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Dynamic characterization of masonry edge vaults

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ABSTRACT: Increasing interest on preservation of historical buildings in seismic areas is observed all over Europe due to extended regions exposed to such natural hazard. This is the background of the activity herein reported that refers to the development of an experimental campaign aiming at vulnerability and damage assessment of an historical masonry building located in Lecce (Southern Italy). The structure is rather complex and this circumstance makes accurate structural analyses difficult. Several uncertainties, in fact, affect materials and structural scheme. Thus, some dynamic tests have been carried out in order to evaluate the possibility to pursue a macro-element approach for the evaluation of seismic safety, according to the suggestions of the current Italian Code.

Since the star vault is a recurrent element in the structural configuration of the building, an experimental campaign based on output-only dynamic tests has been started in order to investigate its dynamic behaviour. Moreover, the presence of a number of vaults characterized by similar geometry but different levels of damage can provide a useful benchmark to improve the knowledge about the effects of damage on the dynamic behaviour and, in particular, on modal parameters of structures. Preliminary activities have been carried out – such as historical research, geometric survey and in-situ material property characterization – in order to obtain important informations for a preliminary numerical model of the vault.

In the present paper, the main results of some dynamic tests carried out on a vault will be extensively described. Structural assessment actions and the main issues related to basic model assumptions will be also reported. Comparisons between numerical and experimental results point out the need of a model optimization. This is due to material, geometrical complexity and uncertainties of ancient masonry buildings but it can be also related to dynamic interaction effects with the adjacent structural elements.

1 INTRODUCTION

Management and maintenance of heritage structures is becoming a relevant issue in earthquake prone regions. However, this is a complex task due to the high degree of uncertainty characterizing such structures, due, for instance, to:

- the presence of degraded materials that impacts on the response in terms of local and global stiffness and strength;

- the extended and significant structural modifications eventually carried out over the building life-time, apart from effects of specific actions on the structure itself;
- the local traditions and experience that affected historical buildings during construction. In particular, most of these structures have been built without taking into account specific rules for earthquakes resistance (Cardoso et al. 2005).

In this paper the attention is focused on a heritage building of Lecce's "Old Town" (Southern Italy). In a recent work (Aiello et al. 2007) a vulnerability assessment of the structure has been attempted by mean of linear dynamic 3D analyses and 3D non linear push-over analyses based on a "three-dimensional equivalent masonry frame" approach (Salonikios et al. 2003). However, incomplete experimental characterization of strength and stiffness parameters of masonry and the geometric complexity of the building, with the presence of singular structural elements such as the masonry vaults, have suggested a new phase of detailed research work. Thus, an experimental campaign started for the characterization of the structure and of its dynamic behaviour through indirect methods.

Since the star vault is a common element in the structural configuration of the building, an experimental campaign based on output-only dynamic tests has been started in order to investigate its dynamic behaviour, so that local vulnerability evaluations could be carried out on the basis of a macro-element approach (Ministero per i Beni e le Attività Culturali 2006). Moreover, the presence of a number of vaults characterized by similar geometry but different levels of damage can provide a useful benchmark to improve the knowledge about the effects of damage on the dynamic behaviour and, in particular, on modal parameters of structures. Preliminary activities have been carried out – such as historical research, geometric survey and in-situ material property characterization – in order to obtain important informations for a preliminary numerical model of the vault.

The work moves from the cooperation between the research group of the Structural and Geotechnical Dynamic Lab "StreGa" at University of Molise, for execution of the experimental modal analysis tests and data processing, and the research group of Structural Engineering of the University of Salento, which has carried out an extensive seismic vulnerability assessment of the structure and has been mainly involved in the numerical modelling aspects.

The main results of some dynamic tests carried out on a vault will be extensively described. Structural assessment actions and the main modelling hypothesis will be also reported. Comparisons between numerical and experimental results point out the need of deeper investigations in order to effectively resolve an identification problem characterized by a high degree of complexity, due to uncertainties about geometry and materials of ancient masonry buildings but also due to dynamic interaction effects with the adjacent structural elements.

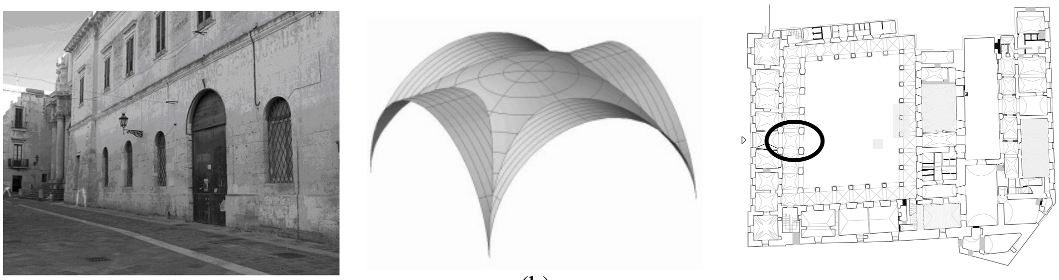
2 THE BUILDING

The structure, also known as "Convento dei Carmelitani Scalzi" (Figure 1a), is built on a "pietra leccese" quarry and it consists of two above-ground floors and some inaccessible underground rooms, discovered during a recent geological survey. A preliminary global visual inspection of the current state of the construction has provided essential qualitative informations about the main structural characteristics:

- the roofs at both levels consist of different types of vaults – *barrel vaults*, *pavilion vaults*, *cross vaults* and *star vaults* – that alternate without a rational organization, defining the unique architectural scheme of the construction; just some roofs, at the first level and along the perimeter of the cloister, are made of plain reinforced-concrete;

- most of the masonry walls are characterized by an irregular texture and the predominant cross section is of the so called "*sack masonry*" typology, made by two external layers of regular stone blocks and a core filled with incoherent materials, without adequate connections between the two external layers.

The structural complexity, also due to the large number of interventions, each one reflecting the knowledge and tradition of its time, does not allow a reliable structural modelling of the whole building. On the other hand, the possibility to consider only a portion of the structure at a time requires the validation of simplified assumptions about the interaction of each substructure with the neighbouring ones. Dynamic tests can be helpful in formulating or validating such assumptions.



(a) (b) (c)

Figure 1. Convento dei Carmelitani Scalzi (a); vault geometry (b); plane view and tested vault – in the circle – (c).

3 THE SAMPLE STAR VAULT

The star vault is typical of local culture in Lecce (it is also known as "*volta a spigolo leccese*") and represents the most common structural element in the building. Therefore, the research work has been focused on the study of the dynamic behaviour of such vaults under operational conditions.

A detailed geometrical study of the curved shapes defining the vault has been necessary: it has been useful also for the Finite Element (FE) modelling of the vault. The star vault is a type of cross vault, where the four barrel groins do not meet at the crown but are moved backwards leaving at the centre a portion with double curvature with a star shape. The complexity of the star vault is associated to the "lines of discontinuity" between the groins and the double curvature. A survey of the 3D shape (Figure 1b) has been carried out, and geometry of the tested vault has been recovered according to the following steps:

- design of two cylinders (barrel vaults) with defined dimensions;
- intersection of the two cylinders and achievement of a cross vault;
- design of ellipsoidal surface with defined dimensions;
- intersection of the ellipsoidal surface with the cross vault, thus obtaining the final geometry of the star vault.

The image of the vault shown in Figure 1b does not reproduce the entire "masonry cell": the boundary arches, representing the extension of the barrel groins, and the masonry piers have been defined directly in the FE model (Conte et al. 2008).

The tested vault is located at the first floor of the building (Figure 1c). It is bounded by the central cloister of the building, and by three adjacent vaults of the same typology. The vault stays on two of the masonry piers surrounding the cloister and on two masonry walls on the rear side.

In this phase of the work, the numerical model is implemented by mean of SAP2000® (Computers and Structures 2006) under the assumptions of linear and homogenous material behaviour. Material properties are gathered from a minimum number of laboratory tests on samples collected on site. The masonry properties and additional details about destructive tests on masonry, mortar and stone samples constituting the building are reported in (Conte et al. 2008).

As the FE modelling of the vault is concerned, an accurate evaluation of the masses acting on it has been carried out, while no live loads have been applied, according to the current state of the structure. The star vault has been modelled by mean of shell elements. The piers have been modelled as one-dimensional elements and linked to the vault by mean of body constraints. Some rotational and translational degree of freedom have been restrained along the borders of the vault adjacent to other structural elements (vaults, masonry walls). A picture of the FE model of the vault is shown in Figure 2a.

4 OUTPUT-ONLY MODAL TESTS

4.1 Test setup

Use of output-only techniques for modal identification of historical structures is spreading (Gentile 2005) since artificial excitation often exhibits problems of test execution and input control while the environmental loads are always present. Identified modal parameters, representative of the structural behaviour in operational conditions, can be used to validate or update finite element models; moreover, changes in modal parameters can be correlated with structural modifications or damage. The problem of input control is the background for the choice of Operational Modal Analysis over traditional experimental modal analysis. In fact, the structure is very massive and, therefore, difficult to be excited. One drawback of this choice was the low level of vibrations due to ambient noise.

For modal parameter estimation in output-only conditions, the Stochastic Subspace Identification (Van Overschee & De Moor 1996, Peeters 2000) and the Enhanced Frequency Domain Decomposition (Brincker et al. 2000) methods have been used.

About the Frequency Domain Decomposition technique, it is an extension of the Basic Frequency Domain method, often called Peak-picking (Bendat & Piersol 1993). It is based on the Singular Value Decomposition of the Power Spectral Density matrix, which has been previously estimated directly from the raw data at discrete frequencies $\omega=\omega_i$:

$$\left[\hat{G}_{yy}(j\omega_i)\right]=[U]_i[S]_i[U]_i^H \tag{1}$$

where the matrix $[U]_i$ is a unitary matrix holding the singular vector u_{ij} and $[S]_i$ is a diagonal matrix holding the scalar singular values s_{ij}. Near a peak corresponding to the k^{th} mode in the spectrum, this mode will be dominant: if only the k^{th} mode is dominant, there will be one term in eq. (1) and the PSD matrix approximates to a rank one matrix as:

$$\left[\hat{G}_{yy}(j\omega_i)\right]=s_i\{u_{i1}\}\{u_{i1}\}^H \quad \omega_i \to \omega_k \tag{2}$$

In such case, the first singular vector $\{u_{i1}\}$ is an estimate of the mode shape:

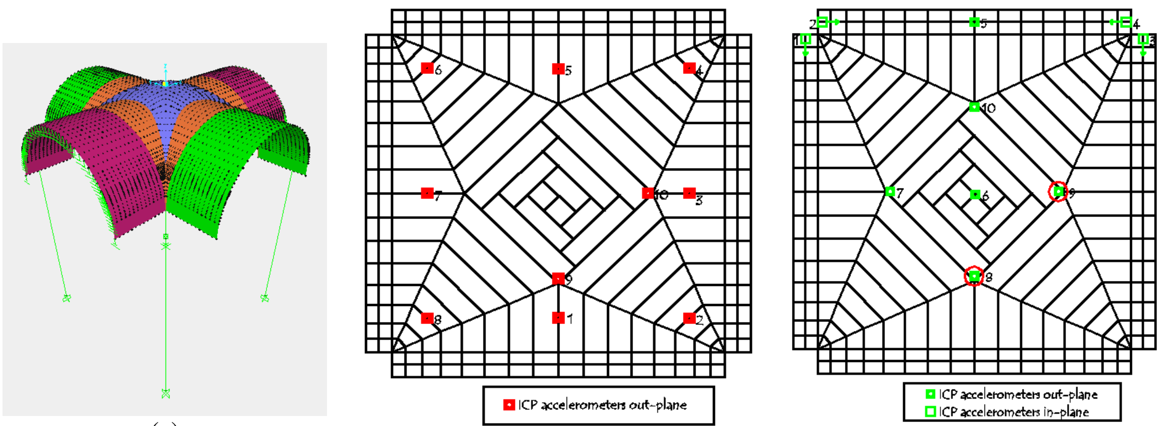
$$\{\hat{\varphi}\} = \{u_{i1}\} \tag{3}$$

and the corresponding singular value belongs to the auto power spectral density function of the corresponding single degree of freedom system. In case of repeated modes, the PSD matrix rank is equal to the number of multiplicity of the modes.

The Covariance-Driven (Cov-SSI) and Data-Driven (DD-SSI) Stochastic Subspace Identification algorithms are, instead, both time domain methods based on a state space description of the dynamic problem, which, in the output-only case, is expressed by the so-called "state equation" and "observation equation" written as follows:

$$\{x_{k+1}\} = [A]\{x_k\} + \{w_k\}; \; \{y_k\} = [C]\{x_k\} + \{v_k\} \tag{4}$$

where $\{x_k\} = \{x(k\Delta t)\}$ is the discrete-time state vector yielding the sampled displacements and velocities, $\{u_k\}$ and $\{y_k\}$ are the sampled input and output, $[A]$ is the discrete state matrix, $[C]$ is the discrete output matrix, $\{w_k\}$ is the "process noise" due to disturbances and model inaccuracies, $\{v_k\}$ is the "measurement noise" due to sensor inaccuracy. Cov-SSI and DD-SSI are two algorithms for estimation of system matrices and, therefore, of eigenproperties: the main difference is related to the fact that Cov-SSI works on output correlations while DD-SSI works directly on raw data.



(a) (b) (c)

Figure 2. Finite Element model of the vault (a); test setup A (b); test setup B (c).

The dynamic response of the structure has been measured by ten accelerometers placed at the intrados of the vault (setup A) and, in a second configuration, also on two column heads (setup B). The first and the second test setups are reported in Figure 2b and Figure 2c respectively. The ten accelerometers have been placed in contact with the vault surface through a little anchor plate where the sensor has been screwed: each sensor has been mounted orthogonally to the vault surface and, in the second configuration, four sensors have been placed parallel to the main directions of the columns, in order to get their translation. The sensors are 393B31 accelerometers by PCB Piezotronics. They are seismic, ceramic shear, high sensitivity ICP accelerometers, characterized by a bandwidth from 0.1 to 200 Hz and by a 10 V/g sensitivity. The full scale range is ±0.5 g. Data acquisition has been carried out by a National Instruments Compact DAQ system. Acceleration data have been acquired through the NI9233 modules. The main characteristics of the data acquisition hardware are: 2-50 KHz sampling frequency range;

AC coupling (0.5 Hz); 24 bit ADC; 102 dB dynamic range; on board analogue anti-aliasing filter. It is worth noticing that, even if the system is AC coupled, the expected values of natural frequencies of the vault were far above 0.5 Hz (as confirmed also by the tests) so that the hardware was suitable for this application. The modal parameter identification has been carried out on the base of two different records: the first one was related to setup A and 1500 s long, while the second was related to setup B and 1800 s long. The sampling frequency was 100 Hz for setup A and 200 Hz for setup B.

4.2 Test results

Data processing has been carried out by a software developed in LabView Environment (Rainieri 2008). Modal identification according to the FDD (Frequency Domain Decomposition) approach was based on spectra computed using a Hanning window, with a 66% overlap. Results of modal identification are reported in Table 1: EFDD (Enhanced Frequency Domain Decomposition) and SSI (Stochastic Subspace Identification) have provided consistent results, in terms of natural frequencies and damping ratios, but also in terms of mode shapes, as pointed out by the CrossMAC values (Figure 4a); however, a reliable identification was possible for just the first two modes, mainly due to interaction effects with the close vaults.

Table 1. Output-only modal identification results

Method	Mode number	Setup A – natural frequency [Hz]	Setup A – damping ratio [%]	Setup B – natural frequency [Hz]	Setup B – damping ratio [%]
EFDD	I	4.35	1.4	4.31	1.5
	II	4.96	1.1	4.94	1.3
Cov-SSI	I	4.34	1.7	4.31	1.7
	II	4.98	0.9	4.95	1.1
DD-SSI	I	4.32	1.3	4.31	1.4
	II	4.99	0.9	4.95	1

In Figure 3 a picture of the identified mode shapes and the corresponding complexity plots are reported, pointing out that the identified modes are normal. Moreover, as pointed out by the AutoMAC matrix (Figure 4b), test setup was effective for a reliable identification of such modes. Setup B has confirmed such results and has pointed out that only two opposite barrel groins among the four constituting the vault are interested by appraisable modal displacements. Such result seems to confirm some hypotheses adopted for implementation of the numerical model.

In Table 2 a comparison between the identified natural frequencies and those ones obtained from the FE model of the structure is reported. The moderate scatter in terms of natural frequencies points out that the global stiffness of the system has been somehow identified, by assuming a low level of uncertainty about mass definition as in the present case. However, the interaction with the adjacent structural elements has not been properly modelled, as pointed out by the low values of MAC (around 0.5). Thus, further refinements of the FE model are needed and some informations could be provided by new tests specifically designed for studying the interaction effects. This aspect will be the subject of a next paper.

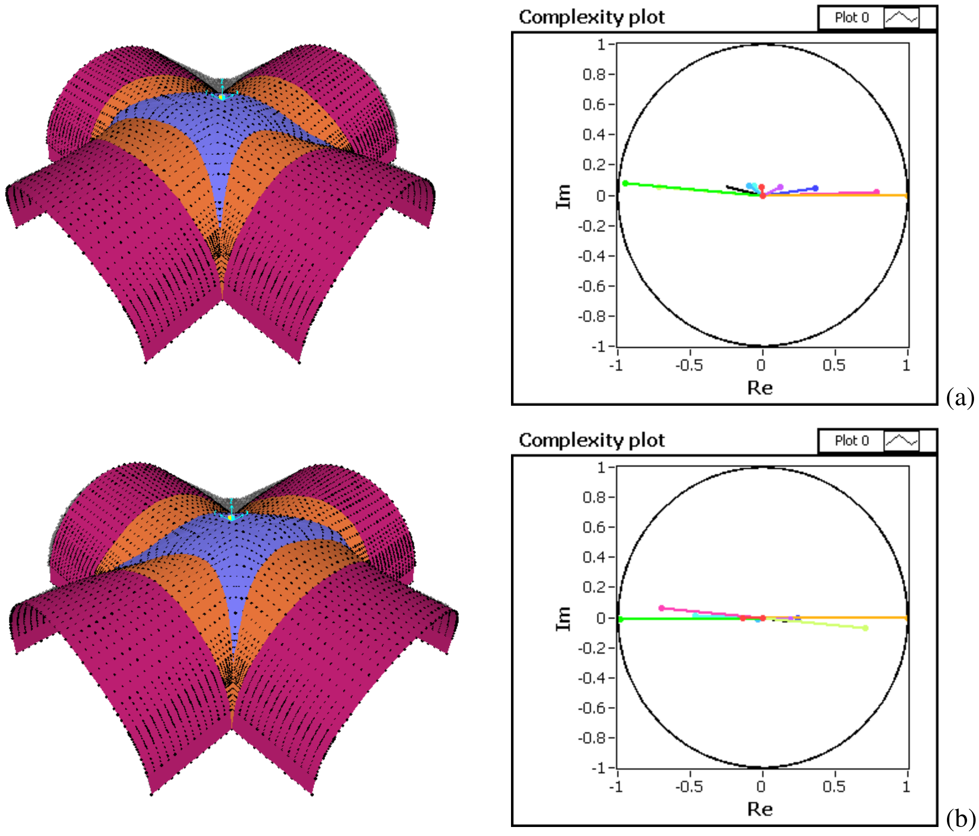


Figure 3. Identified mode shapes and corresponding complexity plots: mode I (a); mode II (b).

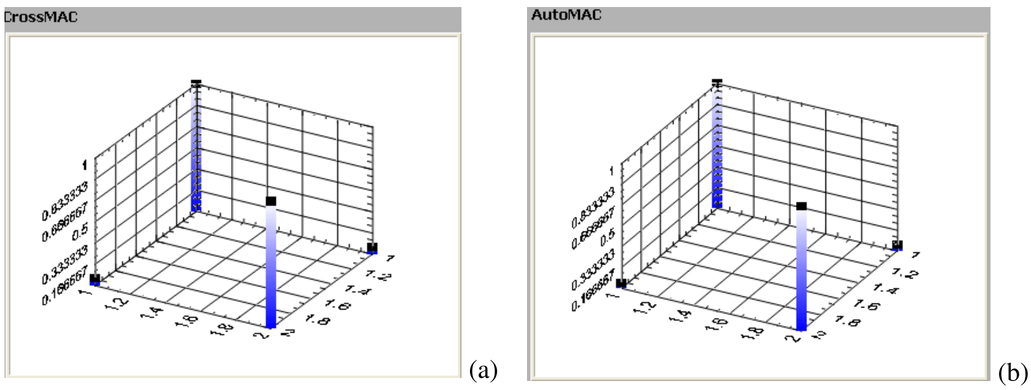


Figure 4. Samples of CrossMAC (a) and AutoMAC (b) matrices.

Table 2. Experimental tests and numerical modelling: comparisons

Mode number	Average natural frequency from tests [Hz]	Natural frequency from FE model [Hz]	Scatter [%]
I	4.32	4.73	9.49
II	4.96	4.92	-0.81

5 CONCLUSIONS

The activity here in reported refers to the development of an experimental campaign aiming at vulnerability and damage assessment of an historical masonry building located in Lecce (Southern Italy). The structure is rather complex and this circumstance makes accurate structural analyses difficult.

Use of output-only dynamic testing represents a powerful tool that complies with requirements of preservation of heritage constructions and give useful data concerning basic properties of the macro-elements and their structural layout.

Comparisons between numerical and experimental results point out a basic agreement, even if an optimization of the structural model is needed. This is due to material, geometrical complexity and uncertainties of ancient masonry buildings but can be also related to dynamic interaction effects with the adjacent structural elements.

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