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Article

Ambient Vibration Testings and Field Investigations of Two Historical Buildings in Europe

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Abstract: In this study, the methodology and results of ambient vibration-based investigations of the historical Tash Mosque in Kosovo and a 3-story historical building in Bulgaria are presented. The investigations include full-scale *in situ* testing of both structures due to ambient vibrations induced by micro-seismic, wind, traffic, and other human activities. To this aim, Ranger seismometers and Kinemetric products were used. Measurements were performed in both horizontal directions in several points along the structures' height utilizing a high-speed data acquisition device. All recorded data have been analyzed and processed by the software developed at IZIIS, and then the processed data were used as input for modal analysis. The basic assumption is that the excitation can be considered as a stationary random process to have a relatively flat spectrum. The paper clearly describes the procedure used for investigations and presents the dynamic properties of the whole structures. The investigated structures are both historical buildings and defined as architectural heritage and the outcome of this study including the natural vibration frequencies and mode shapes) can be very beneficial for the verification stage of the analytical/numerical models for future retrofitting/rehabilitation schemes.

Keywords: Ambient vibrations; natural frequencies; mode shapes; damping; FFT analysis; EFDD; historical building

1 Introduction

The dynamic analysis of structures is mainly based on the idealized models simulated in nonlinear platforms under the influence of ground shakings, winds, impact loads, and other extreme vibrations. One of the main steps in such analyses is to verify the simulated models through experimental works. The experimental investigations can be full-scale ambient or forced vibration testing to calibrate and update the finite element (FE) models. Both techniques can be used to identify the dynamical properties of the structures including frequencies of vibration, damping ratios, and mode shapes [1–6].

The ambient vibration-based techniques deal with the linear behavior of structures and infrastructure. The reason is mainly due to the small amplitude of vibrations considered in this approach. This approach can be used for structural health monitoring of damaged structures and developing time and amplitude-dependent models. The use of this technique for partially damaged structures and the cultural heritage is of considerable interest among both researchers and practitioners. The main advantage of the ambient vibration-based method is that the number of operators and equipment is considerably smaller compared to forced vibration-based experiments. The sources of excitation can be micro-seismic, wind, and other local periodic sources [7–13].

This experimental "*in situ*" testing method has a very wide application in civil and structural engineering, where it is essential to obtain the identity card of the structure taking into account all dynamic characteristics. So, by using this non-destructive method, the fundamental dynamic characteristics for the structure can be obtained, such as natural frequencies and corresponding mode shapes, as well as damping in each mode, without altering their normal operation. The outcome will contain valuable parameters and important information which leads to the correlation of experimental and analytical results as a confirmation for accurate mathematical model formulation [14–18].

In the last decade, data acquisition devices and sensors were significantly improved and the analog procedure has been replaced by digital techniques that are more computationally efficient and accurate compared to previous ones. To this, the application of ambient vibration testing has been significantly highlighted and all types of structures and infrastructure can be tested by this approach. The Institute of Earthquake Engineering and Engineering Seismology—IZIIS from Skopje has a very long experience in the field of ambient vibration testing starting from 1978 where hundreds of tests were performed during the period [19–23].

The subject of this paper is to determine the dynamic properties of the Tash Mosque (Stone Mosque) and a 3-story historical building (Masonry materials) both in Europe, based on ambient vibration measurements data conducted on these structures. It should be pointed out here that for many of the modern rehabilitation/retrofitting of structures and infrastructure, the linear theory of elasticity is considered by consultants and engineers. Hence, the outcomes of such investigations are of great importance to calibrate and verify the various assumptions involved in constructing the numerical models of these historical structures.

2 Investigated Structures

2.1 Tash Mosque in Pristina, Kosovo

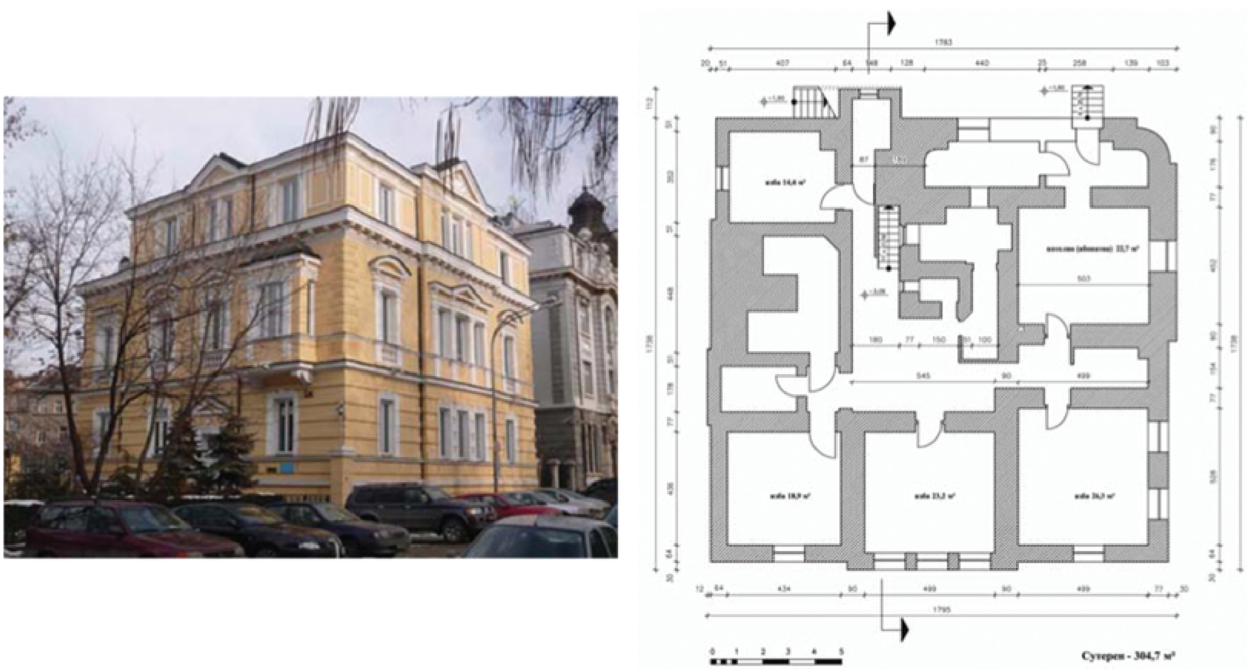
Tash Mosque, which is also known as Carshise Mosque, is located in the center of Pristina, Kosovo, at the intersection of Agim Ramadani Street, Ibraim Lutfiu Street, and Zejnel Salihu Street (Fig. 1). It represents a very old mosque that origins from the early 15th century. In fact, this is the first mosque that was started to be built in Kosovo by the Ottoman Sultan Bayazid, right after the famous Kosovo battle in 1389. The mosque has a square layout of 13.20 m × 13.20 m, with a total height, at top of the dome, of approximately 14.72 m. The dome has an inner radius of 5.20 m, and a height of approximately 4.0 m. The dome is supported on a tambour, which has a height of 1.50 m. The base of the tambour is at level 9.25 m. On the South-West side, there is a porch having dimensions of 4.95 m × 13.55 m in the plan, and a height of approximately 9.0 m at the roof level.

2.2 Historical Masonry Building in Sofia, Bulgaria

The building is a massive three-story construction, a typical representative of the building tradition from the late 19th century. The vertical load-bearing elements consist of a stone foundation and exterior walls in the basement, and brick load-bearing walls which are 60 cm thick (2 'old size' bricks) in the basement and 45 cm thick (1 and a half 'old size' bricks) on the floors. The bricks used to build the walls are size 7/14/28, with a compressive strength of at least 7.5 MPa. There are bonds on the cross walls and the masonries which have been done with lime mortar solution whose compressive strength is at least 2.5 MPa. The building is located at 17, Moskovska Street, in the center of Sofia, Bulgaria (Fig. 2).

(a) (b)

Figure 1: Tash Mosque in Pristina, Kosovo a) 3D model b) Real structure



(a) (b)

Figure 2: a) Photo of the investigated building in Sofia b) The basement plan

3 Field Procedures

Ambient vibration of the investigated structures has been conducted using standard equipment for such purposes, which is composed of:

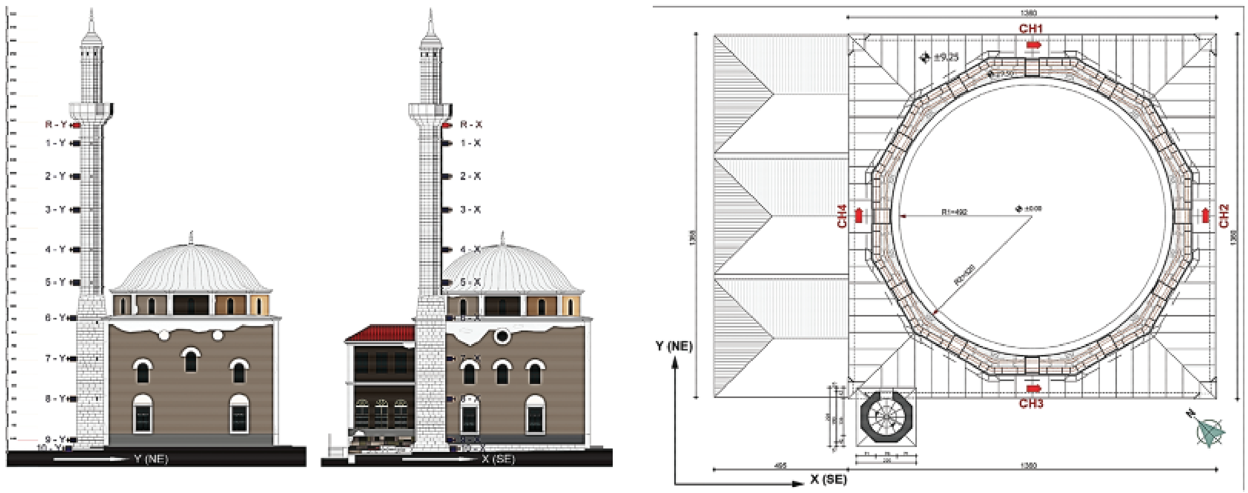
- Seismometers–Kinemetrics SS-1 Ranger Seismometer (total of 4 for each investigation). A detailed description of the device and its properties are given in the Appendix (Fig. 3)
- Signal conditioner–Kinemetrics SC-1 conditioner for SS-1 (Fig. 4)
- System for data acquisition - NI DAQPad-6015 Portable High-Performance Multifunction DAQ for USB 16 analog inputs at up to 200 kS/s,16-bit resolution, Input range ±0.05 V to ±10.0 V (Fig. 4)

Figure 3: Used seismometer in the investigations

Figure 4: Ambient vibration measurements equipment (Left to right: Power supply, Kinemetrics SC-1 conditioner, NI DAQPad-6015, Laptops for recording data)

The measurement points were located as specified by the measurement protocol. It is checked that the selected sites shall not be exposed to steady vibrations generated by eccentric or other rotary steady-state influences. In such cases, the frequencies of the transients shall be determined to be filtered out when records are processed.

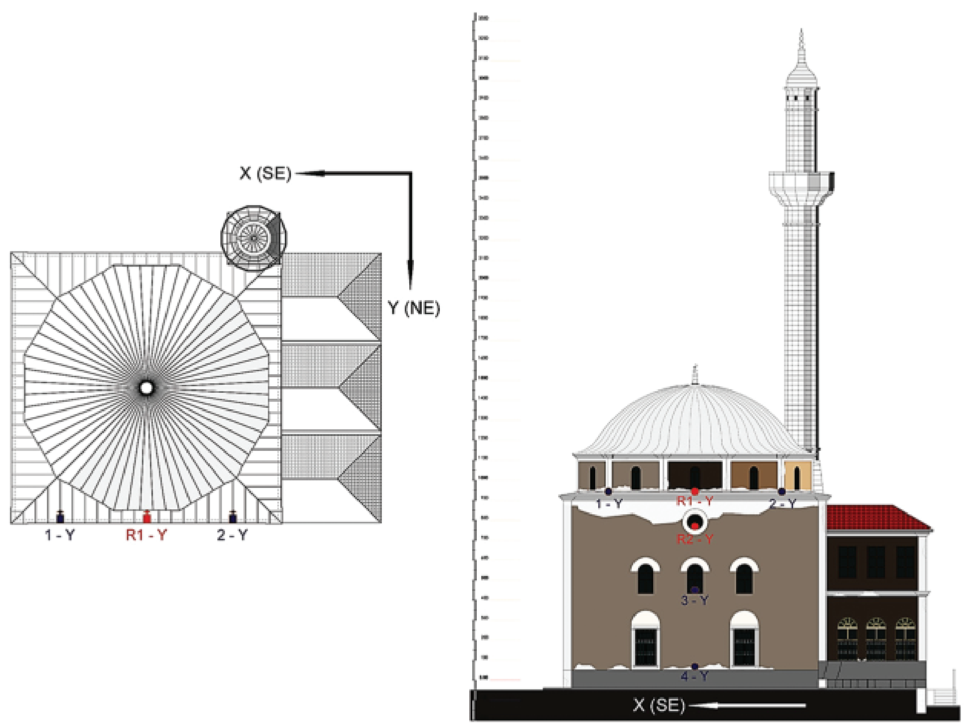
Measurements of the Tash mosque minaret have been conducted in both orthogonal X and Y directions simultaneously. Two Reference SS-1, one in each direction, were positioned at level 23.5 m, and they remain fixed for the whole time of the measurements. The other two, SS-1, were placed on 10 different measuring points along the height of the minaret. A total of 10 measurements have been done. Positions of Reference and measuring points in both SE and NE direction, along the height of the minaret, are given in Fig. 5(a). For the mosque structure, two types of measurements have been done. The first one has been done positioning all four SS-1 at the level of 9.25, as it is shown in Fig. 5(b).



(a) (b)

Figure 5: Instrumentation schemes for the a) Minaret b) Mosque level 9.25

The other measurement was done on the NE facade of the mosque displacing two SS-1 at fixed points along the height, while keeping the other two SS-1 as Reference, as it is shown in Fig. 6. For this case, two measurements have been done.



(a) (b)

Figure 6: Instrumentation scheme for the mosque a) NE façade b) Plan view

In all cases, for minaret and the mosque, each measurement has been done for a duration of 200 s, acquiring data at 200 S/s (samples per second).

Field observations indicated that the mosque main building has both types of structural and non-structural damages. Some of the observed damages on the SE side of the structure are illustrated in Fig. 7. The damages have been the cracking in the main structure and the façade, and some deteriorations in first and second story columns which may lead to the partial or complete collapse of the structure.

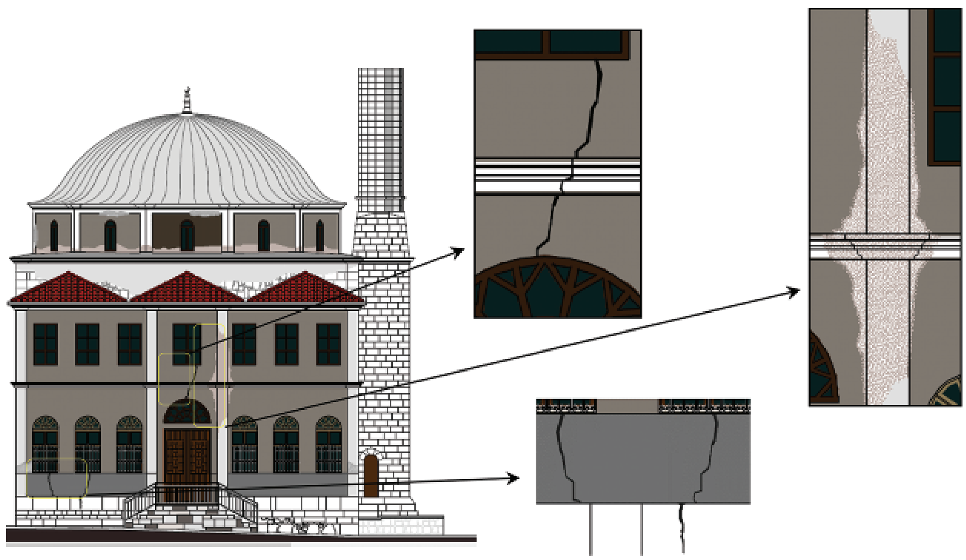


Figure 7: Visible cracking and damages on the SE side of the Tash Mosque

For the second investigated structure in Bulgaria, the ambient vibration measurements have been conducted on the ground, first and second floors separately. Measurements on the roof structure have not been done due to the access restrictions.

Measurements of each floor have been conducted in both orthogonal X (NW-SE) and Y (NE-SW) directions simultaneously. Two reference SS-1 one in each direction were positioned at SE corner on the first floor, and they remain fixed for the whole time of the measurements. The other two, SS-1, were displaced on 10 different measuring points at the corners of the ground and second floors. A total of 10 measurements has been done.

Positions of reference and measuring points on the 2^{nd} floor are given in Fig. 8.

Filed observations and the inspection of the building indicated that the existing trimmer joists do not have the necessary strength characteristics to bear the additional envisaged load of the heavy insulating glass. The most appropriate procedure to secure the envisaged reconstruction is to support the trimmer joists in the basement with a steel frame where the two insulating glass panels touch. The beam should be at least 1.0 m long with a cross-section of 2P No. 12 to support at least two wooden beams. The columns should be positioned around the boiler room separating wall. The insulating glass needs to have a steel frame, P 40 mm, which should be anchored into the walls and the floor with tie-rods.

The detailed internal and external inspection of the building did not find any visible deformities or damages caused by an earthquake, collapse or some other factor that could jeopardize the building's safety.

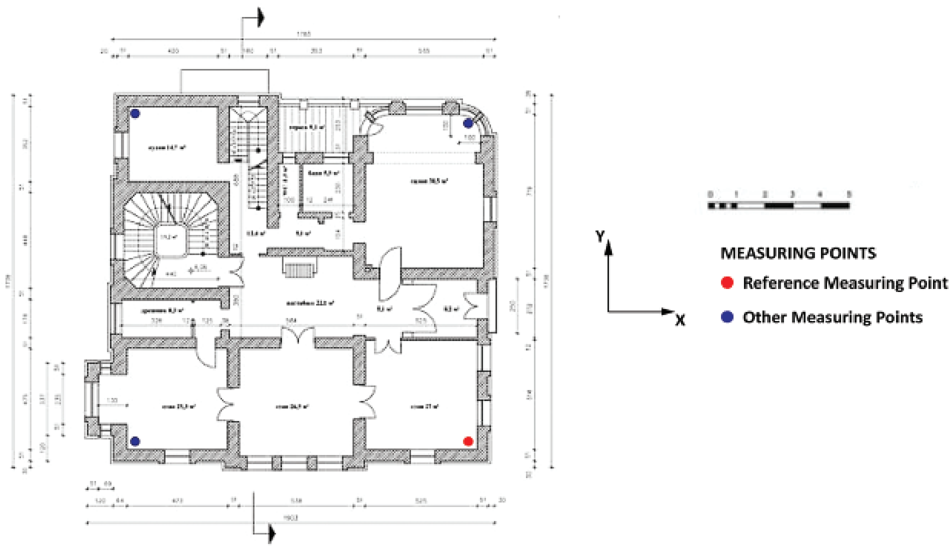


Figure 8: Positions of reference and measurement points on the second floor

4 Data Processing

4.1 FFT Analysis to Determine the Dominant Frequencies

In order to roughly estimate the natural vibration frequencies of the minaret, preliminary analysis of the conducted ambient vibration measurements have been done by applying Fast Fourier Transform (FFT) to all measured channels. For this purpose, a Zoom FFT technique has been used to analyze the frequency spectra of stationary signals. This approach has higher accuracy and is more computationally efficient compared to the standard FFT technique. The procedure will focus on a narrow band of the frequency spectrum with high-frequency resolution [24–26].

4.1.1 First Case Study: Tash Mosque (Minaret and Level 9.25)

Plots in form of RMS averaged Zoom Fourier Magnitude Spectra of recorded velocity response histories of Reference channels, as well as channels at all measuring points along the height of the minaret for X and Y directions, are depicted in Fig. 9. It is very clear that the first mode vibration frequency of the minaret is around 0.94 Hz in both X and Y direction. Higher natural frequencies can be distinguished around 4.0 Hz and 5.0 Hz.

The same procedure of data processing and presenting was done for the Mosque. Plots in form of RMS averaged Zoom Fourier Magnitude Spectra of recorded velocity response histories of all four channels positioned at Level 9.25 on the mosque in X and Y direction are presented in Fig. 10. It is very clear that the first translational natural frequencies of the mosque are around 4.0 Hz and 5.0 Hz, while torsional values are around 6.50 Hz and 7.3 Hz. From the FFT Magnitude Spectrum, it is visible that in the response for CH1, CH2, and CH3 the first natural frequency of the minaret of around 0.95 Hz is detected as well.

4.1.2 Second Case Study: Historical Building in Bulgaria

It is very clear from Fig. 11 that the first natural frequency in the X direction is around 2.68 Hz, in Y direction 2.84 Hz, while the first torsional frequency is around 3.38 Hz. Higher natural frequencies can be distinguished around 6.0 Hz and 10.0 Hz.

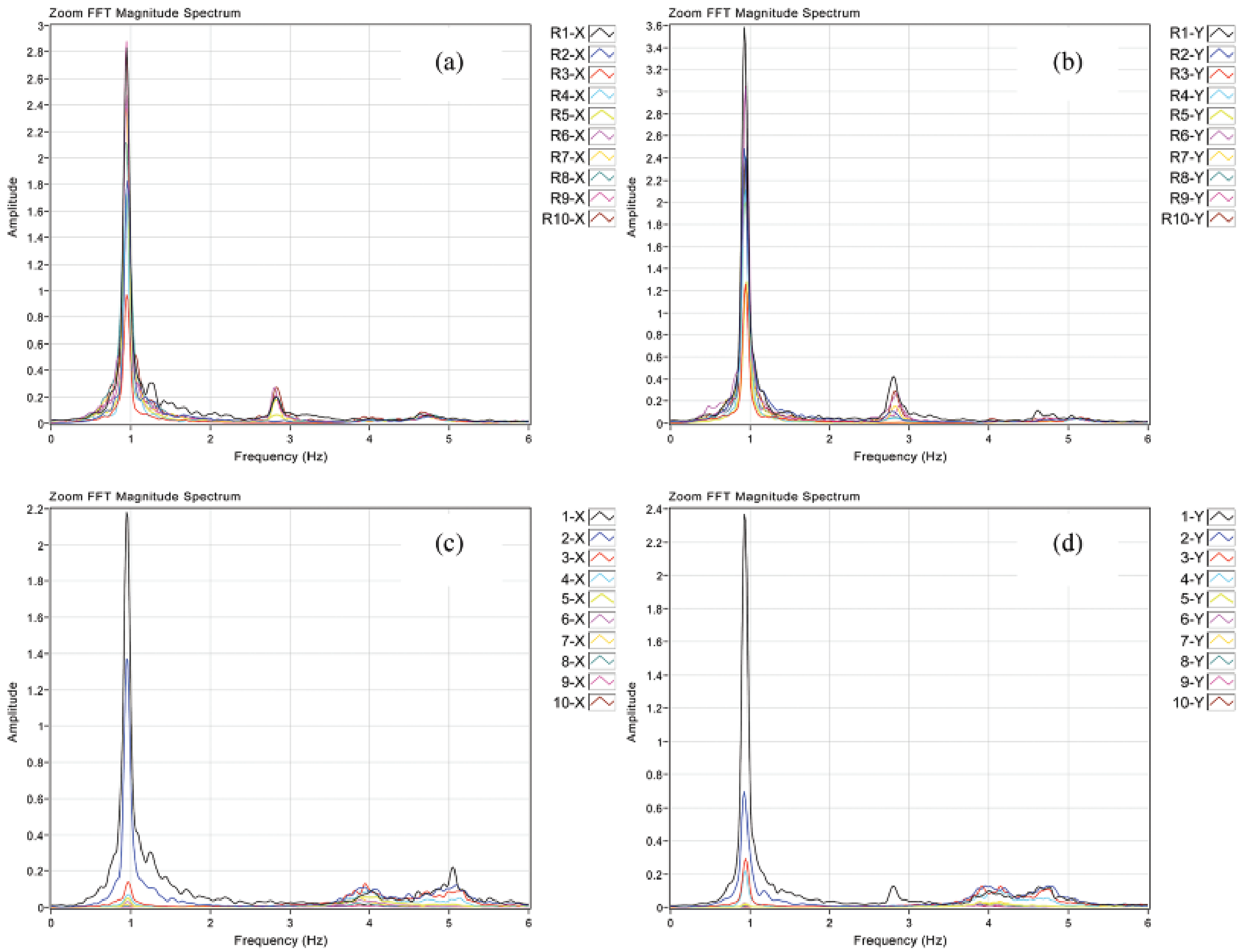


Figure 9: Minaret-FFT amplitude spectra of all measured channels in X and Y directions a & b) Reference channels; c & d) channels at measuring points along the height

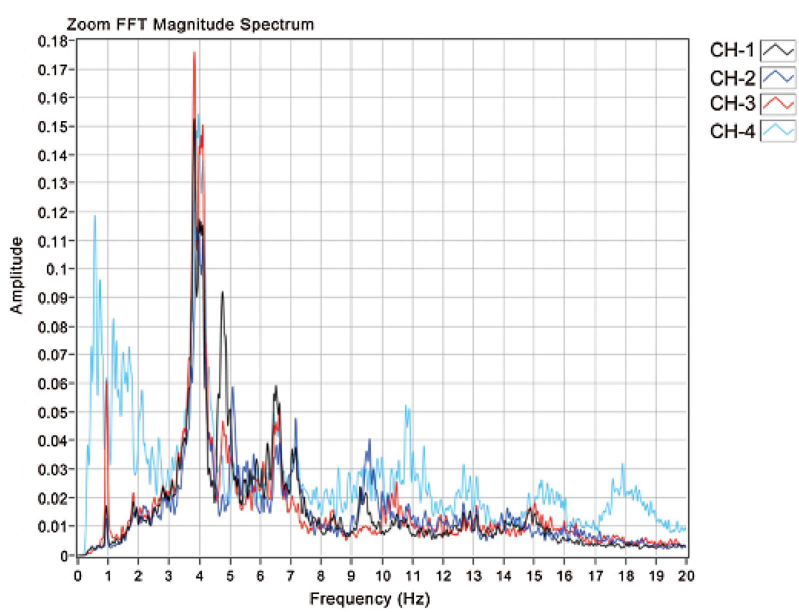


Figure 10: Mosque-level 9.25-FFT amplitude Spectra of all measured channels in X and Y directions

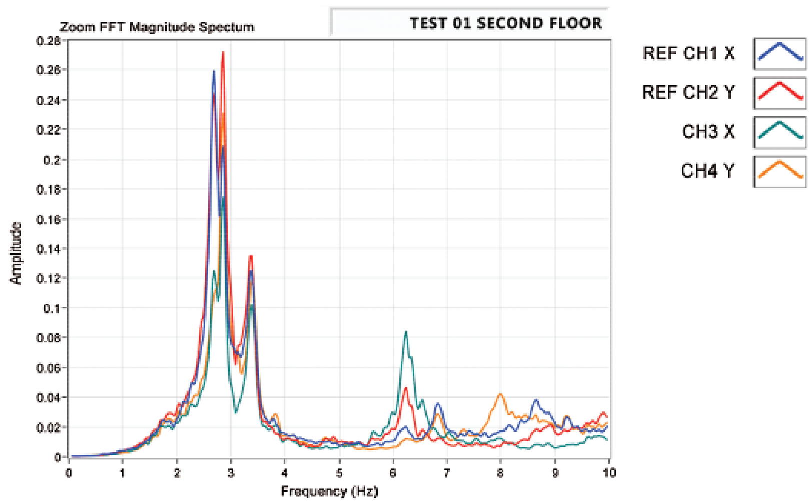


Figure 11: FFT magnitude spectrum up to 10 Hz for the second floor (All channels in X and Y directions)

4.2 Enhanced Frequency Domain Decomposition

The processed data were used as input for ARTeMIS Extractor Pro, commercial software for operational modal analysis developed by Structural Vibration Solutions A/S from Denmark, by which the fundamental dynamic characteristics of the tested structure have been estimated more accurately based on the Peak Picking technique and the Enhanced Frequency Domain Decomposition (EFDD) technique with a graphical presentation of the data [27,28].

The FDD is a non-parametric technique which is an extension of the peak-picking technique. The method is mainly focused on the fact that the vibration modes can be estimated based on the condition of white noise input and from signal processing calculations. The relationship between the input and the output can be defined based on the formulation given in Eq. (1).

$$\left[G_{yy}(\omega)\right] = [H(\omega)]^{*}[G_{xx}(\omega)][H(\omega)]^{T} \tag{1}$$

Both input (G_{xx}) and output (G_{yy}) matrix are in terms of Power Spectral Density (PSD). [H(ω)] is denoting the matrix of the Frequency Response Function (FRF), where * and T superscripts represent the conjugate and transpose matrix respectively. After using a Singular Value Decomposition (SVD) technique, the output PSD matrix can be simplified as follows:

$$\left[G_{yy}(\omega)\right] = [\Phi][\Sigma][\Phi]^{T} \tag{2}$$

where [Σ] represents the SV matrix, and Φ is the matrix of approximated individual mode shapes.

In the current study, an improved version of the FDD technique, known as Enhanced FDD (EFDD) is used. The EFDD is based on auto and cross-correlation functions. The estimated mode shapes by this technique have much higher accuracy compared to standard FDD [29].

4.2.1 First Case Study: Tash Mosque (Minaret and Level 9.25)

Fig. 12 presents generated geometry of the Minaret structure by the computer program ARTeMIS with the presentation of 11 measuring points during "*in-situ*" testing by ambient vibration method for X and Y directions respectively.

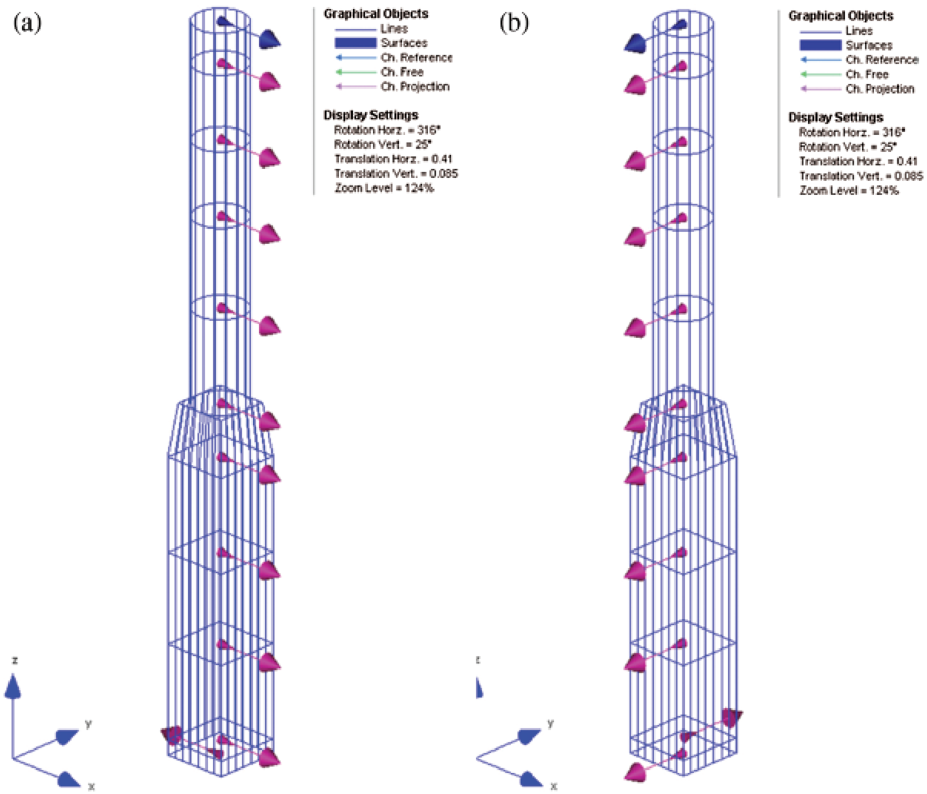


Figure 12: Minaret–Distribution of measuring points for all connected channels a) X-Direction, b) Y-Direction

A total number of 88 tests have been performed. The obtained dominant frequencies using the EFDD technique are given in Figs. 13 and 14, while for the damping coefficient the values are presented in the next section for X and Y directions. The equivalent viscous damping during the ambient vibrations can be estimated by using the half-power point method. This way of determining the damping is based on the assumption that the wind and micro-tremor excitations are nearly stationary during the experimental measurements.

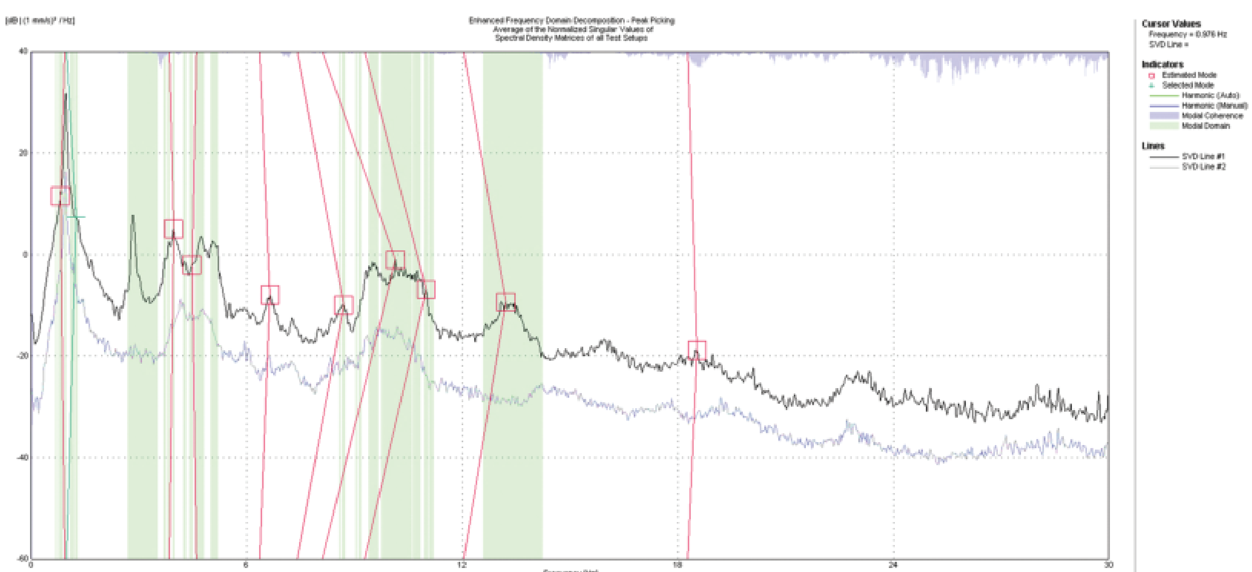


Figure 13: Peak picking of the dominant frequencies in the X direction (EFDD)

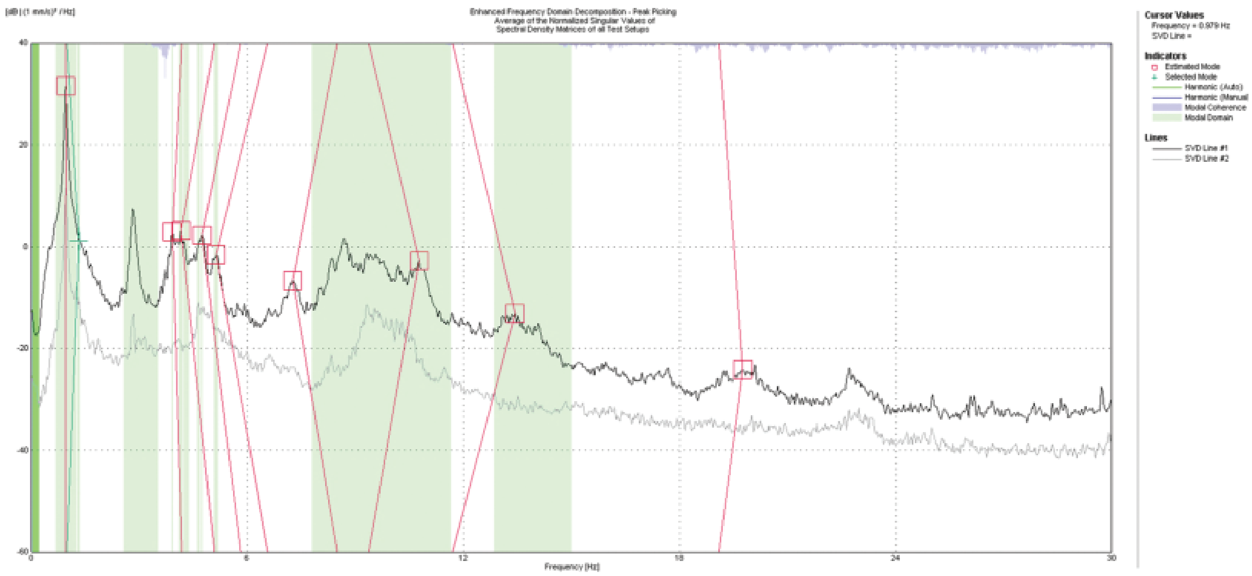


Figure 14: Peak picking of the dominant frequencies in the Y direction (EFDD)

The first natural vibration frequency in the X direction is 0.92 Hz, while in Y direction is 0.94 Hz. The second natural frequencies are 3.83 Hz and 4.17 Hz in X and Y direction respectively. The simulated mode shapes of the Minaret are presented in Fig. 15. Considering the shape of vibrations, the Minaret structure is vibrating in an expected way considering the geometry and plan of the structure itself.

The corresponding damping coefficients for the first mode are 2.04% in the X direction and 1.95% in the Y direction, while for the second mode it is increased and the values are 2.83% and 2.43% in the X and Y directions respectively. The ambient vibration results are presented in Tab. 1.

Fig. 16 shows the distribution of measuring points and Peak picking of the dominant frequencies in X and Y directions. In Figs. 17 and 18 dominant translational and torsional mode shapes of the Mosque on level 9.25 m are presented. The values for the frequencies and corresponding damping ratios are given in Tab. 2.

4.2.2 2nd Case Study: Historical Building in Bulgaria

The simulated model of the 2nd investigated structure with 11 measuring points in both horizontal directions for ambient vibration testing in ARTeMIS is depicted in Fig. 18. Two degrees of freedom have been assigned to each measuring point in X and Y directions.

The obtained dominant frequencies using the EFDD technique are given in Fig. 19, while for the damping coefficient the values are presented in Tab. 3. As noted, the half-power point method has been used to estimate the equivalent viscous damping during the testing procedure.

The first and second natural vibration frequencies in horizontal directions were determined as 2.68 and 2.84 Hz respectively. The vibration frequency for the torsional mode is estimated at 3.37 Hz. The simulated mode shapes of the building are presented in Fig. 20. As the geometry of the investigated structure is nearly symmetrical, the vibration mode shapes are estimated as expected.

The error percentage of the estimated frequency by developed software and the results by EFDD techniques are illustrated in Fig. 21, which shows good conformity between the two approaches.

The results of this study can be used for FE model updating which might be manual or automated. The main part is to perform a sensitivity analysis to indicate the most influential parameters. The most uncertain parameters which should be considered in modeling and analyzing the historical structures are the modules of elasticity, mortar characteristics, and the stone or masonry density. The results of such studies can be very beneficial for both researchers and practicing engineers [30–33].

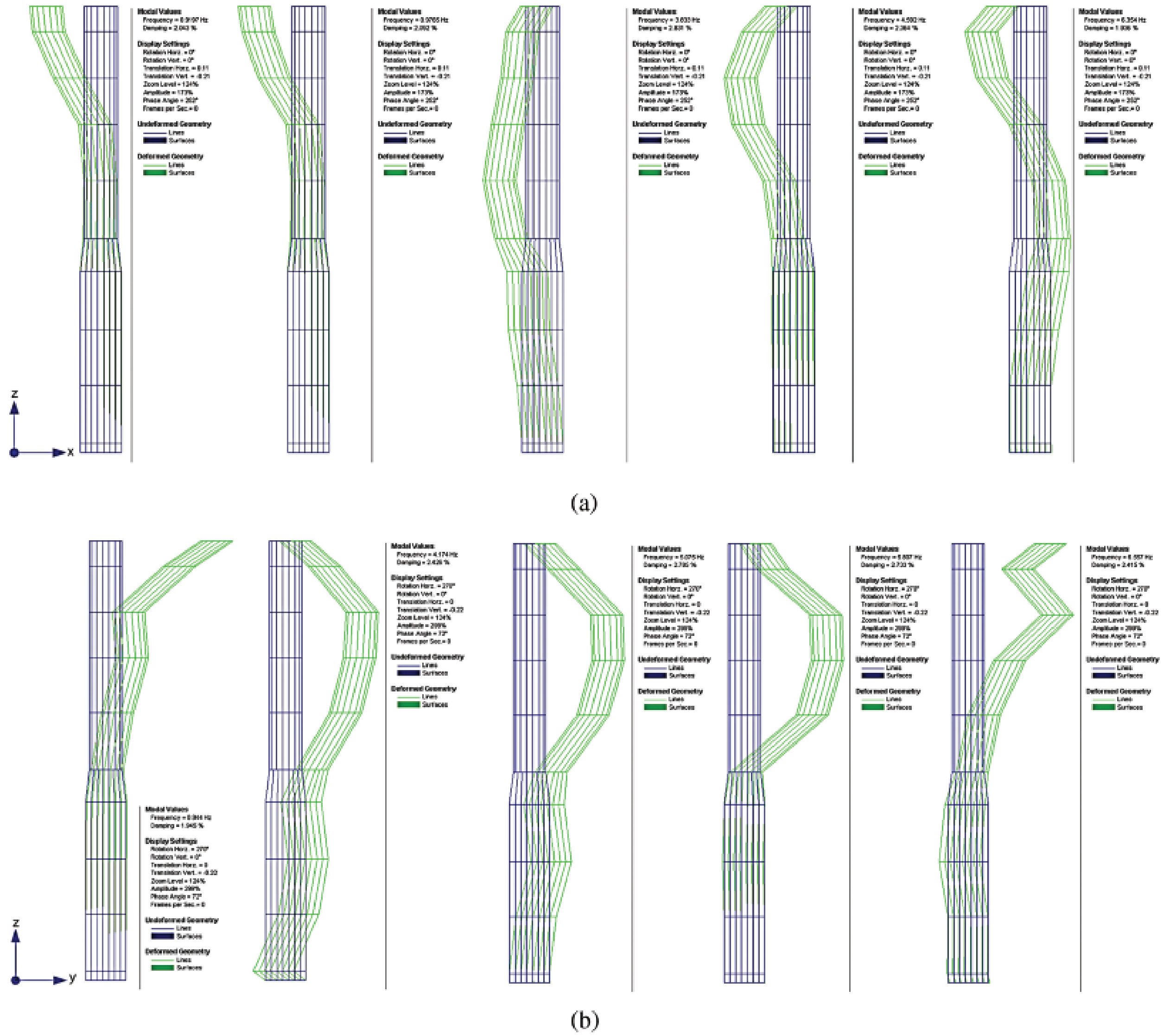


Figure 15: Minaret–Mode shapes: Dominant modes of vibrations a) X-Direction, b) Y-Direction

Table 1: Minaret natural frequencies and damping ratios for corresponding EFDD modes in X & Y directions

Mode	X-Direction		Y-Direction	
	Frequency [Hz]	Damping ratio [%]	Frequency [Hz]	Damping ratio [%]
Mode 1	0.92	2.04	0.94	1.95
Mode 2	3.83	2.83	4.17	2.43
Mode 3	4.59	2.36	5.08	2.79
Mode 4	6.35	1.94	5.81	2.73
Mode 5	7.40	1.93	6.56	2.42
Mode 6	8.10	2.09	8.49	2.77

Table 1 (continued).

Mode	X-Direction		Y-Direction	
	Frequency [Hz]	Damping ratio [%]	Frequency [Hz]	Damping ratio [%]
Mode 7	9.28	1.78	9.36	4.07
Mode 8	12.04	2.50	11.69	3.82
Mode 9	18.27	0.99	19.09	1.05

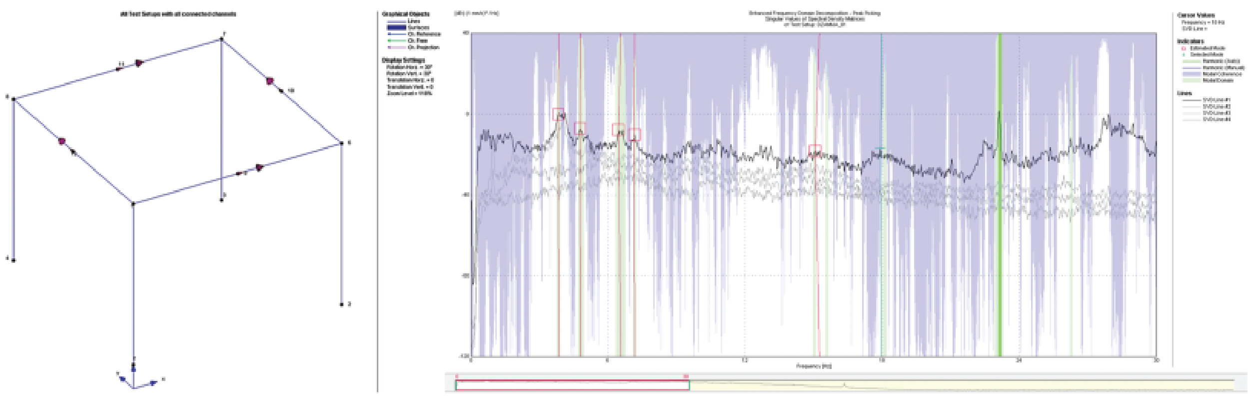
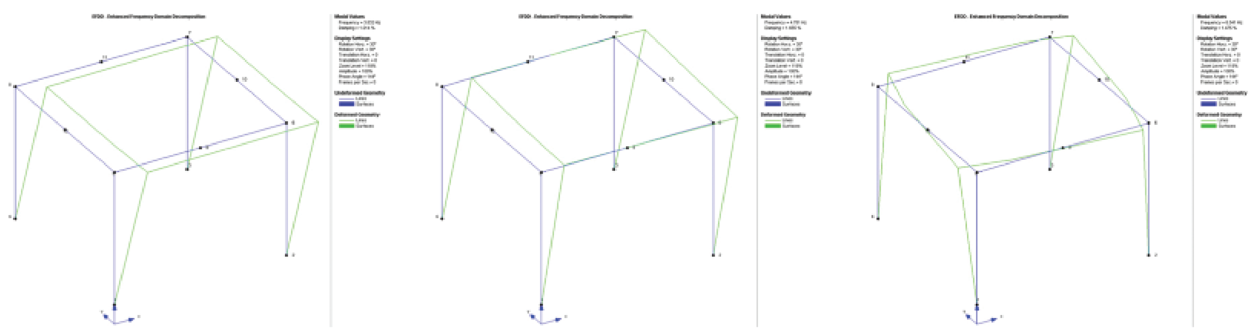


Figure 16: Distribution of measuring points and Peak picking of the dominant frequencies in X and Y directions



(a) (b) (c)

Figure 17: Translational modes in X and Y directions and Torsional mode (Mosque-Level 9.25) a) 1st Mode [Trans.] b) 2nd Mode [Trans.] c) 3rd Mode [Tor.]

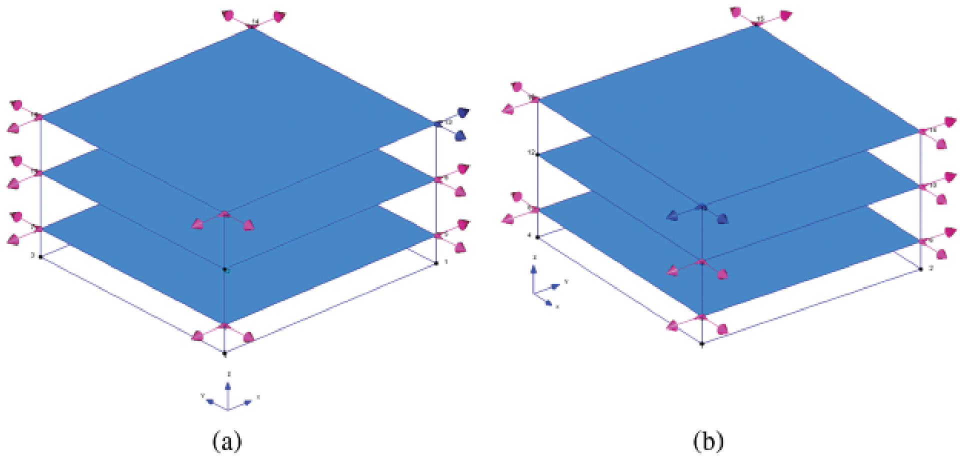


Figure 18: Test setup of all connected channels (2nd Case Study) a) X-Direction b) Y-Direction

Table 2: Natural vibration frequencies and damping ratios for corresponding modes **(**Mosque-Level 9.25**)**

Mode	Frequency [Hz]	Damping ratio [%]
Mode 1	3.82	1.02
Mode 2	4.78	1.66
Mode 3	6.54	1.48
Mode 4	7.16	0.62
Mode 5	15.25	0.10
Mode 6	17.97	2.13

Figure 19: The median of EFDD normalized values of spectral density matrices for all test setups in X and Y directions (2nd case study)

Table 3: Natural frequencies and damping ratios for corresponding modes (2nd case study)

Mode	Frequency [Hz]	Damping ratio [%]
Mode 1	2.68	1.63
Mode 2	2.84	2.09
Mode 3	3.37	1.74
Mode 4	6.24	1.74
Mode 5	6.99	1.77
Mode 6	8.09	0.47
Mode 7	9.41	0.46
Mode 8	10.54	0.47
Mode 9	21.76	0.45
Mode 10	25.11	0.56

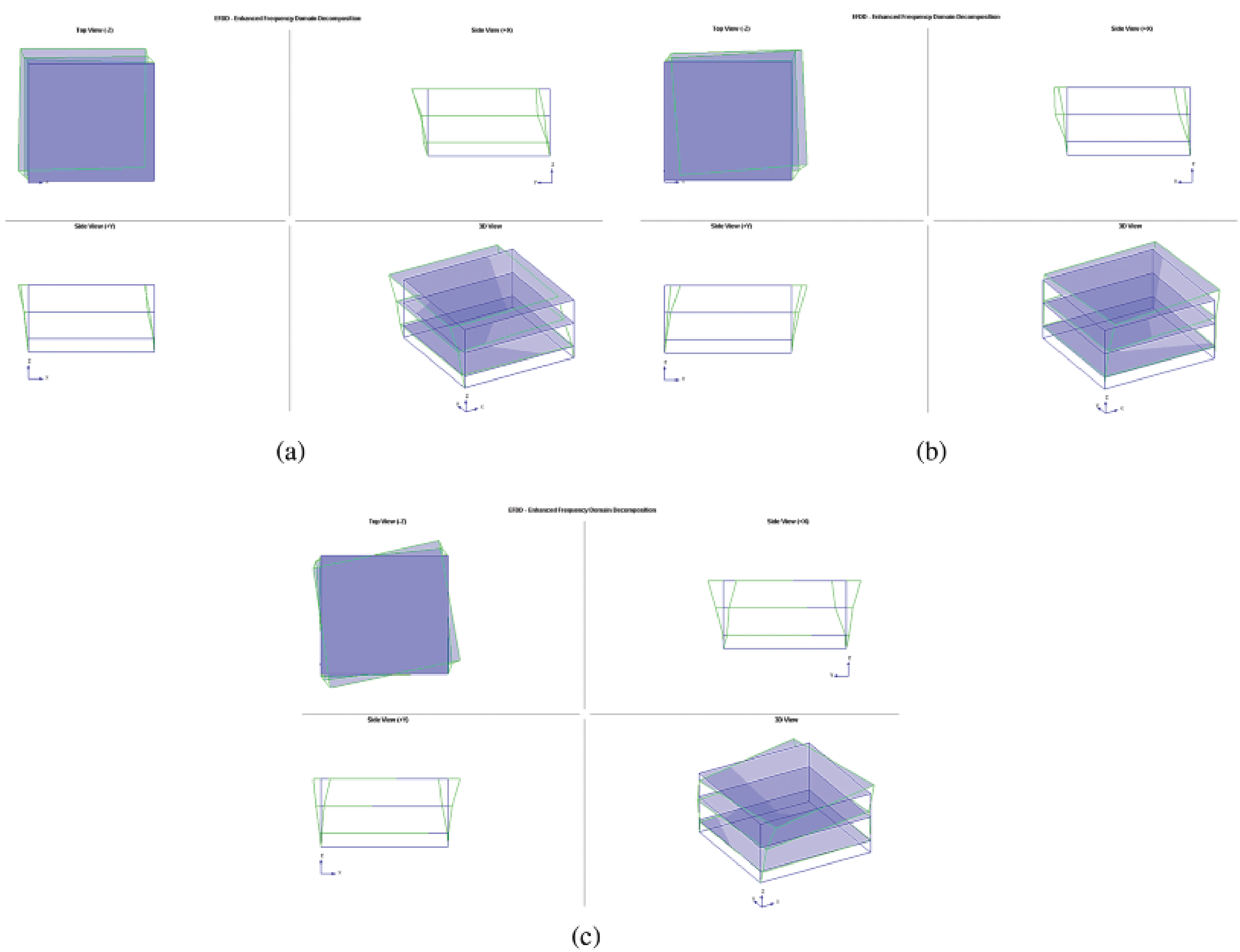


Figure 20: Fundamental translational and torsional mode shapes (2nd case study) a) X-Direction, b) Y-Direction, c) Z-Direction

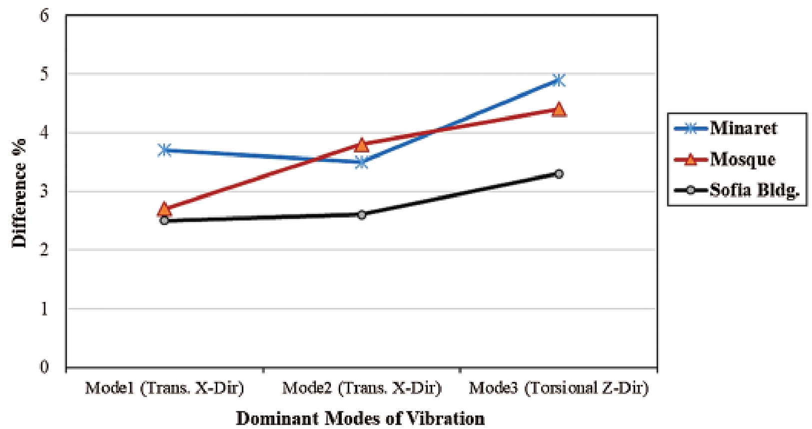


Figure 21: Error % in estimating the dominant frequencies by the developed software and the EFDD technique

5 Conclusions

This paper has presented the methodology for experimental "*in-situ*" testing by ambient vibration tests of two historical buildings in Kosovo and Bulgaria. This approach has been used more than 50 years to define the dynamic characteristics of special structures in terms of mode shapes, damping, and the resonant frequency.

To this aim, preliminary analyses have been conducted using the Zoom FFT technique. For the 1st structure which has been a Mosque, the first natural frequency of the minaret has been around 0.9 Hz in both X and Y directions, while for the mosque structure at Level 9.25 m, the dominant frequencies have been around 3.83 Hz, 4.78 Hz and 6.54 Hz. for translational (X&Y) and torsional modes respectively. For the 2nd investigated structure, which has been a historical building in Bulgaria, the dominant translational frequencies in X and Y directions and the torsional mode frequency values were determined as 2.68 Hz, 2.84 Hz, and 3.37 Hz respectively. The frequency and damping values related to each mode of vibration were calculated according to the EFDD technique as well. In all three cases, A very good agreement was found between natural frequencies obtained from preliminary analysis using the FFT technique (by using the developed software) and the enhanced frequency domain decomposition technique. The maximum difference has been less than 5% in all cases. The obtained results have been in the expected boundaries and correspond with valuable information about the conditions of the investigated structures.

As a conclusion, it can be noted that obtained dynamic characteristics by *in-situ* ambient vibrations represent a very good and comprehensive base for verification of the numerical models of the structures and evaluation of their seismic behavior for possible rehabilitation schemes in the future. The estimated values of vibration frequencies, mode shapes, and damping ratios can be utilized for updating the future finite element models, through the adjustment of the modulus of elasticity of the elements.

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Appendix A

The specifications of the implemented instrumentations in this study are given in Tab. 4. These devices have been the product of Kinematics Inc., and are recognized as excellent short-period field seismometers in the world. The main feature of these devices is their adaptability to be used for both horizontal and vertical directions by simple adjusting of the mass centering spring. The accuracy of these devices have been proved in the previous seismological observations for nuclear power plants, high-rise buildings, dams, and offshore structures.

Table 4: Specifications of the used seismometers

Technical specifications	
Nominal Natural Period:	1 sec.
Weight of Mass:	1.45 kg
Mass Travel:	+/–1 mm
External Resistance for 70% of critical damping:	Approximately equal to coil resistance
Calibration Coil Resistance:	150 Ω
Calibration Coil Motor Constant:	0.4 newtons per ampere (nominal)
Transducer Coil Options:	Transducer Coil–5000 ohms (nominal)
	Approximate Generator Constant V/(m/s)–345
	Approximate CDR at 1 sec.–6530
Physical characteristics	
Housing:	Watertight case
Operating temperature:	–40° to 70° C (–40° to 160 F)
Size:	305 mm × 140 mm diameter (12" × 5.5")
Weight:	5.0 kg (10.9 lbs)