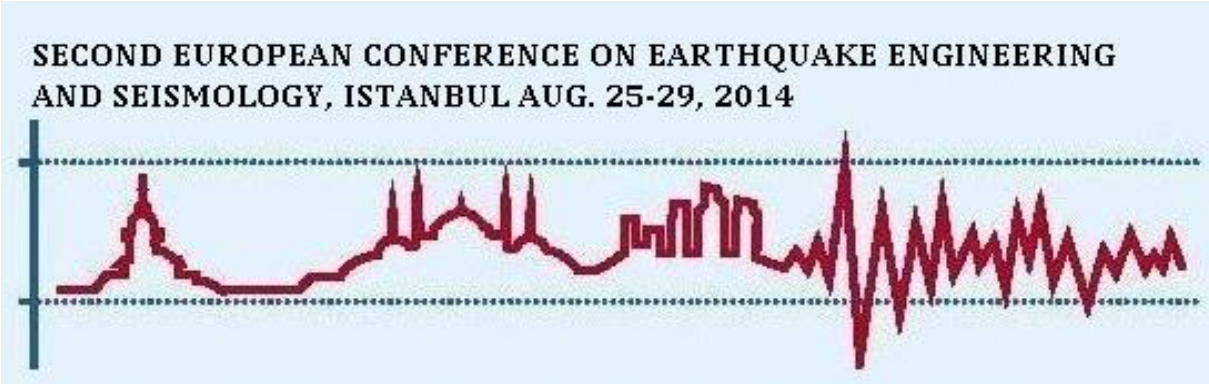

EXPERIMENTAL AND ANALYTICAL INVESTIGATION OF DYNAMIC BEHAVIOUR OF 16TH STOREY RC BUILDING

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ABSTRACT

The paper deals with the results obtained by experimental and analytical investigation of the dynamic behavior of the high-rise RC residential building K49, 16 floor level structure built in 1980, located in Zelezara settlement in Skopje. The dynamic characteristics of this building were obtained by ambient vibration measurements after its construction and before putting it into use in 1981. After 30 years of use, its dynamic characteristics were measured again (2011) in order to see if they have changed and explore the reasons for that. Modal and seismic analysis using the method of equivalent static loading of the structure by using the SAP2000 computer program was performed based on an improved FE model, verified on the basis of experimentally defined dynamic characteristics. The obtained results indicate that the structural system is stable and it is expected that the building will exhibit a favorable dynamic behavior during future earthquakes.

INTRODUCTION

During exploitation of structures, there is a possibility for their dynamic properties to change, thus changing their behavior during any excitation, as well. The changes of the dynamic properties of a structure can consequently appear as a time-dependent process, such as changes in building material, corrosion, fatigue, changes in the ground in which the structure is founded, or changes as a consequence of unpredictable excitations such as earthquakes, explosions, fires, etc. İn general, the estimation of structural stability is a process which determines whether a structure is capable of sustaining actual and expected loads in a given period of time and thus fullfilling its function.

The main objective of the presented activities in this paper was to investigate the actual dynamic behaviour and seismic stability of a representative RC building in Skopje constructed by the end of the seventies' of the last century, using the experimental results obtained by ambient vibration testing for calibration of the analytical model. Considering the fact that, for the selected structure, data on dynamic characteristics measured after its construction were available, the investigation included also activities for estimation of the reasons for changes in dynamic characteristics during the exploitation period of 30 years.

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DESCRIPTION OF THE INVESTIGATED STRUCTURE

The 16 floor level high-rise residential building K49 is located in Zelezara settlement in Skopje. It is designed and constructed as a mixed system of RC walls and RC frames and has a basement, ground floor and 14 stories. The appearance of the building and vertical section are given on Fig. 1, while its characteristic plan is presented in Fig. 2.

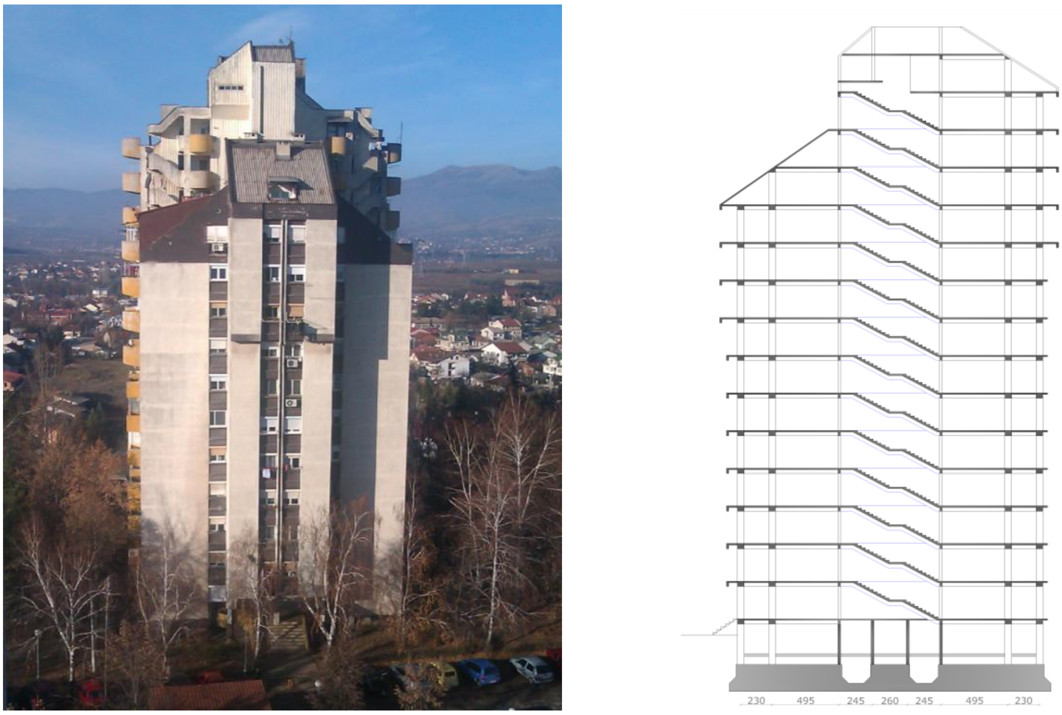


Figure 1. Residential building K49 in Skopje, Zelezara settlement

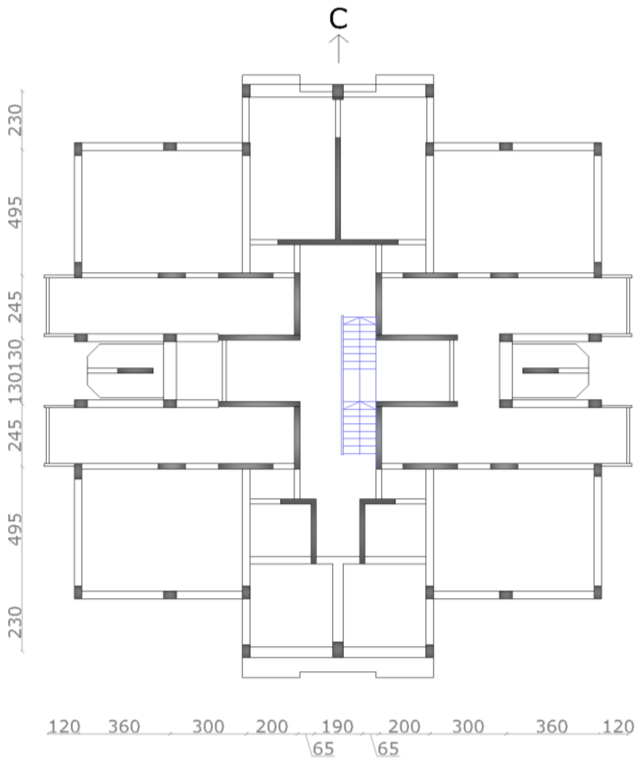


Figure 2. Characteristic plan of the building K49

Within the frames of establishing a data bank on representative newly constructed RC buildings in Skopje, this building was selected as one of such buildings and, in addition to other research activities, the ambient vibration testing method was applied to obtain its dynamic characteristics – natural frequencies, mode shapes of vibration and damping coefficients.

APPLIED METHODOLOGY OF RESEARCH

The main concern in this case was to evaluate the actual dynamic stability of this structure, but also to see if there are any changes in its dynamic properties over the 30 years of its exploitation, i.e., possible changes due to time-dependent processes or unpredictable excitations such as earthquakes. As known, the change in the dynamic characteristics is one of the main indicators resulting from earthquake effects. The applied methodology involved: visual inspection of the building on-site, collection of data about the built-in materials and their mechanical characteristics, structural or non-structural changes if any, seismic events that occurred during the life of the building and numerical analysis of the seismic stability. So, the following activities were performed:

- Experimental testing by ambient vibration method for definition of structural dynamic properties – natural frequencies, mode shapes and damping coefficients. This enabled comparison of the obtained actual dynamic characteristics with the ones obtained after its construction, i.e. in 1981 and direct information about the changes in structural stiffness characteristics.
- Inspection of the actual state of the building regarding existence of cracks and changes in the partition walls in the apartments, as well as possible structural changes (cutting of RC walls or columns) and comparison with the parameters given in the project documentation. Table 1 shows the results of this inspection.
- Providing information from the responsible institution – the Seismological Observatory in Skopje, about the occurred earthquakes (source, intensity, time), considering the high seismicity of the location. Besides several low intensity earthquakes, three seismic events with intensity of 3 degrees according to the Richter scale happened in the life time period of the structure, but no damage to the structural elements occurred. However, some small visible cracks on the walls are probably a result of these quakes, as well as of the soil consolidation over the years.
- Modal and seismic analysis using the method of equivalent static loading of the structure by using the SAP2000 computer program was performed based on an improved FE model. The analysis was done in accordance with Macedonian Building Codes.

Table1. Functional changes in the building

storey	Change
basement	
ground floor	No changes
1	
2	4 new partition walls in the north-east apartment
3	Removal of some partition walls and construction of new ones (redistribution)
4	Removal of chimney in one of the apartments
5	
6	
7	No changes
8	
9	
10	7 newly constructed partition walls, removal of 4 partition walls in the north-east apartments
11	No changes
12	
13	4 newly constructed partition walls, removal of 1 partition wall in the north-east apartment
14	No changes

EXPERIMENTAL RESULTS

For the measurements performed in 2011, four seismometers Ranger type were used to measure the ambient vibrations of the building in both orthogonal directions *x* and *y*. The amplified and filtered signals from the seismometers were then collected by a high-speed data acquisition system which transforms the analogue signals to digital. PC and special software for on-line data processing were used to plot the time history and the Fourier amplitude spectra of the response at any recorded point. The duration of each record was 30 sec and the sampling frequency was 200s/sec. 29 tests in total were performed, including the dynamic calibration test. The reference point was located at the highest level of the structure. The distribution of the measuring points over the structure is given in Fig. 3.

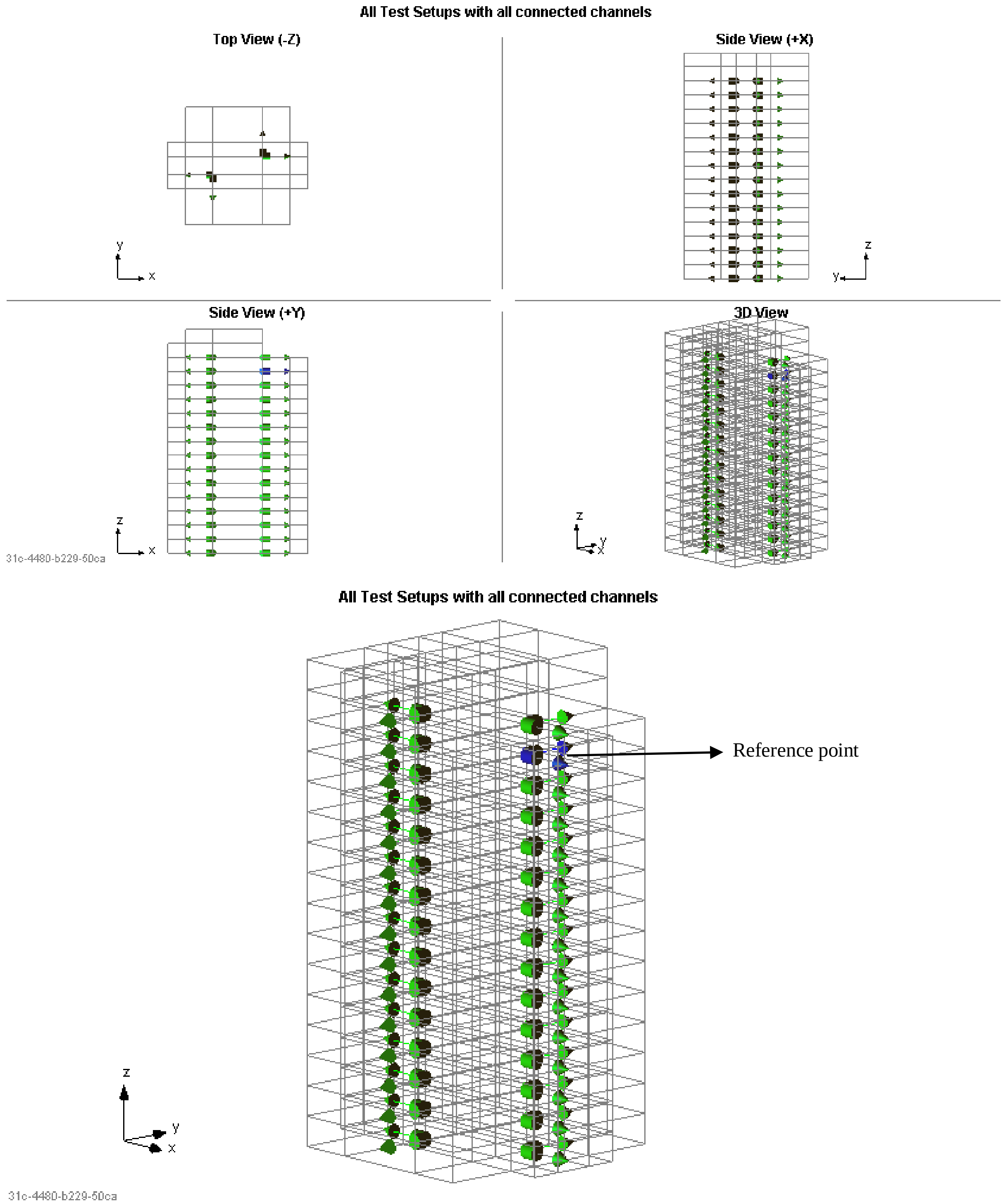
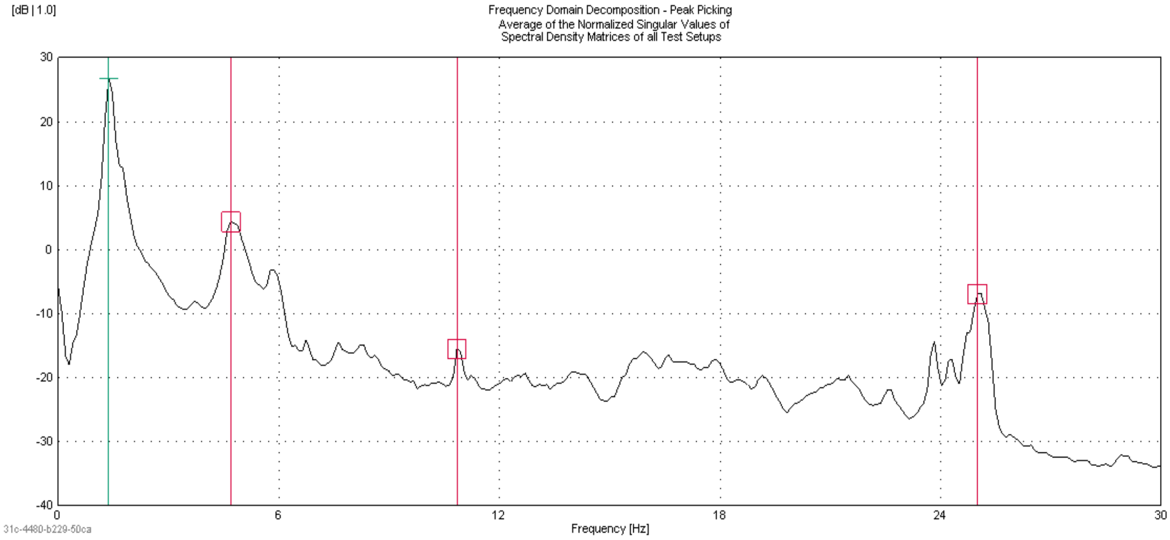


Figure 3. Test set-up – all measured points on the structure

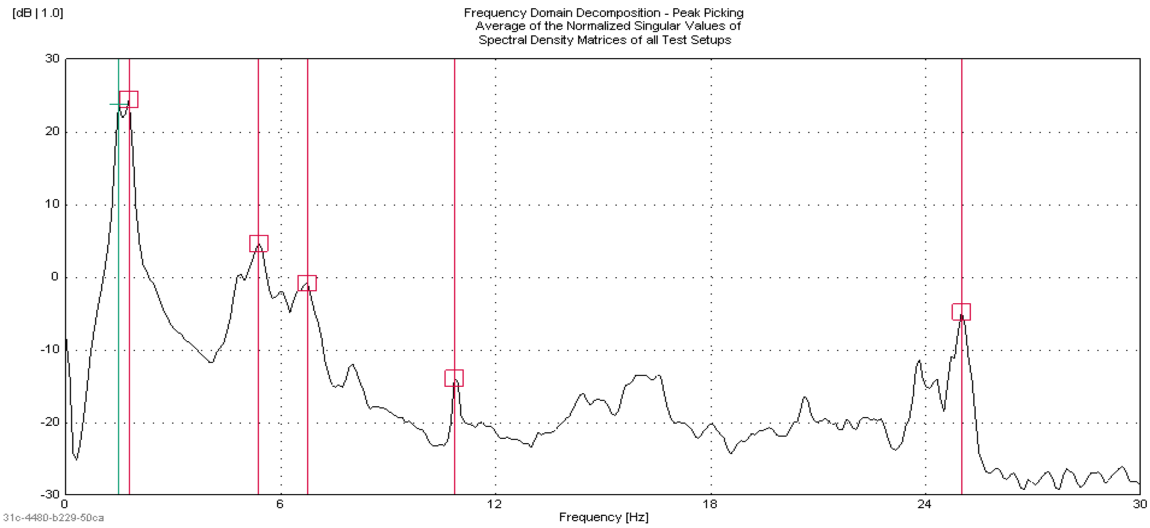
Post processing of recorded signals was done by ARTeMIS software which gives possibilities for very good graphical presentation of the experimental results.

The peak-picking of the dominant frequencies in the frequency range of up to 30 Hz in both orthogonal directions is presented in Figs. 4 and 5.



Dominant frequencies in x-direction	
Mode	frequency [Hz]
1	1.367
2	4.688
3	10.84
4	25

Figure 4. Peak-picking of the dominant frequencies in x-direction (E-W)



Dominant frequencies in y-direction	
Mode	frequency [Hz]
1	1.465
2	1.758
3	5.371
4	6.738

Figure 5. Peak-picking of the dominant frequencies in y-direction (N-S)

The mode shapes for the first and the second mode in x and y directions are presented in Figs. 6 and 7, respectively.

The mode shape for torsion at a frequency of 1.758 Hz is presented in Fig. 8.

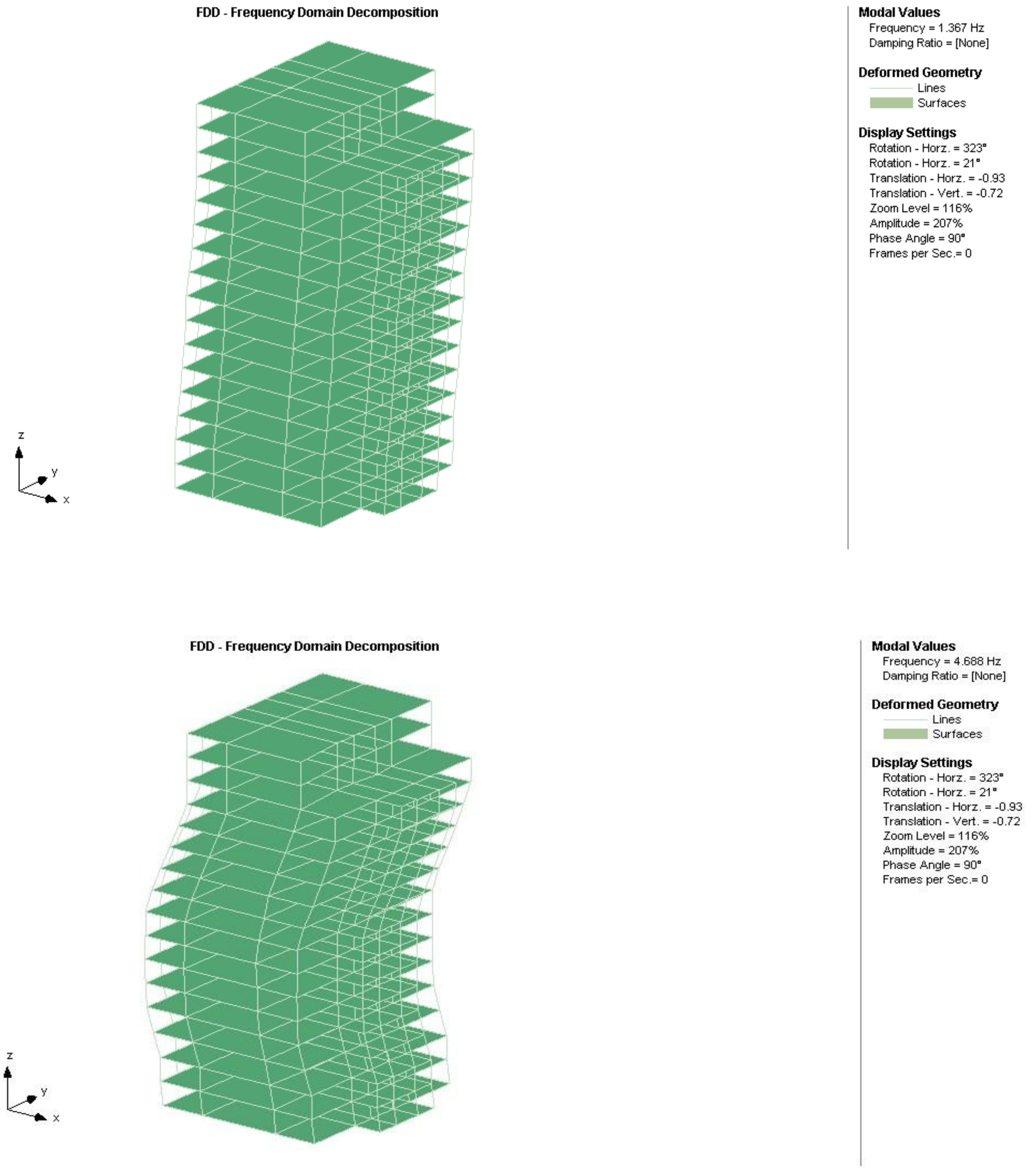


Figure 6. Mode shapes for the first and the second mode in x direction, f1=1.367 Hz and f2=4.688 Hz

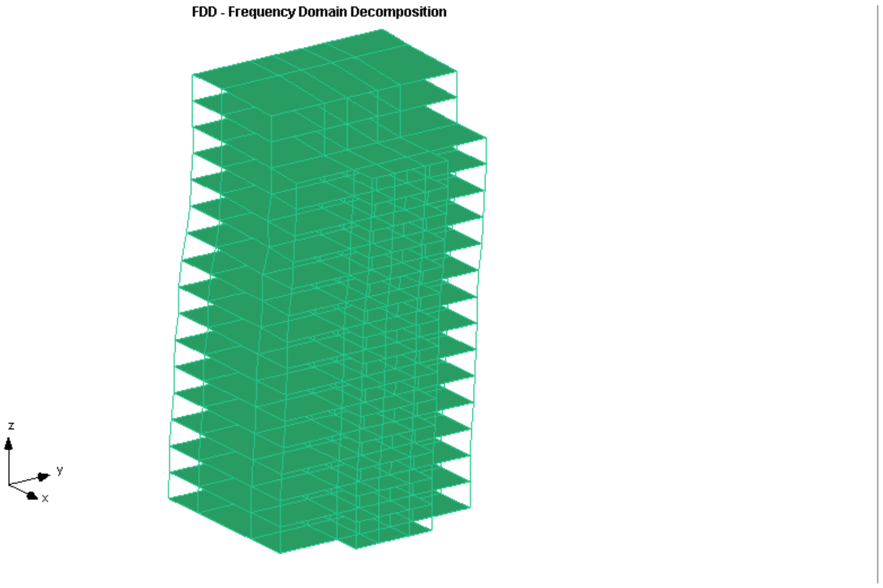


Figure 7. Mode shapes for the first and the second mode in y direction, f1=1.465 Hz and f2=5.371Hz

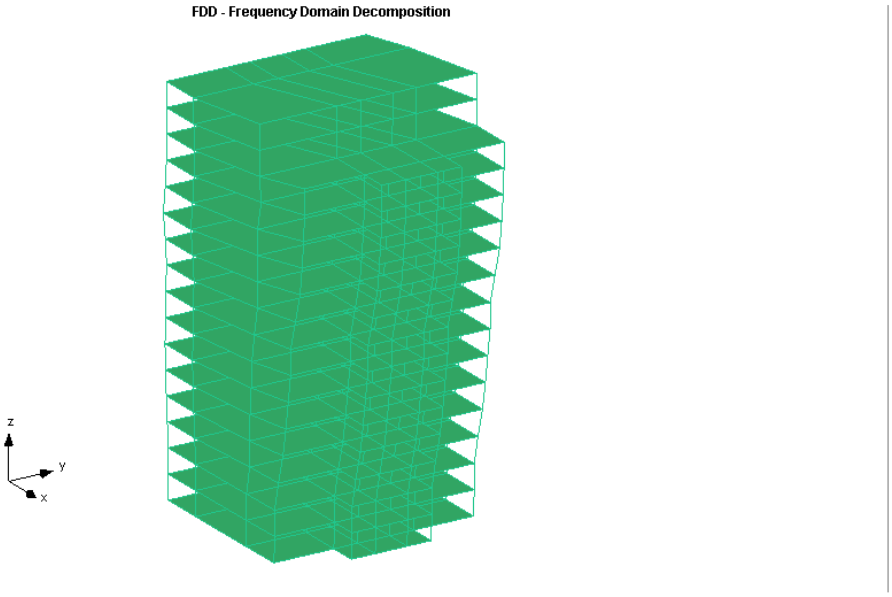


Figure 8. Mode shape for torsion, f=1.758Hz

Comparative presentation of the experimentally obtained natural frequencies for the structure in 1981 and 2011 is given in Table 1. It is obvious that the stiffness has decreased. For example, there is a 15% difference in the first natural frequency.

Table 2. Experimentally obtained frequencies in 1981 and 2011 – comparative presentation

Mode	Testing in 1981		Testing in 2011	
	Frequency (Hz)	Period (s)	Frequency (Hz)	Period (s)
1	1.367	0.732	1.6	0.625
2	1.465	0.683	1.6	0.625
3	1.758	0.569	2	0.5
4	4.785	0.209	6.2	0.161
5	5.371	0.186	-	-
6	6.641	0.151	-	-

The change of the dynamic characteristics of the structure during the 30 years of its use is a result of several factors: soil consolidation under the foundation, earthquakes that occurred during the operational period of the building as well as human interventions on the building like removal of infill walls in some apartments and constructing of new precast walls.

ANALYTICAL INVESTIGATION

The seismic analysis for the structure was performed by applying the SAP2000 computer program and the method of equivalent static load (equivalent static analysis) according to the Macedonian Design Code PBAB/87, with the aim of checking the requirements for max allowed horizontal structural displacement $f_{max} \leq \frac{H}{600}$, as well as max interstorey drift $\Delta f_{max} \leq \frac{h}{350}$, where H is the total height of the structure and h is the storey height.

Two variants were considered for numerical analysis. The first one was a 3D model where the non-structural elements (partition walls) were considered not only with their mass, but also with their stiffness. In the second case, the non-structural elements were considered only as a mass.

Regarding the compatibility of the dynamic characteristics of the analytical models and the experimentally obtained ones, the best results were obtained by adopting a model where partition (infill) walls are included with their stiffness and mass. So, the analytical model was verified on the basis of experimentally defined dynamic characteristics of the building. A comparative presentation of the resonant frequencies for the structure obtained experimentally and by analysis of both considered numerical models is given in Table 3.

Table 3. Comparative presentation of resonant frequencies

Mode	Experimental testing in 2011 -Ambient vibrations		Numerical analysis Case I – partition walls with their stiffness and mass		Numerical analysis Case II – partition walls with their mass only	
	Period	Frequency	Period	Frequency	Period	Frequency
	Sec	Hz	Sec	Hz	Sec	Hz
1	0.732	1.367	0.717	1.394	0.865	1.156
2	0.683	1.465	0.570	1.754	0.584	1.711
3	0.569	1.758	0.522	1.916	0.510	1.960
4	0.209	4.785	0.216	4.626	0.228	4.393
5	0.186	5.371	0.190	5.262	0.193	5.176
6	0.151	6.641	0.150	6.645	0.134	7.436
7	0.092	10.840	0.117	8.551	0.115	8.664
8	0.042	23.830	0.117	8.552	0.110	9.054
9	0.040	25.000	0.117	8.552	0.108	9.300
10	-	-	0.117	8.552	0.104	9.602
11	-	-	0.116	8.593	0.100	9.993
12	-	-	0.115	8.714	0.099	10.088

The equivalent static seismic force S was calculated as a product of the total seismic coefficient K and the weight of the structure G: $S=K\,G$, while the distribution of this force along floor levels (S_i) was according to the following equation:

$$S_i = S \frac{G_i H_i}{\sum_{i=1}^{n} G_i H_i}$$

where G_i and H_i are the weight of the i^{th} floor and the height to the i^{th} floor from the foundation level, respectively. Table 4 presents the obtained values for the seismic forces that were then considered in the calculation of absolute and relative displacements in both orthogonal directions *x* and *y*.

Table 4. Seismic and shear forces

Storey	Hi (m)	mass (kg)	weight (G)	Gi*Hi	Si (kN)	Ti (kN)
Basement	3.4	528.4	5183.8	17625.0	69.8	5573.6
Ground floor	6.2	393.2	3857.5	23916.2	94.8	5503.8
1	9	393.2	3857.5	34717.1	137.5	5409.0
2	11.8	393.2	3857.5	45517.9	180.3	5271.5
3	14.6	393.2	3857.5	56318.8	223.1	5091.2
4	17.4	393.2	3857.5	67119.7	265.9	4868.0
5	20.2	393.2	3857.5	77920.5	308.7	4602.1
6	23	393.2	3857.5	88721.4	351.5	4293.4
7	25.8	393.2	3857.5	99522.3	394.3	3941.9
8	28.6	393.2	3857.5	110323.1	437.1	3547.6
9	31.4	393.2	3857.5	121124.0	479.9	3110.5
10	34.2	393.2	3857.5	131924.9	522.7	2630.6
11	37	376.9	3697.6	136811.1	542.0	2108.0
12	39.8	217.1	2130.2	84780.6	335.9	1566.0
13	42.6	168.5	1653.1	70420.1	279.0	1230.1
14	45.4	65.2	639.5	29033.9	951.1	951.1
Total force S = 5573.6						

The calculations showed that, in the expected seismic conditions, the max horizontal displacement of the structure as well as the max interstorey drift would be below the prescribed limit values. The maximum horizontal displacement at the highest level in x direction produced by the seismic force reached 1. 26cm, while in y direction, it reached 2.30cm, which are lower values than those allowed by the code, namely, 8.03cm. The max relative displacements (interstorey drifts) were 0.18cm and 0.37cm in x and y direction, respectively, which are again much lower than the prescribed value of 0.8cm.

CONCLUSIONS

The paper presents the results obtained from experimental dynamic testing by ambient vibrations and numerical analysis of the seismic stability of the 16th storey RC building structure in Skopje.

Based on the obtained results, the following can be concluded:

- The comparison of the experimental results obtained by ambient vibration tests in 1981 and 2011 (resonant frequency values) showed that the actual values are lower for 15%. The main reason for this is the fact that, during the first testing, only the structural system was completed, without finishing works. However, possible reasons which have lead to change of the principal dynamic properties of the structure throughout its lifetime serviceability could also be: bigger mass (the load from furniture, people, equipment, partition walls...), some micro-damages due to earthquake events that happened within this period, soil consolidation, etc.
- The experimental results were used for calibration of the numerical model. The comparison of the natural frequency values obtained experimentally and numerically shows that the best fitting is achieved when the partition walls are considered with their stiffness.
- Both the experimental and analytical investigation provided high quality knowledge about the actual state of the structure regarding its dynamic behaviour. The obtained results by the seismic analysis of the structure according to the Macedonian building codes indicate that the structural system is stable and it is expected that the building will have favourable dynamic behaviour during future earthquakes.

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