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DYNAMIC IDENTIFICATION AND EVALUATION OF THE SEISMIC SAFETY OF A MASONRY BELL TOWER IN THE SOUTH OF ITALY

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Abstract. *Many countries, especially in southern Europe, are greatly exposed to seismic hazard, which is the cause of severe damage in historical buildings or even destruction in the case of strong earthquake ground motions. The recent experience of Italian seismic events (Umbria and Marche 1997, Puglia and Molise 2002, Abruzzo 2009, Emilia 2012) has highlighted the behavior, the damage and the intrinsic vulnerability of monumental buildings. Historical and monumental constructions are characterized by an inherent vulnerability to seismic action, due to the circumstance that most of them frequently lack basic seismic features and/or were never fitted with adequate provisions against earthquake actions. This entails the need to define urgent strategies for the protection of cultural heritage from seismic hazard. This paper deals with the structural monitoring and seismic assessment of a unique masonry tower in a Apulia region in southern Italy: the bell tower of "Santa Maria di San Luca" in the city of Valenzano. This monument was monitored by means of full-scale environmental vibration testing. Measured responses were then used for modal identification. The assessment procedure includes morphological and structural knowledge, full-scale ambient vibration testing, modal identification from ambient vibration responses, finite element modeling, dynamic-based identification of the model. A satisfactory improvement in modal parameters is so obtained, resulting in a close agreement between the modal properties observed in dynamic tests and those calculated from a numerical model. Nonlinear dynamic analysis allows to identify the potential collapse mechanisms and those dangerous structural weak points which may play a fundamental role in the seismic vulnerability of the towers.*

1 INTRODUCTION

Many countries, especially in the south of Europe, are heavily exposed to seismic risk, which is the cause of destruction or damage of the cultural heritage. The recent Italian experience of seismic events (Umbria and Marche 1997, Puglia and Molise 2002, Abruzzo 2009) has sanctioned considerable information about the behavior, the damage and the intrinsic vulnerability of monumental buildings. The historical buildings are usually characterized by an inherent vulnerability to seismic action, being the masonry, not very resistant to tensile strain, especially along the horizontal planes of the joints normally compressed [9, 10]. On the occasion of an earthquake, the horizontal action involved in fact might exceed the weak resistance of the material for the states of tangential stress and tension, causing injury to slide or detachment of the elements. In addition, the history of these artifacts, marked by different construction phases, accentuates that behavior for parts, which is in itself. The modifications and the addition extensions determine the presence of many facilities within the same building, whose behavior is strongly influenced by the action that strikes them [11, 12, 13, 14]. In the case of an earthquake, the inertial horizontal forces are capable of causing the loss of balance of these elements especially if they are slim or not properly connected to the rest of the building. This intrinsic vulnerability is extremely enhanced in some cases, by the lack of effectiveness assessment of some new construction techniques; solutions such as the remake of a reinforced concrete roof, the inclusion of too rigid curbs at the top of the walls, the use of armed seams as an alternative to traditional metal tie rods, have caused in many cases damages higher than those that the original structure would probably have presented. The safeguard of these historical and monumental buildings from earthquakes would preserve people from a serious hazard to their own safety, but also would protect unique art and architecture masterpieces from severe damage or even from destruction.

The definition of reliable models and methods for seismic risk assessment of historical constructions is thus a very interesting topic. The "knowledge", or better qualification of the traditional buildings, understood as the set of information in order to fully define the historical-material-constructive characters as well as the state of preservation and performance capabilities residual, assumes in this case a decisive role. For this way, a great number of studies in the literature are dedicated to destructive and non-destructive static and dynamic tests on masonry structures, to procedures for the identification of mechanical parameters as well as to calibration of reliable structural models [1, 3, 4]. The dynamic identification through input of environmental nature represents a valid alternative to appraise the characteristics of the materials and the conditions of the tie of the structure, with the purpose to define reliable numerical models, through the procedures of model updating [4, 8]. In particular, dynamic measurements may be very useful for the identification of mechanical properties and soil restraints and, consequently, for the calibration of advanced numerical finite element models. In other words, the knowledge of dynamic properties, together with non-destructive testing, is the starting point for an accurate estimation of the seismic safety of these structures [16, 20]. The main purpose of this article is to investigate the effect of the level of accuracy of the models adopted and the type of analysis performed for the evaluation of the seismic vulnerability of towers in historic masonry, also in relation to the indications of the Italian guidelines "Assessment and reduction of seismic risk of the cultural heritage" with reference to the Technical Code DM 14 2008-01" (DPCM 09 /02/2011). The study is carried out taking into consideration the bell tower of “Santa Maria di San Luca” in the city of Valenzano in Apulia region. In particular, the methodology defined to reach the goals aforementioned consisted of: 1) identifying the historical-material-constructive characters of the building; 2) defining a finite element model; 3) defining localization and direction of the measurement points from modal analysis of the FEM model; 4) identifying mode shapes and frequencies, by environmental vibration measurements; 5) calibrating a refined numerical model; 6) seismic vulnerability analysis; 7) evaluating the need and effectiveness of earthquake recovery interventions.

2 PRELIMINARY INVESTIGATION

2.1 Structural and historic framework

The bell tower of "Santa Maria di San Luca" (Figure 1), in the city center of Valenzano in southern Italy, was built in 1774 beside of the seventeenth century church in the Franciscan convent.

Figure 1: Bell Tower of "Santa Maria di San Luca"

It has a square cross-section with a side of 6.25 m and rises up with a simple and massive tower structure characterized by a rusticated stone exterior just sketched. Its height is 46 m. Internally, in the bottom portion, it was divided into three parts (respectively to the shares of 0, 4.74 and 9.55 m), characterized by barrel vaults in hewn stone limestone**.** The top portion is divided into three compartments by floors with steel beams and brick tiles covered by concrete. The first block is a simple polyhedral volume with a few decorative episodes, which tend to be enriched with friezes; among them, the most significant one goes from the bottom to the top; the corners bend, digging; they extend out in a continuous movement. The simplicity of the initial part gives way to sophistication. The Romanesque style is overwhelmed by the baroque style. The second block is surmounted by a sandwiched crown by a frame bluish of majolica, windows appears the ogival arch. The third bin is composed of a cockpit to cusp, surmounted by a sphere with metal cross.

The tower is constituted by two different kinds of masonry typology: basement is in hewn stone with good weaving while an upper block is in square stone. It shows a fair state of conservation, even if some superficial cracks and damage patterns occur, due to exposure to atmospheric agents throughout the centuries. Even if the tower has no serious structural damage, the safeguard against potential seismic events future is of primary importance.

2.2 Non-destructive Diagnostic Investigation

In order to get more detailed information about the masonry typologies of the tower, a set of non destructive diagnostic technologies was applied to some representative walls. It is worth mention that such an investigation approach is paramount for historical structures, where the acquisition of missing data about materials and techniques by non invasive methods enables the comprehensive qualification of all the building elements - which might be very different due to construction characteristics and/or modifications over the time - as well as the preservation of their integrity and stability. Nevertheless, the selection of the most suitable diagnostic technologies should take into account all the data from the preliminary qualification of the building - through historical research, geometrical surveys, photographic documentation, mapping of materials and construction techniques, decay pattern surveys - in order to address the time and cost effective achievement of significant and reliable results [6,7,18,19].

Specifically, following the described methodology, the investigation concerned (Figure 2):

(i) high frequency radar scanning (IDS DAD 1ch Fastwave reading unit and IDS TRHF 2000 MHz antenna) of masonry surfaces at the ground and second floors up to the fourth floor, where the bells are located, in order to identify the stratigraphy from the reflection/attenuation of electromagnetic waves. For each investigated surface, two radargrams were acquired, at 1m and 1.5m from the corresponding floor.

(ii) semi-direct mode sonic testing (BOVIAR CMS reading unit, piezoelectric hammer up to 20 KHz, piezoelectric receiver 1,25MHz) of masonry corners on the second and fourth floors, belonging respectively to the bottom and the top portion of the tower, in order to assess the compactness from the travel time of mechanical waves. For each investigated corner, three measurement paths were acquired at 1m, 1.5m and 2m from the corresponding floor.

For all the investigated areas, the walls are 150cm thick.

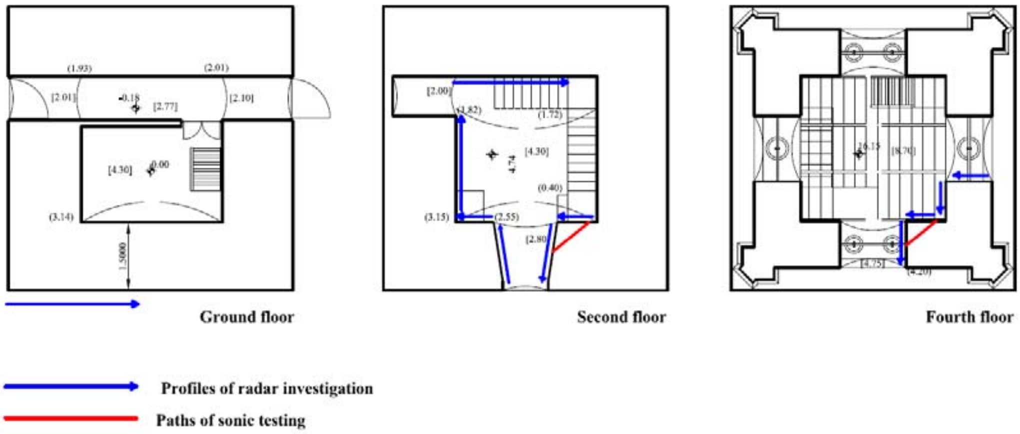


Figure 2. Scheme of diagnostic investigation

From the radargrams at the ground and first floors, it might be observed the presence of three main interfaces, which are all parallel to the external wall surface and respectively about 30cm, 120cm and 150cm deep. The third interface, corresponding to the internal wall surface, is generally about 155cm deep on the ground floor, where the walls are covered by plaster (Figure 3). Otherwise, at the fourth floor, the presence of six regular interfaces might be detected, with relative distance of about 25cm (Figure 4). In the former case, the walls are reasonably cavity masonries, composed of two outer hewn stone leaves and an inner nucleus, made out of stone and mortar, which seems to be quite compact due to the slight reflection of the electromagnetic waves; whereas, in the latter case, the walls are probably solid, and, thus, composed of several squared stone leaves.

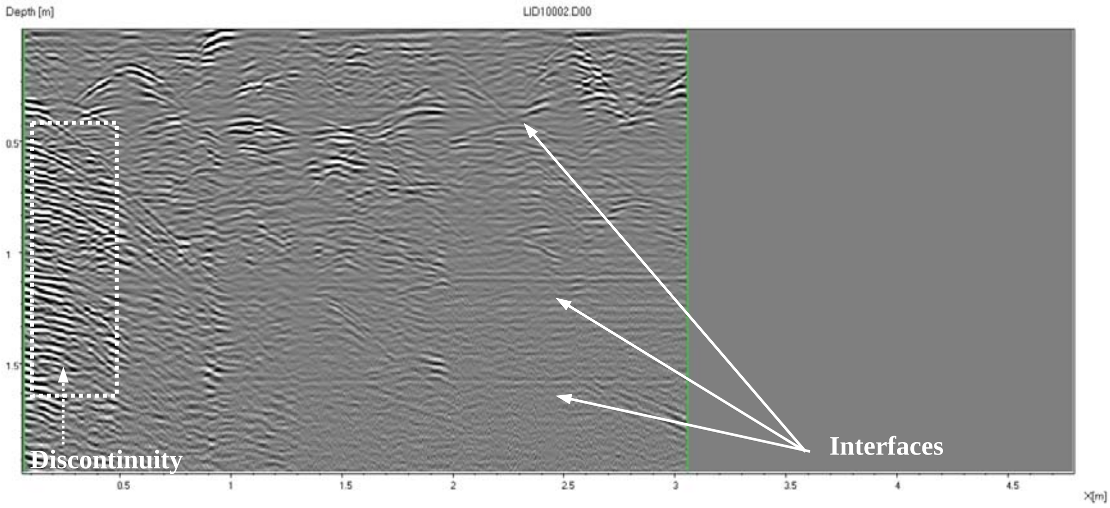


Figure 3. Radargram on an external surface at the ground floor

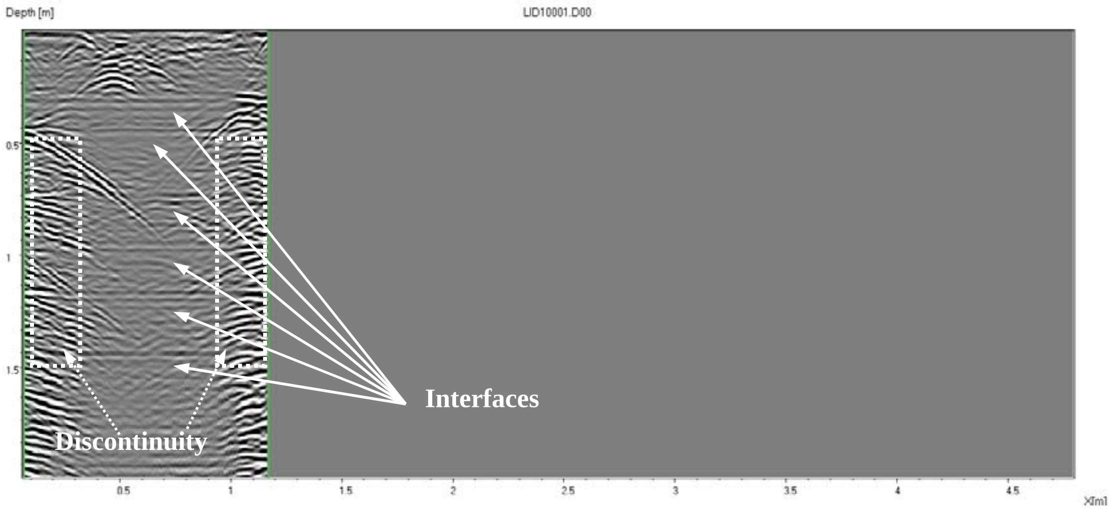


Figure 4. Radargram on an internal surface at the fourth floor

To support such a data interpretation, it should be observed that, at the fourth floor, although the masonry walls are still 150cm thick, the presence of wide and high openings could have made the realization of a cavity less feasible from the technical point of view and less convenient from the static point of view. The results from the radar scanning were confirmed by the semi-direct mode sonic testing (Table 1).

Identification	Range (m)	t_m (μs)	v_m (m/s)	σ_t	σ_v	Δσ (%)
AB01	0,759	928,0	819,6	47,6	41,6	5,1
AB02	0,759	516,0	1475,0	32,2	86,7	5,9
AB03	0,759	472,8	1608,6	24,2	80,3	5,0
AJ01	0.707	305,6	2315,0	8,8	67,4	2,9
AJ02	0,707	480,0	1473,4	10,2	31,0	2,1
AJ03	0,707	336,8	2105,7	21,2	130,0	6,2

Table 1: Semi-direct mode sonic testing

The measurements, repeated six times on three paths for two elements, show an average velocity of 1300 m/s on the second floor (series AJ in Tab.1), where masonries are more heterogeneous due to the cavity, and 1964 m/s at the fourth floor (series AB in Tab.1).

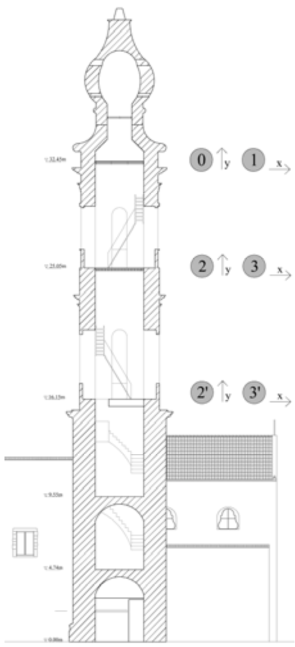
2.3 Tests of dynamic monitoring

Ancient masonry buildings often have a high historical and monumental value and should be preserved. In this way, measurement of environmental vibrations, based on the natural noise and low frequency vibration from wind and traffic, may be carried out without direct excitation of the building. For this structure under investigation, experimental tests have been performed by applying Environmental Test Methods.

These methods, based on a careful choice of sensor positioning, have allowed obtaining correlations between natural frequencies and vibration modes of direct measurement.

The response of the structure in the time domain was assessed by using a combined network of high frequency force-balance accelerometers.

The instrumentation used for dynamic monitoring included a data acquisition system (THOR, www.waveng.it) based on force-balance accelerometers (EpiSensor ES-U2 Kinemetrics) (Figure 5). It is able to manage more distributed sensor networks with real-time acquisition and data processing for structural analyses.



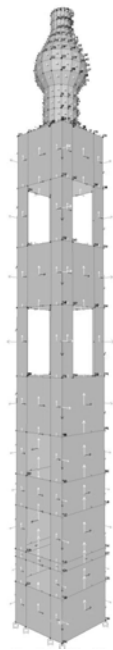


Figure 5: Location of the vibration sensors

Figure 6: Bell tower finite element model

The tests were carried out by considering the action of the traffic and wind, acting on the bell tower in the months of October and December 2012. A preliminary three-dimensional solid element model was developed for selecting the location of the accelerometers during vibration testing. The construction of the model was undertaken using SAP2000© (version 14.2.4) and it is shown in Figure 6. Only structural elements were included in the model whereas non-structural elements are considered as extra masses. A relatively large number of finite elements (8-node brick element) have been used in the model so that a regular distribution of the masses could be obtained.

Although the geological characteristics of the soil were known, while conservation condition of the foundation was unknown, it was decided to model the interaction structure-foundation-ground by means of linear elastic springs. It was uncommonly modeled the interactions between the tower and the adjacent church by the insertion of elastic springs with elasticity coefficient mediated between the two masonry solutions in continuity.

The aim of the structural identification was the verification of the Young's modulus of the masonry in the upper and lower part of the tower, acquired by non-destructive tests so as to optimize consequently the degree of constraint provided by surrounding buildings. In particular, the range of the Young's modulus is 1500÷1980 MPa for the bottom body (masonry in hewn stone with good weaving) and 2400÷3200MPa (masonry in block squared stone) for the top body. The dynamic measurements were carried out inside a 0÷5 Hz frequency range which is selected on the basis of the first six natural frequencies of the tower obtained from the modal analysis. From the spectral analysis of the acquired signals, natural frequencies and the corresponding vibration modes were formed. Since the recorded signal, as well as the signal-to-noise ratio, is proved to be rather low, this was amplified and filtered through a 30 Hz low-pass filter. Data acquisition was driven by software, which allows the acquisition of signals with sampling rate of 1000 Hz, and the real time visualization of accelerograms and Fourier spectra. The identification was performed by using the techniques of modal extraction in the frequency domain (frequency domain decomposition - FDD). These techniques allow evaluating the natural frequencies and modal shapes of the tower. Fast Fourier Transform (FFT) was used to determine the frequency spectrum of the signal. The spectral analysis of the recorded signals gives the natural frequencies and the corresponding mode shapes (fig. 7-8).

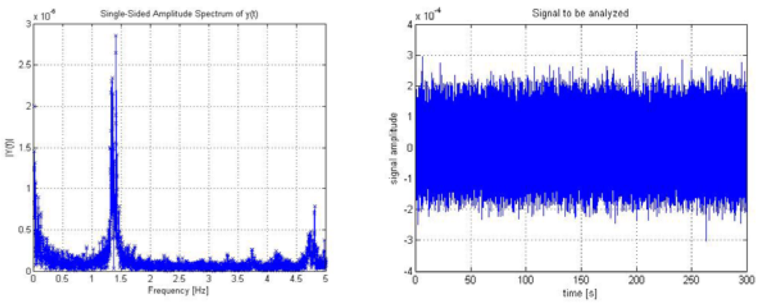


Figure 7: Fast Fourier transform and recorded signal. Accelerometer 0.

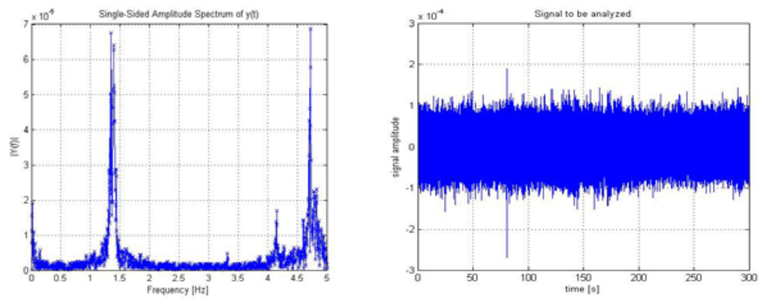


Figure 8: Fast Fourier transform and recorded signal. Accelerometer 1.

3 STRUCTURAL IDENTIFICATION PROCEDURE

The minimization of the error in frequencies, numerically determined, and those resulting from the measurements performed on site, is used to update the model of finite elements. As expected the optimum value of Young's Modulus is related to the parameter chosen for calibration. In this case, mechanical parameters were defined minimizing the total frequency discrepancy (1), calculated with the following weighted mean:

$$D_f = \frac{\sum_{i=1}^{n} \left| \frac{f_{FEM,i} - f_{FDD,i}}{f_{FDD,i}} \right| * a_i}{\sum_{i=1}^{n} a_i} \qquad (1)$$

where α_i is the ith modal mass ratio and n is the number of the experimental mode shapes (figure 9).

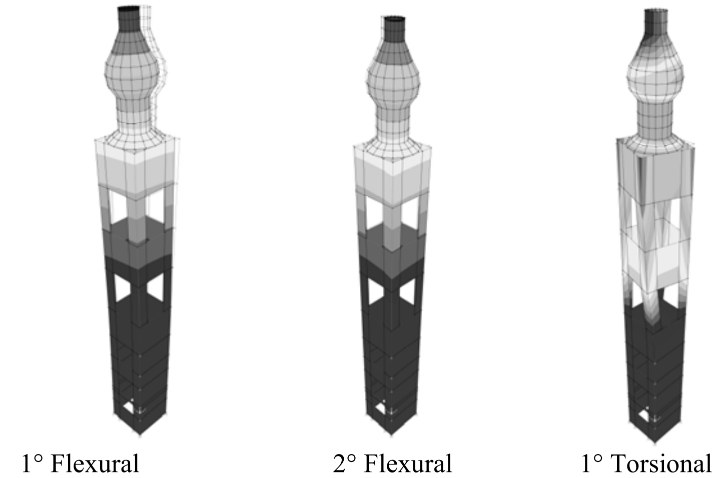


Figure 9. Vibration mode shapes - Bell tower of “Santa Maria di San Luca”.

The minimum total discrepancy D_f =0.9239% is obtained for E_{bottom}=1935 MPa and E_{top}=3200 MPa for the upper levels. The mechanical parameters tuning the finite element model to accurately reflect the dynamic characteristics of the bell tower are reported in table 2.

Masonry	E (MPa)	υ	γ (KN/m^3)
Top	1935	0.15	22
Bottom	3200	0.15	21

Table 2: Optimized mechanical parameters.

The single comparison between the natural frequencies from dynamic identification and those from numerical modelling is reported in table 3.

Mode	f_{FDD} (Hz)	f_{FEM} (Hz)	$D_{fsingle}$ (%)
1°Flexural (x)	1.41367	1.41470	0.0739
2° Flexural (y)	1.39580	1.39830	0.1792
1° Torsional	4.79360	4.890	2.0110

Table 3: The correlation between the measured and calculated frequencies

A good correlation between measured and calculated frequencies was obtained, especially for the 1st flexural X ($D_{fsingle}$=0. 0739%) and the 2st flexural Y mode shape (Df_{single}= 0.17%).

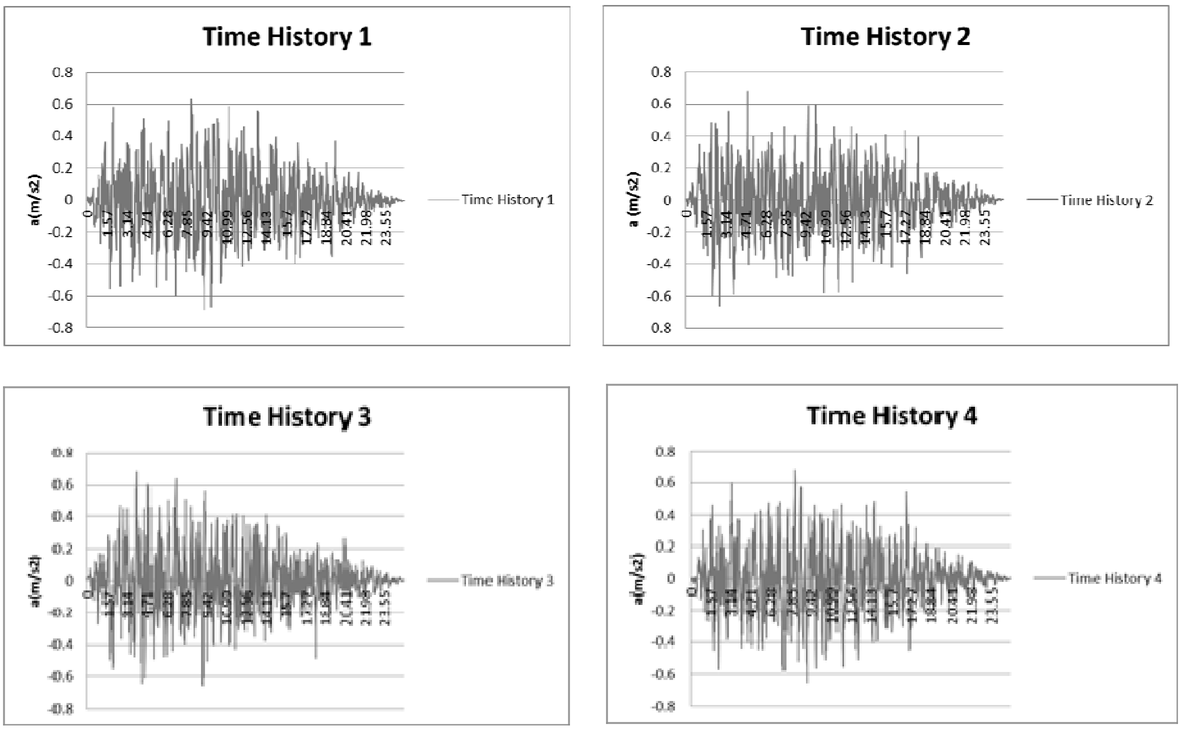
4 SEISMIC VULNERABILITY ASSESSMENT

Different approaches have been developed to analyze the seismic behavior of buildings. The modeling strategies can be classified into micro-modeling or macro-modeling, based on the detail by which they represent structural elements, the computational effort and the information they provide about the behavior of a structure [15]. In this work a micro-modeling approach has been adopted. After being updated and refined on the basis of the modal force tuning, the model was implemented in COMSOL© multiphysic software (nonlinear structural materials module) for the seismic assessment. The compression behavior of the masonry was introduced through the model of Drucker Prager.

The parameters of cohesion c and friction ø were derived from the compression media strength, obtaining the values c = 0.48MPa and ø=13°. The tensile behavior was instead played through a smearing crack model, with a tensile strength of 0.1 MPa, constant cut-off criteria and linear softening up to a value of maximum deformation assumed equal to the 1 ‰.

In this way, the crack is simulated through a diffuse band of lesions and it is modeled through a modification of the materic properties.

The model was initially subjected to non-linear static analysis for gravity loads. After the pushover analysis, a series of non-linear dynamic analyses were carried out by applying at the base of the tower eight artificial earthquakes to safety life state.
They have been generated from the spectrum target, provided by the Italian legislation for the city of Valenzano, through the software REXEL (www. reluis.it), and suitably calibrated (Figure 10), defining specifications of the selection and combination.



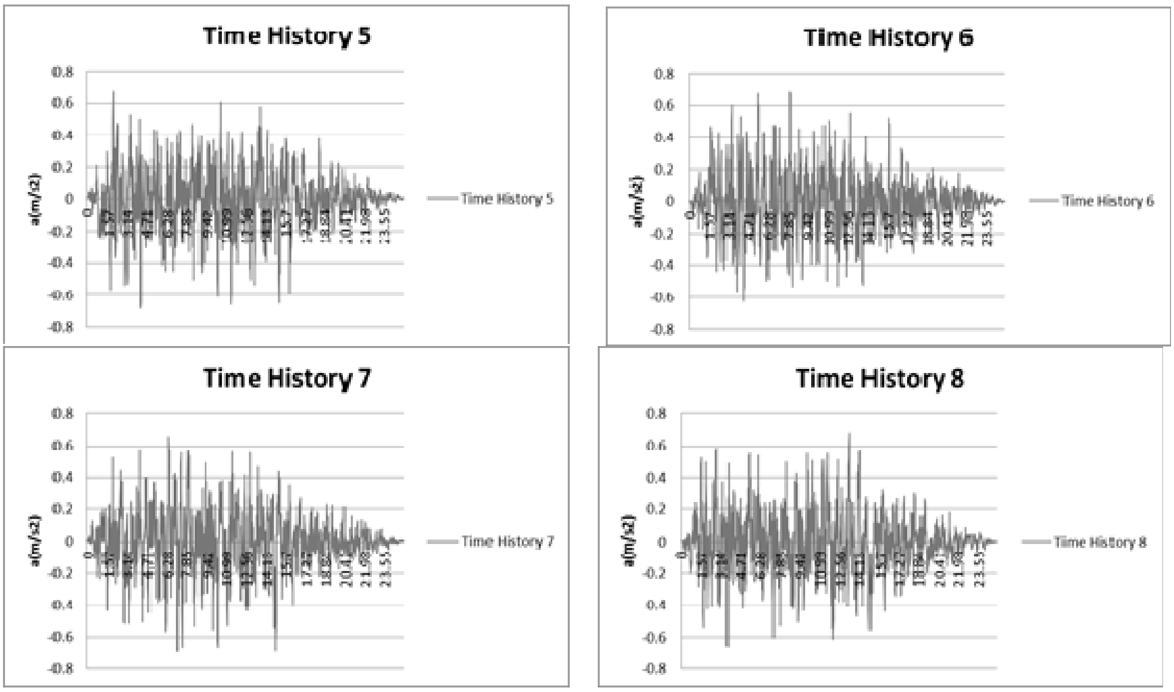


Figure 10. Artificial earthquakes for safety life state of the city of Valenzano

The analysis evidences that the tower is basically in elastic conditions, since the level of stresses is smaller than the strength in all parts of the tower. The structure is able to check all the collapse mechanisms with reference for the state limit adopted (Figure 11). This does not imply the need to define and implement appropriate interventions to enhance the ability of the seismic structure.

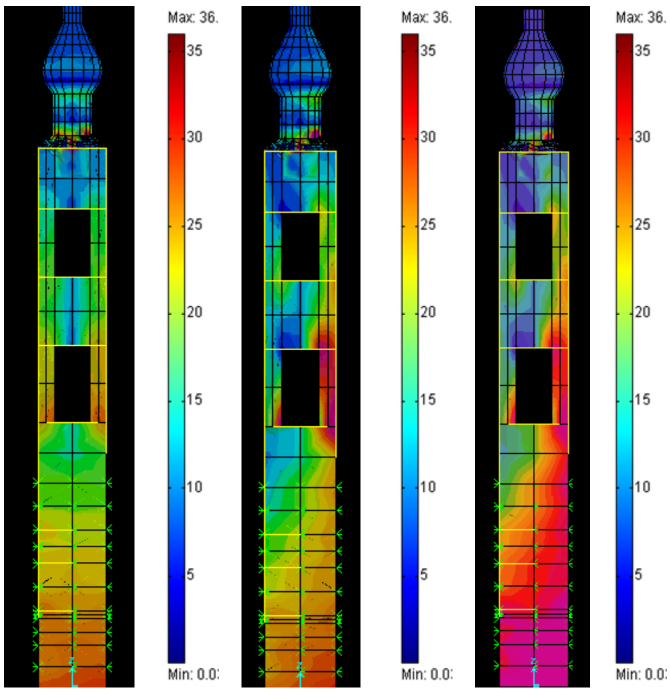


Figure 11. Vertical stresses [kg/cm^2] due to dead and seismic loads. PGA =0; PGA = 0,07g; PGA = 0.1105

This is the result of the correlation between non-destructive diagnostic and dynamic identification techniques. The set of information, suitable to fully define the historical-material-construction characters, in addition to sensitive non-linear dynamic analysis, allows a more reasonable result regarding the real vulnerability of the building. This ensures simultaneous safety and greater conservation of structure, favoring the criterion of minimum intervention, but also highlighting the cases in which it is appropriate to act more effectively.

As long as the seismic action increases its intensity, showing higher values of the safety life limit state, some cracks appear in the lower part of the upper block, mainly due to the "explosion" of some blocks for compression stress (figure 10).

When the compressive stress is greater than the yield strength of masonry, the cracks begin to open. As the amplification factor increases, the high compression stresses appear further in the lower block until the structure collapses.

The PGA for the structural collapse of the tower of “Santa Maria di San Luca” is lower than the reference peak ground acceleration at the Life Safety Limit State (PGALS=0.07g), and so the risk index is α_{LS}= PGAu/PGA_{SLS}=1.578.

5 CONCLUSIONS

The study has helped to define a practice for the evaluation of seismic vulnerability of historic buildings, which can ensure simultaneously safety and conservation, favoring the criterion of minimum intervention, thus avoiding unnecessary interventions, but also by highlighting the cases in which it is appropriate to act more efficiently.

It highlights the fundamental importance of correlation between the dynamic identification techniques and non-destructive diagnostic investigations in the evaluation of the seismic capacity of masonry structures.

Although this presupposes an integrated system of data acquisition and management of information and knowledge, however, it will be able to permeate the concept of structural safety of the historic buildings with all the aspects that are unlikely to be integrated within a mechanical model, even if it is refined.

In this way the intervention, that comes from it, is certainly appropriate, because it poses as not a distortion of the "logic" (formal and spatial-material) of the pre-existent, but in continuity with the "modal logic" (procedural) that it involves.

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