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AMBIENT VIBRATION TESTS AT "CAROL I" ROYAL MOSQUE IN CONSTANŢA, ROMANIA

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ABSTRACT

The paper presents ambient vibration measurements performed at the "Carol I" Royal Mosque in Constanţa, Romania. The mosque built in 1910-1913 is one of the first constructions using reinforced concrete in Romania. It has an RC dome (reaching a top height of 26.3 m) supported by masonry walls and columns and a ~40m height RC minaret, probably one of the oldest RC minarets in the world. Large earthquakes are expected from Vrancea subcrustal source in Romania and from shallow sources in Bulgaria: Dulovo, Shabla and Gorna. The long-term climatic aggression had a negative impact on the structure, water infiltrations having a significant damaging effect on the concrete and on the reinforcement. Seismic, wind and climatic actions and material degradation are threatening the mosque and its safety. Ambient vibration measurements were performed with 1-second velocity sensors. The mosque architecture did not allow extensive sensors disposals. The presented results focus on the minaret structure. The identified spectral peaks indicate stable dynamic characteristics in all measurements and sensors disposal layouts. As expected, the frequencies corresponding to peak spectral amplitudes on two orthogonal horizontal measurement directions show minor/negligible differences. The first modal periods of the minaret identified from ambient vibration measurements are: T_1=0.42s, T_2=0.26s. The results characterize the minarets' linear dynamic behaviour in case of low-amplitude vibrations. The results are part of a wider study including the mosque seismic evaluation according to the Romanian regulation P100-3/2008 and the minaret seismic evaluation according to the Japanese Standard for Evaluation of Existing Reinforced Concrete Chimneys, 2015.

Keywords: Cultural Heritage; RC Minaret; Ambient Vibration Tests

1. INTRODUCTION

The "Carol I" Royal Mosque is located in Constanţa, in South-Eastern Romania, in the old city centre, close to the Black Sea shore (Figure 1 and Figure 2). It is officially listed as a historical monument in the architecture category and it represents a major cultural asset and a historic proof of the multicultural understanding in Constanţa city inhabited by Romanians, Turks, Bulgarians, Tatars and others. The mosque was built in between 1910 and 1913 and is one of the first non-industrial constructions in Romania with reinforced concrete structural elements (RC construction started in Romania with silos at Brăila, Galaţi and Constanţa in the last decades of 19th century). The long-term climatic aggression had a negative impact on the structure, water infiltrations having a significant damaging effect on the concrete and on the reinforcement. Seismic, wind and climatic actions and material degradation are threatening the mosque and its safety.

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Figure 1. "Carol I" Royal Mosque in old Constanţa city centre (1930's postcard)

The mosque experienced, without significant damage, major and medium size earthquakes originating from the subcrustal Vrancea seismic source in Romania: 1940 (M_W=7.7), 1977 (M_W=7.5), 1986 (M_W=7.2), 1990 (M_W=6.9 and 6.4) and 2004 (M_W=6.0). Modified Mercalli Intensities were estimated (Konrod et al, 2013) in Constanţa as follows: VII in 1940 and 1977, V in 1986, VI and V in 1990 and IV in 2004. The peak ground acceleration was estimated (Pavel et al, 2016) as ~0.1 g in 1940 and 1977. Large earthquakes are potentially expected from Vrancea subcrustal source (M_{max} = 8.1) and from shallow sources in Bulgaria: Dulovo (M_{max} = 7.1), Shabla (M_{max} = 7.8) and Gorna (M_{max} = 7.4).

Figure 2. "Carol I" Royal Mosque in Constanţa (2017 photos)

Ambient vibration tests were frequently used in the last decades for identifying structural modal parameters (Quek et al., 1999, Ivanovici et al., 2000, Wenzel and Pichler, 2005, Giraldo et al., 2009, etc.). The method is applied on a wide typology of constructions: buildings, steel towers, bridges, nuclear power plants, dams, etc. It was also used in case of minarets (Doğangün et al., 2008, , Sezen et al., 2008, Bayraktar et al., 2008, Oliveira et al., 2012, Turkeli et al., 2013, Cakti et al., 2013, etc.).

1.1 "Carol I" Royal Mosque description

The 200 m^2 mosque's prayer hall (Figure 3) has a reinforced concrete dome (Figure 4) reaching a top height of 26.3 m. The dome is supported by masonry walls and large columns.

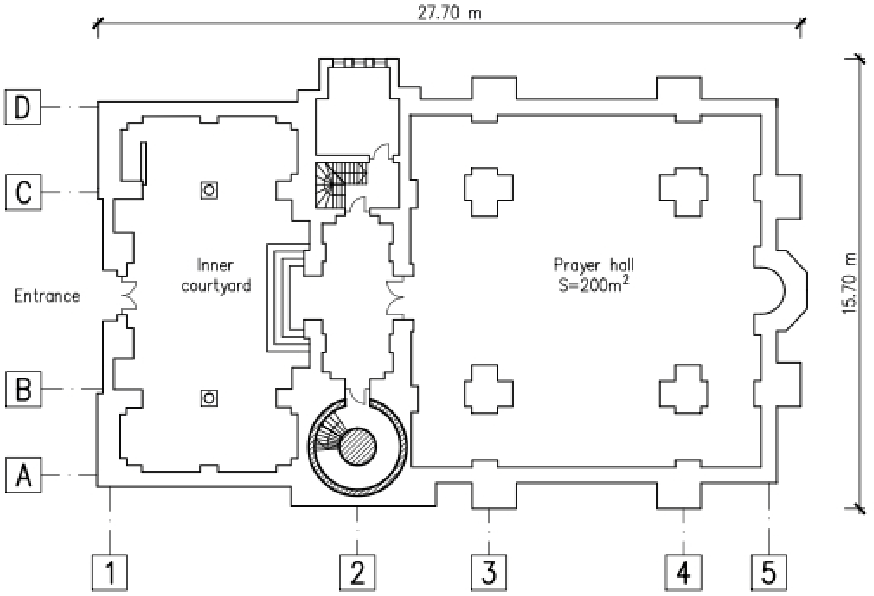

Figure 3. Ground floor layout of "Carol I" Royal Mosque in Constanţa

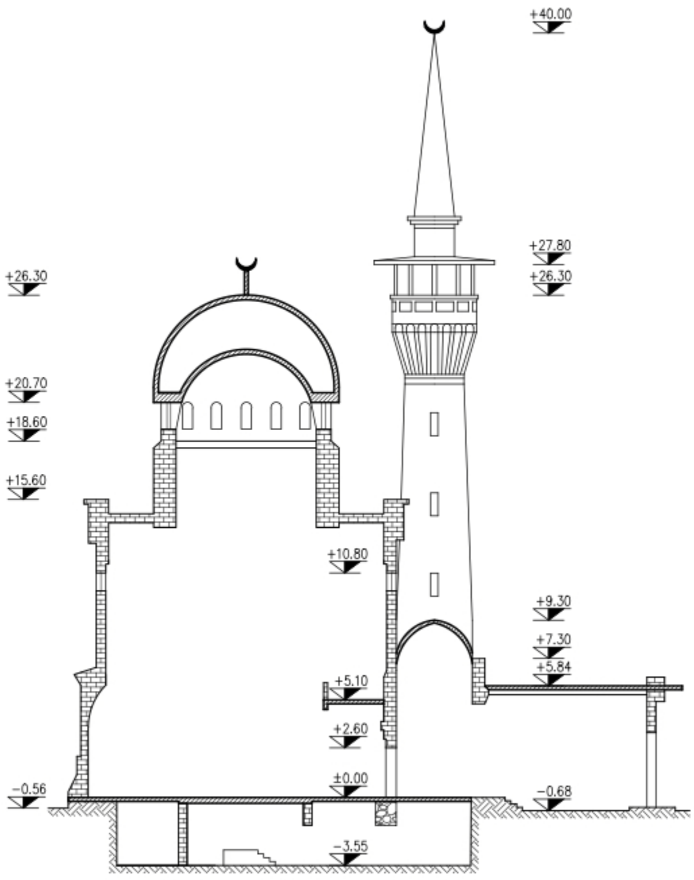

Figure 4. Vertical cross section of "Carol I" Royal Mosque in Constanţa

The mosque has a ~40m height reinforced concrete minaret, probably one of the oldest RC minarets in the world (Figure 5, left). The minaret has a circular shape, with a diameter of ~4m at the base and ~3 m at the balcony level (at 24.8 m). Inside the minaret there is an internal circular reinforced concrete column having a diameter of 1.75 m at the base and 0.64 m at the platform level (Figure 5, right). The minaret's interior spiral staircase goes up to the balcony level. The reinforced concrete staircase is fixed at both ends in the outer minaret wall and in the inner tube. Investigations performed by Beleș (1957) indicated a minaret RC outer wall thickness of 20 cm at the base and 15 cm at the top.

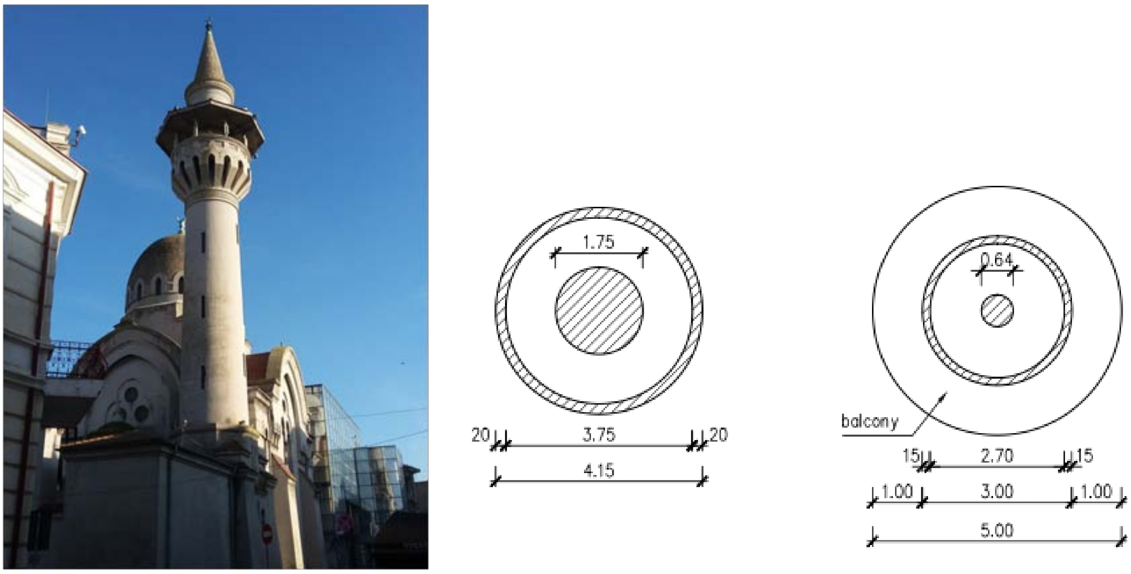

Figure 5. Minaret (left) and minaret cross-sections (right) - "Carol I" Royal Mosque in Constanţa

2. AMBIENT VIBRATION MEASUREMENTS AND ANALYSIS

2.1 Equipment

Ambient vibration measurements were performed as one of the main steps toward the seismic evaluation of the “Carol I” Royal Mosque.

The measurement equipment consisted of a portable 24 bits GEODAS acquisition system and 1-second velocity sensors (with frequency bandwidth 1÷20 Hz) produced by Buttan Service-Tokyo & Tokyo Soil Research Co., Ltd, Figure 6.

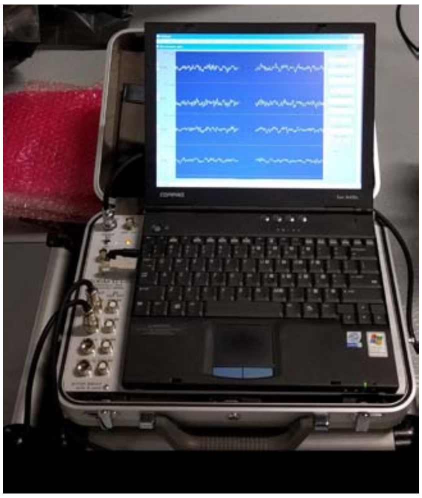

Figure 6. GEODAS acquisition station for ambient vibration measurements

The ambient vibration measurements were performed in May 2017 using 3 to 8 velocity sensors simultaneously. Several sensor disposal layouts were considered. For each measurement layout, two samples of 3 minutes were recorded with a 100 Hz sampling frequency. The mosque architecture did not allow extensive sensors disposals. The results presented in this paper focus on the RC minaret structure. Preliminary results were presented in Aldea et al. 2017 and 2018.

The modal frequencies of the minaret are estimated from ambient vibration time-history records through a Fourier spectral analysis and the Eigensystem Realization Algorithm (ERA) method. The frequency domain approach (Fourier spectra) allows a reasonable estimation of modal characteristics (Iiba et al., 2004, Kohler et al., 2005, Aldea et al., 2007, Demetriu et al., 2012). The ERA method formulated by Juang and Pappa (1985) is presented in (Juang, 1994, Juang et all. 2001). Applications for modal identification of structures are given in (Giraldo,2009, Caicedo, 2011, etc.).

2.2 Sensor layouts 1 and 2

The first two measurement layouts targeted the ambient vibration of the minaret from the base to the balcony level, Figure 7. Pairs of two-sensors were disposed at the basement, mid-height and balcony level and other sensors were placed at intermediate levels. Since the minaret has a circular shape, measurements were made on two orthogonal horizontal directions, and the sensors orientation followed the NS and EW directions. Sensors were located on the RC spiral stair platforms, close to the inner RC tube.

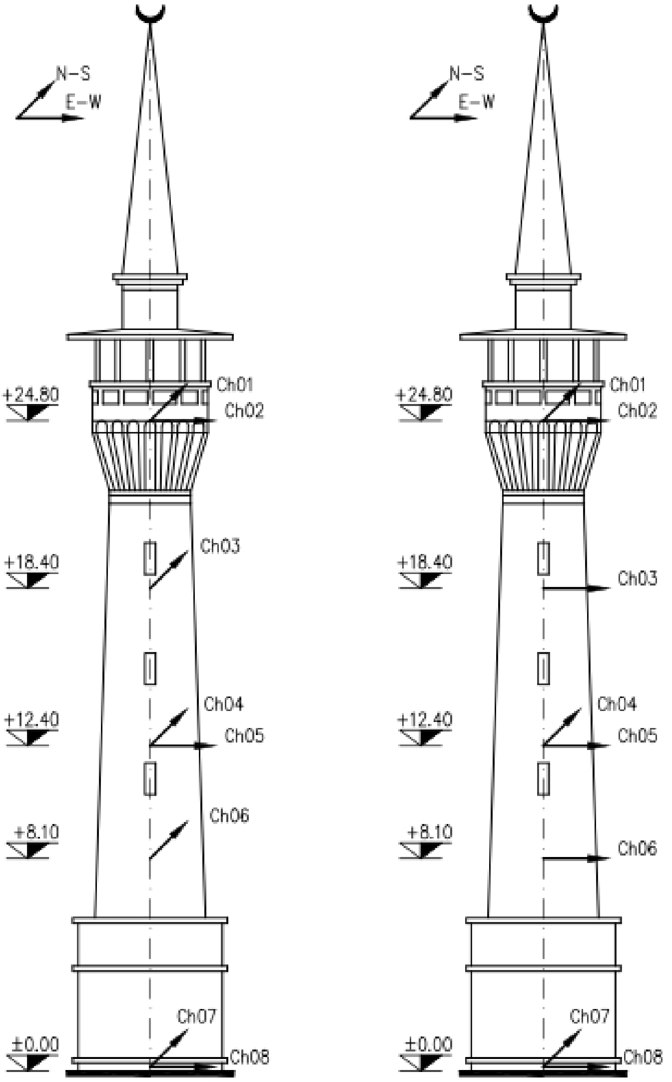

Figure 7. Sensor layouts 1 (left) and 2 (right)

In Figures 8 ÷ 10 are presented the Fourier amplitude spectra of the velocity records obtained in Layout 1 and Layout 2, for the two orthogonal directions and for the two time-history samples (m1 and m2).

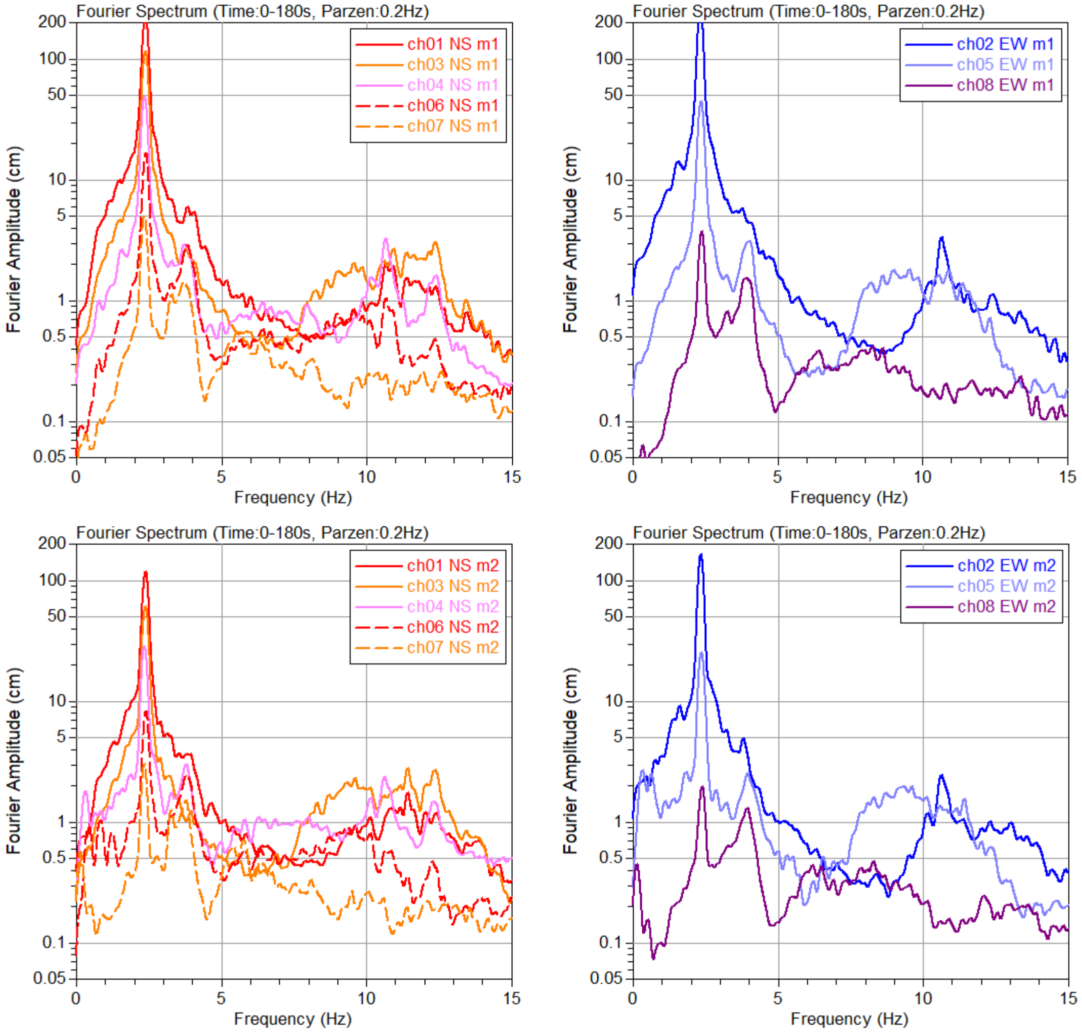

Figure 8. Layout 1, Fourier Amplitude Spectra for NS and EW directions - measurements 1 (m1) and 2 (m2)

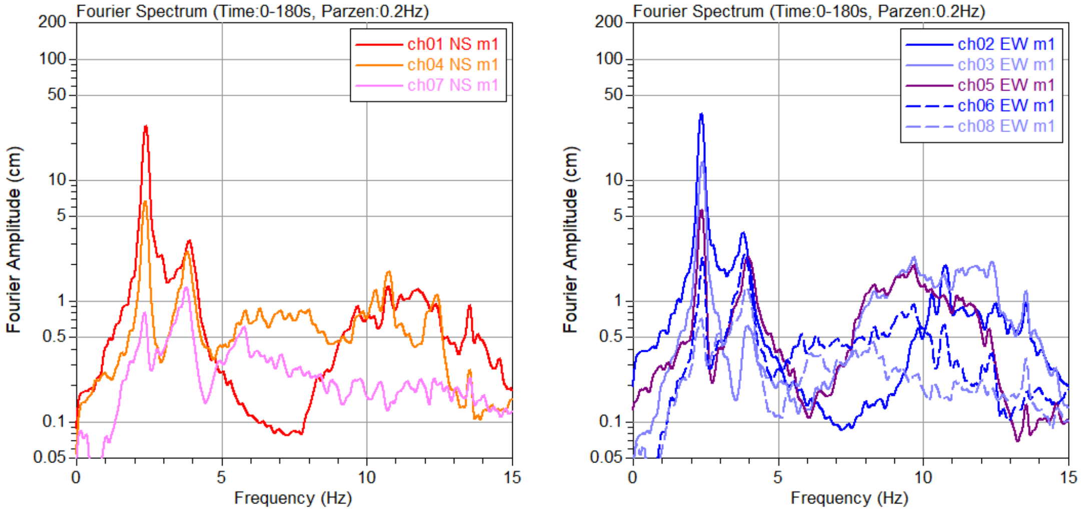

Figure 9. Layout 2, Fourier Amplitude Spectra for NS and EW directions - measurement 1 (m1)

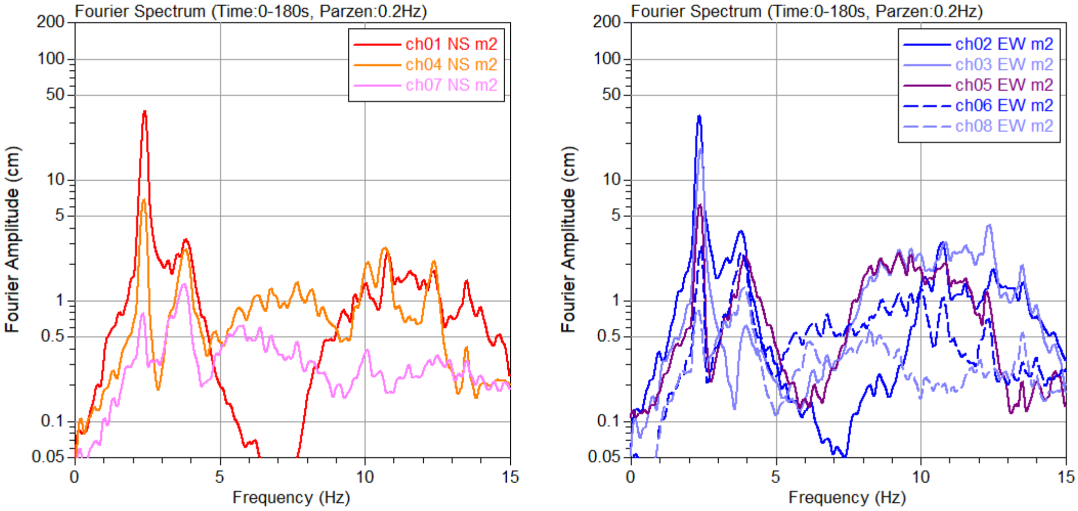

Figure 10. Layout 2, Fourier Amplitude Spectra for NS and EW directions - measurement 2 (m2)

2.3 Sensor layout 3

The 3^{rd} measurement layout targeted the ambient vibration of the minaret at the balcony level, Fig. 11 (left), on the same NS and EW directions. Central sensors were located on the top platform of the RC spiral stair, close to the inner RC column, and the outer sensors were located on the RC belt on the balcony, near the outer RC minaret wall (Fig. 11, right). In Fig.12-13 are presented the Fourier amplitude spectra of the records, for the 2 orthogonal directions and for the 2 time-history samples.

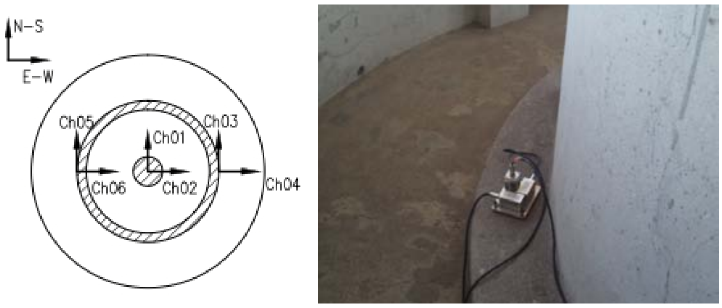

Figure 11. Layout 3 sensors disposal (left), photo of sensors during measurements (right)

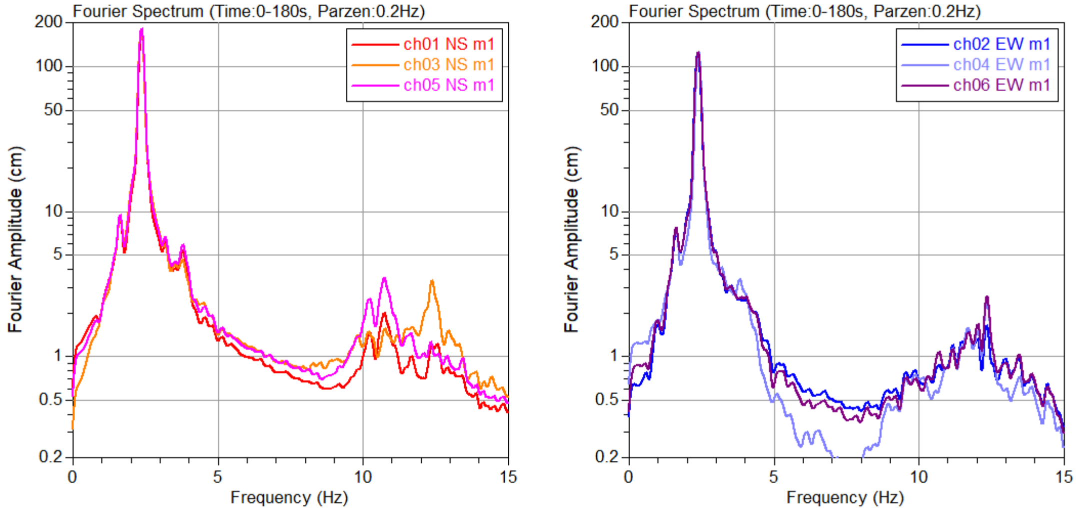

Figure 12. Layout 3, Fourier Amplitude Spectra for NS and EW directions - measurement 1 (m1)

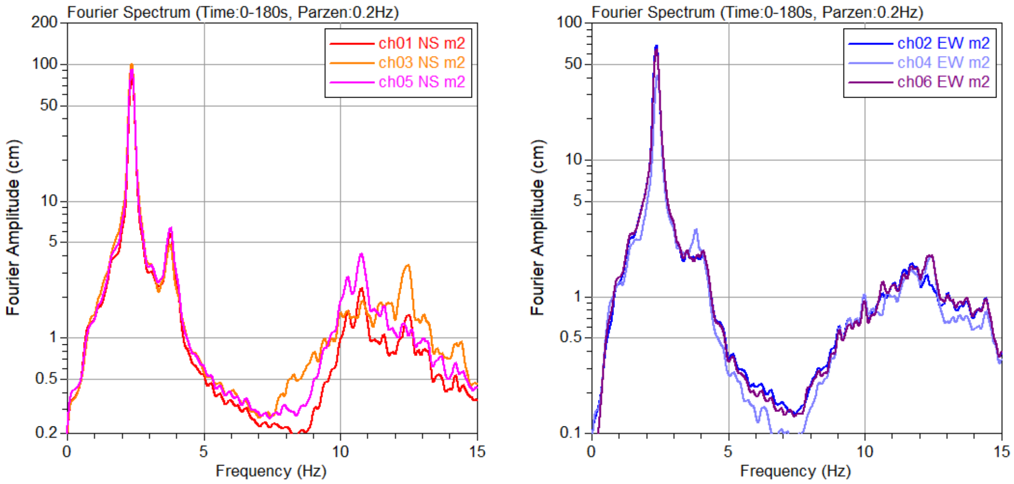

Figure 13. Layout 3, Fourier Amplitude Spectra for NS and EW directions - measurement 2 (m2)

2.4 Sensor layouts 4 and 5

Two measurement layouts focused on the vibration of the minaret in its lower part, Fig. 14 (left), where the RC structure is embedded in masonry, Fig. 14 (right). Measurements were made on the same NS and EW directions. Sensors were located on the RC spiral stair platforms, close to the inner RC tube. In Fig. 15-16 are presented the Fourier amplitude spectra of the velocity records obtained in Layouts 4 (left) and 5 (right), for the 2 orthogonal directions and for the two time-history samples.

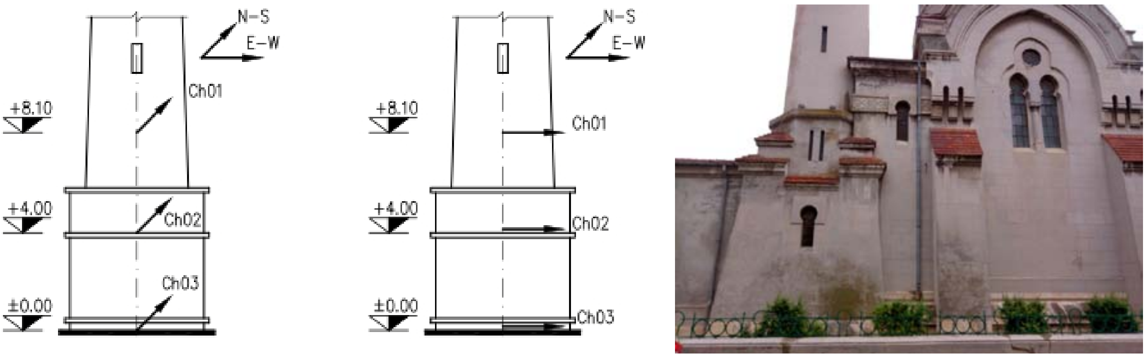

Figure 14. Sensor layouts 4 (left) and 5 (middle), photo of the masonry embedment of the RC minaret (right)

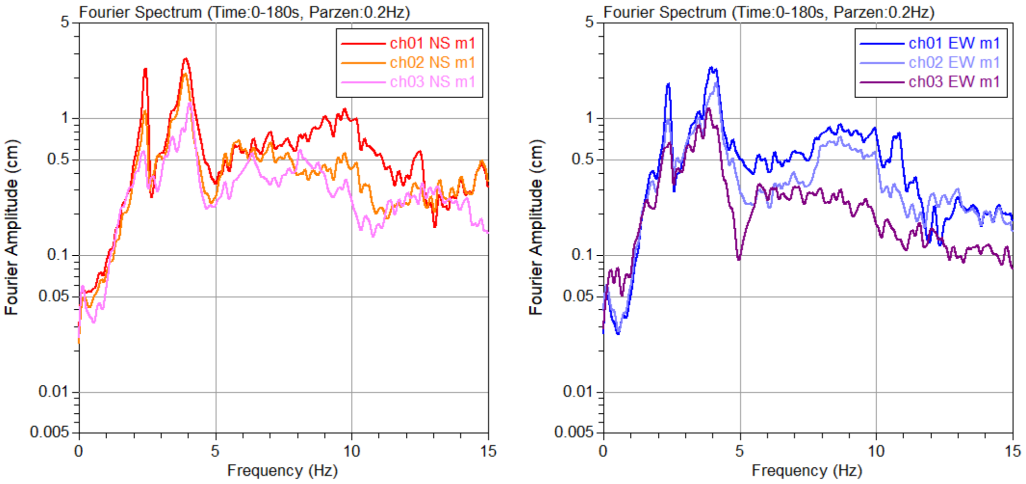

Figure 15. Layout 4 (left) and Layout 5 (right), Fourier Amplitude Spectra for NS and EW directions

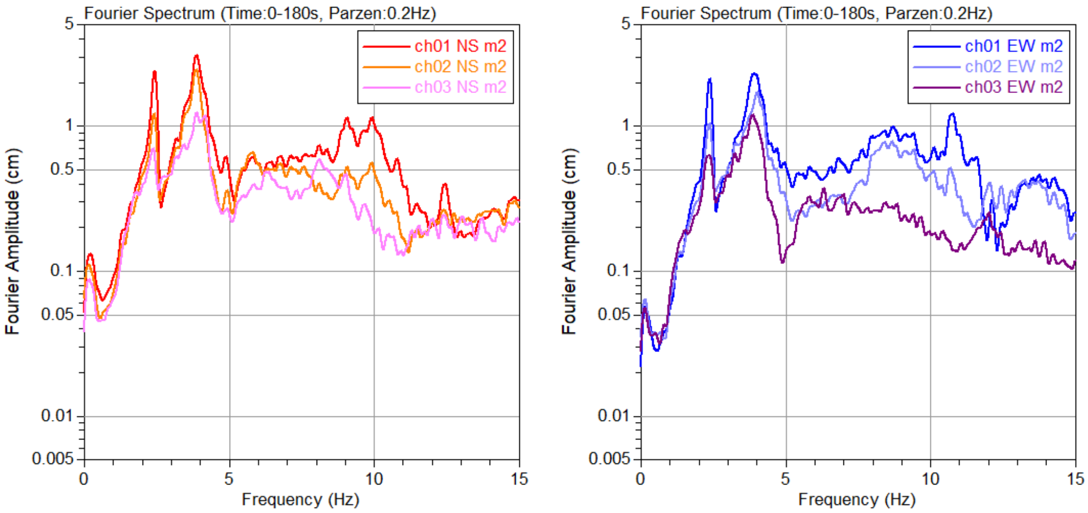

Figure 16. Layout 4 (left) and Layout 5 (right), Fourier Amplitude Spectra for NS and EW directions - measurement 2 (m2)

3. CONCLUDING REMARKS

The identified spectral peaks indicate stable modal characteristics in all sensors disposal layouts and measurements. The frequencies corresponding to peak spectral amplitudes on the two orthogonal horizontal measurement directions show quite small differences. In Tables 1÷4 are presented the average values of the first identified modal frequencies, estimated through the two selected methods.

Table 1. Minaret modal frequencies (average values), NS direction, identified from Fourier spectral analysis

Modal frequencies (average values, Hz)	**f_1**	**f_2**	**f_3**	**f_4**
Layout 1	2.37	3.75	10.44	12.28
Layout 2	2.38	3.81	10.37	12.39
Layout 3	2.37	3.79	10.49	12.43
Layout 4	2.41	3.91		12.41

Table 2. Minaret modal frequencies (average values), EW direction, identified from Fourier spectral analysis

Modal frequencies (average values, Hz)	**f_1**	**f_2**	**f_3**	**f_4**
Layout 1	2.36	3.89	10.58	
Layout 2	2.37	3.89	10.75	12.37
Layout 3	2.39	3.72		12.35
Layout 5	2.38	3.95	10.62	

Table 3. Minaret modal frequencies (average values), NS direction, identified from ERA method

Modal frequencies (average values, Hz)	**f_1**	**f_2**	**f_3**	**f_4**
Layout 1	2.41	3.89	10.73	12.33
Layout 2	2.42	3.94	10.69	12.37
Layout 4	2.44	4.01	10.50	12.41

Table 4. Minaret modal frequencies (average values), EW direction, identified from ERA method

Modal frequencies (average values, Hz)	**f_1**	**f_2**	**f_3**	**f_4**
Layout 1	2.36	3.88	10.69	
Layout 2	2.37	3.76	10.69	12.35
Layout 5	2.38	4.15	10.94	

The identified modal frequencies through the spectral analysis and ERA method show relatively small differences in frequency domain, the corresponding modal periods being practically identical: T_1=0.42s on both directions (spectral analysis) and T_1=0.41s on NS and 0.42s on EW (ERA method); T_2=0.26s on both directions (spectral analysis) and T_1=0.25s on both directions (ERA method); T_3=0.10s on NS and 0.09s on EW (spectral analysis) and T_1=0.09s on both directions (ERA method), and T4=0.08s on both directions and with both approaches.

Modal damping ratios were also estimated using ERA method. Average values of damping ratios for first modes are: 1% on NS direction and 1.3% on EW direction.

In case of low-amplitude vibrations, the obtained results characterize the minarets' linear dynamic behaviour.

The present paper results confirm the preliminary results from Aldea et al. 2017 and 2018: f_1=2.38 Hz (T_1=0.42s), f_2=3.80 Hz (T_2=0.26s).

The paper is part of a wider study aiming the mosque seismic evaluation.

A first step toward the seismic evaluation according to the Romanian enforced regulation P100-3/2008 (Aldea et al., 2018) was the assessment of the existing damage state induced by previous earthquakes and/or other actions (index R2). The minaret considered as an independent structure was ranked in the seismic class RsIII (associated to the buildings that after the design level earthquake might suffer some structural damage not affecting the overall structural safety).

The minaret seismic evaluation according to the Japanese Standard Evaluation of Existing Reinforced Concrete Chimneys, 2015 (Lozincă et al., 16 ECEE Proceedings, 2018) indicate that above the level +9.25m (where the minaret is embedded in the masonry structure of the mosque), the shear capacity represents 60% of the required value associated to the seismic conditions in Constanța. Thus, an adequate strengthening method should be applied in order to increase its shear capacity.

4. ACKNOWLEDGMENTS

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