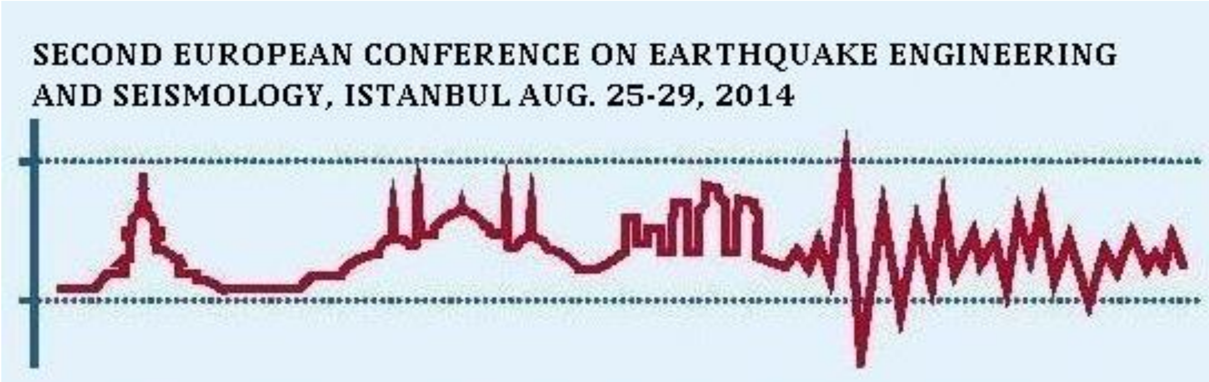

EXPERIMENTAL IN-SITU TESTING OF NINE STOREY BUILDING BY FORCED AND AMBIENT VIBRATION METHODS

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ABSTRACT

Testing of structures to understand their behavior under seismic conditions can provide an important source of information for safe and economical design and for dynamic properties of the structure. The need for testing the behavior of full scale structures under dynamic loads stems from the fact that the analytical calculations cannot account for all complexities involved. This paper presents the results obtained by application of forced vibration testing and ambient vibration testing of a 9 storey reinforced concrete building having a lift core, shear walls, columns, beams and slabs, to find out its dynamic characteristics. Experiments have been carried out using shakers and sensors within the IZIIS' Dynamic Laboratory. In-situ experiment results have been compared with the results obtained by finite element numerical model. It is emphasized that response of complex structural systems may be understood better by using the presented experimental results.

INTRODUCTION

The subject of the analysis was a 9 storey residential building in Skopje. The scope was in-situ identification of the building's dynamic parameters and the building's behavior under resonant conditions of forced vibration. The building's behavior under dynamic conditions of loading was measured and identified by applying two in-situ testing methods: measuring forced vibration and ambient vibration of all the storeys, including the basement levels.

The objective of the testing was to investigate the dynamic response of the full scale building based on which the dynamic properties - natural frequencies, mode shapes and damping coefficients could be defined. These parameters are important to be defined due to their strong relation to prediction of seismic behavior of the structure under earthquake excitation as well as for calibration of the numerical model to be used for analysis.

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DESCRIPTION OF THE STRUCTURE

The building was newly constructed while tested. The structural system consists of 18 cm thick reinforced concrete interstorey slabs, reinforced concrete beams with cross sectional dimensions 60/60 cm, reinforced concrete columns with cross sectional dimensions 60/60 cm in the two underground basement levels and 60/80 cm in the ground level and upper storeys and 20 cm thick reinforced concrete shear walls surrounding the stairs and the elevator utilities. The foundation consists of 100 cm thick reinforced concrete foundation plate.

Regarding the Macedonian national seismic codes, the adequate seismic influence on the structure was included in the design process.

Figure 1. Tested building

TESTING METHODOLOGY AND EQUIPMENT

The forced vibration testing methodology is based on the resonant concept. By application of a dynamic harmonic force on the top of the building, the resonant frequencies are excited, if the frequency of the force is equal to one of the natural frequencies of the building in the corresponding direction. The frequency of the force can be gradually changed in small steps. The resonant state is reached when the acceleration response at the measurement point becomes maximum and then decreases while the frequency of the force still increases. In this manner, frequency response curves can be obtained for each orthogonal direction and torsion. On the other hand, the ambient vibration testing methodology is based on ambiental excitation such as wind, trafic, influences from the regular usage of the building, etc. Sensitive seismometers are capable of catching the produced vibrations which are of a random type of signal, consisting of excitation frequencies in a broad frequency range, enough to excite several modes of structural vibration.

For forced vibration generation in horizontal direction, two GSV-101 (Geotronix, USA) vibration generators were used for generating sinusoidal excitation force with frequencies in the range from 1.0 to 8.0 Hz. Each generator is capable of producing excitation force with an amplitude of up to 2.5 tons.

Accelelerometers PCB Piesotronics Model 393B12 with sensitivity of 10,000 mV/g, with a range of up to 4.9 m/sec^2 (0.5g) were used for signal registration. The vibrations were registered with a sampling frequency of 2048 Hz. The data acquisition system consisted of module NI cDAQ-9178 and 3 card module NI 9234.

Figure 2. GSV-101 (Geotronix, USA) – position of the shaker baskets for maximal excitation force (left) and zero excitation force (right)

The sinusoidal force is basically a centrifugal force generated from rotational movement of lumped mass on the shaker's rotating baskets and its intensity depends on the value and angular frequency of the rotating mass.

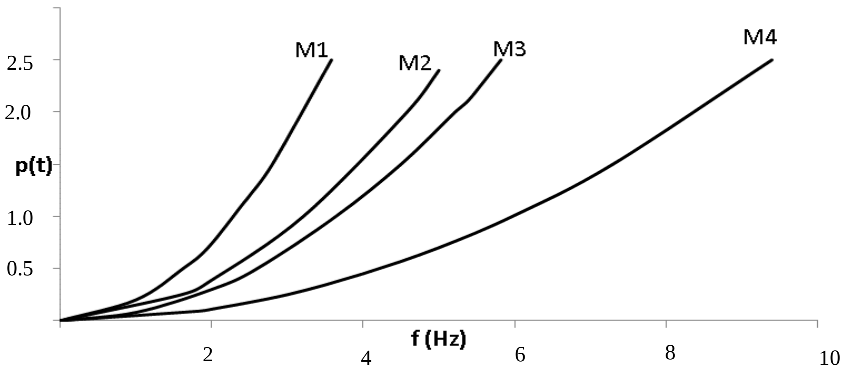

Figure 3. Relations among excitation frequency, rotational lumped mass and generated excitation force (M1>M2>M3>M4)

Figure 3 clearly shows that the excitation force is weak for low frequency excitation due to its centrifugal nature, regardless the lumped mass on the shaker baskets. Therefore, difficulties occur often in the atempts for producing excitation force with high intensities and excitation frequency lower then 1.5 Hz. Besides the mentioned disadvantages, the main advantage of the forced vibration tests over the ambient vibration tests is the high signal-to-noise ratio (S/N) which means that the recorded signal consists of mainly usable and noise-free components, which allows application of conventional structural dynamic analysis techniques, while in ambient vibration records, the noise is often a dominant component along the spectrum. The second advantage is the fact that the excitation force is a controlled and measurable quantity.

TESTING PROGRAM

Forced vibration testing was carried out for determination of the structure's dynamic characteristics in both horizontal orthogonal directions and torsion, in frequency range from 1.0 up to 8.0 Hz, by forced vibration generation (developing resonance conditions in the structure).

For the purpose of successful forced vibration testing, the force was applied at the top of the building where zero point of any mode shape never occurs and the values of the mode shape vectors are the highest for the first mode and among the highest for the higher modes.

The excitation forces were sinusoidal, with an excitation frequency range estimated to include the natural frequency of the structure in the corresponding direction.

In this particular case, the shakers were mounted on the 9th floor, in a mutual position from which the effects of torsional components of transversal excitation would be minimal. The measuring equipment was placed at the two diagonal edges of the building. The measurement was carried out for two orthogonal directions, at each measuring point. The structure was tested by applying 5 different levels of lumped masses on the shaker baskets.

The recorded data of the forced vibration measurements were processed in MATLAB based on software codes, programmed in IZIIS for real time data processing and post processing. Butterworth band pass zero-phase digital filter was used for clearing the recorded data from harmonic components and noise in the non-observed frequency ranges.

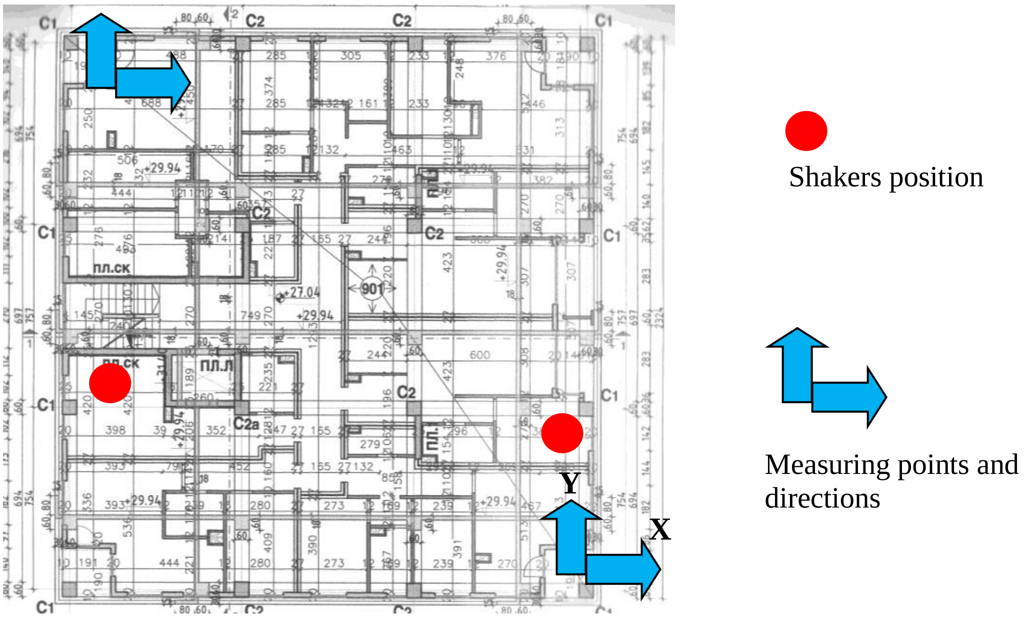

Figure 4. Plan of the 9th floor – placement of shakers and measuring sensors

Ambient vibration measurements were carried out along with the forced vibration tests for the purpose of verification of the obtained results and identifying dynamic properties that were unable to be identified by forced vibration testing due to higher frequencies that the shakers were unable to withstand. The recorded data of the ambient vibration measurements were processed in ARTeMIS Extractor 5.3 computer software package.

A total of 12 sensors were used (6 in each orthogonal direction). Four sensors were used as referent on the 9th floor and the remaining 8 were relocated on the lower floors for mode shape determination in both, forced and ambient vibration tests.

TEST RESULTS

Forced Vibration Test

The natural frequencies for the first three mode shapes (X-X, Y-Y and torsion) of the structure as well as the second mode shape in the Y-Y direction were obtained by gradually increasing the excitation frequency and locating the frequency of the most intense structural response, which is the natural frequency of the structure. The obtained frequency response curves for the first modes in two horizontal orthogonal directions and torsion are presented in Figures 5, 6 and 7.

By generation of forced vibrations in both orthogonal directions, as well as torsional vibrations, the resonant frequencies and the vibration modes in these directions were defined.

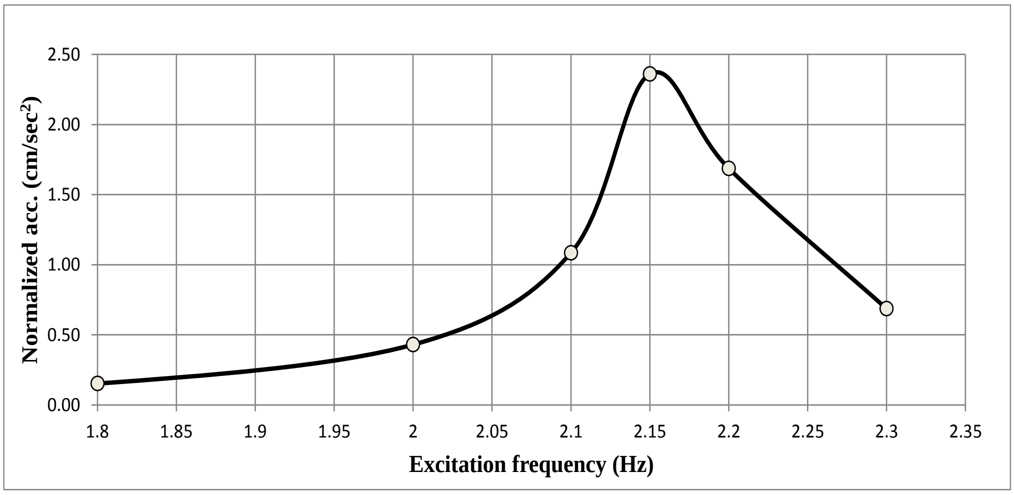

Figure 5. Excitation frequency response curve in Y-Y direction

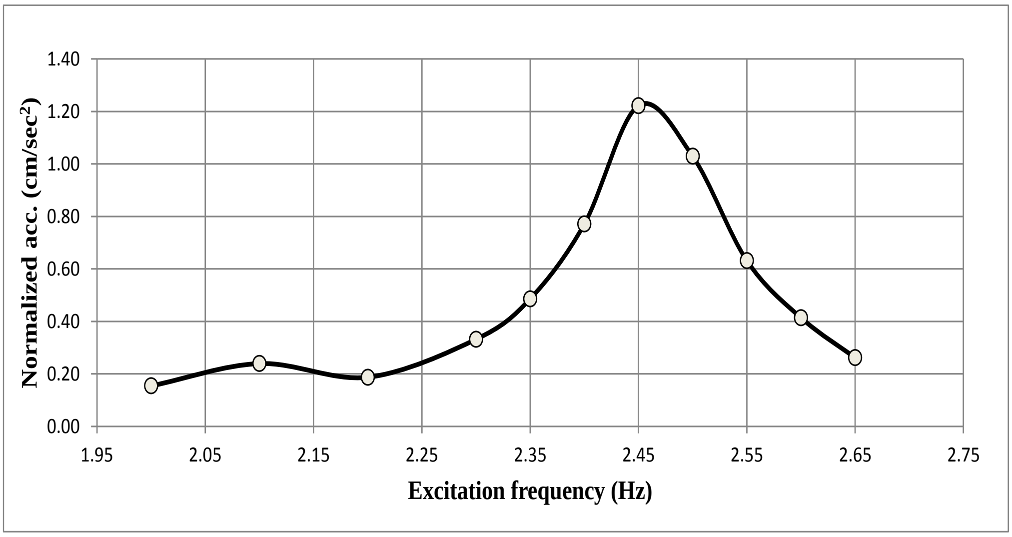

Figure 6. Excitation frequency response curve in X-X direction

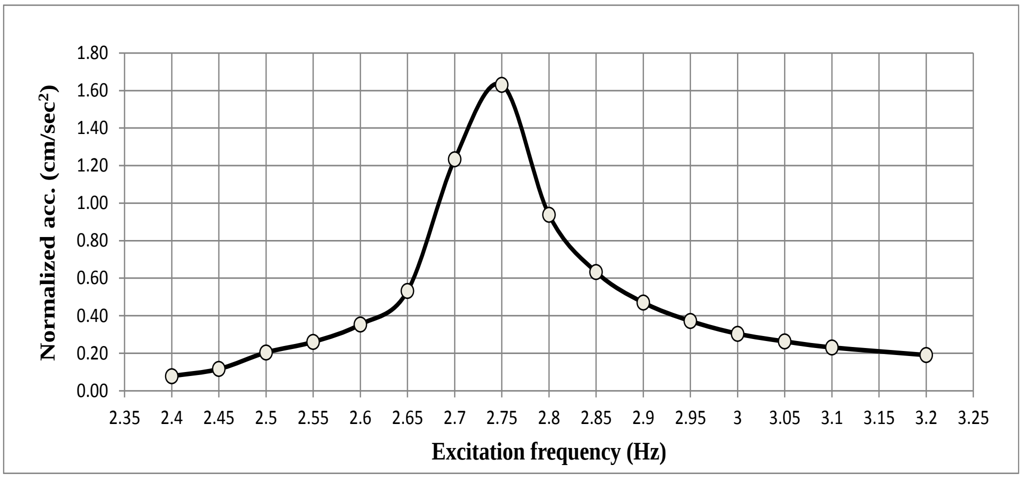

Figure 7. Excitation frequency response curve in torsion

Damping coefficient ξ of each identified mode in the state of resonance was obtained applying the half-power method and the logarithmic decrement method. For the logarithmic decrement method, the decaying curve was obtained along the response amplitudes using the least square exponential curve fitting, observing the response after the sudden stop of the harmonic excitation by switching off the shakers during excitation in resonant state.

Table 1 provides a review of the recorded frequencies in different directions and the damping coefficients defined from the resonant curves.

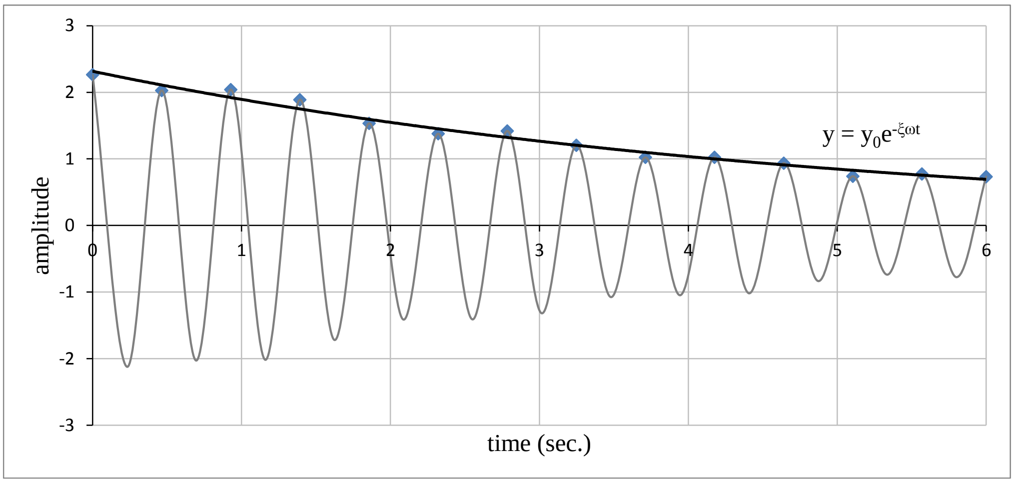

Figure 8. Logarithmic decrement curve fitting

Table 1. Natural frequencies and damping ratios from forced vibration testing

Mod shape	Freq. (Hz)	Damping ratio - Half power (%)	Damping ratio – Logarithmic decrement (%)
I mode, Y-Y	2.15	1.8	1.5
I mode, X-X	2.45	2.3	2.1
I mode, torsion	2.75	1.6	1.2
II mode, Y-Y	6.85	3.4	3.2

The mode shapes of the structure were obtained by instrumentation of each storey from the top storey down to the foundation level. The top storey was constantly instrumented with 4 sensors and considered as referent, while the remaining 8 sensors were shifted to lower storeys after each test.

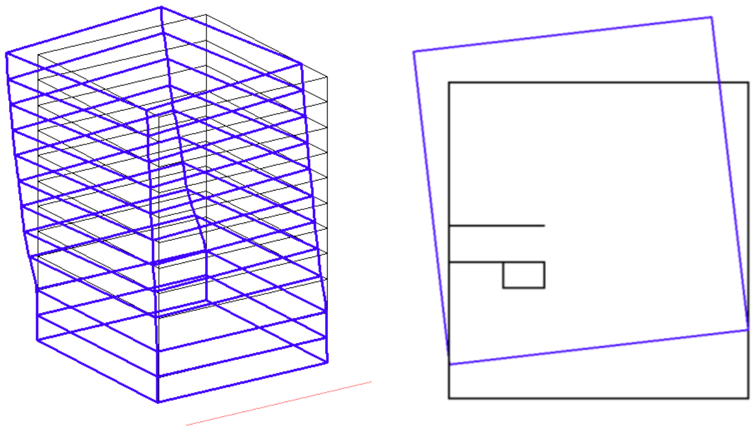

Figure 9. I Mode shape in Y-Y direction (2.15 Hz) - the whole structure (left), the 9th floor (right)

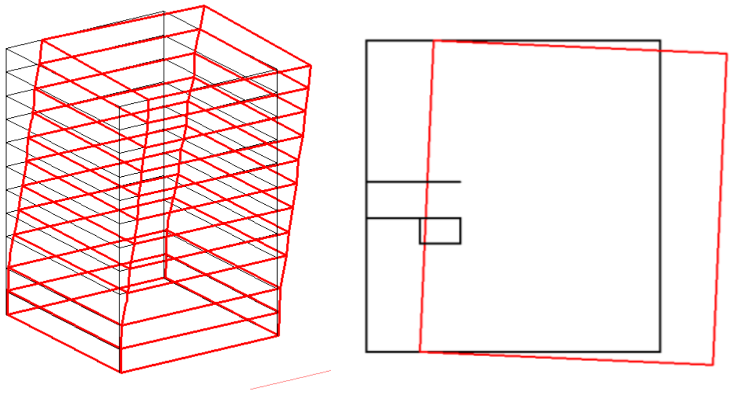

Figure 10. I Mode shape in X-X direction (2.45 Hz) - the whole structure (left), the 9th floor (right)

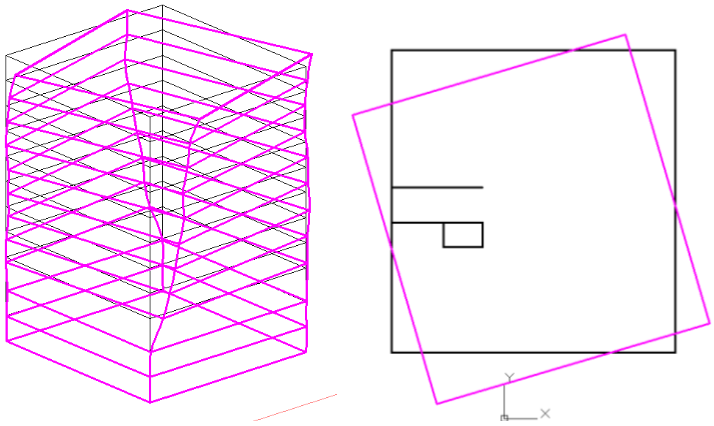

Figure 11. I Mode shape in torsion (2.75 Hz) - the whole structure (left), the 9th floor (right)

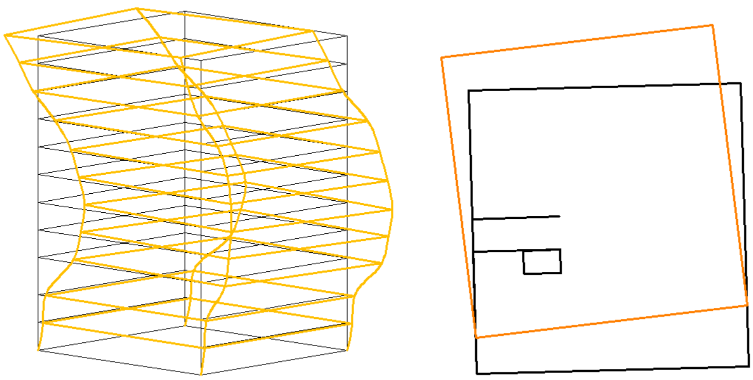

Figure 12. II Mode shape in Y-Y direction (6.85 Hz) - the whole structure (left), the 9th floor (right)

The torsional effect presence in the first mode shape in Y-Y direction was the result of the significant discrepancy between the center of mass and the center of stiffness due to the concentration of shear walls on only one peripheral side of the building.

Ambient Vibration Measurements

The measurements were performed along with the forced vibration measurements with the same instrumentation scheme for verification of the forced vibration testing results and capturing modes that forced vibration testing was unable to detect due to the previously mentioned limitations. In this case, only the second torsional mode was identified besides the modes identified in the forced vibration tests. The recorded ambient vibration data were processed in ARTeMIS Extractor 5.3 software applying the Enhanced Frequency Domain Decomposition (EFDD) identification method. The obtained results are presented in Table 2.

Table 2. Natural frequencies and damping ratios from ambient vibration testing

Mod shape	Freq. (Hz)	Damping ratio (%)
I mode, Y-Y	2.17	1.8
I mode, X-X	2.48	2.6
I mode, torsion	2.83	1.1
II mode, Y-Y	6.87	3.4
II mode, torsion	8.69	2.3

In the numerical model created in SAP2000 for the purpose of analysis and design of the structure, the following natural frequencies were identified:

Table 3. Natural frequencies identified in the SAP2000 numerical model

Mode shape	Freq. (Hz)
I mode, Y-Y	1.04
I mode, X-X	1.41
I mode, torsion	1.25

CONCLUSIONS

In this paper, the results from experimental in-situ testing of a nine story building are presented. Two independent tests were performed. Firstly, a forced vibration testing was carried out. The horizontal excitation was generated by two GSV-101 (Geotronix, USA) vibration generators which were placed on the top floor. Finally, ambient vibration measurements were carried out for the purpose of verification of the obtained results. The dynamic properties such as natural frequencies, mode shapes and damping coefficients were obtained from both tests. From the performed tests, it was concluded that there was a good correlation between the results obtained from force and ambient vibration tests.

Finally, the in-situ experimental results were compared with the results obtained by the finite element numerical model, which was used for the design purposes. It was concluded that the numerical model was significantly flexible compared to the building structure. One of the reasons for such a difference in natural frequencies is that the non-structural infill walls were not modeled. It is emphasized that the performed experimental investigations enabled understanding of the response of the building. For further research, it is recommended to investigate the need and methods of modeling the influence of non-structural infill walls on the global linear and nonlinear structural behaviour under seismic load.

REFERENCES

Garevski M, Cifliganec V, Jekic G, Gjorgjiev I, Naumovski N, Zurovski A. (2013) “Analysis of Dynamic Properties of 9-Storey Residential Building by Application of Forced Vibration Testing and Ambient Vibration Measurements” *IZIIS Report 2013-30.* Skopje, Republic of Macedonia, Institute of Earthquake Engineering and Engineering Seismology – UKIM-IZIIS

Petkovski M, Tashkov Lj, Born CS (1992) “Full Scale Dynamic Test of the 105-storey Ryugyong Hotel in Pyongyang”, *Proceedings of the Tenth World Conference on Earthquake Engineering,* Madrid, Spain, 19-24 July, 2789-2793

Taleb R, Bouriche F, Remas A, Boukri M, Kehila F (2012) “Use of Ambient and Forced Vibration Tests to Evaluate Seismic Properties of an Unreinforced Masonry Building Rehabilitated by Dampers”, *Proceedings of the Fifthteenth World Conference on Earthquake Engineering*, Lisbon, Portugal

Tashkov Lj, Krstevska L (2011) “Experimental In-Situ Testing of Residential Building Built in Dc-90 System, Located in Becici, Montenegro by Ambient and Forced Vibration Methods”, *Report IZIIS 2011-39,* University "St. Cyril and Methodius", Skopje, Republic of Macedonia, Institute of Earthquake Engineering and Engineering Seismology – UKIM-IZIIS