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On-site assessment of masonry vaults: Dynamic tests and numerical analysis

Carla Conte[1], *Carlo Rainieri*[2], *Maria Antonietta Aiello*[1]
and Giovanni Fabbrocino[2]

[1] Department of Engineering for Innovation, University of Salento, Lecce, Italy

[2] Structural and Geotechnical Dynamics Laboratory *StreGa*, Department of S.A.V.A.,
University of Molise, Campobasso, Italy

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This paper concerns the structural identification of historical masonry buildings with reference to a case study, which is discussed in detail. The building is located in Southern Italy (Lecce). It has an ancient vaulted roof that is complex and commonly found in old masonry structures. This study takes advantage of extensive historical and structural investigations of the building. Preliminary activities have been conducted to obtain information about the current state of the structure including the geometry, morphology, structural details, material properties, prior interventions, and existing damage. This process was supported by an historical investigation into the conceptual background and construction methods used to build the structure. After the historical investigation, a series of experiments, including dynamic tests, were conducted on a number of the vaults to determine their dynamic response characteristics under operational conditions. A numerical model was also determined. In this paper, the primary dynamic test results and modelling assumptions are reported. Comparisons between numerical and experimental results are discussed.

Keywords: heritage structures, ambient vibration tests, operational modal analysis

1. Introduction

The increasing interest in the dynamic behaviour of ancient masonry buildings has arisen from a desire to preserve these culturally significant structures and to ensure a sufficient level of safety (Direttiva del Presidente del Consiglio dei Ministri – NTC 2008, 2010; Consiglio Superiore dei Lavori Pubblici, 2008). When assessing the seismic performance of heritage structures, the following aspects should be considered:

– the presence of deteriorated materials and the consequences of degradation on local and global stiffness and strength;

– relevant structural changes that may have occurred during the service lifetime, often irrespective of the effects on the seismic performance of the structure; and

– local construction traditions and experience, which often do not take into account exceptional loads, such as earthquakes (Cardoso et al., 2005).

This paper focuses on an ancient masonry building that is representative of many historical-cultural buildings in the Lecce's city centre, in Southern Italy. In a recent paper (Aiello et al., 2007), the seismic vulnerability of the overall structure of this building was evaluated using 3D linear dynamic and non-linear push-over analyses that were conducted according to the "three-dimensional equivalent masonry frame" approach (Salonikios et al., 2003).

A review of available experimental data about masonry strengths and stiffness, as well as the complex geometry of the structural elements, such as the masonry vaults, suggested that an additional phase of research was required. Therefore, a series of experiments was initiated in the framework of the INTERREG Project. The aim of these experiments was to characterise the dynamic behaviours of the structure using indirect assessment methods. The complex structural configuration, the large variety of materials and the relevant dimensions of the building suggested that the experiments should focus on the sub-elements (i.e., the vaults). Information from experimental tests and numerical modelling results were compared to investigate and properly account for interactions with nearby structural elements.

This study was a cooperative effort between the Structural and Geotechnical Dynamics Lab (StreGa) at the University of Molise, which was responsible for experimental modal analysis and data processing, and the Structural Engineering research group at the University of Salento, which was responsible for numerical modelling and seismic assessment.

After a description of the building and its historical relevance, the paper is devoted to a discussion of the dynamic tests that were conducted on a star vault of the building, as well as to the finite element (FE) modelling of this vault. Promising results from comparisons between experimental and numerical values of the modal properties are presented. These results provide a basis for further refinement of the numerical model, which is beyond the scope of the present paper.

2. The "convento dei carmelitani scalzi" building

2.1 Description

The structure under investigation is located in the Lecce city centre in Southern Italy. The building is characterised by a unique structural scheme, as well as by a certain degree of uncertainty about the material properties and the structural modifications that occurred over the last two centuries. Numerical modelling, supported by dynamic identification test results, is a useful tool for reducing these uncertainties and enhancing knowledge of the building's structural behaviour, while limiting interference and interventions to the structure under investigation.

The structure was built on a "pietra leccese" ("Leccese" stone) quarry and it consists of two above-ground floors, as well as several inaccessible underground rooms, discovered during a recent geological survey. In particular, the ground floor and the first floor are organised around a central internal cloister, with a main entrance from Libertini Street (Figure 1, left). This central cloister is connected, through a short covered passage, to a secondary cloister with an entrance from Marco Basseo Street. A preliminary global visual inspection provided the following qualitative information about the current state of the structure and the main structural characteristics:

– The roofs consist of different types of vaults – barrel vaults, pavilion vaults, cross vaults and star vaults – that alternate without a rational organisation, so that an original architectural texture is obtained. Some of the roofs on the first level, along the perimeter of the cloister, are made of plain reinforced concrete.

– Most of the walls are characterised by an irregular texture. The predominant wall cross section has a "multiple-leaf" typology. This technique only partially ensures a monolithic behaviour, due to the absence of adequate connections between the two external layers and the core material.

The building's structural configuration is fairly complex and, therefore, difficult to numerically model. As a consequence, assessment of the vault geometry and the mechanical properties of the masonry were crucial for proper characterisation of the structural performance of the building under dead- and earthquake-loadings.

Figure 1. "Convento dei Carmelitani Scalzi": view from Libertini Street (*left*) and cadastral map (*right*).

2.2 Historical background

The structure under investigation is known as the “Convento dei Carmelitani Scalzi” because it was built in 1627 to host the religious congregation of the “Teresiani” Fathers.

A cadastral view (Figure 1, right) shows the building location. The structure, together with the neighbouring Church of St. Teresa, covers a wide area of 65 m × 50 m, which is called the “Island of St. Venere” because the monumental block is entirely surrounded by roads.

An historical research study (Conte, 2006) identified the following primary structural modifications, some of which influenced the seismic performance of the structure:

– In 1813, the building was modified to be used as a military headquarters;

– In 1826, small maintenance projects were performed in the military headquarters, affecting mainly the functionality of the building without changing the original configuration;

– From 1841 to 1850, several repairs were made, including the installation of tie rods to ensure effective connections between old and new masonry walls, which were built to separate the military headquarters from the Church of St. Teresa, and to balance the lateral actions in the vaulted systems;

– From 1860 to 1871, stone masonry walls were built and a number of non-structural interventions were implemented;

– From 1875 to 1889, damaged masonry panels and masonry columns around the central cloister were repaired, interventions on the foundations were also implemented;

– From 1894 to 1970, the architecture of the building was renewed and the original configuration (with external and internal facades) was lost;

– In 1970, the building architecture was again renewed and it was turned into a school;

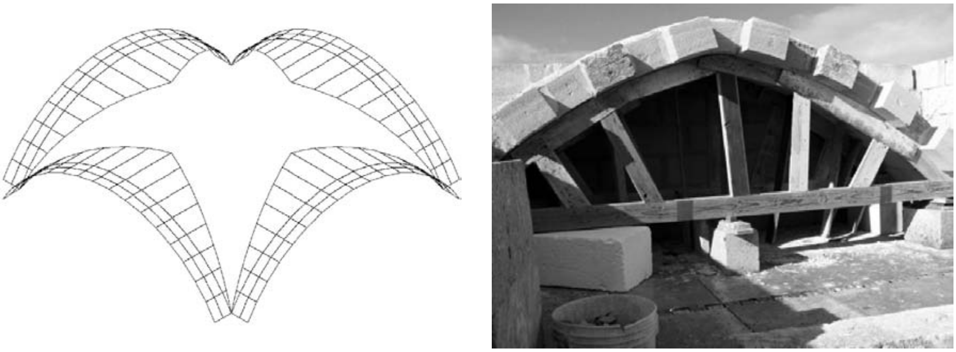

Figure 2. The four barrel groins in a star vault.

– From 1994 to 1997, a series of experiments were conducted to assess the static performance of the foundations.

The largest structural modifications occurred between the 19th and the 20th centuries, when the religious building was turned into a military headquarters (also known as “Caserma Cimarrusti”).

2.3 The star vault

Understanding the technology and behaviour of local historic masonry vaults is the first step towards assessing the degree of structural safety and planning structurally compatible conservation and preservation programmes. Local literature (Colaianni, 1967; Arlati and Accoto, 1998) represented the starting point for this scientific work.

In general, the local subsoil is rich with the following two types of stones that are very popular in construction, artistic and architectural fields: “carparo” and “pietra leccese”. The workability of these calcarenitic stones is fundamental for the construction of the typical structural elements known as “volte a spigolo leccese” (Lecce’s edge vaults).

The star vault is typical of local culture and is common in historical architectural compositions of the era. Moreover, star vaults are still used in modern roofing projects, due to the robust structural properties of these vaults.

In general, the vaulted surface is generated by defining reference lines, according to the available spaces and heights, and moving them along the generant lines. The geometrical shape of the vault that was considered in this case study is characterised by a complex curvature, which did not allow for rapid schematisations; instead it required a careful and thorough analysis of the curved elements. For this reason, a detailed mathematical-geometrical study of the curved shape of the vault was conducted as a preliminary step towards developing the numerical model.

The star vault is “groined” because it is composed of barrel vaults that intersect at right angles. The four barrel groins do not meet at the crown; instead they are moved backwards leaving a double curvature similar to a star at the centre (Figure 2). The complexity of the star vault is associated with the lines of discontinuity between the groins and the double curvature. In particular, a 3D reconstruction (Figure 3) of the vault geometry was performed in the following phases:

– Step 1: define two cylinders (barrel vaults) with given dimensions;

– Step 2: define the intersection of the two cylinders to achieve a cross vault;

– Step 3: define an ellipsoidal surface with given dimensions;

– Step 4: determine the intersection of the ellipsoidal surface with the cross vault to achieve the star vault.

Another type of vault that is common in this region is a square vault. The square vault can be considered as an evolution of the star vault. In particular, its geometry can be reconstructed by following the same steps of geometrical characterisation of a star vault. The only geometrical difference is the presence of a new curved surface at the angles, which consists of a quarter-pavilion vault. The ellipsoidal surface intersects the cross vault and the quarter-pavilion vault at the four angles (Figure 4). The structural properties of this type of vaulted system can be analysed using the same techniques reported in this work.

3. Material characterisation

A numerical model was defined under assumptions of linear and homogenous material behaviours. The material properties were gathered from a minimum number of laboratory tests on stone samples extracted on site.

The analysed stone (also known as “Leccese” stone) is a calcareous stone that is common in Southern Italy. The stone samples were extracted from different locations in the building. Each sample was classified according to the extraction place, because changes in the quality of the stone could occur among different structural members and even within the same member.

Several experimental tests were conducted to determine the mechanical properties of the stone. The compressive strength, f_b, of the stone samples was obtained from compression tests on 7 cubes with 50 mm long edges, according to UNI EN 1926:2004. The average compressive strength was $f_b = 7.6$ MPa with a coefficient of variation of 29%. The bending strength, f_f, of the stone samples was obtained from three-point bending tests on 12 prisms (50 mm × 30 mm × 180 mm), according to UNI EN 12372:1999. The average value of

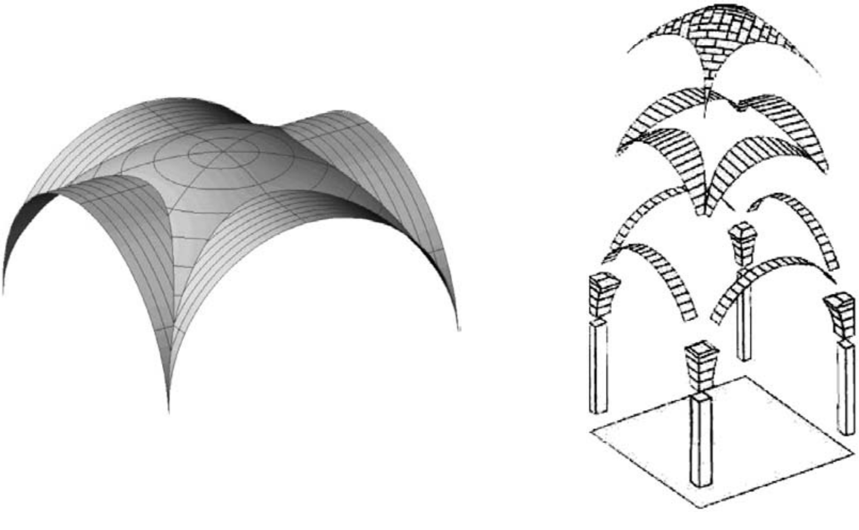

Figure 3. Schematic geometry of a star vault (*left*) and their components (*right*).

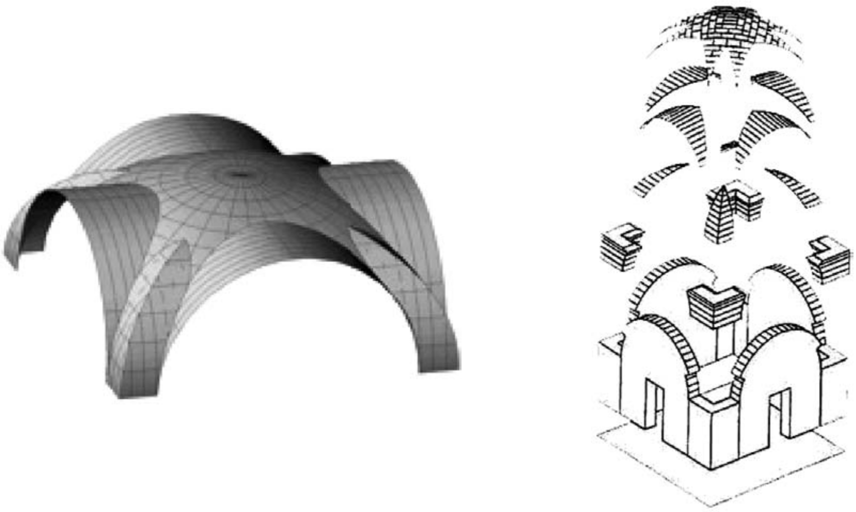

Figure 4. Schematic geometry of a square vault (*left*) and their components (*right*).

the bending strength was $f_f = 4.17$ MPa with a coefficient of variation of 41%. The Young's modulus of the stone, E, was obtained from compression tests on 4 prisms (50 mm × 50 mm × 200 mm), according to UNI 9724-8:1992. The average values and the coefficients of variation are reported in Table 1.

In the absence of specific experimental investigations, the mechanical properties of the masonry were estimated from those of the constituent materials, in compliance with correlations reported in the Italian Code (Direttiva del Presidente del Consiglio dei Ministri – NTC 2008, 2010; Consiglio Superiore dei Lavori Pubblici, 2008). The average value of the compressive strength of masonry, f_m, was obtained based on the average values of the compressive strengths of stones and mortar. The experimental results were used as reference values for the stone and a poor quality mortar was assumed, in agreement with the deterioration observed during in-situ visual inspections. The elastic modules, E and G, were estimated from the average value of the compressive strength of masonry.

Table 1. Elastic modules of the tested "Leccese" stone.

	Average value [MPa]	Coefficient of variation [%]
Mean elastic modulus, E_m	7331.28	11
Secant elastic modulus, E_s	7402.83	3
Tangent elastic modulus, E_t	7753.37	1

The FE model of the vault was determined by adopting the values reported in Table 2 for the mechanical properties of the masonry. For the most part, these values agree with the ranges provided by the Italian Seismic Code concerning the assessment of masonry structures.

Due to the level of uncertainties affecting the experimental values, a sensitivity analysis to assess the effects of mechanical properties variability on the natural frequencies and mode shapes of the vault is recommended, but is beyond the scope of this paper. The primary aim of this paper is to present an approach to seismic assessment of heritage structures and the role of output-only modal analysis in this context. The results of the above mentioned sensitivity analyses will be the object of a future publication, which will focus on refinement of the FE model of the vault.

4. Dynamic testing

Effective protection of structures against seismic risk can be obtained by increasing the knowledge about their dynamic behaviour, particularly in the case of existing buildings and/or historical structures. Experimental modal analysis is, therefore, becoming more relevant because most heritage structures are characterised by unique structural techniques (Direttiva del Presidente del Consiglio dei Ministri – NTC 2008, 2010) and because uncertainties about geometry and materials make accurate structural assessment difficult. As a consequence, the availability of experimental modal parameters for historical structures plays a primary role in the assessment of structural performance in operational conditions and in the presence of extreme events, such as earthquakes (Gentile, 2005; Rainieri et al., 2008).

For historical structures, output-only techniques are preferred (Gentile, 2005), because artificial excitation is often difficult to execute in the presence of environmental loads. In addition, output-only tests are cheap, fast and impose minimal interference on the normal use of the structure (Mohanty, 2005). The identified modal parameters are representative of the structural behaviour in operational conditions and they can be used to validate or update FE models. Moreover, changes in the modal parameters can be correlated with structural damage. Finally, the combination of numerical models and experi-

Table 2. Mechanical properties of the masonry.

Property	Average value
Density, γ [kN/m^3]	16.0
Compressive strength, f_m [MPa]	3.5
Normal secant elastic modulus, E [MPa]	3500.0
Tangent secant elastic modulus, G [MPa]	1400.0

mental data offers interesting opportunities in the field of seismic protection of strategic or historical structures. In fact, updated analytical models can be used to effectively evaluate the seismic risk of these structures.

The problem of input control is one of the reasons for the choice of Operational Modal Analysis (OMA) over traditional experimental modal analysis for the present application. In fact, the structure is large and, therefore, difficult to excite. In addition, static deficiencies were recognised before testing. The main drawback of this choice is related to the low level of vibrations in operational conditions, which required the installation of high sensitivity and low noise sensors, as well as high performance data acquisition hardware.

4.1 The modal parameter identification technique

Output-only modal parameter estimation was performed according to the Enhanced Frequency Domain Decomposition (EFDD) method (Brincker et al., 2000; Gade et al., 2005). The EFDD technique is a non-parametric frequency domain output-only modal identification procedure. It is an extension of the Basic Frequency Domain (BFD) technique (Bendot and Piersol, 1986), often called the peak-picking technique, because it applies Singular Value Decomposition (SVD) to the output Power Spectral Density (PSD) matrix at each frequency to decouple the contributions of the different modes. As described in the original paper (Brincker et al., 2000), structural resonances are identified from the singular value plots through peak picking; the singular vector at a resonance is a good estimate of the associated mode shape.

EFDD also allows for estimation of damping. The Auto Power Spectral Density function of the Single Degree Of Freedom (SDOF) system corresponding to a mode is identified around the selected peak in the singular value plot by comparing the mode shape estimate at the resonance with the singular vectors associated with the frequency lines around the peak. Every line that is characterised by a singular vector, which gives a MAC value with higher than a user-defined MAC Rejection Level, belongs to the SDOF PSD function, where the MAC index (Allemang and Brown, 1982) is defined as:

$$MAC\left(\{\psi_1\},\{\psi_2\}\right) = \frac{\left|\{\psi_1\}^H\{\psi_2\}\right|^2}{\left(\{\psi_1\}^H\{\psi_1\}\right)\left(\{\psi_2\}^H\{\psi_2\}\right)} \qquad (1)$$

where $\{\psi_1\}$ and $\{\psi_2\}$ are the vectors under comparison and the superscript ^{H} denotes Hermitian operator. Damping ratio estimation is then conducted by transferring the SDOF PSD function back to time domain through Inverse Fast Fourier Transform and applying the logarithmic decrement technique to the obtained approximated correlation function (Gade et al., 2005).

4.2 Test setup

The dynamic response of the vault was measured by ten accelerometers placed at the intrados (setup A) and, in a second stage, also on two column heads (setup B). The two layouts are shown in Figure 5. The sensor location was defined in compliance with the results of a preliminary FE model of the vault. However, modelling uncertainties (in particular, uncertainties regarding the effects of interactions with the adjacent elements of the structures), were taken into account by installing the sensors according to a regular mesh covering as many portions of the vault as possible. Due to the limited number of available sensors, a second sensor layout was necessary to characterise the behaviour of the piers the vault stands on. Accelerometers were placed in contact with the vault surface through a small anchor plate. Sensors were screwed onto the plates and mounted orthogonally to the vault surface. In the second test layout, four sensors were aligned parallel to the main directions of the columns, to observe their translation.

The adopted sensors were seismic, ceramic shear, high sensitivity (10 V/g) IEPE accelero-meters, characterised by a bandwidth in the range 0.1 to 200 Hz. The full scale range was ±0.5 g. The choice of the sensors was informed by the low level of ambient vibrations, which required a high performance measurement chain.

Data were acquired using a customised measurement system (Figure 6) developed by the StreGa Lab research group. This system was based on a National Instruments™ CompactDAQ system made by NI9233 DAQ modules. Such modules, containing built-in anti-aliasing filters, 24-bit resolution, 102 dB dynamic range and 56 dB CMRR, were originally designed for vibration measurements. The measurement hardware was controlled by software developed in LabView (Figure 6b). The software continuously recorded and saved the dy-

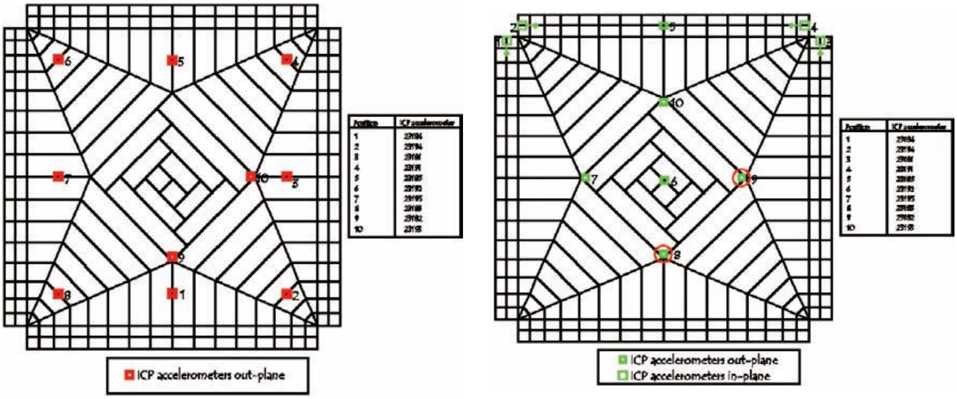

Figure 5. Test layouts: A (*left*) and B (*right*).

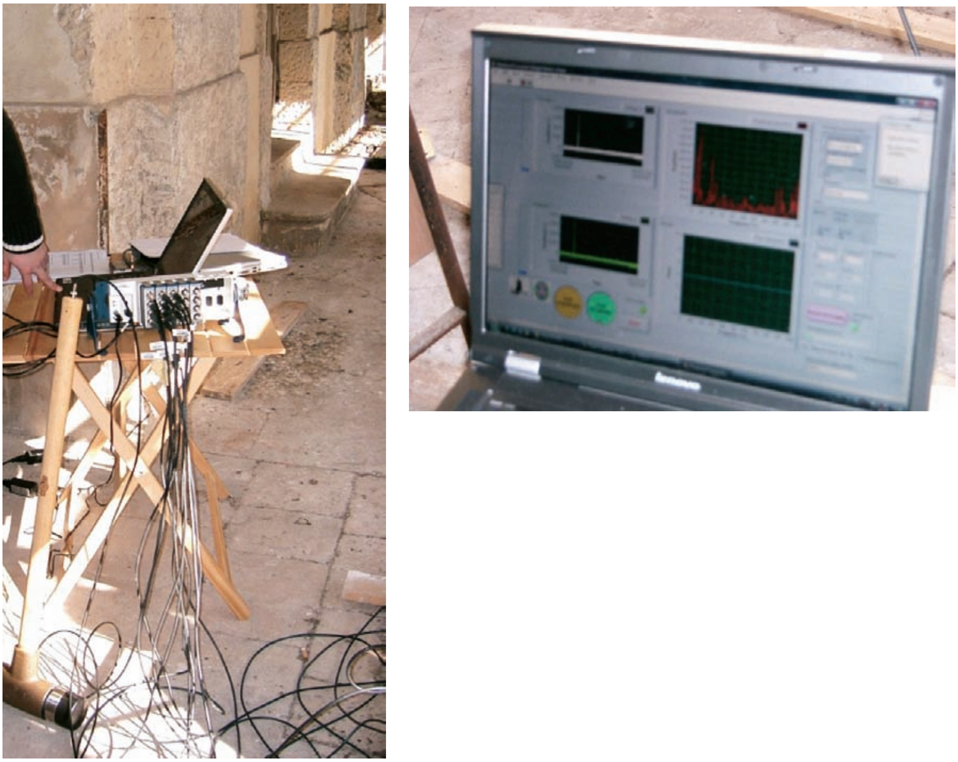

Figure 6. Data acquisition hardware (*left*) and software (*right*).

namic response of the structure to ambient vibrations. Data were sampled at 2 kHz, but it is possible to apply a decimation factor before saving. Power spectra were continuously computed and shown on the screen during the measurement process, together with the measured acceleration responses in the time-domain. Thus, it was possible to monitor the quality of the acquired signals and their frequency content in real-time.

The output power spectra represent a basic tool for a quick, preliminary identification of modal parameters (Bendat and Piersol, 1986). A comprehensive analysis, according to the BFD approach (Bendat and Piersol, 1993), can be performed off-line by stopping acquisition for a while and by recalling the analysis module directly from the data acquisition module.

The link between the accelerometers and the data recorder was made using RG-58/U coaxial cables. It is worth noting that, even if the measurement system was AC coupled, the expected values of the natural frequencies of the vault were far above 0.5 Hz (as confirmed by the tests); therefore, the adopted measurement hardware was suitable for the present application.

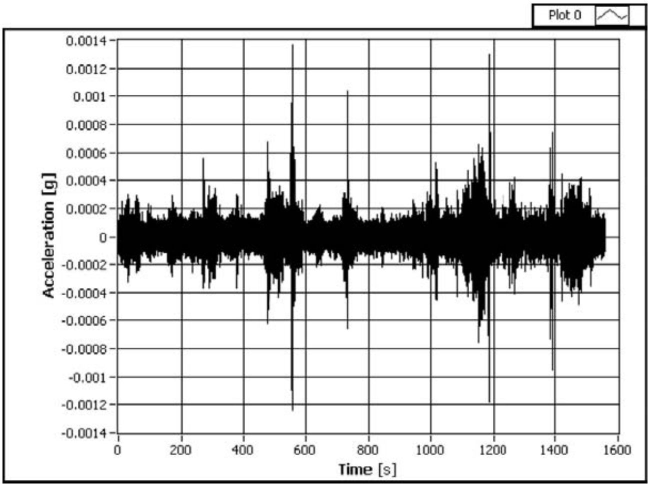

Figure 7. Sample record.

The modal parameters of the vault were identified from two different records, related to setup A and setup B, respectively. Both datasets were 30 minutes long and were acquired at a sampling frequency of 2 kHz. They were pre-treated and decimated before processing. In Figure 7, a sample record of the dynamic response of the vault to ambient vibrations is shown. Fairly low acceleration values can be observed.

4.3 Test results

Data processing was performed using software (Rainieri et al., 2007) developed in the LabView environment (www.ni.com/labview), in the framework of the activities related to the design and installation of the Structural Health Monitoring system of the School of Engineering Main Building at University of Naples (Rainieri, 2008). The ambient vibration response of a structure can be analysed by the EFDD method. Additional tools for validation of results and correlations with those provided by numerical models are also available.

A specific module for data pre-processing was implemented to assess the quality of measurements and to remove the mean and spurious trends in the records. Data pre-treatment was performed according to the methods described in Bendat and Piersol (1986). In particular, measurement offsets and spurious trends were filtered. Moreover, the probability density plots of the data are shown and were analysed to validate the data distribution and to identify anomalies, such as signal clipping, intermittent noise, power line noise, and signal drop-outs, which are clearly highlighted by the probability density plots. If anomalies in the data were identified, the corresponding measurement channels were removed from the dataset. Finally, a basic assess-

Table 3. Modal identification results: natural frequencies and damping ratios.

Setup	Mode number	Natural frequency [Hz]	Damping ratio [%]
A	I	4.35	1.4
	II	4.96	1.1
B	I	4.31	1.5
	II	4.94	1.3

ment of the presence of non-linearities and spurious harmonics, due to rotating equipment, was conducted through the computation and visual inspection of the Short Time Fourier Transform (STFT) of the data. The validated and pre-treated data were then processed by OMA algorithms.

For the present application, data standardisation before processing confirmed approximately normal distributions. In addition, the quality of the acquired signals (e.g., the absence of clipping and drop-out) was confirmed.

After data pre-treatment, including mean and spurious trend removal, the modal parameters of the vault were identified by the EFDD method. Spectra were computed using Hanning windows with a 66% overlap to reduce leakage.

Natural frequencies and damping ratios are summarised in Table 3. In Figure 8, the Complexity Plots for the identified mode shapes are shown. These plots demonstrate that the modes are normal. The identified mode shapes are also illustrated.

In the next section, numerical and experimental results are compared to assess the capability of the model to represent the actual behaviour of the vault under operational conditions.

5. Finite element modelling of the vault

In this section the primary assumptions underlying the FE modelling of the vault are discussed. In particular, attention is focused on the masonry cell made by a star vault that was representative of those located in the central cloister (Figure 9, left), the boundary arches (representing the connection between consecutive vaults) and the masonry piers supporting the vault itself. The numerical model of the cell (Figure 9, right) was set by the SAP2000® Advanced FEM code (Computers and Structures, 2006). The 4-joint shell elements, characterised by a thickness of 20 cm, were used. The adopted value for the thickness of the shell elements was obtained from *in-situ* investigations on the vault.

The main issue in setting the numerical model was related to the definition of the boundary conditions, because the masonry cell was not isolated. To set a representative model of the actual behaviour of the single masonry cell, in its operational conditions, specific attention was devoted to the careful modelling of the system, in terms of geometry and, therefore, of mass and stiffness.

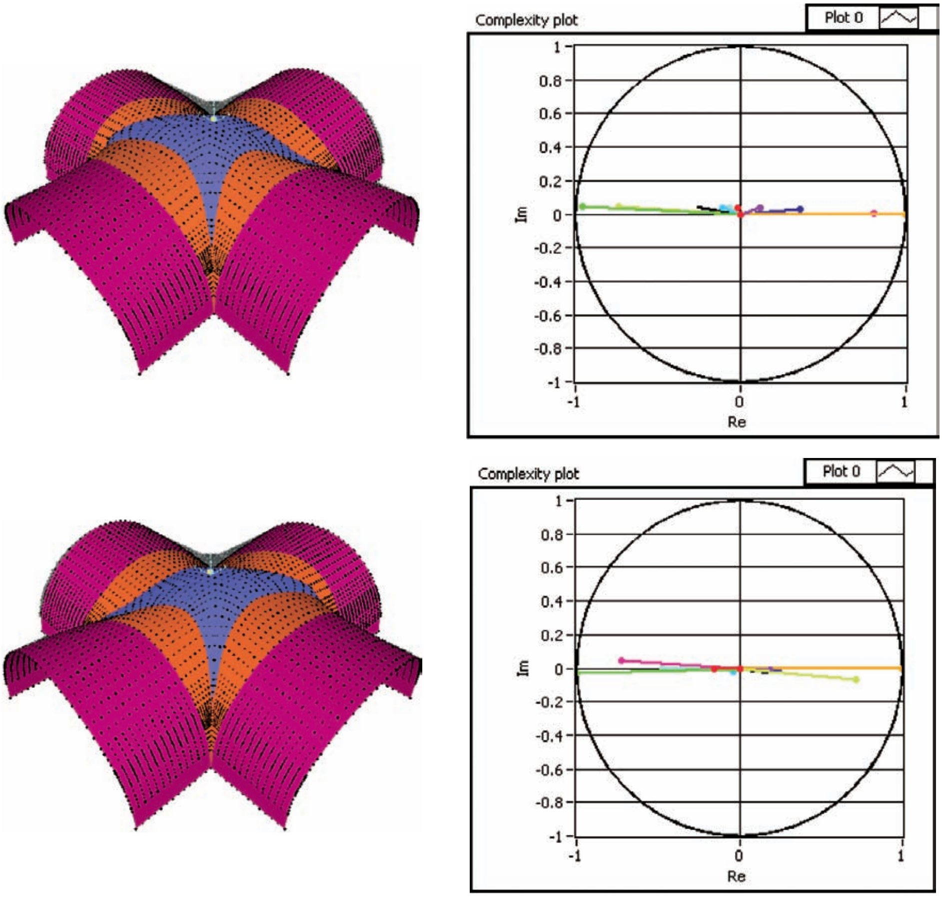

Figure 8. The identified mode shapes and corresponding complexity plots: mode I (*above*); mode II (*bellow*).

The masonry piers were modelled as fixed at the base. Dead loads were applied by taking into account the contributions of filler at the vault extrados, as well as plaster and flooring. No live loads were applied in compliance with the current state of the structure.

Moreover, interactions with the nearby structural elements were modelled, according to simplified assumptions, through the introduction of additional masses and elastic restraints distributed along the contour. The calibration of the added masses and restraints will be one of the main objectives of the refinement of this preliminary FE model on the base of the experimental results. However, results of model updating are beyond the scope of the present paper.

The modal parameters obtained from the FE model of the vault were compared with the results of the experimental modal analysis. The values of mate-

Figure 9. External view of the central cloister (*left*) and FE model of the masonry cell (*right*).

rial density and elastic modules, shown in Table 2, were adopted in the numerical modal analysis. In Table 4, the numerical and experimental values of the natural frequencies of the fundamental modes of the vault are compared.

Comparisons between numerical and experimental mode shapes are in progress. The main issues in this case are related to possible spatial aliasing effects. A dense mesh has been adopted and sensor locations have been accurately identified during installation; nevertheless, to avoid spatial aliasing, more accurate checks and comparisons between the numerical model and the sensor layouts are required. Thus, results of correlations between numerical and experimental mode shapes will be described elsewhere together with the refinement of the numerical model. The sensitivity of the modal properties to variations in the mechanical properties of the masonry is also out of the scope of the present paper. Current comparisons, in terms of natural frequency, show a good agreement between numerical and experimental results, suggesting that a refined FE model that is representative of the behaviour of the cell under operational conditions, can be obtained without large efforts.

Table 4. Comparisons between numerical and experimental values of the natural frequency of the fundamental modes of the vault.

Mode number	Natural frequency (FEM) [Hz]	Natural frequency (tests-average) [Hz]	Scatter [%]
I	4.73	4.33	9.2
II	4.92	4.95	–0.6

6. Conclusions

A structural and dynamic assessment of an historical masonry building was described in this paper. In particular, attention was focused on the local dynamic response of a star vault in the building. Output-only modal identification tests were conducted to obtain information about the vault dynamics under operational conditions. Ambient vibration tests were described in detail and the main results were discussed. These results demonstrated that such tests can be conducted on massive structures under low levels of excitation by adopting a high performance measurement chain and advanced data processing procedures. Results of modal tests were compared with those provided by a FE model of the vault; promising results were obtained.

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References

Aiello, M. A., Conte C. and Valente L. (2007): Analysis and seismic retrofit of historical masonry building under earthquake loading: A case study, in *Proceedings of the 4th International Specialty Conference on the Conceptual Approach to Structural Design,* Venice, Italy, edited by Mola, F., Mola, E. and Tan John, S. Y., Singapore, CI-PREMIER PTE LTD, ISBN: 978 -981-05-7586-1.

Allemang, R. J. and Brown, D. L. (1982): A correlation coefficient for modal vector analysis, in *Proceedings of the 1st SEM International Modal Analysis Conference*, Orlando, FL, USA, 110–116.

Arlati, E. and Accoto, L., (1998): *Le volte leccesi tra tradizione e innovazione: riformulare la vocazione edilizia delle cave*. Galatina, Italy, edited by Congedo M., 78 pp, ISBN: 8880864289.

Bendat, J. S. and Piersol, A. G. (1986): *Random data: Analysis and measurement procedures*. John Wiley and Sons, New York, USA, 566 pp.

Bendat, J. S. and Piersol, A. G. (1993): *Engineering applications of correlation and spectral analysis*. Second Edition, John Wiley and Sons, New York, USA, 458 pp.

Brincker, R., Zhang, L. and Andersen, P. (2000): Modal identification from ambient responses using frequency domain decomposition, in *Proceedings of the 18th SEM International Modal Analysis Conference*, San Antonio, TX, USA, 625–630.

Cardoso R., Lopes M. and Bento R. (2005): Seismic evaluation of old masonry buildings. Part I: Method description and application to a case-study, *Eng. Struct.*, 27, 2024–2035.

Colaianni, V. G., (1967): Le volte leccesi, Dedalo libri, Italy, 80 pp.

Computers and Structures (2006): *SAP2000® v*.11. *Manual*. Computers and Structures Inc., Berkeley, California, USA, 477 pp, accessed April, 2011 – http://www.comp-engineering.com/SAPManE.htm

Consiglio Superiore dei Lavori Pubblici (2008): *Nuove Norme Tecniche per le Costruzioni, D.M. Infrastrutture 14/01/2008*, published on S.O. n. 30 at the G.U. 04/02/2008 n. 29, 428 pp. (in Italian)

Conte, C. (2006): Analysis and seismic adjustment by innovative technique of existent masonry building, M.Sc. Thesis, University of Salento, Lecce, Italy, 213 pp.

Direttiva del Presidente del Consiglio dei Ministri – NTC 2008 (2010): Linee Guida per la valutazione e riduzione del rischio sismico del patrimonio culturale allineate alle nuove Norme tecniche per le costruzioni (d.m. 14 gennaio 2008), published at G.U. 23/07/2010 n.26/2010, 431 pp. (in Italian)

Gade, S., Møller, N. B., Herlufsen, H. and Konstantin-Hansen, H. (2005): Frequency domain techniques for operational modal analysis, in *Proceedings of the 1st International Operational Modal Analysis Conference*, edited by R. Brincker and N. Møller, Copenhagen, Denmark, 261–271.

Gentile C. (2005): Operational modal analysis and assessment of historical structures, in *Proceedings of the 1st International Operational Modal Analysis Conference*, Copenhagen, Denmark, 213–224, http://www.iomac.org/pages/2005/CDPre/

Mohanty, P. (2005): Operational modal analysis in the presence of harmonic excitations, Ph.D. Thesis, Technische Universiteit Delft, The Netherlands, 98 pp.

Rainieri, C., Fabbrocino, G., Cosenza, E. and Manfredi, G. (2007): Implementation of OMA procedures using LabView, in *Proceedings of the 2nd International Operational Modal Analysis Conference*, Copenhagen, Denmark, 1–12, http://www.iomac.org/pages/2007/CDPre/

Rainieri, C., Fabbrocino, G. and Cosenza, E. (2008): Integrated systems for structural health monitoring: Worldwide applications and perspectives, in *Proceedings of the 4th European Workshop on Structural Health Monitoring*, Cracow, Poland, edited by Uhl, T., Ostachowicz, W. and Holnicki-Szulc, J., DEStech Publications, Inc., ISBN 978-1-932078-94-7, 357–364.

Rainieri, C. (2008): Operational Modal Analysis for seismic protection of structures, PhD Thesis, University of Naples “Federico II”, Naples, Italy, 363 pp.

Salonikios, T., Karakostas, C., Lekidis, V. and Anthoine, A. (2003): Comparative inelastic pushover analysis of masonry frames, *Eng. Struct.*, 25, 1515–1523.

SAŽETAK

In-situ procjena zidanih svodova: Dinamička ispitivanja i numerička analiza

Carla Conte, Carlo Rainieri, Maria Antonietta Aiello i Giovanni Fabbrocino

U ovom se članku razmatra konstrukcija jedne kulturno-povijesne zidane zgrade, detaljno obrađena još u jednoj ranijoj studiji. Zgrada se nalazi u Južnoj Italiji (Lecce). Zgrada ima složenu konstrukciju krova, sa svodovima, kakva je česta kod starih zidanih zgrada. U članku se uzimaju u obzir ranija opsežna povijesna i statička istraživanja. Ta ranija istraživanja bila su usmjerena ka dobivanju informacija o prethodnim ispitivanjima te o sadašnjem stanju konstrukcije, uključujući geometrijske karakteristike, oblikovnost, konstruktivne detalje, svojstva materijala i oštećenja zgrade. Pri tome su pomogla i ranija istraživanja o koncepciji i načinu gradnje zgrade. Nakon ovih istraživanja, obavljene su serije ispitivanja, između ostalog i dinamički pokusi na mnogim svodovima da se ustanove svojstva njihovog dinamičkog odziva u uvjetima standardne uporabe. Postavljen je i numerički model. U ovom su članku prikazani rezultati prvih dinamičkih ispitivanja i svojstava modela. Diskutira se odnos rezultata dobivenih numerički i eksperimentalno.

Ključne riječi: kulturno-povijesne građevine, ambijentalna vibracijska ispitivanja, operativna modalna analiza

Corresponding author’s address: Carla Conte, Department of Engineering for Innovation, University of Salento, Via per Arnesano, 73100 Lecce, Italy, tel: +39 0832 297 386, fax: +39 0832 297 279, e-mail: carla.conte@unisalento.it