AMBIENT VIBRATION TESTING OF HISTORICAL MONUMENTS WITHIN MONASTERY COMPLEX "TRESKAVEC" NEAR PRILEP

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ABSTRACT

The paper presents the obtained experimental results for historical monuments within the monastery complex "Treskavec" near Prilep, Macedonia, tested by the ambient vibration method for definition of their dynamic characteristics - natural frequencies, mode shapes and damping coefficients. The testing was performed as part of the complex activities within the projects for evaluation of their existing seismic stability. All five structures of this complex are constructed of stone masonry. The equipment used for the measurements consisted of accelerometers, 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 will be further used for calibration of the mathematical models in evaluation of the seismic stability and the design procedure for their retrofitting.

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

1. INTRODUCTION

Historical monuments are structures constructed of brittle materials, with high rigidity, which limits the possibilities for ductile behaviour during earthquakes. Several important aspects should be considered in evaluation of their seismic stability (Krstevska at all, 2007; Aras at all, 2011). The estimation of earthquake ground motions based on intensity 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 influencing 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 - resonant frequencies, mode shapes and damping capacity should be considered also among the main aspects, meaning that definition of the actual state of a monument in respect to its dynamic characteristics should be performed by experimental in-situ testing. Several studies related to evaluation of seismic stability of different types of historical monuments have been performed in IZIIS in last 10 years, within scientific projects and cooperation with universities of Naples, Istanbul, Pescara, Mostar (Tashkov at all, 2010; Kustura at all, 2010; Formisano at all, 2012; Krstevska at all, 2009, 2010). Within the activities of the project for evaluation of the existing seismic stability of all building structures within the monastery complex "Treskavec", non-destructive ambient vibration testing method was applied in order to investigate the dynamic behaviour of the structures in environmental conditions based on which the dynamic properties - natural frequencies, mode shapes and damping coefficients could be defined. The obtained experimental results will be further used for calibration of the numerical models to be used for their analysis and design procedure of their retrofitting.

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2. DESCRIPTION OF THE TESTED STRUCTURES

The monastery complex "Treskavec" is located on the slopes below Zlatovrv, near Prilep, at an altitude of about 1300 meters. It is one of the most beautiful monasteries in Macedonia, in whose complex there is the church "The Assumption of the Mother of God", as well as the facilities: dining room, oven, bell tower and homes.

The church is a one-aisled building, with three-sided altar apse in the east and chapels on the sides. It was built in the 13th century on the remains of the early Christian church. The middle section of the church is surmounted by a dome and divided by pilasters at several ends. From the outside, the altar apse is three-sided. Under the deep layer of plastered walls of the northern chapel, frescoes dating back to the 14th century are visible. Dating back to this century are also the two towers, located on the west side of the church. The structure of the church "The Assumption of the Mother of God" was built in several stages, while the frescoes in the church date back to different periods.

The monastery's dining room dates from the 14th century and contains frescoes from the 17th and the 19th century. Below these frescoes, remains of fresco paintings from the 14th century are visible. These are quite damaged, and most of the middle part of the southern wall is ruined.

The appearance of the church is shown in Fig. 1, while the plan and the longitudinal section are presented in Fig. 2. The monastery's dining room is presented in Fig. 3.

Figure 1. The church of "The Assumption of Mother of God" – Treskavec

Figure 2. The plan of the church and its longitudinal section
The oven was built in the 14th century, the monastery home was built towards the end of the 18th century - the beginning of the 19th century and was restored in the period between the two World Wars. The bell tower was built in the 14th century, and the upper zone was also rebuilt in the period between the two World Wars. During the fire in 2013, the roof construction of the bell tower was destroyed, and there were damages to the floor structures. Figure 4 presents the structures before the fire, and Fig. 5-8 presents the appearance of these structures during the testing.
3. TESTING PROCEDURE AND USED EQUIPMENT

3.1 Ambient Vibration Testing Method

The dynamic characteristics of the structures within the monastery complex "Treskavec" 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 (Ivanovic at all, 2000). 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

To record vibrations caused by ambient excitations, a system of accelerometers, an acquisition system and a computer for processing of the signals are used. Through special cables, the signals are transferred from the accelerometers to the acquisition system and the computer for signal processing. During the measurements, 4 accelerometers of the type of Model Number 393B12 accelerometer, ICP® were used. The amplified and filtered signals from the accelerometers were then collected by a twelve-channel acquisition system of the type of NI 9234C Series dynamic signal acquisition module that transforms analogue signals into digital. To control the obtained time histories, the Fourier amplitude spectra and the acquisition of data, a personal computer with special software was used. The recorded data sets consisted of time histories of acceleration with duration of 100 seconds, with sampling of 2000 s/sec.

For post-processing and analysis of the recorded vibrations, the ARTeMIS computer program was used. It consists of an ARTeMIS Testor, in which the geometry of the tested structure is generated and the data sets from the tests are applied and ARTeMIS Extractor that processes the data and provides possibilities for their good graphic presentation by simulation of mode shapes of vibration.

4. DISPOSITION OF MEASURING POINTS

During the dynamic tests on the monastery complex, the measuring points were selected in accordance with the realistic possibilities for placement of the accelerometers. There were selected points on the windows, points on the domes and on the roof as well as points on the floor by which a sufficient number of high quality data was obtained for definition of the dynamic characteristics.

In the following figures, the measuring points and generated geometry is presented for each building. The measuring points of the church were placed on the outer points of the walls of all four facades, the altar, the roof (cupolas), and the floor, as shown in the geometry of the church generated in the Artemis program in Figure 9. The reference point was point R, placed high on the inner wall of the church, in which 2 accelerometers were placed for measuring the vibrations in transverse and longitudinal direction. Including the points on the floor of the church, the total number of measuring points was 24. A total of 23 tests were carried out.

The measuring points in the dining room were placed at the outer points on the walls, on all four sides, as shown in Figure 10 of the geometry of the structure generated in the Artemis program. At reference point, two accelerometers were placed to measure vibration in transverse or longitudinal direction. On the floor, 3 points were measured. A total of 12 tests were carried out, with a record length of 100 sec. Figure 11 presents the geometry of the monastery home. For this building, 15 measuring points were used and 14 tests performed in order to obtain high quality data.
Figure 9. Generated geometry of the church and position of the measuring points

Figure 10. Generated geometry of the dining room and position of the measuring points

Figure 11. Generated geometry of the monastery home and position of the measuring points
Figure 12 presents the Artemis model of the oven and the bell tower, respectively. For these 2 buildings, 6 and 11 measuring points were used and 5 tests for each structure were performed.

![Artemis model of the oven and the bell tower](image1)

5. EXPERIMENTAL RESULTS

5.1 Experimental results obtained for the church

The recorded data from the measurements made in both orthogonal directions for the church were processed in a frequency range of 0-25 Hz. The obtained spectrum of dominant frequencies is shown in Fig. 13 and their values are shown in Table 1 together with the damping coefficients.

The natural frequency of the church in transverse direction is $f=4.98\text{Hz}$, while in longitudinal direction, it is $f=6.74\text{Hz}$. Torsion has the frequency of 7.80Hz.

The mode shapes of vibration during the first two dominant frequencies are shown in Figures 14 and 15. It is obvious that the church has a complex form of vibration, due to its playful geometry and architecture, as well as the partial discontinuities in the construction, i.e., the existence of certain damages and cracks in the walls.

![Spectral density curves and peak picking of dominant frequencies for the church](image2)
Table 1. The dominant frequencies and damping coefficients for the church

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>Damping coefficients [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.98</td>
<td>2.3</td>
</tr>
<tr>
<td>6.74</td>
<td>1.2</td>
</tr>
<tr>
<td>7.8</td>
<td>-</td>
</tr>
<tr>
<td>8.8</td>
<td>-</td>
</tr>
<tr>
<td>9.27</td>
<td>-</td>
</tr>
<tr>
<td>11.1</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Figure 14. Mode shape of vibration for the church at frequency f=4.98Hz

Figure 15. Mode shape of vibration for the church at frequency f=6.74Hz

5.2 Experimental results obtained for the dining room

The obtained spectrum, i.e. the peak-picking of dominant frequencies for the dining room is shown in Fig. 16 and their values are shown in Table 2. Although structural damage and cracks were obvious in the dining room, the frequency of the fundamental mode in the longitudinal direction, which is equal to $f = 5\text{Hz}$, can be distinguished from shapes of vibration at the other dominant frequencies, Fig. 17. The frequency of torsion, $f = 9.0\text{Hz}$, is also relatively clear. In transverse direction, there is no clearly defined shape of vibration of the structure as a whole, and there are separate more intense vibrations at some frequencies of parts of the walls.
Figure 16. Spectral density curves and peak picking of dominant frequencies for the dining room in both orthogonal directions

Table 2. Dominant frequencies of the dining room

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
</tr>
<tr>
<td>6.7</td>
</tr>
<tr>
<td>9.0</td>
</tr>
<tr>
<td>12.9</td>
</tr>
</tbody>
</table>

Figure 17. Mode shapes of vibration for the dining room in longitudinal direction (f=5.00Hz, f=6.7Hz), and torsion (f=9.0Hz, f=12.9Hz)

5.3 Experimental results obtained for the monastery home

The obtained spectrum for the monastery home is shown in Figure 18, with selected dominant frequencies. Table 3 shows the values of these frequencies, as well as the damping coefficients expressed as a percentage of the critical damping.

The natural frequencies of the monastery home are clearly expressed: in the transverse direction \( f = 4.98\text{Hz} \), in the longitudinal direction \( f = 7.72\text{Hz} \), while torsion has the frequency of \( f = 9.18\text{Hz} \). The corresponding mode shapes are presented in Figure 19.
Figure 18. Spectrum of dominant frequencies obtained by analysis of data from the measurements on the monastery home made in both orthogonal directions

Table 3. Dominant frequencies of the monastery home

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>Damping coefficients [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.98 (transversal dir.)</td>
<td>2.4</td>
</tr>
<tr>
<td>6.64</td>
<td></td>
</tr>
<tr>
<td>7.72 (longitudinal dir.)</td>
<td>2.1</td>
</tr>
<tr>
<td>8.40</td>
<td></td>
</tr>
<tr>
<td>9.18 (torsion)</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Figure 19. Shapes of vibration for the monastery home - transversal direction, longitudinal direction and torsion

5.4 Experimental results obtained for the oven

The obtained spectra for the oven in the frequency range 0-25 are shown in Figure 20, while the values of the dominant frequencies and the damping coefficients are given in Table 4.

In order to obtain a clear representation of the natural frequencies of the main structure, an analysis of the data was made without taking into account the chimney measurement point and the corresponding spectrum is shown in Figure 20 (right). In this way, the stack of the chimney is clearly defined, that is, the frequencies associated with its vibration as a substructure.

According to the defined values of the frequencies and the analysis of the shapes of vibration presented in Figure 21, the following is stated:
- The natural frequencies of the oven are: f=11.0Hz and f=12.0Hz, while the torsion has a frequency of 15.0Hz. The chimney, as a substructure, has a natural frequency of 7.23Hz;
- Since the oven as a structure is in contact with the monastery home, i.e., it is not a free-standing structure, the orthogonality of the modes is not clearly expressed, although the structure generally has a symmetrical square shape.
Figure 20. Spectrum of dominant frequencies obtained by analysis of data from the measurements on the oven with all measuring points - left, without the point on the chimney – right

Table 4. Dominant frequencies of the oven

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>Damping coefficients [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.23 (chimney)</td>
<td>1.0</td>
</tr>
<tr>
<td>7.8 (oven)</td>
<td>-</td>
</tr>
<tr>
<td>11.0 (oven)</td>
<td>1.9</td>
</tr>
<tr>
<td>12.0 (oven)</td>
<td>2.1</td>
</tr>
<tr>
<td>15.0 (oven, torsion)</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 21. Mode shape of vibration for the oven, f= 7.8 Hz – influence of monastery home, longitudinal direction

5.5 Experimental results obtained for the bell tower

The obtained spectrum of the vibrations of the bell tower in the frequency range 0-25 is given in Figure 22. Table 5 shows the values of the dominant frequencies, as well as the values of the corresponding damping coefficients. The values of the natural frequencies are: \( f = 3.91 \text{Hz} \) for the transverse direction, \( f = 5.71 \text{Hz} \) for the longitudinal direction, and \( f = 6.7 \text{Hz} \) for the torsion. The mode shapes are presented in Figure 23 and in the transverse direction the mode is clearly expressed.

Although there is a visible crack at the contact wall of the bell tower and the home, there is nevertheless an influence of the frequencies of the home on the vibrations of the bell tower. This is more pronounced in the vibrations in longitudinal direction, as can be seen from the shape of vibration given in Figure 23.

In the higher parts of the bell tower where there is no longer contact with the neighboring structures, the torsion is distinguished by larger amplitudes at its frequency.
Figure 22. Spectrum of dominant frequencies obtained for the bell tower

Table 5. Dominant frequencies of the bell tower

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>Damping coefficients [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.91 (transversal dir.)</td>
<td>1.4</td>
</tr>
<tr>
<td>5.47</td>
<td>-</td>
</tr>
<tr>
<td>5.71 (longitudinal dir.)</td>
<td>-</td>
</tr>
<tr>
<td>6.7 (torsion)</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Figure 23. Mode shapes of vibration of the bell tower in transversal direction, longitudinal direction and torsion

6. CONCLUSIONS

- Experimental in-situ testing of the historical structures of the monastery complex “Treskavec” was performed with the objective of obtaining the dynamic characteristics, 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 structure.

- The church has a complex form of vibration, due to its playful geometry and architecture, as well as the partial discontinuities in the construction, i.e., the existence of certain damages and cracks in the walls. The natural frequency of the church in transverse direction is $f=4.98$ Hz, while in longitudinal direction, it is $f=6.74$ Hz. Torsion has the frequency of 7.80 Hz. General conclusion is that the global integrity of the church is solid.
• In the dining room, despite the evident extensive structural damage and the presence of cracks, the frequency of the fundamental mode in the longitudinal direction can be distinguished, as well as the frequency of torsion.

• The natural frequencies of the monastery home are clearly expressed, in transverse direction $f=4.98\text{Hz}$, in longitudinal direction $f = 7.72\text{Hz}$, while torsion has the frequency of $9.18\text{Hz}$.

• For the oven structure the orthogonality of the modes is not clearly expressed, as a result of the contact with the monastery home. The chimney has its own natural frequency.

• All the structures within the monastery complex are placed next to each other, although they are built in different periods of time. So, due to the existence of greater or lesser contact between each other, in the shape of vibration, especially in the oven and the bell tower, the influence of the neighboring structure, i.e. there are effects of mutual interaction. This is easily noticeable in the animations of the mode shapes at certain frequencies.

• General conclusion, except for the dining room, is that the global integrity of the structures is solid. The obtained dynamic characteristics represent a good basis for verification of the mathematical models to be used for analysis of these structures.

7. REFERENCES


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