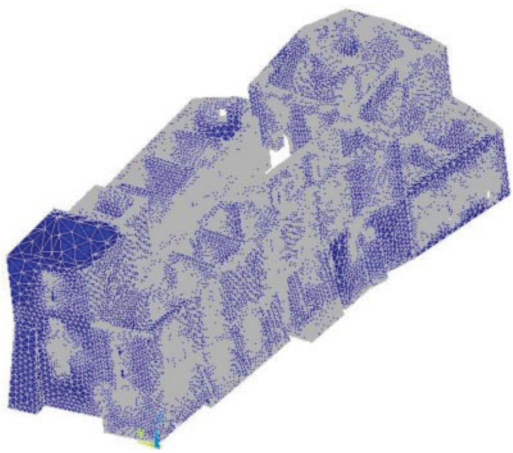

Figure 6. Mesh with solid elements.

be assumed as structural resonances. In Tab. 3 the structural resonances and the corresponding modal shapes are listed. The modal shape obtained with accelerometric recordings is in Fig. 5c.

4.4 *Comparison with the accelerometric recordings*

The low level of excitation and the stiffness of the structure determine a higher influence of the noise in both accelerometric and velocimetric recordings. The analysis showed significant values of the coherence function, while the phase factor is always equal to about $\pi/2$, due to the derivation in the frequency domain. The power spectral densities have very similar shape but some differences in the amplitudes are apparent. These could be related to the distance between accelerometers, which are often just below the floor or at the vault springing, and the velocimeters, which are above the corresponding floor.

5 FINITE ELEMENT MODEL

A finite element model was set up by using the code ANSYS. The elastic modulus was equal to 2120 N/mm^2 and was obtained by matching the first frequency with the experimental value. The model has 189236 nodes, and a total of 567 708 degrees of freedom. Finite element SOLID45 of prismatic or tetrahedral shape were used.

The mesh with solid elements is shown in Fig. 6. In the first step, here reported, the building was considered as a whole, without seismic joints. This hypothesis could be useful to analyze the behaviour under very low vibrations, such as the ambient vibrations. Then the mesh was generated obtaining. The frequencies of vibrations and the corresponding modal shapes were extracted by mean of the *subspace iteration method*. The first eleven modes were found, whose frequencies are listed in Tab. 4.

The first and second modal shapes are associated to a transversal and to a longitudinal movement of the tower, respectively (Figs. 7 and 8). The portion around the tower is also involved in the modes. The third modal shape consists in the transversal movement (Y direction) of building B (Fig. 9), while the fourth mode interests building C, not considered in

Table 4. Numerical frequencies.

Mode	Freq. (Hz)	Building
1	5.73	T
2	6.50	T
3	6.74	B
4	6.96	C
5	7.43	A
6	7.87	A
7	8.20	All
8	8.36	All
9	8.43	All
10	8.62	All
11	9.08	All

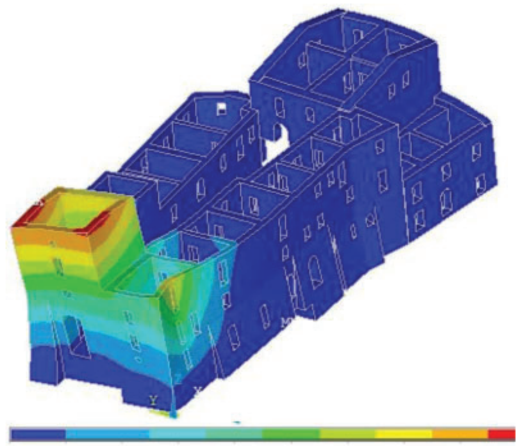

Figure 7. Mode 1 ($f = 5.73$ Hz).

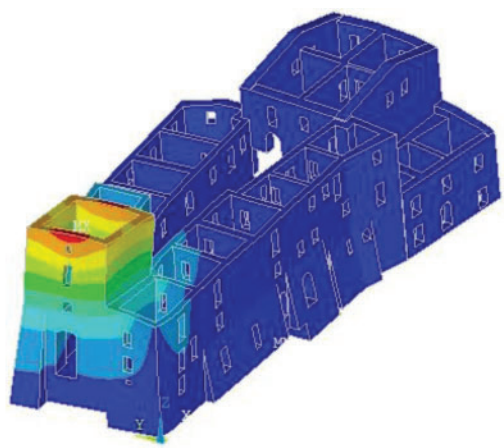

Figure 8. Mode 2 ($f = 6.50$ Hz).

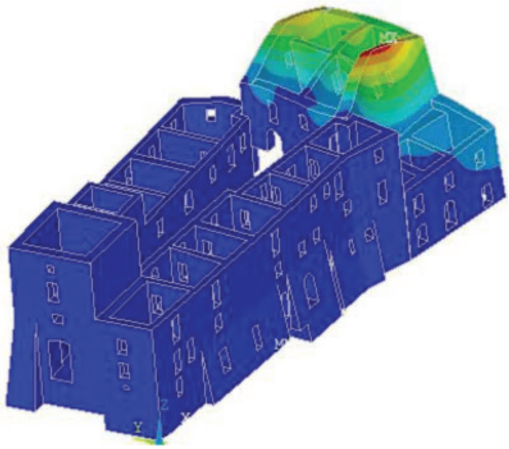

Figure 9. Mode 3 ($f = 6.74$ Hz).

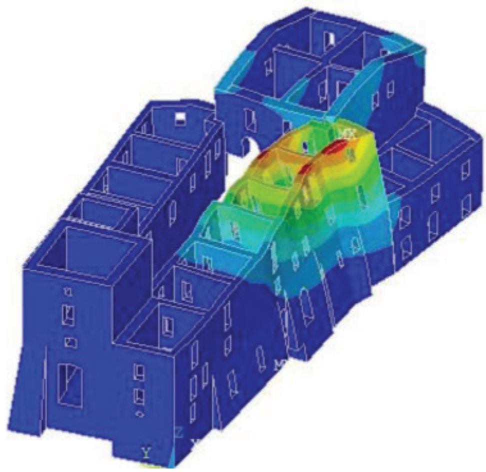

Figure 10. Mode 5 ($f = 7.43$ Hz).

the seismic monitoring. Modes 5 and 6 are relative to the longitudinal building A (Figs. 10 and 11).

The model was updated in order to obtain the coincidence between the first experimental and numerical frequencies. The comparison with the other frequencies gave quite good results (Tab. 5) and the same conclusion can be gathered in terms of modal shapes (Fig. 5 with Figs. 7–10). The comparison between the higher frequencies and the corresponding modal shapes is quite hard, especially for building *A*. Further recordings, including seismic events, could be useful.

6 CONCLUSIONS

The experimental campaign on Palazzo Marchesale by using both a temporary array, composed by velocimeter sensors, and a permanent array, composed by accelerometer sensors, gave the following results:

- the first three resonance frequencies of the tower were found; due to its slenderness its vibrations were detected using ambient noise only, which was quite hard for the other portions;
- the resonance frequencies of building B were also found but the modal shapes are not very clear;
- the longitudinal building A requires more data and a more detailed analysis;
- the comparison between accelerometric and velocimetric recordings gave good results.

The numerical model seams to interpret very good the experimental results. Anyway, further analyses will be very useful, especially in case of seismic recordings.

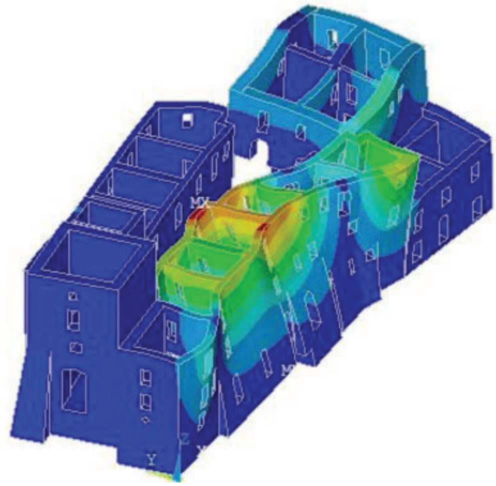

Figure 11. Mode 6 ($f = 7.78$ Hz).

Table 5. Comparison between experimental and numerical frequencies.

Num. Freq. (Hz)	Exp. Freq. (Hz)	Modal shape	Building
5.73	5.73	Translational Y	T
6.50	6.59	Translational X	T
6.74	6.22	Translational Y	B

ACKNOWLEDGEMENTS

The activities here described are part of a research project funded by the Office for the reconstruction of San Giuliano di Puglia.

REFERENCES

Clemente, P. et al. 2012. *Palazzo Marchesale. Dynamic test and modeling*. Report to Office for the reconstruction of San Giuliano di Puglia. ENEA

Spina, D., Lamonaca, B.G., Nicoletti, M., Dolce, M. 2011. Structural monitoring by the Italian Department of Civil Protection and the case of 2009 Abruzzo seismic sequence, *Bulletin of Earthquake Engineering*, Vol. 9, No.1.