Ambient Vibration Testing of Historical Monuments within Monastery Complex "St. Marry Perivleptos" in Ohrid

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SUMMARY:
As a part of complex activities of the project for evaluation of the existing seismic stability of the monastery complex St. Mary Peribleptos in Ohrid, Republic of Macedonia, experimental in-situ testing of the church, the bell tower and the doss-house was performed by use of the ambient vibration testing method. The objective of the test was to obtain the dynamic characteristics of these structures, namely, the natural frequencies, mode shapes and damping coefficients. All these structures are constructed of stone masonry. The equipment used for the measurements consisted from Ranger seismometers, signal conditioner, data acquisition system and PC, while the post processing of the records was done by use of the Artemis software. The obtained experimental results presented in this paper were further used for calibration of the mathematical models in evaluation of the seismic stability and the design procedure for retrofitting of these structures.

Keywords: Historical monuments, ambient vibrations, natural frequencies, mode shapes, damping

1. INTRODUCTION

Most of the historical monuments are constructed of brittle materials, with high rigidity which limits the possibilities for ductile behaviour during earthquakes. They are structures for which several important aspects should be considered in evaluation of their seismic stability. The estimation of earthquake ground motions based on amplitudes as well as frequency content of both local and distant seismic sources considering modification by local soil conditions is one of these aspects. Other important factors that influence the determination of seismic response are the strength and deformability characteristics of the materials, as well as the interaction between the local soil and the structure. Further, the dynamic properties of the structure - the natural (resonant) frequencies, mode shapes, and damping capacity should be considered also as one of the main aspects, which means that definition of the actual state of a monument in respect to its dynamic characteristics should be performed by experimental in-situ testing.

Within the activities of the project for evaluation of the existing seismic stability of the historical structures in the monastery complex St. Mary Peribleptos in Ohrid, experimental in-situ testing of the church, the bell tower and the doss-house was performed by use of the ambient vibration testing method. The objective of the testing was to investigate the dynamic behaviour of the above mentioned structures in environmental conditions based on which the dynamic properties - natural frequencies, mode shapes and damping coefficients could be defined. The obtained experimental results are further used for calibration of the numerical models to be used for their analysis and design procedure of their retrofitting.

2. DESCRIPTION OF THE TESTED STRUCTURES

The monastery complex St. Mary Peribleptos in Ohrid is located in the old town of Ohrid, near the Upper Gate and it consists of several buildings among which the church, the bell tower and the doss-house. All of them are stone masonry structures.

2.1. The Church of St. Mary Peribleptos

The church of the Holy Mother of God Beautiful (St. Mary Peribleptos) is one of the most beautiful churches in Ohrid. The extraordinary architecture and stunning wall paintings make this church, which dates back to 1295, one of the most significant mediaeval monuments in Macedonia. It consists of three units built in different periods: the church itself, the paraklesis and the portico. Its main dimensions at plan are 21.17 x 17.14 m and its height is 12.7 m. The appearance of the church is shown in Fig. 1, while the plan together with the paraklesis and the portico are presented in Fig. 2.

Figure 1. The western facade of the church - the main entrance

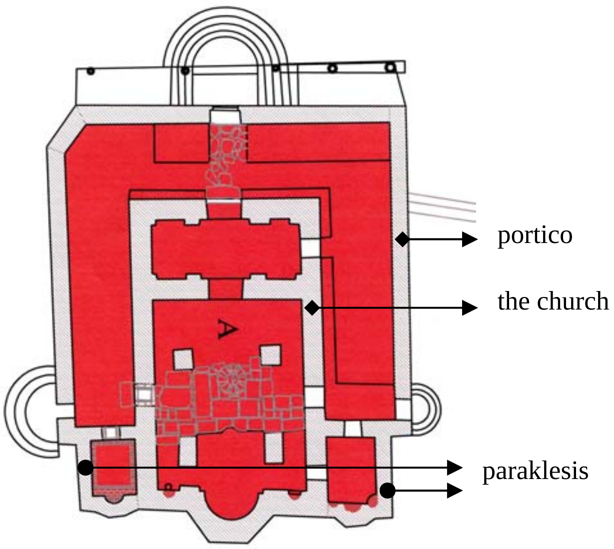

Figure 2. The church plan

2.2. The Doss-house and the Bell tower

The doss house has a basement and one floor. It consists of stone walls and has an irregular rectangular shape. The bell tower is also constructed of stone. 2/3 of its height has a square shape, while the top part has an octagonal shape. The appearance of these two structures is shown in Fig. 3.

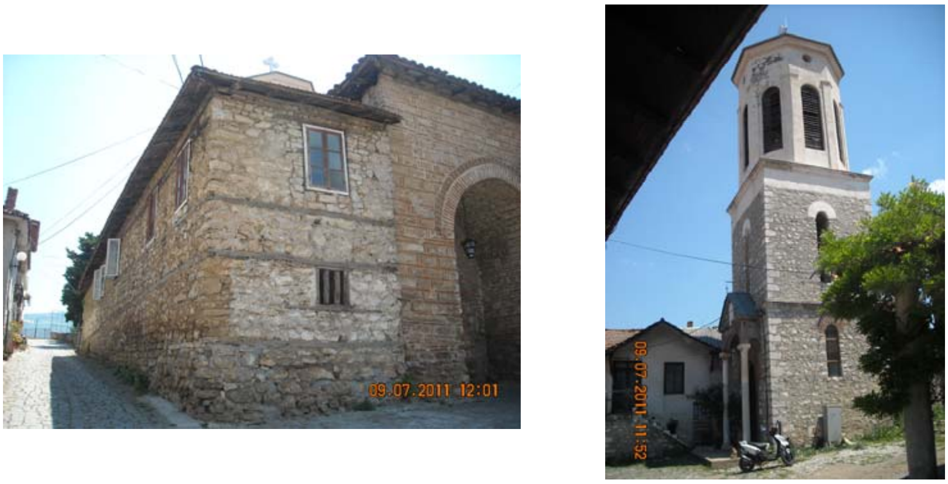

Figure 3. The doss house and the bell tower

3. TESTING PROCEDURE AND USED EQUIPMENT

3.1. Ambient Vibration Testing Method

The dynamic characteristics of the structures were obtained applying the ambient vibration testing method, which is a widely applied and popular full-scale testing method for experimental definition of structural dynamic characteristics. It is based on measuring the structural vibrations caused by the ambient. As ambient forces can be treated the wind, the traffic noise or some other micro-tremor and impulsive forces like wave loading or periodical rotational forces produced by some automatic machines. The method represents, in fact, a very fast and relatively simple procedure that can be done without disturbing the normal functioning of a structure. The basic assumption used in this method is that the excitation forces represent a stationary random process, having an acceptably flat frequency spectrum. In such conditions, the structures will vibrate and their response will contain all their normal modes.

The ambient vibration testing procedure consists of real time recording of vibrations and processing of records. The initial test is the dynamic calibration test after which the seismometers are placed at different levels and different points of the structure, but in the same direction, for simultaneous recording. This is necessary for obtaining the mode shapes of vibration. One point is chosen as a referent one, usually at the highest level of the structure. The duration of the recording should be long enough to eliminate the influence of possible non-stochastic excitations which may occur during the test.

3.2. Equipment Used for the Measurements

For measuring the ambient vibration of the monuments, four seismometers of the Ranger type (produced by Kinemetrics) were used and the measured signals were amplified by a four channel Signal Conditioner, which is also a product of Kinemetrics. The amplified and filtered signals from the seismometers were than collected by a high-speed data acquisition system, which transforms the analogue signals into digital. PC and special software for on-line data processing has been used to plot the time history and Fourier amplitude spectra of the response at any recorded point.

For post-processing and analysis of the recorded vibrations at all measured points, the ARTeMIS software was used. This software is based on the Peak Picking technique and Frequency Domain decomposition and has the possibilities for good graphical presentation of the obtained data and simulations of the mode shapes of vibration.

4. TEST SET-UP

The measurements of the structures were performed in both orthogonal directions - transversal and longitudinal, at selected points. The data sets consisted of records with a duration of 100 seconds, while the sampling frequency was 200 s/sec.

The church was measured at 18 points located on the roof, the tambour, the windows, the beams and the ground floor in both orthogonal directions, as shown on the geometry of the church generated by the Artemis software, Figs. 3 and 4. The referent instruments were placed at the window on the southern facade under the tambour. Additional measuring points were selected on the walls of the paraklesis as well as on the wooden beams connecting the walls of the portico and the walls of the church, in order to see if they have the same dominating frequencies. The distribution of all measured points is given in Fig. 5.

The doss-house was measured at 8 points on 2 levels: the level of the basement and the level of the first floor. The bell tower was measured on 4 levels along its height. The measuring points were located on each side of the tower and the seismometers were set on the windows in both orthogonal directions.

The distribution of the measured points for the doss-house and for the bell tower is given in Fig. 6.

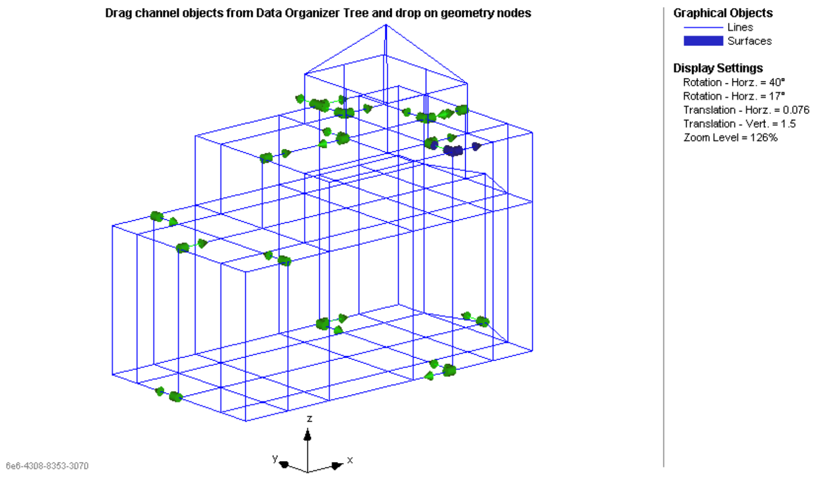

Figure 4. Test set-up for the church

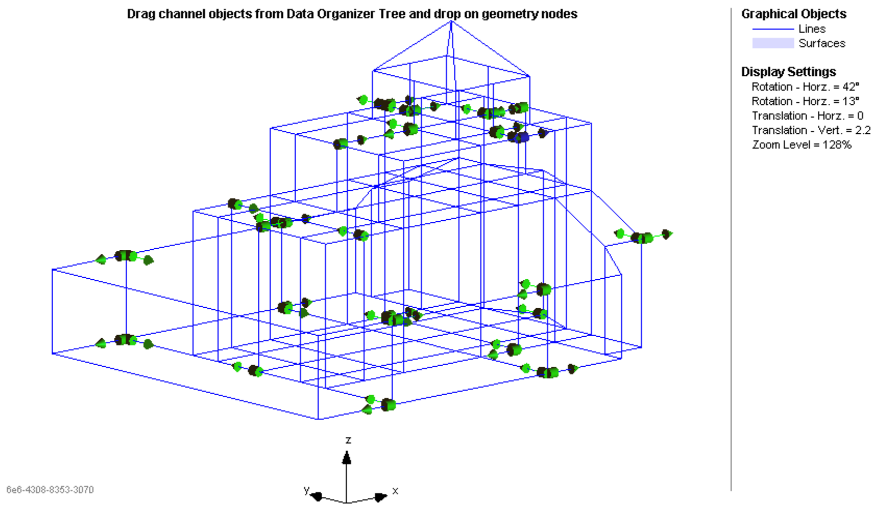

Figure 5. Test set-up for the church, the paraklesis and the portico

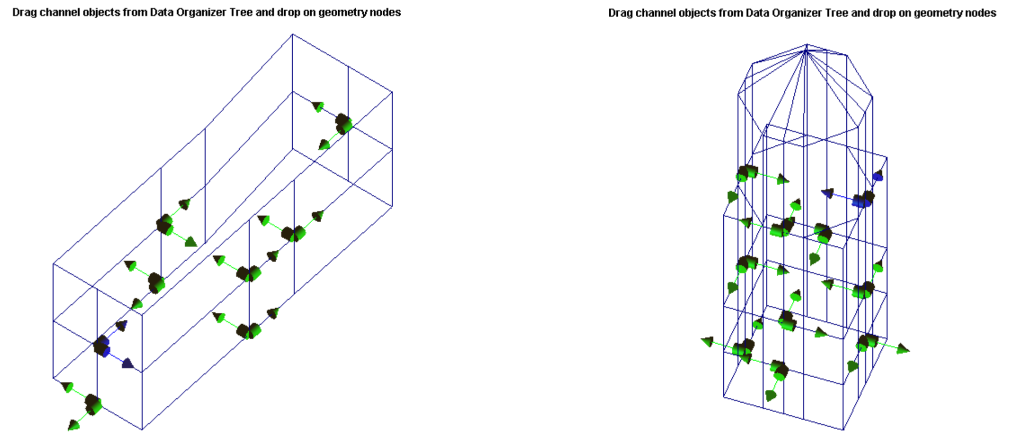

Figure 6. Test set-up for the doss-house and the bell tower

5. EXPERIMENTAL RESULTS

5.1. Experimental Results Obtained for the Church

The spectral density curves and the peak-picking of the dominant frequencies for the church considered as a whole i.e. including the portico and the paraklesis are presented in Fig. 7. The dominant frequencies are well expressed and they are presented in Table 1 together with the corresponding damping coefficients. The resonant frequency in lateral (transversal) direction of the church is 5.08Hz, in longitudinal direction, it is 6.45 Hz, and for torsion, it is f=7.6 Hz. The mode shapes at these frequencies are given in Fig. 8.

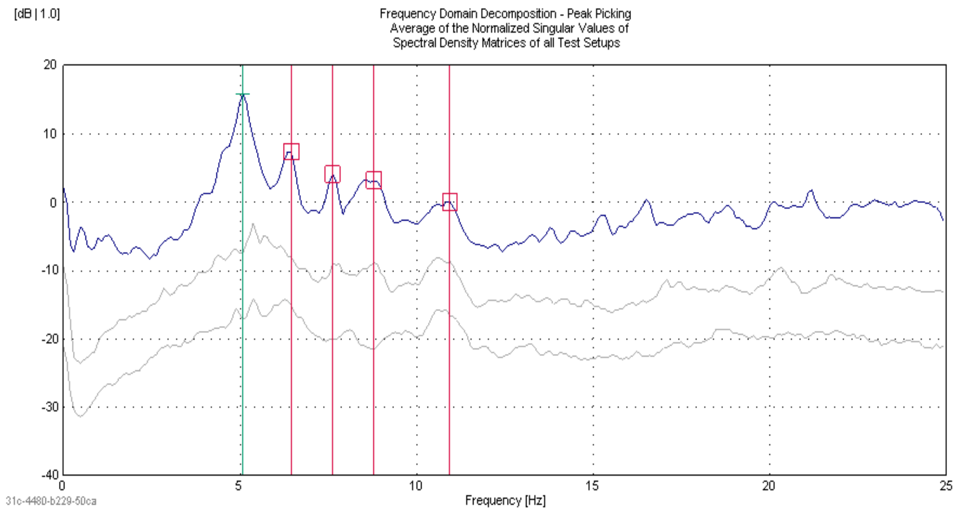

Figure 7. Spectral density curves and peak picking of dominant frequencies for the church

Table 1. The dominant frequencies and damping coefficients for the church

Mode	Frequency [Hz]	Damping Ratio [%]
FDD Mode 1	5.08	3.8
FDD Mode 2	6.45	2.2
FDD Mode 3	7.6	1.8
FDD Mode 4	8.8	2.3
FDD Mode 5	10.9	1.3

At all frequencies related to vibration in lateral direction, the church and the portico are vibrating together having almost the same amplitudes of deformation, which is the result of the wooden beams connecting the walls of the church and the portico. Their high axial stiffness is enabling the church and the portico to vibrate together.

The frequency of f=8.8Hz belongs to lateral (torsion) vibration of the longitudinal walls of the portico. The frequency of 10.9 Hz is the torsion frequency, too, and it is interesting to mention that, at this frequency, the west wall of the portico vibrates very intensively at the end where the connection between the wooden beam and the wall of the church does not exist. The parakleses are vibrating mostly independently, which is the result of the existing separation joints between them and the church.

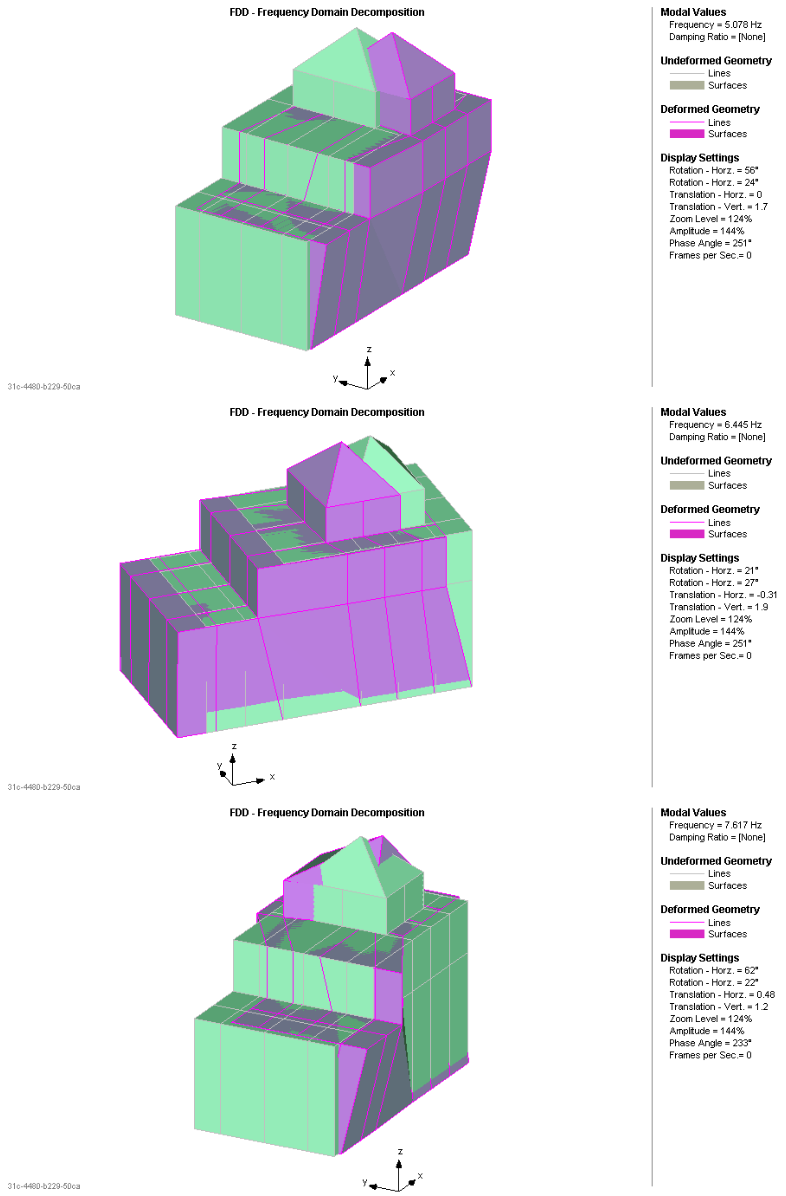

Figure 8. Mode shapes of vibration for the church in transversal direction, longitudinal direction and torsion

5.2. Experimental Results Obtained for the Doss-house

Presented in Fig. 9 is the peak-picking of the dominant frequencies for the doss-house and their values together with corresponding damping coefficients are presented in Table 2.

The fundamental frequencies in transversal direction are prevailing in almost all the recorded modes with the maximum amplitude in the middle of the length (f=6.055Hz; f= 8.2Hz; f=10.25Hz). This indicates that the lateral direction is more deformable than the longitudinal one i.e. the longitudinal walls are very weak.

The torsion is also present in the mode shapes, especially at frequencies f= 7.129Hz; f=9.86 Hz; f=10.25Hz; f=12.4Hz. The mode shapes of vibration at particular frequency values are given in Figs. 10-11. They clearly show that the deformation of the western part and the west facade of the structure is highly expressed.

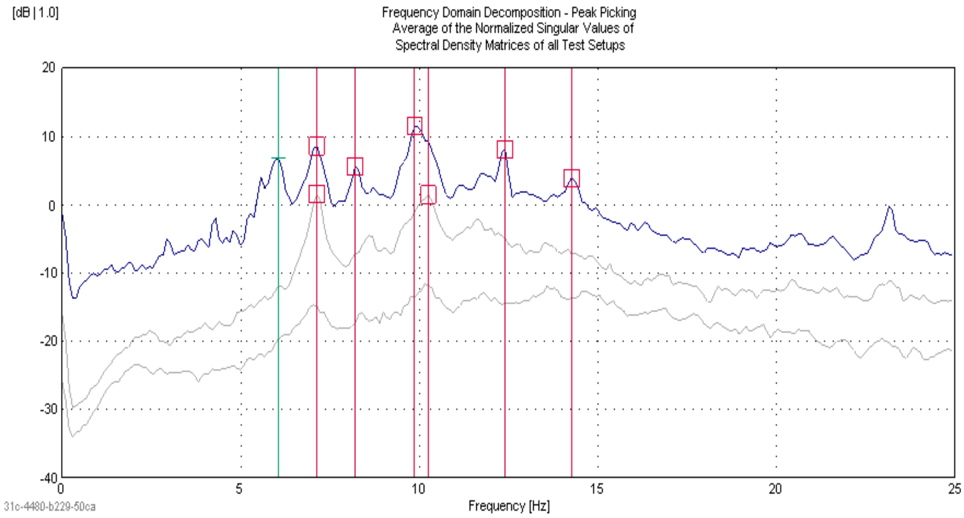

Figure 9. Spectral densities and peak picking of the dominant frequencies for the doss-house

Table 2. The dominant frequencies and damping coefficients for the doss-house

Mode	Frequency [Hz]	Damping Ratio [%]
FDD Mode 1	6.055	2.66
FDD Mode 2	7.129	1.4
FDD Mode 3	8.203	1.9
FDD Mode 4	9.863	1.25
FDD Mode 5	10.25	2.0
FDD Mode 6	12.4	-
FDD Mode 7	14.26	-

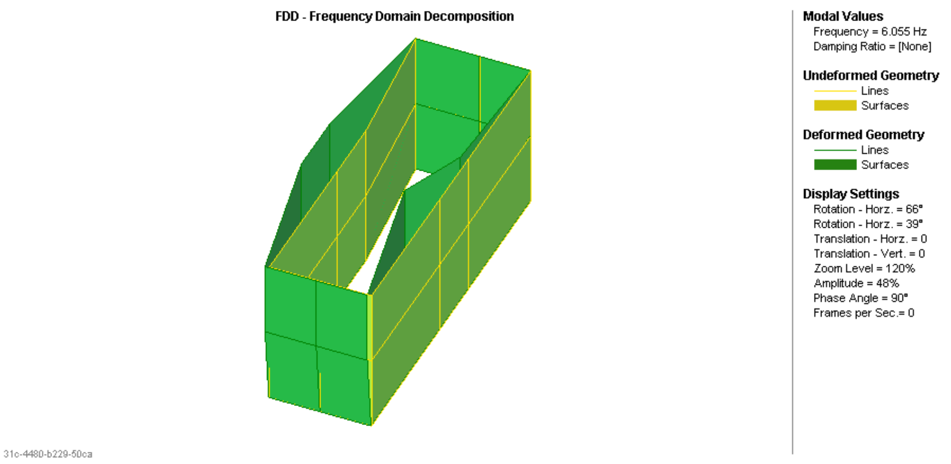

Figure 10. Mode shape of vibration for the doss house at a frequency of 6.05Hz

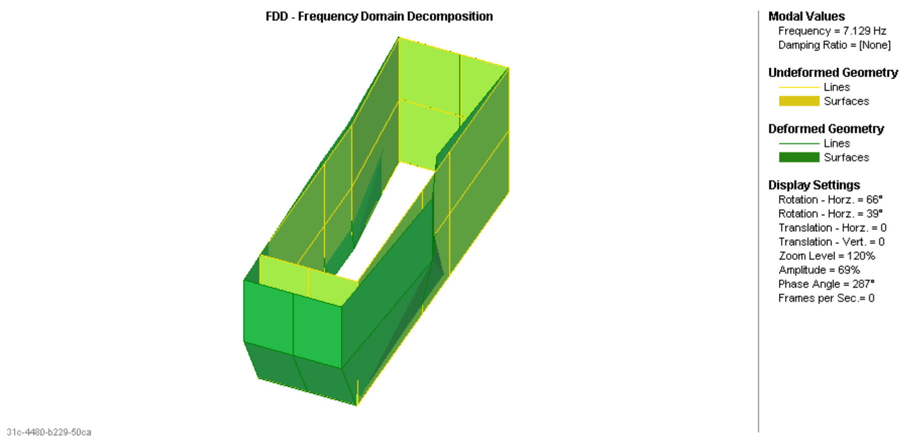

Figure 11. Mode shape of vibration for the doss house at a frequency of 7.13Hz

5.3. Experimental Results Obtained for the Bell Tower

Presented in Fig. 12 is the peak-picking of the dominant frequencies of the bell tower by ARTeMIS software together with the corresponding damping coefficients. The values of these dynamic characteristics are presented in Table 3, as well.

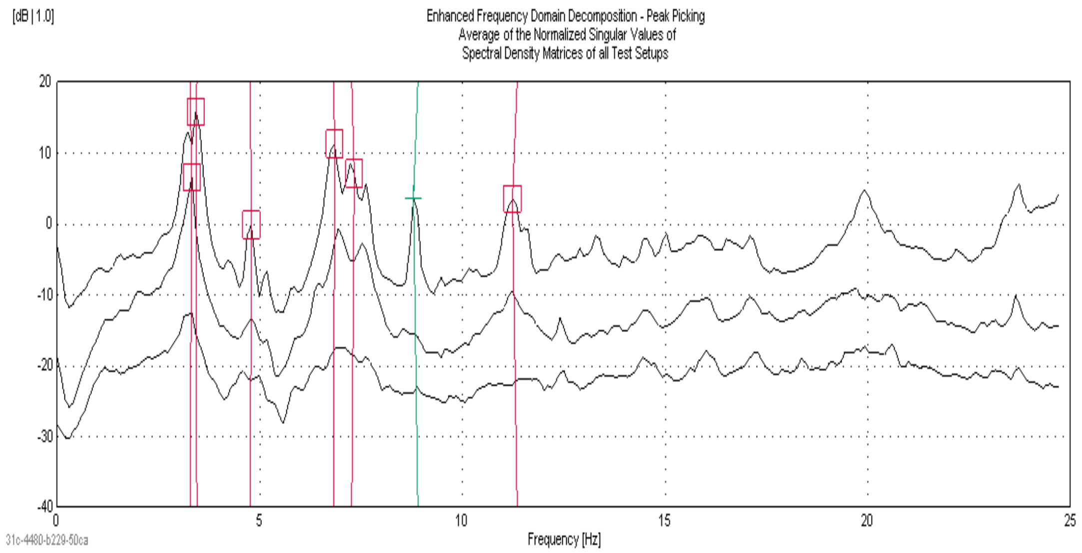

Figure 12. Spectral densities and peak picking of the dominant frequencies for the bell tower

Table 3. The dominant frequencies and damping coefficients for the bell tower

Mode	Freq. [Hz]	Damping Rat.[%]
FDD Mode 1	3.2	2.0
FDD Mode 2	3.44	2.2
FDD Mode 3	4.76	1.6
FDD Mode 4	6.83	1.4
FDD Mode 5	7.26	1.5
FDD Mode 6	11.34	1.2

The fundamental frequencies for translation in *x* and *y* direction are very close but not the same, even the tower is symmetric in geometry (f_{1x}=3.2 Hz; f_{1y}= 3.44 Hz). Some similar close frequencies are obtained for the second mode (f_{2x}=6.83Hz; f_{2y}=7.26 Hz). The torsion frequency is higher (f_t=11.34 Hz). The shapes of vibration at a particular frequency value are given in Figs. 13-15.

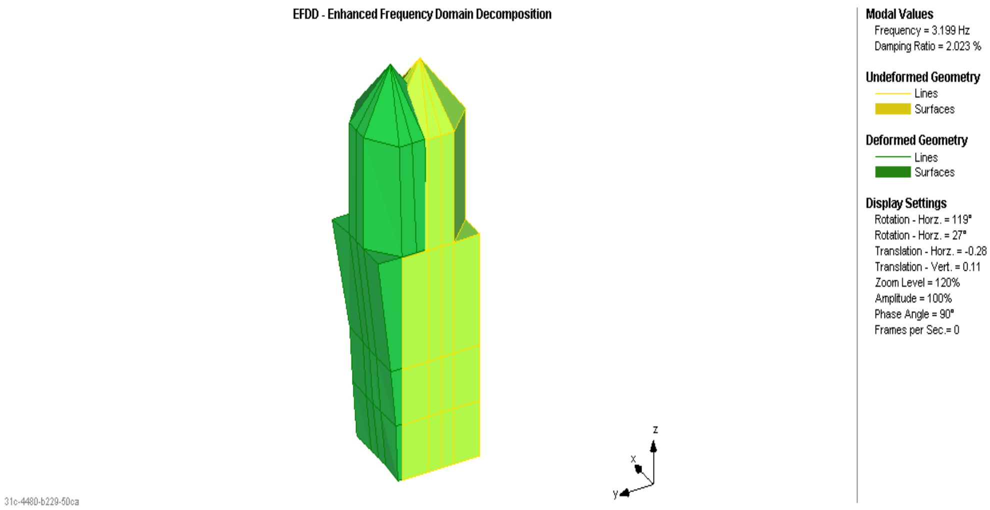

Figure 13. Mode shape of vibration in *y* direction for the bell tower at a frequency of 3.2Hz

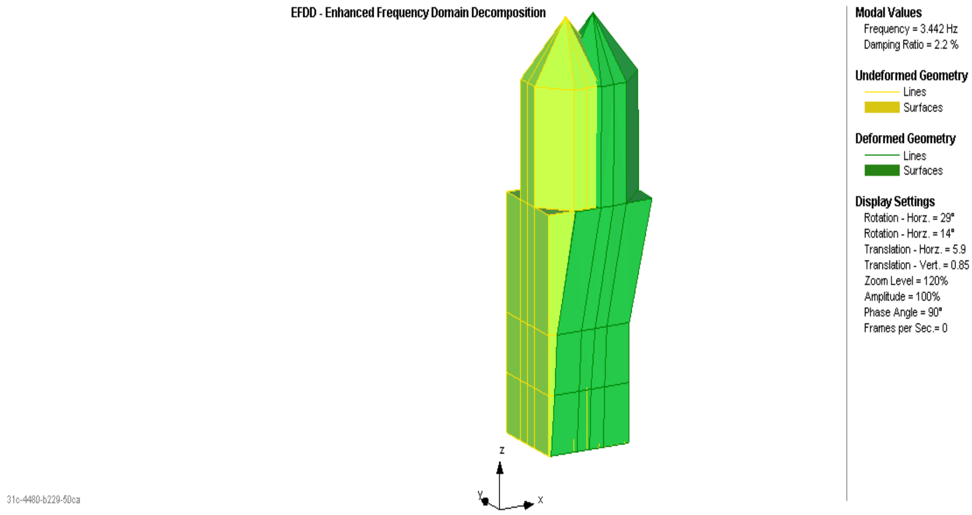

Figure 14. Mode shape of vibration in *x* direction for the bell tower at a frequency of 3.44Hz

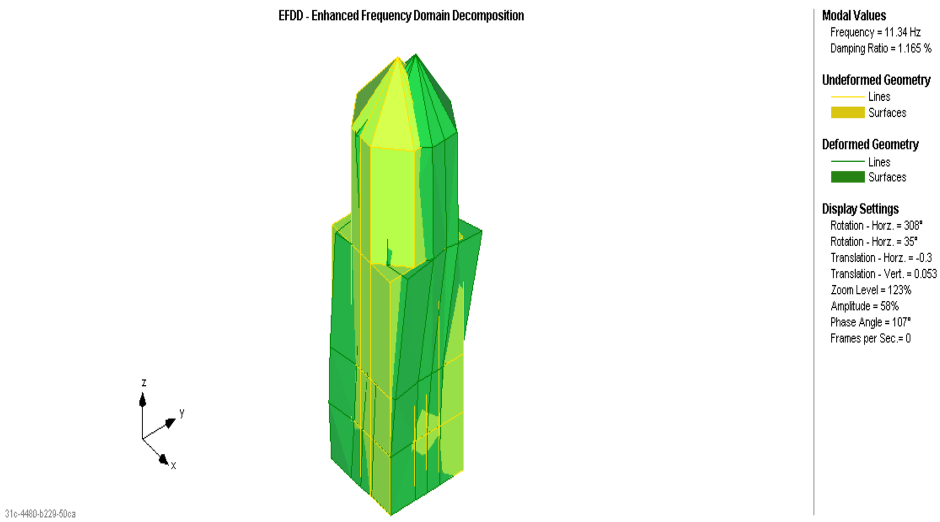

Figure 15. Mode shape for torsion at a frequency of 11.34Hz

6. CONCLUSIONS

Experimental in-situ testing of the historical structures within the monastery complex St. Mary Peribleptos in Ohrid was performed with the objective of obtaining the dynamic characteristics of the church, the bell-tower and the doss-house, applying the ambient vibration testing method. The measurements were performed at selected points, in two orthogonal directions. In the frequency range of 0 - 25 Hz, the dominating frequencies, damping and corresponding mode shapes were defined for each of the three above mentioned structures.

The church itself has clear and well expressed natural frequencies and corresponding mode shapes of vibration. The church complex (the church, the paraklesis and the portico) works mostly together, as a result of the existing wooden beams connecting the walls of the church and of the portico, but also independently, at higher frequencies, because of the existing separation joints.

The doss-house is characterized by weak longitudinal walls deformable out of plane which dictates the dynamic behaviour of the whole structure. There is an indication that the stiffness of the floor slab is very low and not enough, too, which enables independent vibration of the walls at some of the dominating frequencies. This must be taken into account during the retrofitting process.

The bell tower is characterized by a clear response, well expressed modes and close frequencies in both orthogonal directions.

The obtained damping values are in the range 1.2-3.8% of the critical damping, which is generally low for masonry structures.

The dynamic characteristics obtained by this experimental testing can be further used in verification of numerical models used for analytical investigation of the seismic stability of tested structures, increasing the reliability of the numerical approach and correct implementation of the retrofitting intervention.

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