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IN SITU TESTS AND EXPERIMENTAL DYNAMIC CHARACTERIZATION OF THE SANCTUARY OF MADONNA DELLA LIBERA IN PRATOLA PELIGNA (AQ)

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Abstract

The recent seismic events in the Apennine area of Italy have highlighted the extreme seismic vulnerability of Italian art and monumental heritage. The collapse of the cathedral of Norcia due to the october 2016 earthquake is the most emblematic example of how high is the seismic vulnerability of such structures. In the Abruzzo region, some buildings already seriously damaged in april 2009 have undergone a sensitive aggravation been affected by the effects of such new events. Some churches previously damaged suffered an aggravation of the cracking framework and of the global stability. Following this scenario, the MIBACT has devoted resources addressed to structural investigations, vulnerability assessments, and security work on some of the most important sites, including the Sanctuary of Madonna della Libera in Pratola Peligna (AQ). A campaign of experimental tests, field surveys and dynamic investigations have been implemented to get a complete characterization of the structure and the soil. Large space is dedicated to the OMA experimental method and to the highly dedicated instrumentation. A comparison with the numerical studies carried out by the designers is reported to prove the reliability of the in situ measurements and the almost total correspondence with the modelling performed. The experimental dynamic characterization combined with the site investigation of soil resonance allow to quickly identify the more sensible artifacts to seismic effects.

Keywords: operational modal analysis, accelerometer, vulnerability.

1. Introduction

Religious buildings, and in particular churches, because of the peculiar geometry that characterizes them, generally show a greater seismic vulnerability than other types of historic artifacts in masonry. Large nave without load-bearing walls, high slender walls, thrust elements, colonnades, vulnerable decorative elements, as well as the almost total lack of intermediate horizontal elements and strong transversal elements make the seismic response of these buildings extremely variable depending upon the building techniques used and degree of conservation. The best practice developed over time thanks to the experience and the constructive tradition of the master builders has identified some empirical solutions that can counter the seismic action. Some examples are the good quality of the masonry with transverse connections between the wall edges, the effective binding and tying of orthogonal walls at the cantons, the insertion of chains or rims, the use of artifacts of adequate stiffness, the insertion of buttresses to counterbalance the overturning mechanisms, etc. The importance of an adequate assessment of the vulnerability of churches is connected both to the seismic exposure and to the historical and architectural value of these artifacts [3]. There is therefore a need to analyze the seismic response of churches in order to identify effective structural improvement strategies geared to both protection and conservation of architectural good in accordance with constructive techniques dating from the era of edification. For a more accurate and even quantitative evaluation of the seismic performance of the church in question, a global three-dimensional model has been developed [1], with the aim to simulate the response to seismic actions of all the resistant elements of the artifact (walls, masonry pillars, bows and vaults, etc.) and their mutual interactions, while simultaneously modeling the behavior in the plan and out of the plan of the masonry. The model also took into account the widespread presence of injuries resulting from the 2009 earthquake that strongly struck the Apennine dorsal, with epicenter around the city of L'Aquila.

In order to carry out the dynamic experimental characterization of the structure and compare the resulting output with those deriving from the theoretical model above mentioned a campaign of vibrational measures was fulfilled. For this purpose, the Operational Modal Analysis (OMA) methodology was used, that is a consolidated method for dynamic experimental identification of structures in large scale for which it is difficult, or economically disadvantageous, to provide measurable excitement by using artificial means [2].

Figure 1. Façade of the Sanctuary

2. Sanctuary description

The sanctuary of Madonna della Libera, inaugurated in May 1912 at the end of the works started in 1851, stands in the heart of the beautiful town of Pratola Peligna, dominated and almost protected by the imposing mountainous massif of Majella mountains. The church dominates the square bearing its own name where in the center also insists a fountain made at the end of the nineteenth century in stone and cast iron. The façade, in neoclassical style covered with a cladding of Majella's stone, is characterized by two large belfries and by the presence of four niches that house as many statues, while the center opens up the portal at the end of a stairway. The interior of the temple, in classical latin cross, stands out for its sumptuous harmony, in the vastness of the three naves and in the rich baroque robe. It develops according to an ancient iconographic model with transept and apse area with a choir and many chapels distributed along the perimeter. Vaulted roofs cover the central nave and lateral ones, the two transepts, and the apsidal section.

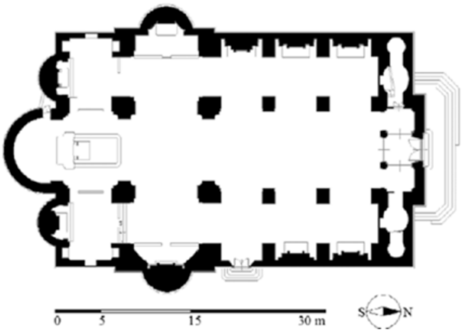

Figure 2. Plant of the Sanctuary (base level)

The sanctuary has been seriously damaged by the L'Aquila strong earthquake of april 2009 and it has undergone a sensible aggravation been affected by the effects of such new events. Probably his situation was further worsen by the many seismic shocks that had bedeviled Central Italy in the second half of 2016 and early this year. In particular, an inspection immediately after the seismic event of October 2016, with epicenter near Norcia, and which has caused the almost complete destruction of the cathedral of this laughing town, provided a momentary closure of the sanctuary until no intervention was carried out making the structures safe. The central nave and the two transepts were so cramped to suggest an imminent collapse. For this reason, waiting for the restoration work, a series of provisional support works (scaffoldings, shoring systems, underpinning etc.) have been put in place to prevent this from happening. A survey in a glance can already provide a clear visualization of the state of the sites. The arc above the transept is damaged and there are cracks in the intersection of the latter one with the side nave extending into the upper wall of the windows located above the ceiling of the nave. There is a large crack in the central dome that has also damaged part of the cylindrical drum. The longitudinal arches of the central nave are damaged, and there are horizontal cracks at the base of the columns. There are cracks in the transversal arches of the lateral nave and vertical crevices on the external walls in proximity of the openings. Cracks in the perimeter openings of the presbytery and apse show their vulnerability to seismic actions. The façade has no injuries except those caused by the horizontal sliding of some stone elements on the belfries.

3. Operational Modal Analysis

The Operational Modal Analysis (abbreviated with OMA acronym) is used in cases where the excitation is unknown, because it is not measured or because it is impossible or it makes no sense to measure it. This is the case when a random excitation occurs, such as the background noise in which the structure is located, caused by traffic, wind, anthropogenic sources, and seismic micro-tremors. Although the excitation source is not measured, some of its own features, which derive from its stochastic nature, are known a priori, whose property is to have a constant frequency spectrum (white noise). Therefore it is sufficient to have only data about the structure response from which, with appropriate algorithms of modal extraction (output-only type analysis), it is possible to determine its dynamic features. Such a method of analysis is based on the study of cross power spectrum function of the various signals sampled at the measuring points with the respect to a fixed one, taken as a reference between the set of collected data (reference point). This function can be related to the function of system frequency response. Obviously, being in the presence of multiple measuring points, the calculated functions are collected in matrices, to form the cross-spectrum output matrices and the frequency response functions matrices. Eventual peaks in the graphic representation of the cross-spectrum function indicate the presence of predominant frequencies in the signals that compose it. In particular, a generic cross spectrum function is defined as the Fourier transform of the cross-correlation function of the sampled signals in the time domain, weighed by applying a windowing to reduce the leakage effect. The cross spectrum function for the same measured data set varies its trend in relation to the choice of the reference points. The presence or absence of distinguishable peaks is the first aspect to consider for the correct conduction of measurement.

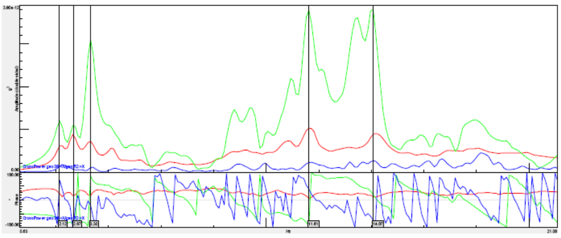

Figure 3. Cross-power spectrum

Under the assumption that the surveyed system is excited by white noise, as in any case of randomized excitation, the measured cross power spectrum functions can be treated, from the computational point of view, in the same way as in the classical modal analysis or EMA (where the measured input and output allow to calculate the frequency response function, universally indicated with its acronym FRF). In this way, in the OMA technique the relationship between the transfer function of the system (known as derived from measured quantities) and its modal parameters that characterize it can be defined analytically by the following relation [4]:

$$[S_{yy}(j\omega)] = \sum_{i=1}^{n} \frac{(v_i)\langle g_i \rangle}{j\omega-\lambda_i} + \frac{(v_i^*)\langle g_i^* \rangle}{j\omega-\lambda_i^*} + \frac{\langle g_i \rangle (v_i)}{-j\omega-\lambda_i} + \frac{\langle g_i^* \rangle (v_i^*)}{-j\omega-\lambda_i^*}$$

Therefore, by the knowledge of the first member of the above equation, computational methods for the modal parameters estimation allow to determine the parameters contained in the second member, such as systems poles (λ_i), frequencies, modal shape vectors (ν_i) and operational modal factors (g_i). For data processing, calculation of cross-power spectrum functions and subsequent modal parameter estimation, the LMS Test.Lab - *Operational Modal Analysis* software (actually owned by Siemens) has been used, of which ESSEBI is licensee. The

LMS Polymax extraction algorithm implemented in the software, belonged to the multiple degree of freedom frequency domain method, is a further evolution of the least-squares complex frequency-domain (LSCF) estimation method. That method was first introduced to find initial values for the iterative maximum likelihood method [5]. The method estimates a so-called common-denominator transfer function model. Quickly it was found that these “initial values” yielded already very accurate modal parameters with a very small computational effort. The most important advantage of the LSCF estimator over the available and widely applied parameter estimation techniques is the fact that very clear stabilization diagrams are obtained

4. Measuring points and measuring apparatus

The site measurement campaign was carried by 11 measuring points, appropriately arranged along the perimeter walls at a height of approximately +13,7 m from the ground. These points were instrumented with monoaxial seismic accelerometers, which have been composed according to the need to form biaxial measuring points, with axes oriented in the horizontal plane in two orthogonal directions X-Y. The accelerometers used were globally 22 and they were connected to two different data acquisition systems.

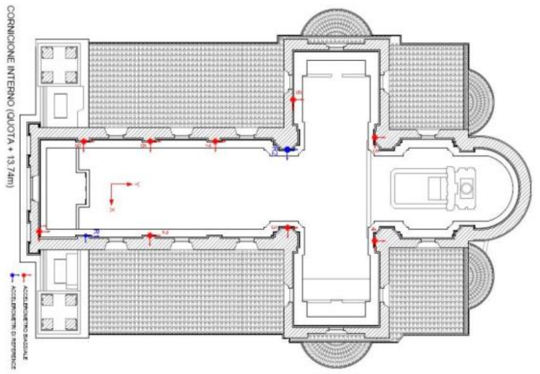

Figure 4. Sensors layout (11 positions – all biaxial)

For operational reasons and to minimize the invasiveness, thus avoiding holes on the walls, it was chosen to take advantage of the ledge that runs along the entire inner perimeter of the central nave and the transepts for positioning the measuring sensors. Despite this apparent limitation, it is believed that the predetermined size configuration has allowed to correctly determine first modal shapes of the structure, thus providing the comparative parameters useful for a subsequent verification of the reliability of the numerical model developed.

Figures 5. LSM Scadas mobile

Figures 6. Biaxial accelerometers

Two independent high performance (dynamics up to 150 dB) data acquisition systems eight channels each (LMS Scadas and DEWESOFT Sirius) were used. The synchronization of the sampling times was done by GPS time by means of integrated antennas. For each channel, the measurements were performed at a sampling frequency of 200 Hz, with appropriate anti-aliasing analog filter and consequent bandwidth up to about 80 Hz, thus having a frequency band more than adequate with reference to typically significant frequencies for civil engineering applications. IEPE piezoelectric seismic accelerometers (PCB 393A03 and PCB 393B12), high sensitivity, low-bandwidth and low-frequency acquisition have been used.

4. OMA results

The following table summarizes the results obtained in terms of frequency, damping and prevailing direction of the associated modal shape. Modes 1, 2 and 4 relate to global oscillatory shapes of the structure. These are classic translational shapes along the two main directions of planimetric development, plus the torsional mode. In particular the mode 3 presents a simple shape, similar to that of a shelf, in which the attack with the transept represents the ideal fixed joint. Finally, the façade too is excited in global behavior modes: a sign that there is some degree of continuity with the rest of the structure. To perform a first level overturning verification, it can refers to the global mode 2, with the direction of the motion orthogonal to the plane of facade.

Mode	Frequency f [Hz]	Damping ζ [%]	Shape
1	2,19	2,83	Traslational (X)
2	2,65	2,17	Traslational (Y)
3	3,27	2,06	Traslational (X) - Only nave
4	4,18	1,26	Torsional
5	7,02	1,63	Local - Only nave

Table 1. Modal parameters

Here below the modal shape 1, 2 and 3 are represented, in a wireframe visualization, referred to the undeformed configuration.

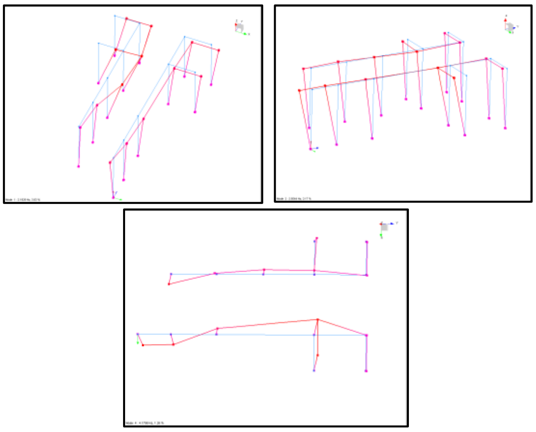

Figure 7. First three wireframe modal shapes

5. Comparison with the FEM analysis outcomes and conclusions

The table below shows the comparison of experimental data deriving from the present investigation and the values obtained from the numerical FEM analysis, achieved also taking into account the current conditions of the artifact. With reference to the theoretical model, two hypotheses were made regarding the wooden roof at the eave line: the first based on a rigid diaphragm, the second on a flexible floor. The resulting frequency values do not differ much. Comparison could however refer to the average value reported in the last column.

		FEM			***OMA***
mode	*shape*	*Tigid floor T [sec]*	*Flex floor T [sec]*	*Medium T [sec]*	*T [sec]*
1	Trasl. X	0,39	0,46	**0,43**	**0,46**
2	Trasl. Y	0,33	0,41	**0,37**	**0,38**
3	Torsional	0,26	0,38	**0,32**	**0,31**

Table 2. Experimental and FEM results

The figures below shows a comparison between numerical and experimental mode shape considering, as example, the first three modes (with permission of [1]).

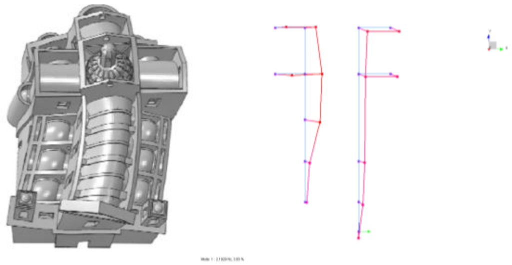

Figure 8. Modal shape n. 1 – num. vs. exp.

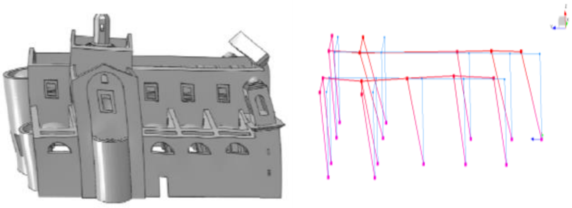

Figure 9. Modal shape n. 2 – num. vs. exp.

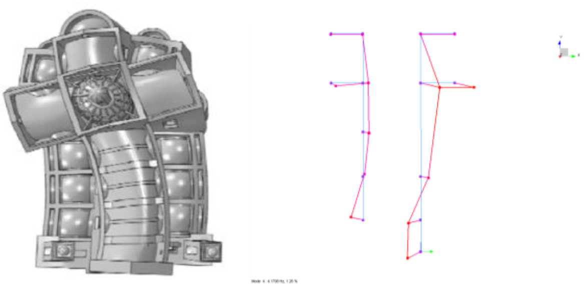

Figure 10. Modal shape n. 3 – num. vs. exp.

The following table shows the mechanical characteristics (strength value and Young modulus) adopted in the numerical model, compared to those obtained from on-site tests using double flat-jack, carried out during the measurement campaign. There is a good overlapping of values, as far as elastic behavior is concerned, between experimental results and theoretical values recommended by Italian technical standards modified to take into account the increased strength and stiffness for the better quality of the mortar.

Parameters	*Experimental (flat jack tests)*	*Theoretical (NTC2008)*	*Theoretical (NTC2008 mod.)*
f_m [MPa]	3,73	3,8	5,4
E [MPa]	2.690	1.980	2.574

Table 3. Mechanical characteristics of masonry

Theoretical analysis on the FEM model was performed prior to conducting field surveys and investigations. Hence, the results that emerged from the experimental tests and dynamic measurements confirmed the validity and goodness of the mathematical model with all subsequent assumptions. The same operational analysis should be repeated at the end of future restoration work to verify its effectiveness and quantify the improvement achieved in terms of variation of modal parameters.

Considering also the high zone seismicity, the same instrument can be extremely useful for an immediate control, aimed at verifying the maintenance of dynamic characteristics, after the occurrence of future not necessarily destructive vibratory events.

Bibliography

- [1] F. Comodini, M. Mezzi, P. Petrella "*Comparison of methodologies for evaluating the seismic vulnerability of the sanctuary of Madonna della Libera in Pratola Peligna*" Int. J. Masonry Research and Innovation, Vol. 2, Nos. 2/3, 2017.
- [2] G. Sforza, L. Sbaraglia, D. Galeota *"Dynamic characterization of the Basilica of S. Maria di Collemaggio after the earthquake of 2009 by means of operational modal analysis*" – CMEM 2015 – 17th International Conference on Computational Methods and Experimental Measurements – 5th – 7th May 2015 – Opatija, Croatia (WIT Press).
- [3] B. Peters, G. Sforza, L. Sbaraglia, F. Germano "*Efficient operational modal testing and analysis for design verification and restoration baseline assessment: Italian case studies*"- EVACES 2011 Experimental Vibration Analysis for Civil Engineering Structures – Varenna (IT) 3-5 Ott 2011.
- [4] D. J. Ewins "*Modal Testing: Theory, practice and applications*" 2nd edition -2000 - Research Studies Press LTD. Baldock, Hertfordshire , England.
- [5] W. Heylen, S. Lammens, P. Sas "*Modal Analysis Theory and Testing*" Aug 2003 – Katholieke Universiteit Leuven (Heverlee) Belgium