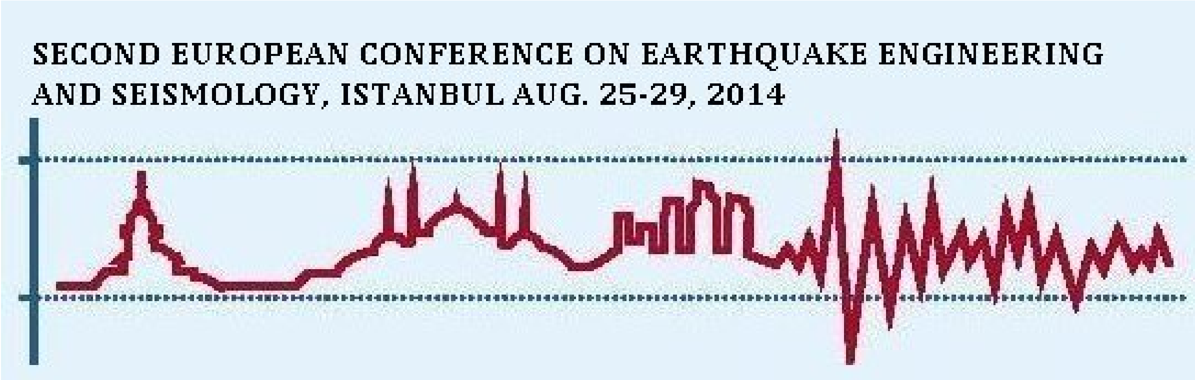

STRUCTURAL IDENTIFICATION OF A BYZANTINE CATHEDRAL IN VEROIA TOWN, GREECE

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ABSTRACT

The present research effort aimed at the instrumentation and structural identification of the Old Byzantine Cathedral in the town of Veroia, Greece. The load bearing system of the Cathedral consists of stone masonry walls, with a large degree of material inhomogeneity and severe cracking, making difficult a reliable assessment of its actual strength and material properties. Thus, in the framework of a restoration/strengthening study of the church, it was decided to complement the analytical investigations with an experimental identification of the actual dynamic characteristics of the structure, through recording of its dynamic response to ambient vibrations. The obtained results are presented in the paper, together with a discussion on the capabilities and limitations of each of the structural identification methodologies used.

INTRODUCTION

The instrumentation of a structure for the recording of its response to dynamic excitations helps towards both the evaluation of its structural integrity, as well as the assessment of its dynamic characteristics before and after its possible strengthening. It also leads to a better understanding of its actual behaviour and the role of several factors that affect it. During the experimental, on-site investigations, the excitations of the structure can be either of a deterministic nature (e.g. earthquake, forced excitations) or a random (ambient) one (e.g. wind and traffic). Ambient vibration and environmental data are easily acquired under operation conditions from the instrumentation system. From the recordings of the response, the dynamic characteristics (eigenvalues, eigenmodes, damping factors) can be experimentally evaluated, using suitable methodologies. The evaluated modal properties can then serve as a basis for the proper updating of finite element models of the structure, as well as to calibrate the finite element models, in order to better predict its actual behaviour under various dynamic excitations.

Thus, within the framework of a general study for the restoration and strengthening of the Old Byzantine Cathedral in the town of Veroia, Greece, it was decided to assess the monument's actual modal characteristics through its instrumentation with a special accelerometer array. A special accelerometer array was used to record the structure's response to ambient excitations. The recorded

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response data were properly processed for offset and baseline correction and removal of noise through bandpass filtering, based on the long experience of the research team on instrumentation projects (Lekidis et al. 2004, 2005, Karakostas et al. 2003, 2006). The data were then processed using two different methodologies, i.e. Canonical Variate Analysis and Enhanced Frequency Domain Decomposition, leading to the identification of various excited modes in both structures.

THE VEROIA CATHEDRAL

The Cathedral is a partially destroyed 11th century Orthodox Christian basilica (Figure 1). It follows the typical architectural form of a three-aisle stone masonry basilica with wooden roofs. However, the southernmost secondary aisle was destroyed in the past, resulting in two-nave structure (Figure 2). On the eastern end of the central aisle, lies the typical hemi-cylindrical sanctuary topped by a half-dome. The original half-dome was also destroyed and replaced by a reinforced concrete one. The interior walls of the existing structure are covered by religious frescoes, the majority of which dates back to the 13th century. During the Ottoman period, the basilica was used as a Muslim mosque, and a minaret was constructed in contact with the northern wall. At the same time, all exterior and interior walls were plastered, covering the existing frescoes. A later addition is also a low shed built in contact to the northernmost wall, next to the minaret (Figure 2).

Figure 1. The Veroia Cathedral (view from southeast)

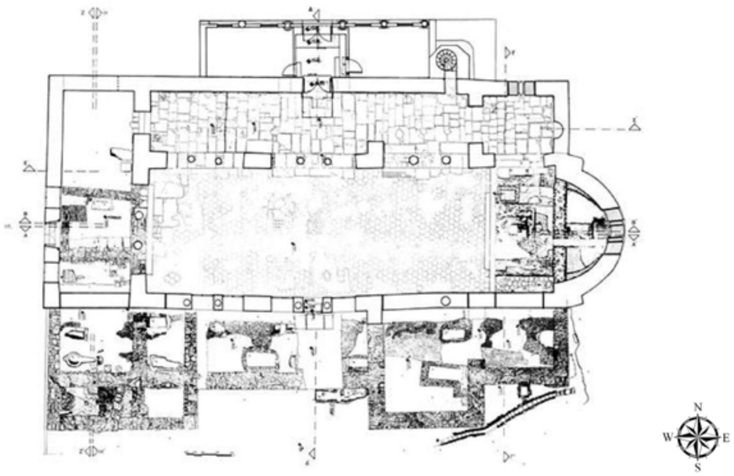

Figure 2. Plan of the Veroia Byzantine Cathedral

The whole complex is being currently restored to its original condition under the supervision of the 11th Ephorate of Byzantine Archeology (operating under the auspices of the Hellenic Ministry of Culture and Sports). Thus, within the framework of a general study for the structural strengthening of the Cathedral, it was decided, among others, to assess the monument's actual modal characteristics through its instrumentation with a special accelerometer array (Lekidis et al. 2013). The geometric horizontal and vertical irregularity of the basilica, the significant inhomogeneity in the stone masonry used for the wall construction, the existence of cracks of various size and depth in the walls, the reinforced concrete half-dome of the sanctuary and other factors lead to a complex load-bearing system, with inherent difficulties in both defining and assessing its modal properties.

INSTRUMENTATION OF THE VEROIA CATHEDRAL

For the instrumentation of the cathedral, the research team had to take into account the complex condition of the load-bearing masonry walls, as it is described in the previous section. Further restrictions were imposed by the existence of frescoes along the height of the cathedral walls (not allowing the placement of sensors) and the existence of thick scaffolding throughout the church interior for the restoration works going on at the time.

All these factors, in combination with a limited budget, led the research team to finally decide on the instrumentation of the topmost end of the masonry walls of the central aisle, where the wooden roof also sits (Figure 3). A special structural array was deployed consisting of 12 uniaxial accelerometers (*Kinematrics Inc.* Uniaxial Force balance sensors *ES-U2*© and *FBA-11*©), together with a *Kinematrics Inc. Aitna*© high-resolution (19 bit) recording unit. The technical specifications of the recording system are presented in Table 1.

Table 1 Technical specifications of the recording system

Sensor :			**Trigger :**	
Type	FBA-11©	ES-U2©	*Type*	IIR Bandpass filter
Full scale range	± 2g	± 2g	*Trigger bandwidth*	0.1 Hz – 12.5 Hz
Natural Frequency	50 Hz	200 Hz	*Trigger threshold*	0.01% - 100 % Full scale
Damping	70%	70%	*Channel triggering*	Independent threshold for all channels
Dynamic range	> 135 dB 0.01 to 50 Hz > 145 dB 0.01 to 20 Hz	> 140 dB 0.01 to 200 Hz	*Trigger voting*	Internal, external trigger votes with arithmetic combination
Data Acquisition (Aitna©) **:**			**Storage :**	
Dynamic range	108 dB @ 200 sps		*Type*	20 Mb flash memory
Resolution	19-bit @ 200 sps		**Environment :**	
Sampling rate	100, 200 sps		*Operating temperature*	-20° to 70° C
Input range	± 2.5 V		*Humidity*	0 – 100 % RH

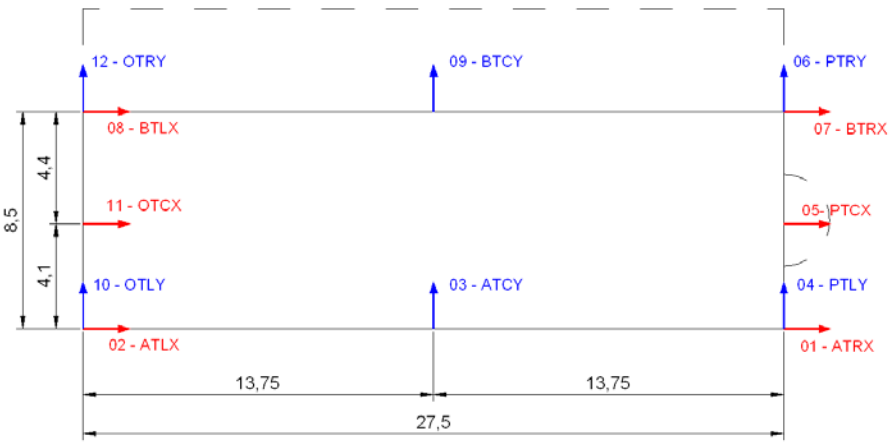

Figure 3. Instrumentation layout at the top of the central aisle walls. Dashed lines denote the northern aisle (top) and the sanctuary (right)

The 12 sensors are connected through cables to the central recording unit, which, in turn, is connected to a PC for setting the system parameters and data acquisition (Figure 4). The sensors were bolted on a wooden beam that runs along the top of the masonry walls, which serves as a base for the wooden roof beams, and which is firmly attached to underlying walls with bolts and mortar, following their response. In this way, drilling of the walls was avoided, especially since at several places frescoes reached their top.

(a)

(b)

(c)

(d)

Figure 4. (a) Central recording unit (b), (c), (d) sensors at top walls of central nave

STRUCTURAL IDENTIFICATION OF THE CATHEDRAL THROUGH AMBIENT EXCITATIONS

For the assessment of the dynamic characteristics of the cathedral its response to ambient excitations was used (Lekidis et al. 2013). One advantage of this approach is that it does not demand extra equipment for exciting the structure (e.g. vibrators for forced –typically harmonic- excitation, or pull-out systems for free vibration response). Especially in the present case, use of forced vibration/pull-out procedures is more or less prohibitive, due to the high risk of causing damage to a cultural heritage structure, given the non-ductility and the extensive cracking of the masonry walls, in combination with the inability to reliably assess their – locally varying – actual strength. The inhomogeneity and cracking of the walls would also render inefficient the application of impact hammer techniques. It has to be noted, however, that the assessment of the modal characteristics of the structure through low-level ambient excitations corresponds to an elastic response of the structure, and should hence be used for the calibration of analytical models that only describe a similar behaviour.

Long duration (30 min) recordings were made of the structure’s response to a low-level ambient-type excitation from the motor of a JCB excavator running at low revs and standing near the NE corner of the complex. The recorded response (Figure 5) was used to obtain estimates of excited modes of the central nave, as it is described later herein.

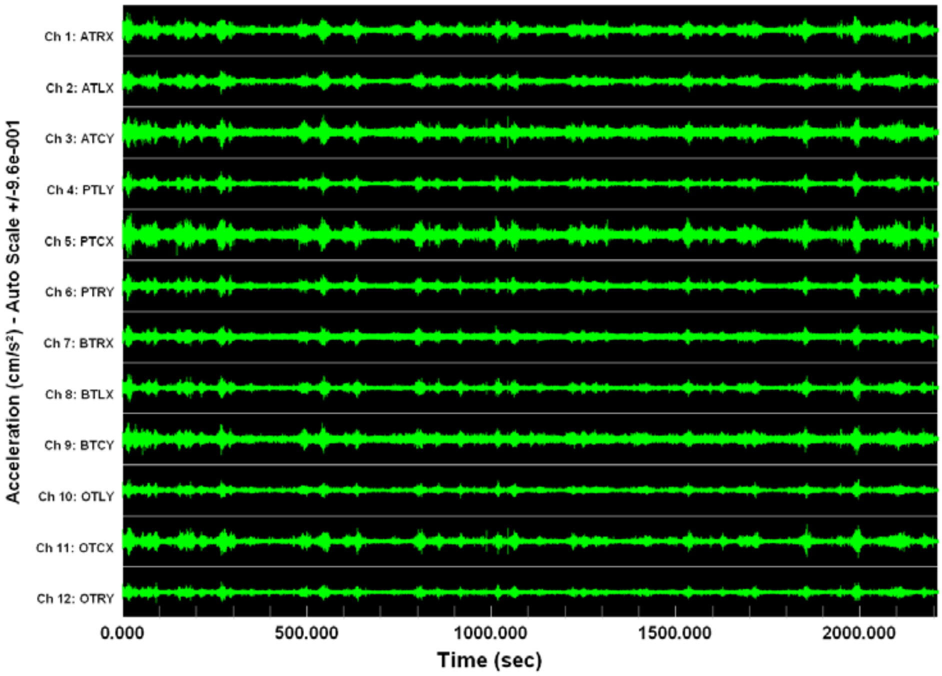

Figure 5. Recordings of the Cathedral response to ambient vibration excitations

The recordings were properly processed in order to eliminate to the highest possible degree errors from the recording procedure (through application of offset και base correction), as well as for filtering out frequencies not related to the structural response (through proper use of a band-pass Butterworth filter).

In Figure 6, the Power Spectral Density at sensor ATCY is presented, which will be commented on later in the paper.

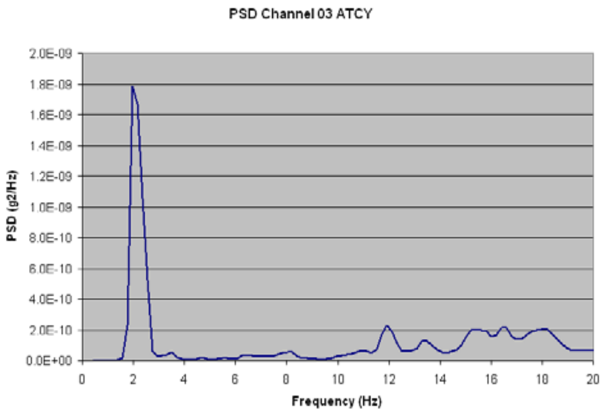

Figure 6. Power Spectral Density - sensor ATCY

For the assessment of the modal properties (eigenvalues, eigenvectors and damping ratios) of the instrumented structure, the structural identification program *Artemis Pro* (©*Structural Vibration Solutions A/S*) was used. The Canonical Variate Analysis (CVA) was first used, leading to the identification of the following eigenmodes:

Eigenvalue at 2.07 Hz (T= 0.48 sec)

The mode is related mainly to out-of-plane vibration of the longitudinal walls of the central nave (Figure 7). The similar spectral amplitude at the wall midpoints (Fig. 3, sensors 03-ATCY and 09-BTCY) indicates their potential coupling in the vibration direction (Y-axis) through the wooden roof. The mode corresponds to the high value at 2Hz of the Power Spectral Density diagram of sensor ATCY presented at Figure 6. The corresponding damping ratio for this mode was found to be 3.2%.

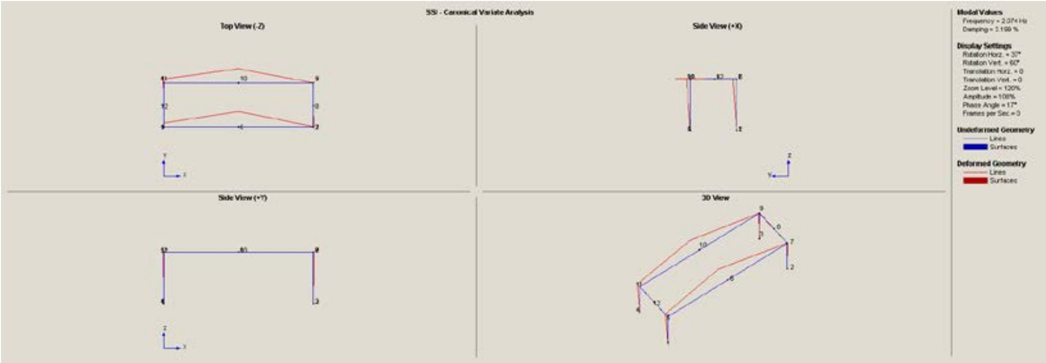

Figure 7. CVA technique – eigenvalue at 2.074 Hz

Eigenvalue at 3.49 Hz (T=0.30 sec)

The eigenmode is coupled in both (X and Y) horizontal directions (Figure 8). It is noted that, as before, the spectral amplitudes are similar in the Y-direction, however it is obvious that the wooden roof does not enforce a diaphragmatic behaviour of the perimetric walls. The corresponding damping ratio for this mode was found to be 2.7%.

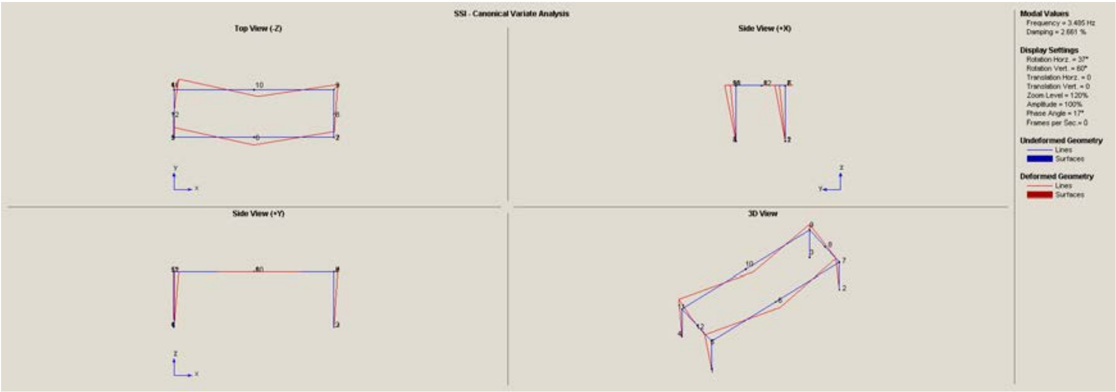

Figure 8. CVA technique – eigenvalue at 3.485 Hz

Eigenvalue at 5.74 Hz (T= 0.17 sec)

A higher-order eigenmode, also coupled in both horizontal directions (Figure 9) with a corresponding damping ratio of 3.2%.

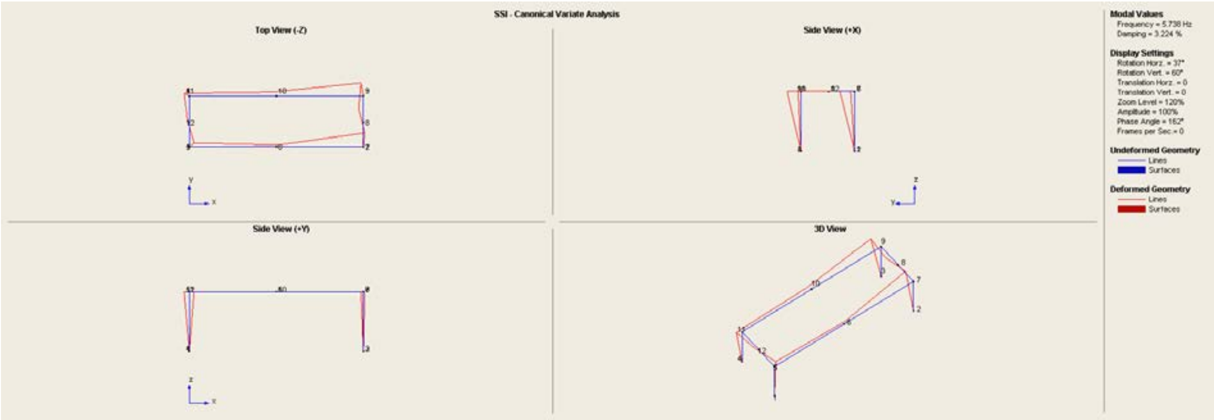

Figure 9. CVA technique – eigenvalue at 3.485 Hz

It is noted that the CVA technique was initially chosen, since it gives an indication of the stability of the identified modes through a corresponding Stabilization Diagram. A second technique was also applied (Enhanced Frequency Domain Decomposition – EFDD), yielding similar results with those obtained through CVA. The second approach was used to validate the results of the first investigation, thus excluding any bias inherent in each identification technique.

CONCLUSIONS

In the framework of a restoration/strengthening study of a Byzantine Cathedral in the town of Veroia, Greece, it was necessary to recourse to an experimental assessment of its actual dynamic characteristics, due to the inhomogeneous materials and severe cracking of the stone-masonry load bearing system that made difficult the evaluation of its strength and material properties. A special accelerometer array with 12 uniaxial sensors was used to record the monument's response to ambient excitations. The recorded data were processed with two different methodologies and the excited modal parameters were evaluated. The experimentally evaluated dynamic properties can help to properly calibrate analytical models of the Cathedral leading to more reliable predictions of its dynamic behaviour and the necessary strengthening measures. After strengthening, a new experimental evaluation of the dynamic properties of the monument should be carried out, in order to validate the success of the interventions.

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