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Of dynamic properties of RC buildings in Skopje by in-situ testing

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Abstract

The behaviour of structures subjected to earthquake excitation is mostly defined by their dynamic properties. Also, they indicate the potential structural response to any unwanted dynamic excitations which may lead to uncomfortable feeling of the occupants. One of the factors that influences the structure's dynamic properties of cast-in-place concrete systems is the construction technology. Furthermore, there is concern about matching the analytically obtained dynamic properties in the design stage with the ones of the real structure. The dynamic response of the structure is completely determined by the structural natural frequencies, damping and corresponding mode shapes which can be evaluated by ambient and forced vibration measurements. The objective of this study is experimental determination of the dynamic properties of full-scale RC building structures right after their construction.

In this study three residential buildings in Skopje were selected for in-situ determination of their dynamic properties. First one was a 9-story RC frame structure with central shear wall core. Second one was a 10-story building with similar structural system to the first one. The last one was a high-rise shear wall 42-story RC building. The dynamic properties of all three buildings were identified and conclusions regarding the construction quality were drawn. These results will be used as reference values in their continuous structural health monitoring process.

Key words: structural health monitoring, forced vibration, ambient vibration, dynamic parameters

1. Introduction

The assessment of the dynamic properties of existing buildings are mainly performed to discover any uncertainties during construction or to confirm analytically used values during design process. Also, the dynamic properties indicate the potential structural response to any unwanted dynamic excitations which may lead to uncomfortable feeling of the occupants. Because the dynamic response of the structure is completely determined by the structural natural frequencies, damping and corresponding mode shapes, it is very important for structural analysis those values to be close to the expected and designed ones. Those parameters can be evaluated by using non-destructive in-situ tests such as ambient and forced vibration tests.

The forced vibration testing methodology is based on the resonant concept. By application of a dynamic harmonic force, most convenient on the top of the building, the resonant frequencies are excited, if the excitation frequency is equal to one of the structure's natural frequencies in the corresponding direction. The excitation frequency can be gradually changed in small steps. The resonant state is reached when the response at a particular excitation frequency is maximum in this manner, accurate 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, traffic, influences from the regular usage of the building, etc. Sensitive accelerometers are used to register the micro-vibrations in a form of a signal which, containing building's natural frequencies.

The objective of this study is to present the experimentally identified dynamic properties of three full scale residential buildings obtained by non-destructive in-situ tests [1-4]. These parameters (natural frequencies, mode shapes and damping coefficients) are important for next stages of the investigations such as prediction of seismic behaviors of the structure under earthquake excitation as well as for calibration of the numerical model to be used for analysis. First residential building was a 9-story RC frame structure with central shear wall core. Second one was a 10-story building with similar structural system to the first one and the last one was a high-rise shear wall 42-story RC building. The dynamic properties of all three buildings were identified. These results will be used as reference values in their structural health monitoring process.

2 Description of structural systems of tested residential buildings

All three tested building were newly constructed without occupants. The structural system for 9 story building (Figure 1a) consists of 18 cm thick reinforced concrete 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.

Figure 1. a) 9 story building; b) 10 story building under construction; c) 42 story buildings

The structural system of the 10-story building (Figure 1b) is a reinforced concrete frame structure combined with stair core and reinforced concrete share walls. The floor consists of two underground levels, ground floor level and ten floors. The two shear walls with thickness of 20 cm are placed along the outer contours of the building. The reinforced concrete slabs are 16 cm thick, reinforced concrete beams are with dimensions 55/60 cm and columns are with dimensions 60/90, 60/60, 60/80 cm. The building was tested while still was under construction.

The last tested building – one of the four skyscrapers (Figure 1c), a reinforced concrete shear wall structural systems, consisted of 40 cm, 30 cm and 25 cm thick reinforced concrete shear walls, 20 cm thick reinforced concrete story slabs and reinforced concrete foundation piles with a diameter of 100 cm and a length of 24 m, interconnected with 175 cm thick reinforced concrete foundation slab. The story scheme consists of two basement levels, ground floor and 40 stories. The full structural height is 134 m.

Regarding the Macedonian national seismic codes, the adequate seismic load was included in the design process.

3 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. Therefore, two GSV-101 (Geotronix, USA) vibration generators were used for generating sinusoidal excitation force with frequencies in the range from 0.4 to 8.0 Hz. Each generator can produce excitation force with an amplitude of up to 2.5 tons (Figure 2).

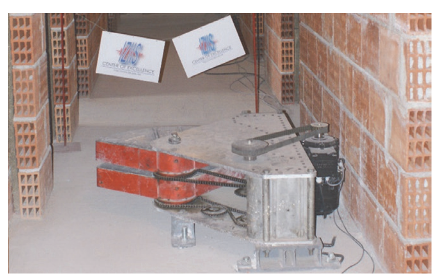

Figure 2. GSV-101 (Geotronix, USA) – display of the shaker

For the purpose of 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. For all tests, the shakers were mounted symmetrically around both orthogonal axes. This configuration allows exciting the structure in both orthogonal directions and simulation of torsional loading without changing shakers position. The excitation forces were harmonic in transversal, longitudinal and torsional direction, with a frequency range estimated to include the natural frequency of the structure in the corresponding direction. The measuring instruments were located at the two diagonal edges of the building in two orthogonal directions.

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.

A total of 12 sensors were used (6 in each orthogonal direction). Four sensors were used as referent on the top floor and the remaining 8 were relocated on the lower floors for mode shape determination in both, forced and ambient vibration tests. The accelerometers PCB Piesotronics Model 393B12 with sensitivity of 10000 mV/g, with a range of up to 4.9 m/sec2 (0.5g) are used for registration of the structures' response. The vibrations were registered with a sampling frequency of 2048 Hz. The data acquisition system consists of module NI cDAQ-9178 and 3 card module NI 9234.

The data of the measurements were processed in custom made software developed in IZIIS for real time data processing and post processing.

4 Dynamic properties of residential RC buildings

The dynamic properties (natural frequency, damping and mode shapes) of three residential buildings with 9, 10 and 42 stories were identified by forced vibration tests and ambient vibration measurements.

4.1 Forced vibration test

The natural frequencies for the first three mode shapes (X-X, Y-Y and torsion) of the structure 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. 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.

The measured acceleration in respect to the excitation frequency for the first modes for 9 and 10 story buildings and for second modes for 40-story building in two horizontal orthogonal directions and torsion are presented in Figure 3.

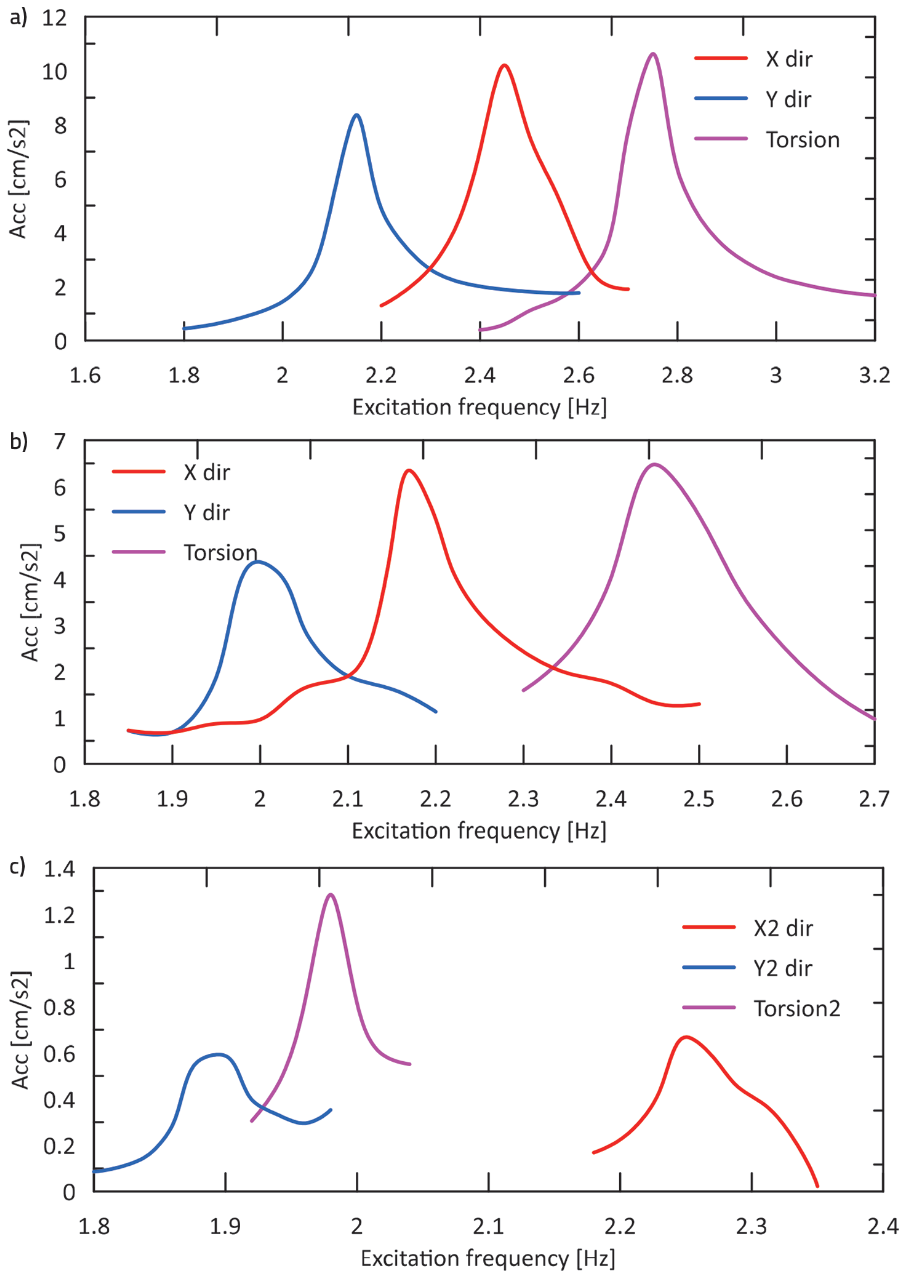

Figure 3. Frequency response from force vibration tests a) 9 story building; b) 10 story building; c) 42 story building

Damping coefficient ξ of each identified mode in the state of resonance was obtained applying the half-power method and the logarithmic decrement method. The half-power bandwidth method consists of defining the resonant frequency and two nearby frequencies ω_1 and ω_2 located in the frequency spectrum by application of equation 1:

$$X(\omega_1, \omega_2) = \frac{X(\omega_n)}{\sqrt{2}} \tag{1}$$

After defining the required frequency values (ω_n, ω_1 and ω_2) in the frequency spectra the damping value can be calculated applying equation 2.

$$\xi = \frac{\omega_2 - \omega_1}{2\omega_n} \times 100\% \tag{2}$$

In order to obtain the damping coefficient by logarithmic decrement method, the decaying response of the structure was measured after stopping the excitation force in the resonant state. The exponential function of the decaying curve that fits the amplitudes of the damped vibration is defined by equation 3.

$$Q(t) = Q_0 e^{-\xi \omega_n t} \tag{3}$$

where ξ represents the damping coefficient, ω_n is the oscillation angular frequency measured in rad/sec^2 ($f = \omega_n/2\pi$), t is the duration of the observed signal in seconds. The modal damping coefficient for the measured modes of vibration for all three residential buildings are presented from Table 1 to Table 3.

Table 1. Natural frequencies and damping ratios from forced vibration testing of 9-story building

Direction / Mode	**Freq.** [Hz]	**Half-power** [%]	**Logarithmic decrement** [%]
Y / I	2.15	1.8	1.5
X / I	2.45	2.3	2.1
T / I	2.75	1.6	1.2

Table 2. Natural frequencies and damping ratios from forced vibration testing of 10-story building

Direction / Mode	**Freq.** [Hz]	**Half-power** [%]	**Logarithmic decrement** [%]
Y / I	2.00	1.75	1.6
X / I	2.17	1.57	1.7
T / I	2.35	1.02	1.0

Table 3. Natural frequencies and damping ratios from forced vibration testing of 42-story building

Direction / Mode	**Freq.** [Hz]	**Half-power** [%]	**Logarithmic decrement** [%]
Y / II	1.89	1.5	0.5
T / II	1.98	0.8	0.4
X / II	2.25	1.3	0.6

4.2 Ambient vibration measurements

The ambient measurements were performed along with the forced vibration measurements with the same instrumentation scheme for verification of the forced vibration testing results. This method enables capturing the modes that forced vibration testing was unable to detect because are outside the shaker's vibration frequency range.

The recorded ambient vibration data were processed in custom-made application where the Enhanced Frequency Domain Decomposition (EFDD) identification method was included. The aim of developed custom application is to create an advanced tool for signal processing and EFDD analysis. The algorithm is written in C++ language with full support for parallel processing. The graphical visualization of the input and output data is created in order to present a 3D mode shapes. The main graphical user interface of custom developed application used for operational modal analysis is shown in Figure 4.
he developed software tool contains the following functions:

- Signal analysis and processing functions: signal decimation, signal detrending, several types of digital filters in the form of high-pass, low-pass, band-pass and band-stop zero-phase and non-zero-phase filter functions with manually predefined order and cut-off frequencies;
- Functions for Fourier transforms (FFT), power spectra (PS), power spectral density (PSD) with support of additional functions for averaging;
- Signal windowing functions (Hamming, Hann and Bartlett);
- Fully automated operational modal analysis in real time applying singular value decomposition (SVD) and frequency domain decomposition (FDD);
- Calculation of the damping coeffitient(half-power, logarithmic decrement method and modal damping estimation - IRF);

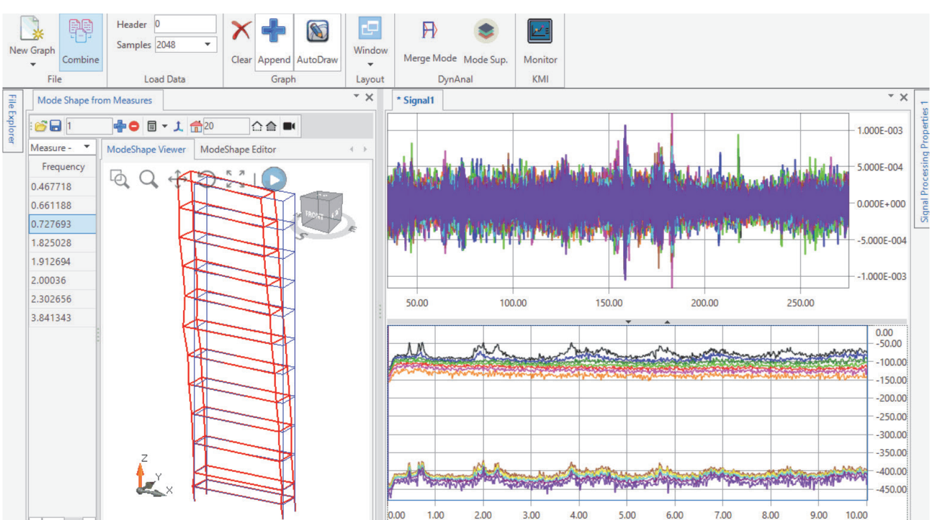

Figure 4. Custom developed application for operational modal analysis

The frequency domain decomposition FDD method is a simple and user-friendly technique that allows separation of closely spaced modes and identification of the corresponding modal damping coefficients. It is a frequency domain non-parametric method that interprets output spectrum matrices estimated with the cross power spectral density CPSD method. The singular value decomposition (SVD) of the complete output spectrum matrix are calculated from the measured signals by applying equation 4.

$$\hat{S}_{yy}\left(\omega_j\right) = U_j S_j U_j^H \tag{4}$$

where Uj is an orthogonal matrix (UjUjH=I) containing the singular vectors of $\hat{S}_{yy}\left(\omega_j\right)$ and S_j is a diagonal matrix holding the corresponding singular values.

The calculated SVD values from ambient vibration tests for all three residential building are presented in Figure 5.

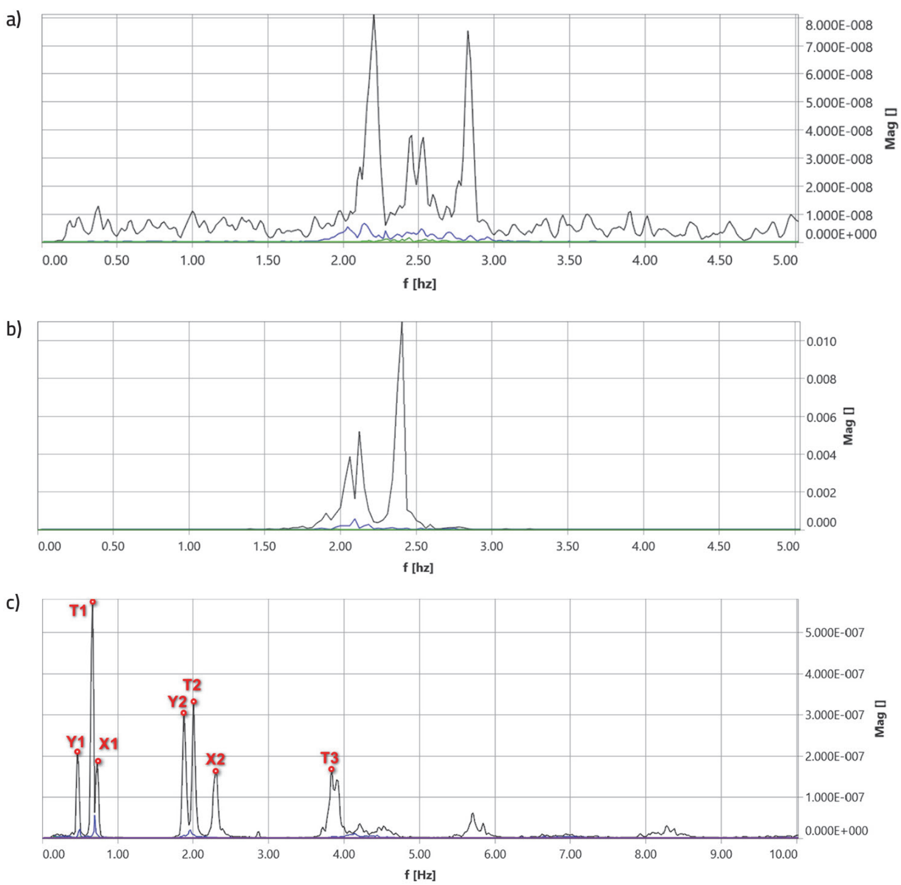

Figure 5. SVD values calculated from ambient vibration tests a) 9 story building; b) 10 story building; c) 42 story building

For each detected structural frequency, a segment of an auto-spectrum is converted to a time domain and an auto-correlation function with the contribution of a single mode is obtained. As the output correlation of a dynamic system excited by white noise is proportional to its impulse response, it is possible to estimate the modal damping coefficient (Figure 6). This can simply be performed by fitting an exponential function to the relative maxima of the correlation function and extracting the modal damping ratios from the parameters of the fitted expression taking into account the classical expression for the impulse response of a single degree of freedom (equation 5):

$$y(t) = ae^{-\xi_k 2\pi f_k t}\sin(2\pi f_k t) \qquad (5)$$

where a is a constant. The parameters ξ_k and f_k are the damping coefficient and the corresponding natural frequency in Hz.

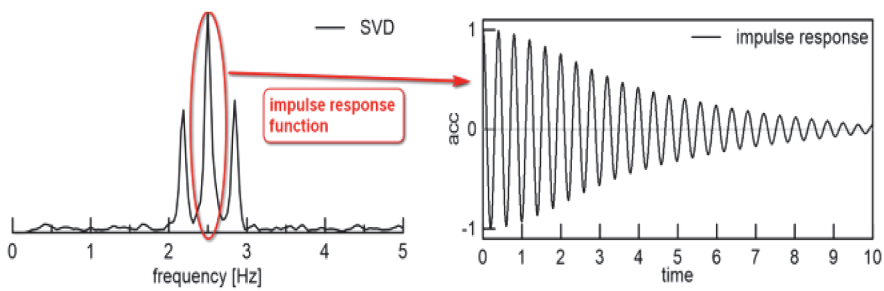

Figure 6. Estimation of the modal damping ratio

The estimated damping for each detected natural frequency for all three residential buildings are presented from Table 4 to Table 6.

Table 4. Natural frequencies and damping ratios from ambient vibration testing of 9-story building

Direction / Mode	**Freq.** [Hz]	**Damping ratio** [%]
Y1	2.20	1.79
X1	2.44	0.71
T1	2.83	0.79

Table 5. Natural frequencies and damping ratios from ambient vibration testing of 10-story building

Direction / Mode	**Freq.** [Hz]	**Damping ratio** [%]
Y1	2.06	1.03
X1	2.13	0.98
T1	2.40	0.68

Table 6. Natural frequencies and damping ratios from ambient vibration testing of 42-story building

Direction / Mode	**Freq.** [Hz]	**Damping ratio** [%]
Y2	1.89	0.75
T2	2.01	0.71
X2	2.28	0.88

4.3 Test result summary

The first comparison of dynamic properties obtained from force and ambient vibration tests is made for natural frequencies. Considering 9-story building the calculated error of frequency obtained from vibration test in respect to force vibration test is -2.3 %, 0.41 % and -2.91 % for mode directions Y1, X1 and T1, respectively. In the case of 10-story building the calculated error is -3.0 %, 1.84 % and -2.13 % for mode directions Y1, X1 and T1. For 42-story building the error is 0.0 %, -1.51 % and -1.33 % for mode directions Y2, T2 and X2. The obtained errors in estimated frequencies between forced and ambient vibration test are less than 3 %, which belongs in range of high accuracy.
The damping coefficient ξ of each identified mode in the state of resonance was calculated by using half-power and logarithmic decrement method. It has been observed that the damping coefficient obtained by logarithmic decrement method is lover that value calculated by half-power method. The largest difference is observed for 42-story building which is due to the lack of data in frequency response curve obtained by force vibration test. Also, an acceptable difference in estimated modal damping coefficients from ambient vibration method was observed. Generally, the damping coefficient obtained from free vibration tests (using logarithmic decrement method in force vibration test) for first mode shape for 9 and 10 story buildings ranges between 1 % and 2 %. The equivalent damping coefficient for second mode shape for 42-story buildings ranges between 0.4 % and 0.6 %.

5 Conclusions

In this paper, the results obtained from experimental in-situ testing of three residential buildings are presented. A forced and ambient vibration testing were performed to identify the structural dynamic properties such as natural frequencies, mode shapes and damping coefficients. Additionally, a custom application for signal processing and frequency domain decomposition and modal analysis was developed to perform an advanced analysis of recorded data. The benefit of this application compared to commercial software is the ability to improve the methodology and to implement some additional methods for obtaining more reliable results.
From the presented results, it is concluded that there was a good correlation between the results obtained from force and ambient vibration tests. The natural frequencies of all buildings are similar, which indicates that there have been no temporary or local

imperfections in the construction process. The estimated modal damping coefficients by three different methods fits quite well and all obtained values are in the range of expected modal damping values. It is also, concluded that the developed application for signal processing and FDD analysis has sufficient accuracy and speed for its application in real time processing. Finally, the identified natural frequencies are indicating to the conclusion that there have been no imperfections in the construction process. The identified structural mode shapes indicated that the structural stiffness distribution for all buildings is favourable and it follows the structural design recommendations for such building in seismic prone regions.

It can be 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 structural modelling the influence of non-structural infill walls. The importance of gathering information about the state of the structures right after they are constructed, is of crucial importance since provides important reference values which represent the healthy state of the structure. Information about the dynamic properties of the buildings, gathered by performing non-destructive tests of forced and ambient vibration tests combined, will be further used for continuous buildings' structural health monitoring process during exploitation period of those buildings.

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