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Techniques for Improving Assessment of the Seismic Vulnerability of a Masonry Bell Tower

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ABSTRACT: *Many countries, especially in southern Europe, are heavily exposed to earthquake hazard, that caused severe damage to buildings or even destruction in case of earthquake strong ground shaking [9]. The recent experience of earthquakes showed the behavior, the damage and the intrinsic vulnerability of monumental buildings. Historical buildings and monuments are characterized by an inherent vulnerability to seismic action, due to the fact that most of them frequently lack basic seismic characteristics and/or never were equipped with adequate provisions against the actions of an earthquake. This implies the need for urgent strategies for the protection of cultural heritage from the seismic risk. This paper deals with the structural monitoring and seismic evaluation of a single masonry Tower in a region Puglia in southern Italy: the Bell Tower of the "monastery of St. Clare" in the city of Casamassima. This monument was monitored by means of environmental vibration tests on a large scale. Measured responses were then used for modal identification. The assessment procedure must include morphological and structural knowledge, environmental vibration tests on a large scale, modal identification from ambient vibration feedback, finite element modeling, dynamic model identification. A satisfactory improvement in modal parameters is obtained, resulting in an agreement between the modal properties observed in dynamic tests and those calculated by a numerical model. Nonlinear dynamic analysis helps you identify potential mechanisms of collapse and dangerous structural weaknesses may play a key role in the seismic vulnerability of the towers.*

Keywords: *bell tower, sensor networks, structural identification, model updating, non-linear dynamic analysis*

I. INTRODUCTION

Many countries, especially in southern Europe, are heavily exposed to seismic risk, which is the cause of the destruction or damage of cultural heritage [9]. The recent Italian experience of seismic events sanctioned considerable information about the behavior, the damage and the inherent vulnerability of monumental buildings. The preservation of these historic buildings and monuments from earthquakes would save people from a serious risk to your safety, but also would protect only art and masterpieces of architecture from serious damage or even de-struction. The definition of reliable models and methods for evaluation of the seismic risk of historical buildings is a very interesting topic. "Knowledge", or better qualification of tradi-tional buildings, understood as the set of information in order to fully define the historical characters-material-construction and conservation status and residual performance features, in this case plays a decisive role. For this, a large number of studies in the literature is devoted to destructive and non-destructive static and dynamic tests on masonry structures, procedures for identification of mechanical parameters regarding the calibration of reliable structural models [1, 3, 4]. Dynamic identification through environmental input represents a valid alternative to evaluate the characteristics of the materials and the conditions of the tie of the structure, in order to establish reliable numerical models, through the procedures of the model update [4, 8]. Specifically, dynamic measurements can be very useful for the identification of mechanical properties and soil restraint systems and, therefore, for the calibration of the finite element numerical models advanced. In other words, the knowledge of non-destructive testing, dynamic properties together, is the starting point for an accurate estimation of seismic safety of these structures [16, 20]. The main purpose of this article is to study the effect of the level of accuracy of the models used and the type of analysis performed for evaluation of the seismic vulnerability of historic masonry towers, also as regards the indications of Italian guidelines "earthquake risk assessment and reduction of cultural heritage" with reference to the technical code DM 14 2008-01 "(DPCM 2/9/2011). The study is carried out taking into consideration the Bell Tower of the "monastery of St. Clare" in the city of Casamassima, Italy. In particular, the methodology defined to achieve the above objectives consisted of: 1) identifying historical characters-material-construction of the building; 2) definition of a finite element model; locale definition 3) and direction of measuring points from modal analysis of FEM model; 4) locate mode shapes and frequencies of vibration environmental measures; 5) calibration of a numerical model. 6) analysis of seismic vulnerability; 7) assess the need and efficacy of earthquake recovery interventions.

II. PRELIMINARY INVESTIGATION

II.I Structural and Historic Framework

This study aims to analyze the structural behavior of the bell tower of "Santa Chiara Mon-astery" (Fig. 1), in the city center of Casamassima, that can be considered as representative of the architectural and construction typology of most historical towers in Southern Italy.

A preliminary historical research is a fundamental requirement for the analysis of such a building: in fact, it allows to obtain valuable information, within the overall qualification pro-cess, that leads to the definition of a reliable structural model, with reference to original de-sign and construction, architectural and technical phases, as well as transformations occurred during time.

From the second volume of the book "Casamassima nella storia dei tempi" (Casamassima in the history of the times) written by Don S. Montanaro , we learn that the current bell tower of the church of Santa Chiara, belonging to the eponymous former Monastery of Clausura, dating back to 1660, is not that original. In fact it was, together with the barrel-vaulted room on which rests, partly built during an important restoration work dating back to the thirties of the nineteenth century, which regarded the church and, in general, the entire monumental complex. Testimonials for this substantial work are, today, the two carved engravings respec-tively on the ashlar arch above the via Scesciola portal (S.CHIARA AD 1832) and the lintel that supports the pyramidal roof of the bell tower (A 1833 D). During the restoration of the thirties of the nineteenth century, were also rebuilt the church vault and the bell tower which has continued to have the windows hidden by accurately worked wrought iron grilles, with kneeling shape, until the end of the 40s of this century. The following bibliographical source, accompanied by architectural evidences, and the epigraphic evidences mentioned above, sup-port the claim that today's structure of the former church building is not the result of a unitary design, but rather the sum of alterations and historical - architectural stratifications succeeded one another over the centuries, linked to the life cycles and the associated intended use of the building. The new bell tower is then erected on the western wall of the existing factory and according to the neoclassical style of that time, as shown by the other bell towers of churches in town, built or rebuilt between the second half of 1700 and the first half of 1800. On 17 February 1861 the Italian Government emanates a decree on the abolition of communities and religious orders. A decade later, August 29, 1874, an inspection is carried out at St. Chiara Church because of a lightning strike. From file n. 60 of the Historical Archive of the Town, we learn that until that moment the roof has been spherical and not cuspidal, as can be seen today. To repair the damage occurred, in the same document we read that architects Angelo Michele Pesce and Ascanio Amendoni proposed the removal of precarious bricks and cover-age of the dome with asphalt. However, the proposal of these was rejected, in fact currently the top portion of the tower ends by a cuspid shape. Although the Church of St. Chiara has undergone an important work of consolidation in the 50s of the last century, because of a demolition that interested two floors of the building adjacent to it, the bell tower does not seem to have been affected by further changes and alterations.The bell tower, in Neoclassical style, is located in the northwest corner of the church, as is customary in western Countries (Fig. 2-3), and is grafted onto the body of the building, as we can often notice in southern Italy and in many regions of central Italy, where the bell towers are in solidarity with the building of the church.It has a square shape, with 3 meters length side, and is constituted by a limestone blocks masonry with filling core. Therefore it seems to follow a rule on the construction of bell tow-ers, officially written for the first time in 1577 by San Carlo Borromeo in the Treaty 'De fab-brica ecclesiae', according to which they were to be placed on the facade of the Church, on the right of the entrance; of preferably square shape, well closed and possibly provided with a clock. The high, towering over the top surface of the roof of the church, is divided into four parts: the base, concluded by a band frame crowned by a straight throat molding; the tower, divided into three horizontal planes of different sizes marked by two moldings (having the same profile as that of the base) and ending with an Doric order entablature; the belfry, which looks more slender than the tower because of the Ionic order and the high and slender open-ings, flanked by pairs of pilasters juxtaposed; finally, the pyramid-shaped roof, introduced by a short tambour with ovolo shape molding crowning, lightened by four small openings in axis with the underlying openings. The tower had to be characterized by a double kind of openings: on the east and west sides higher, with round arched crowning; on the northern and southern with architraves. Currently of these four have survived three: one on the western side, two on the north. The arc surmounting the western opening, reaching almost to the Doric frieze of the entablature crowning, shows a straight throat profile, as the molding on which it rests. While the architrave openings, stopping at the second of the moldings that mark the tower in three portions, fit perfectly inside it. In origin, both types must have been protected, on each side, by a stone balustrade, the height of which occupies the first of the three horizontal parts of the tower. It consists, for each opening, by five column-shaped balusters, enclosed between two corner pillars, resting on a base and connected by a coping. The profile of these elements is the same of the moldings described above. The belfry is enriched with a Ionic order decoration: on each prospectus, two pilasters on each side flanked the opening, which is in turn framed by a stone balustrade with arched pattern and two ovoids that support the architrave on which it is engraved the name of the former place of worship "S.CHIARA".

II.II 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 net-work 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) (Fig. 4). It is able to manage more distributed sensor networks with real-time acquisition and data processing for structural analyses.

The tests were carried out by considering the action of the traffic and wind, acting on the bell tower in the months of November and December 2015. 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 5. 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 distribu-tion of the masses could be obtained.

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 sig-nal-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 sig-nals 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. 6-7).

III. 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 cali-bration. In this case, mechanical parameters were defined minimizing the total frequency dis-crepancy (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 αi is the ith modal mass ratio and n is the number of the experimental mode shapes. The minimum total discrepancy Df =0.9239% is obtained for E_{bottom}=1935 MPa and E_{top}=3200 MPa for the upper levels. The mechanical parameters, enshrined by destructive diagnostic tests, tuning the finite element model to accurately reflect the dynamic characteristics of the bell tower are reported in table 1.

The single comparison between the natural frequencies from dynamic identification and those from numerical modelling is reported in table 2.

A good correlation between measured and calculated frequencies was obtained, especially for the 1st flexural X ($D_{fsingle}$=0. 1053%) and the 2st flexural Y mode shape ($D_{fsingle}$= 0.0805%).

IV. SEISMIC VULNERABILITY ASSESSMENT

Different approaches have been developed to analyze the sesimic behaviour 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 behaviour of a structure [17]. 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 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 Casamassima, through the software SEISMOARTIF (www. seismosoft.it), and suitably calibrated (Fig. 8), defining specifications of the selection and reducing the convergence error.

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 (Fig. 9). This does not im-ply the need to define and implement appropriate interventions to enhance the ability of the seismic structure.

This is the result of the correlation between mechanical model 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.

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 Chiara” is lower than the reference peak ground acceleration at the Life Safety Limit State (PGA_{SLS}=0.07g), and so the risk index is α_{LS}= $PGAu/PGA_{SLS}$=1.236.

V. FIGURES AND TABLES

Figure 1: Bell Tower of “Santa Chiara”

Figure 2: Bell Tower of “Santa Chiara”

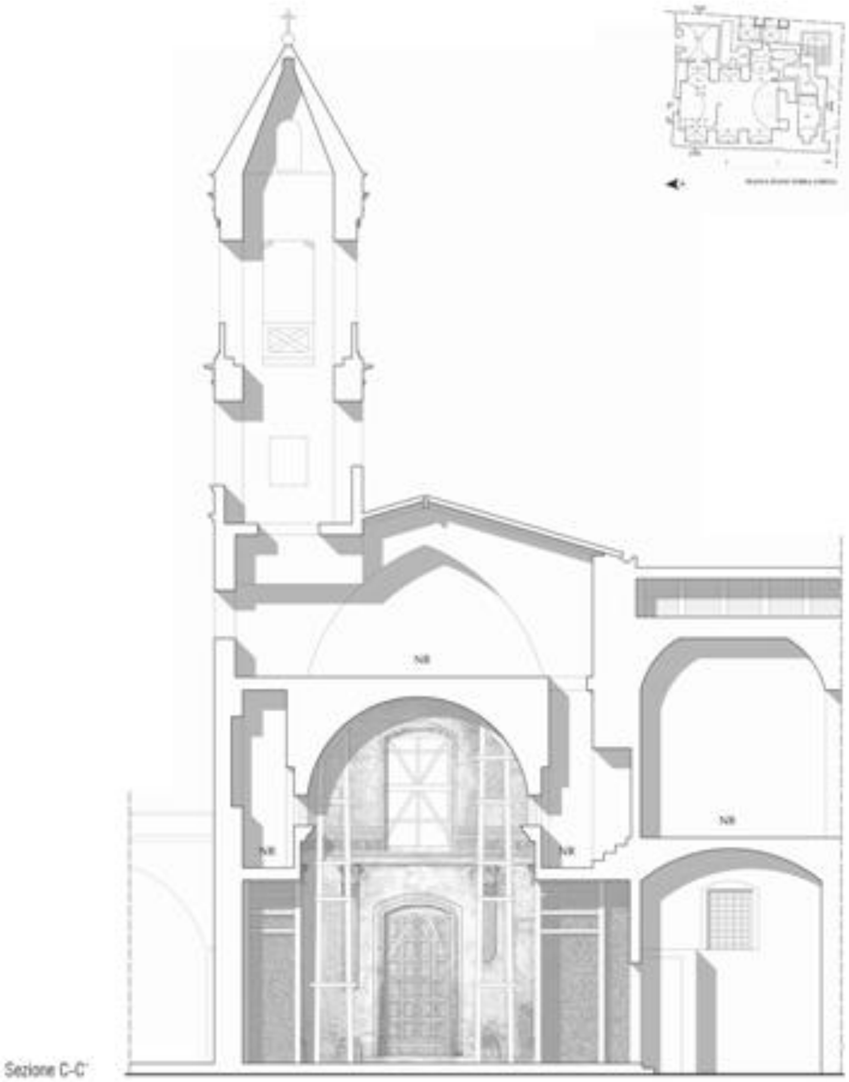

Figure 3: Bell Tower of “Santa Chiara”

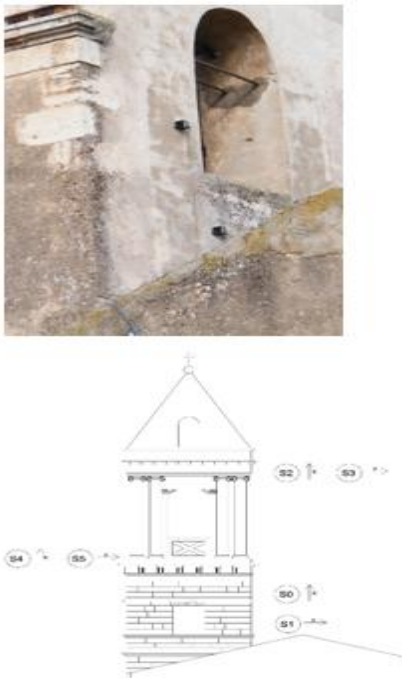

Figure 4: Location of the vibration sensorsFigure 5: Finite element model

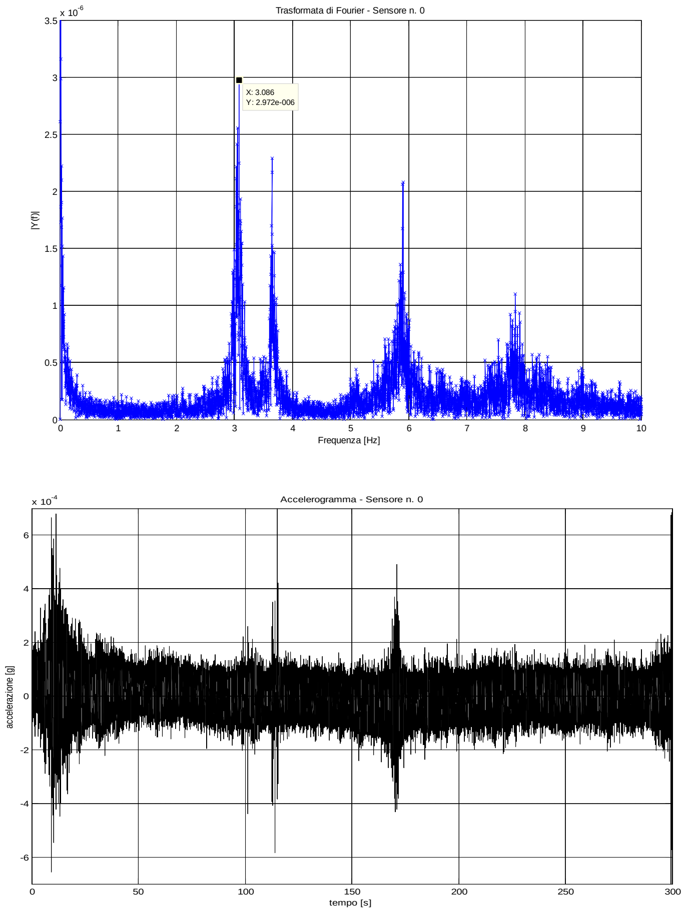

Figure 6: Fast Fourier transform andrecorded signal. Accelerometer 0.

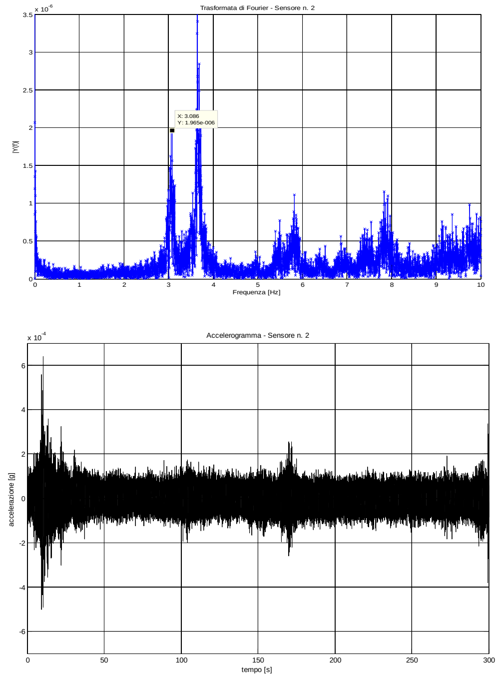

Figure 7: Fast Fourier transform and recorded signal. Accelerometer 2.

Table 1: Optimized mechanical parameters.

Masonry	E (MPa)	υ	γ (KN/m^3)
Top	1930	0.15	22
Bottom	3100	0.15	21

Table 2: The correlation between the measured and calculated frequencies

Mode	f_{FDD} (Hz)	f_{FEM} (Hz)	$D_{fsingle}$ (%)
1°Flexural (x)	1.40541	1.40689	0.1053
2° Flexural (y)	1.37845	1.37956	0.0805
1° Torsional	4.54689	4.56874	0,4805

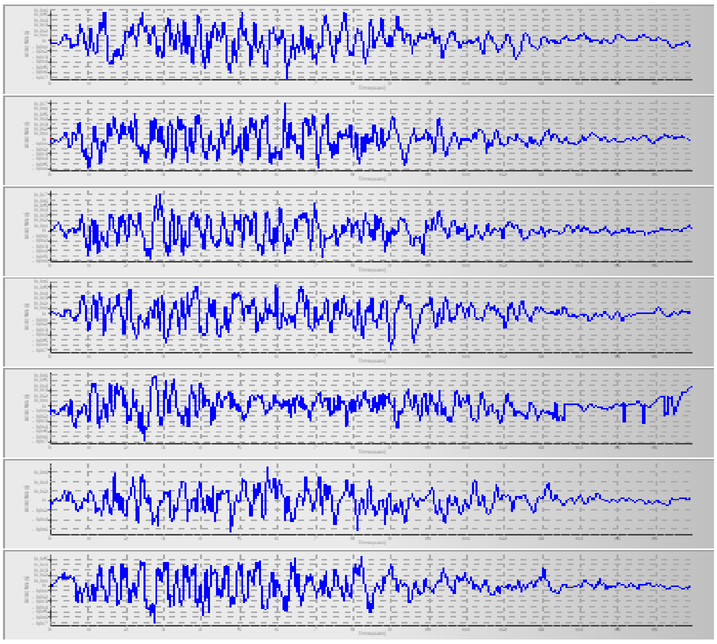

Figure 8. Artificial earthquakes for safety life stateof the city of Casamassima

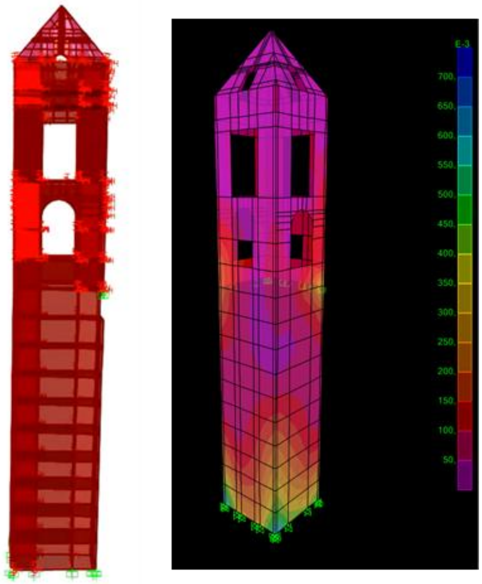

Figure 9. Compression stresses due to seismic load (daN/cm^2). PGA = 0,07g;

VI. CONCLUSION

The study defined a practice for seismic vulnerability assessment [9] of historic buildings, ensuring at the same time safety and preservation, promoting the policy of minimum intervention, thus avoiding unnecessary interventions, but also highlighting the cases where it is appropriate to act more efficiently. Although this requires an integrated system of data acquisition and information and knowledge management, however, will be able to imbue the con-cept of structural safety of buildings with all aspects that are unlikely to be integrated into a mechanical model, although it is refined. In this way the intervention, which comes from it, it is certainly appropriate, because it poses as non-distorting "logic" (formal and spatial-material) of the former, but in keeping with the "modal logic" (procedural) that involves.

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