

## Dynamic Identification for Representative Building Typologies: Three Case Studies from Bucharest Area

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Received 08 November 2019; Accepted 18 January 2020

### Abstract

The paper presents results from an experimental program implemented for three representative buildings in Bucharest metropolitan area and aimed to explore the potential of various dynamic identification methods in providing information about building state changes. The objective is to establish reference values of potential use in rapid earthquake damage detection systems. Each of the selected buildings was designed according to a different seismic code, in force at the time of its construction. The methods employed for this study were: the analysis of Fourier spectra, the analysis of the transfer function and the random decrement technique. To validate the results, the fundamental periods of vibration determined experimentally were compared with the corresponding values predicted by the empirical formulas specified in the corresponding editions of the Romanian seismic code. The results revealed consistent values for both the fundamental period and the damping ratio of the buildings. However, small variations of the two parameters were identified, depending on the time the recordings were performed, noise sources and levels and building occupancy. The results, in terms of validated data on the dynamic characteristics of Romanian building stock and of assessment of methods performance, add up to the information pool needed for the development of countrywide pre- and post-earthquake assisted decision tools.

*Keywords:* Ambient Vibrations; Reinforced Concrete Buildings; Dynamic Parameters.

### 1. Introduction

Vibration monitoring of buildings represents an important source of information about their state, in terms of material degradation, structural changes or damage [1, 2]. With the advancement of vibration recording instruments, data transmission technologies and numerical methods for dynamic characteristics identification, more and more applications have been implemented, from structural health monitoring of critical infrastructures to decision support systems for natural hazards mitigation in urban areas. The technique is of particular interest for earthquake-prone areas, case in which monitoring is performed for low-amplitude vibrations, as ambient vibrations, as well as for seismic ground motions. The basic idea of ambient vibration monitoring is to rapidly detect changes in the building's dynamic characteristics (natural periods, damping) and to reliably relate these changes to potential damage or degradation. The advantages of the method are its simplicity and the relatively low costs of its application. From the practical point of view, the time required by the deployment of a building instrumentation system for vibration

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 <http://dx.doi.org/10.28991/cej-2020-03091480>



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monitoring is rather short; moreover, the system can be installed only for a limited period of time. Typically, a building instrumentation system consists of vibration measurement instruments installed on the ground floor, at the top of the building and, optionally, on intermediate floors. An additional instrument, installed at a certain distance from the building, can provide reference information about free-field vibrations. Various methods have been developed during the past decades for the identification of the dynamic characteristics. The most frequently used are the analysis of Fourier spectra, the analysis of the transfer function and the random decrement technique.

The paper presents results from an ambient vibration monitoring study performed on three different multistory buildings located in Bucharest area, and in which all the above methods were applied for dynamic characteristics identification. To assess the influence of building occupancy, measurements were performed both during working days and during the weekend. The obtained values were analyzed comparatively, for each analysis method and measurement interval. In addition, the fundamental periods of vibration determined experimentally were compared with the corresponding values predicted by the empirical formulas specified in the seismic regulations used for the design of each building.

A short background on the use of ambient vibration in civil engineering and structural dynamics is given, followed by a description of the selected buildings, data, methods and signal processing. The results are presented in a comparative manner, both in the time domain and in the frequency domain. Finally, conclusions are drawn on the consistency of the results, as well as on the possible effects of diurnal and weekly variations of some parameters. The usefulness of the study is also highlighted, in the larger context of the development of a pre- and post-earthquake assisted decision platform.

## 2. Background

One of the simplest methods used for detecting structural damage in buildings is related to the fluctuation of its fundamental period (frequency) [3-6]. Two key parameters used in seismic design and that control the building's response during an earthquake are the fundamental period and the damping. The influence of these parameters can be simply explained by reducing the building to an inverted pendulum, with a time-varying acceleration (the ground motion,  $\ddot{u}_g(t)$ ) applied at its base. The equation of motion of the pendulum is that of a damped single-degree-of-freedom (SDOF) system:

$$m\ddot{u}(t) + c\dot{u}(t) + ku(t) = -m\ddot{u}_g(t) \quad (1)$$

Where  $m$  is the mass,  $k$  – the lateral stiffness and  $c$  – the viscous damping (Equation 1). Based on the known relations:

$$\omega^2 = \frac{k}{m} \text{ and } \xi = \frac{c}{2m\omega} \quad (2)$$

With  $\omega$  denoting the angular frequency and  $\xi$  – the damping ratio, Equation 1 can be written:

$$\ddot{u}(t) + 2\xi\omega\dot{u}(t) + \omega^2u(t) = -\ddot{u}_g(t) \quad (3)$$

Given that:

$$\omega = 2\pi f = \frac{2\pi}{T} \quad (4)$$

It results:

$$T = \frac{1}{f} = 2\pi\sqrt{\frac{m}{k}} \text{ and} \quad (5)$$

$$\xi = \frac{c}{2\sqrt{km}} \quad (6)$$

Where  $T$  is the natural period and  $f$  is the natural frequency. As shown by Equations 5 and 6, both the fundamental period and the damping ratio are directly related with the mass and the stiffness of the building. Assuming that mass is constant in Equation 5, a reduction of the system's lateral stiffness will lead to an increase of its fundamental period. Stiffness reduction in real buildings can occur due to several causes, among which material degradation and/or structural damage. Thus, the detection of a period increase could give an indication about possible degradation/damage occurring in a building.

A simple and relatively inexpensive method to evaluate the building state consists of monitoring the variation with time of its fundamental period and damping. In practice, this is done by recording and processing building oscillations caused by ambient sources of vibrations [7-12], to detect potential changes of these parameters. Once changes are detected, their nature and magnitude are analyzed with respect to the reference values, and warnings are issued if

damage is identified. In practice, this is generally done by performing ambient vibration measurements during the normal service of the building (to determine the reference values) and after significant seismic events (to identify potential changes). Applied for critical infrastructures and buildings, as well as, at a larger scale, for densely urbanized areas, the method can provide quickly available information after destructive earthquakes, supporting decision-makers in taking rapid intervention measures. The approach of using ambient vibrations to identify the dynamic characteristics of buildings was previously applied on a number of Romanian buildings [13, 14]. Other studies, conducted by URBAN-INCERC, focused on the concept of health monitoring and instrumental diagnosis [15, 16].

Empirical formulas of fundamental periods, specified by seismic design codes for various structure types, can provide complementary information in the process of structural health assessment. They can be used for a quick evaluation of the periods used in the design of the monitored building, especially when the original project is not available. Moreover, they can give a certain indication of the actual initial period values, for buildings lacking measurements for the establishment of reference values. The potential of structure-soil resonance [17] can be then assessed, by corroborating this information with site-specific data [18, 19].

### 3. Data and Methods

The research methodology was developed based on the flowchart presented in Figure 1.

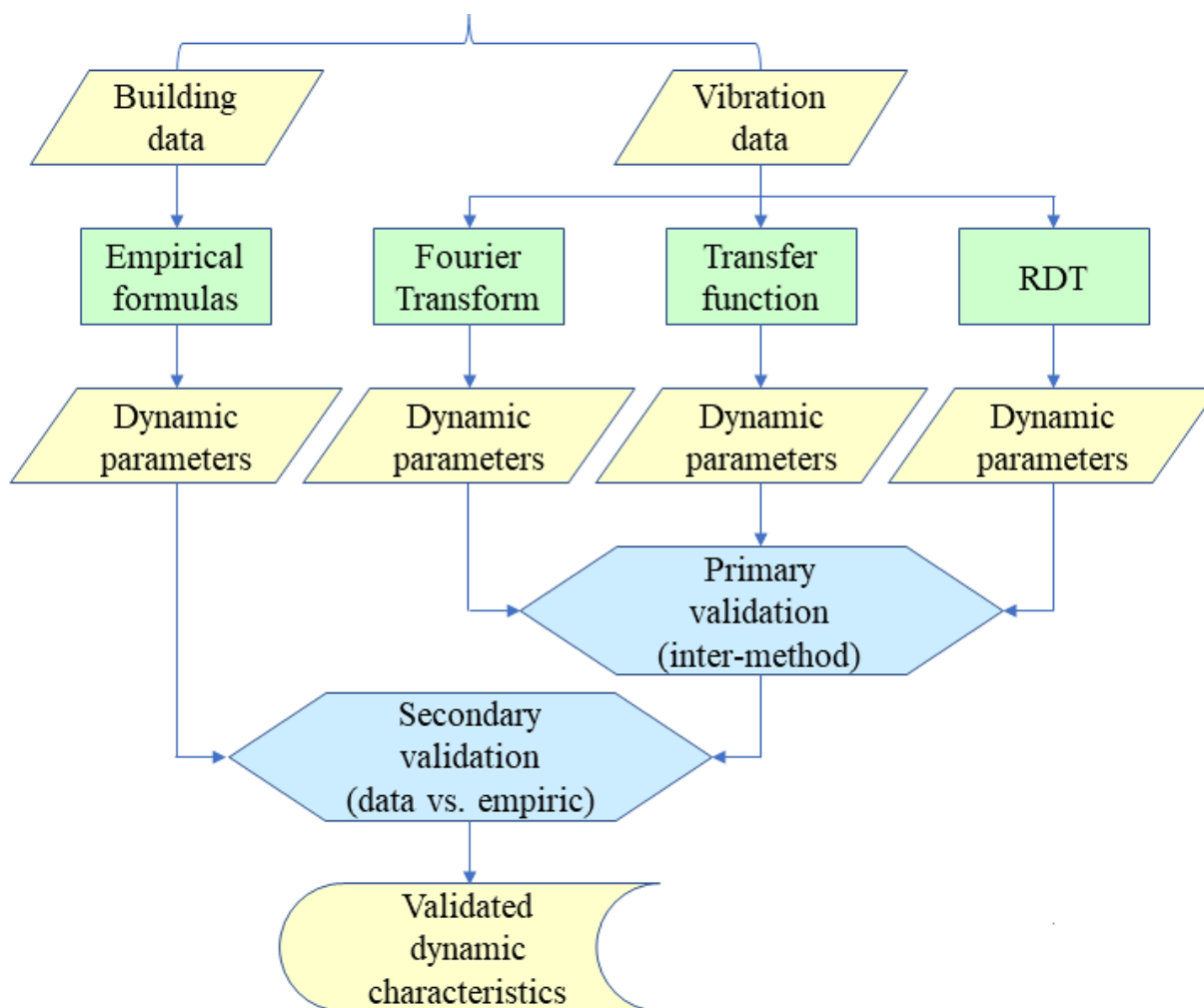


Figure 1. Proposed research flowchart

#### 3.1. Buildings

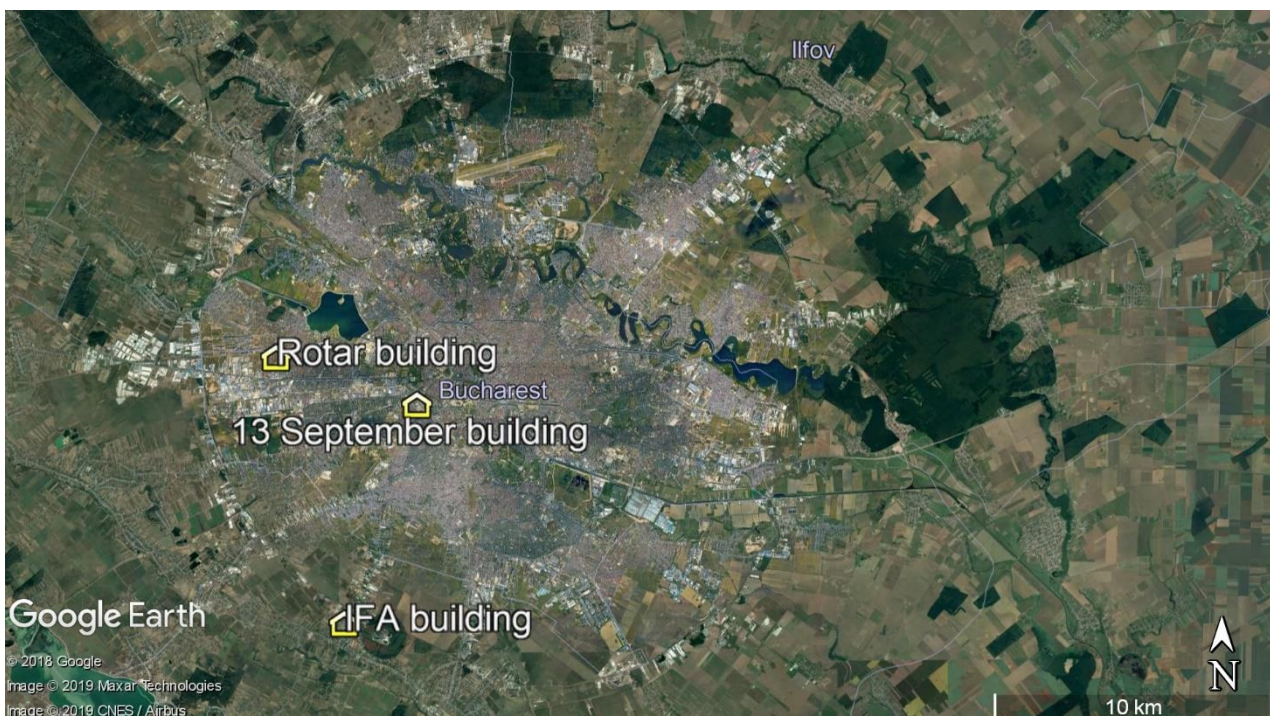
The first analyzed building is the headquarters of the Institute of Atomic Physics, IFA (Figure 2, left), located in Magurele, a city close to Bucharest. Completed in 1974, the 11-story office building has a total height of about 40 m above ground level, the vertical circulation being provided by two elevator shafts. The structure consists of reinforced concrete shear walls. The building was retrofitted twice, first after the  $M_w = 7.4$  earthquake in 1977 and then in the early 90's. This building is representative for a class of low-code high-rise buildings in Romania that suffered damage from the 1977 earthquake, due to a combination of factors pertaining to the knowledge available at the time of their construction. The second building, located in Bucharest, on 13 September Avenue, was completed in 1986. This is a

residential building, made of precast reinforced concrete panels, with basement and 9 stories. The building consists of multiple wings, separated by seismic gaps (Figure 2, right). This type of structural system is characteristic for the time of its construction, when a large number of large panel buildings were erected in Bucharest and in other cities of Romania, in response to the need of accommodating laborers during the communist industrialization period.



**Figure 2. The analyzed buildings: IFA tower (left), Rotar building (middle) and 13 September building (right)**

The third analyzed building, called “Rotar” for the purposes of this paper, is a residential building, located in the western part of Bucharest and completed in 2016. It is an approximately 35 meter-tall building, with basement, ground floor and ten floors. The structural system consists of reinforced concrete shear walls and frames with masonry infills. There are two wings separated by a 15 cm seismic gap. Each wing is symmetrical on the longitudinal direction, as shown in Figure 2 (middle). This building is representative for a large class of new group condominiums, erected by various developers during the two past decades in Romania.



**Figure 3. Map with the location of the three analyzed buildings in Bucharest area**

Building locations are presented in Figure 3. Building typologies are shown in Table 1, according to RISK-UE classification [20]. In the table, RC2 denotes reinforced concrete shear wall buildings, the second parameter refers to code severity (Low, Moderate and High Code, respectively), while HR identifies high-rise buildings (i.e.  $\geq 8$ -story height).

**Table 1. Editions of the Romanian seismic code used in the design of the analyzed buildings**

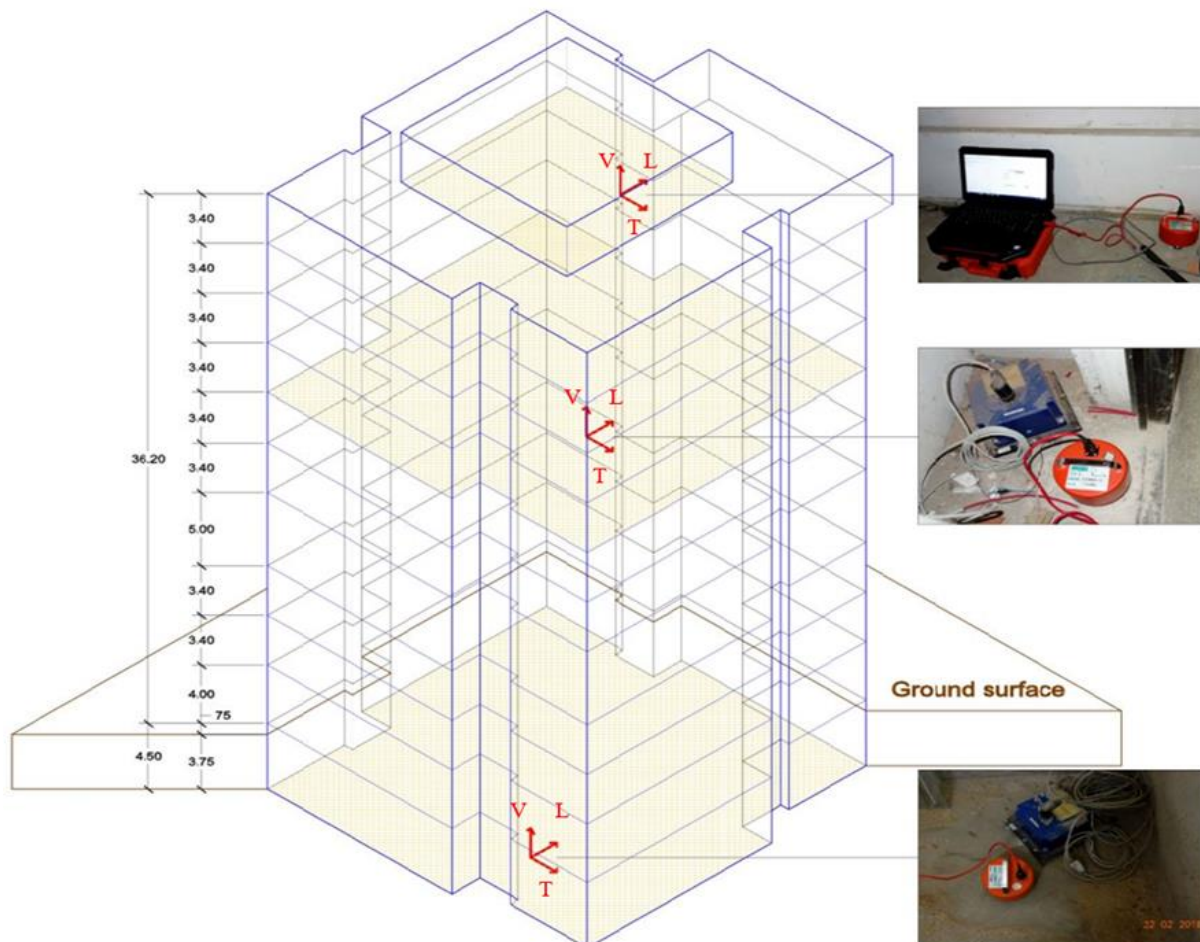
| Building     | Seismic code used in design | Typology according to RISK-UE classification |
|--------------|-----------------------------|--|
| IFA          | P13-70                      | RC2 -LC-HR                                   |
| 13 September | P100-81                     | RC2-MC -HR                                   |
| Rotar        | P100-1/2013                 | RC2 -HC-HR                                   |

For all the three buildings, the fundamental periods were computed both from ambient vibrations and according to the empirical formulas specified by the seismic design codes in force at the time of construction. It is of interest to mention that each building was designed according to a different edition of the Romanian seismic design code (Table 1). As no detailed information on the design notes was available at the time of the study, it was assumed that these formulas provide a good estimate of the fundamental period used for computing the seismic forces.

**3.2. Data**

The vibration measurements were carried out using a three-component velocity sensor with a natural frequency of 2.5 Hz (GEMINI 3D Land Geophone). The data consists of 30 minutes of ambient vibration recordings (velocity). The acquisition sampling rate in the time domain was 0.01 seconds. For all the buildings, recordings were made in the basement, at an intermediate floor and on the top floor.

The measurement setup for the IFA building is shown in Figure 4. Here, the noise measurements were done only during a working day (Thursday). However, this building is equipped also with permanent instrumentation (accelerometers) and data recorded during weekends and during nighttime were compared in order to capture the noise level variability.



**Figure 4. Schematic representation of the IFA building, showing sensor location and orientation (bold red arrows) and photos taken during the measurement campaign**

For the other two buildings (Rotar and 13 September), the noise measurements were carried out during working days (Friday and Thursday), and during the weekend (Sunday) and a comparative analysis was performed.

### 3.3. Methods

Different methods for signal processing and for extracting the dynamic characteristics of the buildings were employed for this study.

The first and simplest method was the analysis of Fourier Spectra (FS) of the top recording. The value corresponding to the peak amplitude in Fourier domain represents the system's fundamental period (soil + building). If two sensors (base and top) are installed, this gives the possibility to compute a deconvolution of the signals, in the frequency domain, thus obtaining the transfer function (TF) [21].

The value corresponding to the peak amplitude of the transfer function represents the fundamental period of the building. This was the second method used in the study. Using the top recording and under the assumption that the building is modeled by a SDOF system, the random decrement technique (RDT) was used to extract the fundamental frequency and the corresponding damping ratio [22]. This method is able to detect very small frequency fluctuations (<0.1%) [23].

Values of fundamental periods computed with the empirical formulas in the corresponding editions of the seismic code were compared with values obtained by using the experimental methods. According to the Romanian seismic design code P13-70 [24], the fundamental period for a rigid or semi-rigid tower-type structure, as the IFA building, was:

$$T = 0.065 \frac{H}{\sqrt{B}} \quad (7)$$

In Equation 7,  $H$  represents the building height and  $B$  is the plan dimension on the considered direction, both in meters.

For the 13 September building, designed according to the P100-81 code [25] for a semi-rigid rectangular structure the fundamental period on the transverse direction was:

$$T = 0.055 n \quad (8)$$

While on the longitudinal direction the period was given by the relation:

$$T = 0.045 n \quad (9)$$

Where  $n$  is the number of stories.

For the Rotar building, designed according to the newest edition of the seismic code, P100-1/2013 [26], the empirical formula of the fundamental period is:

$$T = C_t H^{3/4} \quad (10)$$

Where  $H$  is the building's height, measured from the foundation level, and  $C_t$  is a coefficient that depends on the structure type. In the considered case,  $C_t = 0.05$ .

### 3.4. Signal Processing

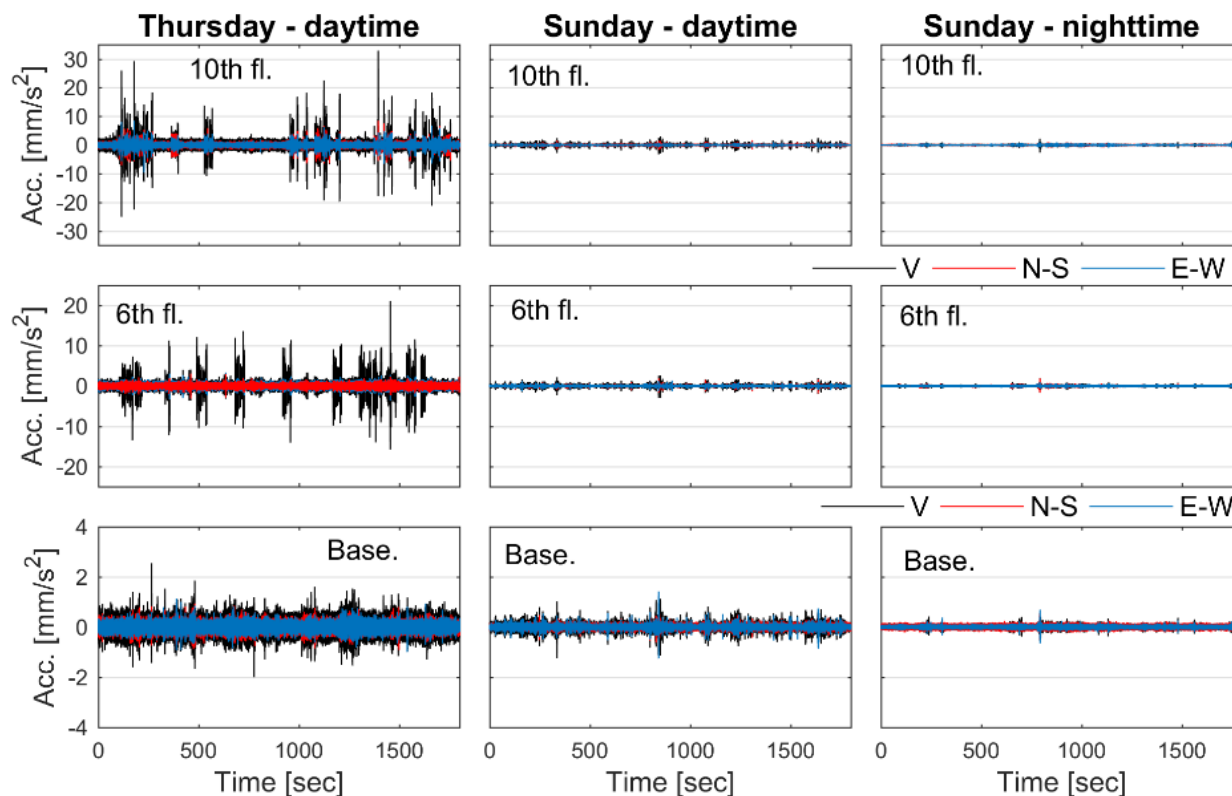
For all the methods that involved signal processing, sensitivity studies were performed, in order to select stable values of the key parameters: window length, smoothing and filtering. Based on these studies, for all the analyzed buildings a window-length of 40 seconds and smoothing of 2% were considered. For filtering purposes, the minimum frequency was set to 0.2 Hz, while the maximum frequency taken into account was the following: for the IFA building - 10 Hz, for the 13 September building - 15 Hz and for the Rotar building - 20 Hz.

In order to apply the RDT technique, the signal was first pre-filtered, with the bandpass limits centered on the expected fundamental frequency of the building. This frequency was inferred from the Fourier spectra of the top recorded signal. A bandpass 4<sup>th</sup> order Butterworth filter was applied. For instance, for the IFA building, the limits of the filter were chosen as 1.4 Hz and 1.8 Hz for both directions, taking into account that the Fourier spectra analysis revealed a peak at about 1.6 Hz. Another parameter that needs to be set when performing an RDT analysis is the window length. Calibration tests performed by other authors showed that, in order to obtain reliable results, a window length that captures at least ten complete cycles of vibration should be selected. For example, given that the fundamental period of the IFA building is 0.625 s (1.6 Hz), the corresponding window length to run RDT was chosen as 6 seconds. One should notice that this type of analysis is performed using only one sensor, located on top of the building.

## 4. Results and Discussion

### 4.1. Analysis in Time Domain

In the time domain, the differences of amplitude of vibration were highlighted, when comparing records made on a working day (Friday or Thursday) with records made during the weekend (Sunday). As expected, for the IFA office building, the noise level during the weekend (Sunday – daytime) is, on average, 5.5 times lower than on a regular working day (Thursday - daytime). This is exemplified in Figure 5, for the 10<sup>th</sup> floor vertical component.



**Figure 5.** 30 minutes-long records of accelerations on 3 components: vertical (V, black line), North-South (N-S, red line) and East – West (E-W, blue line) obtained on the IFA building during a working day (Thursday at 12:30 p.m.) and during the weekend (Sunday at 12:30 p.m. and 00:30 a.m.)

On the other hand, for a residential building, 13 September, the velocity amplitude is similar, on average, both during a working day and over the weekend. However, for the Rotar residential building, the amplitude of the signals recorded on Sunday are, on average, 1.7 times lower than that of signals recorded on Friday (Figure 6). This high difference found for the Rotar building may be explained by the fact that close to the building there is a construction site that is open on Friday and closed during Sundays.

An example of another procedure in the time domain (RDT) applied on the recordings obtained on top of the IFA building is presented in Figure 7. The mean value of the filtered signals is shown with solid black line. This was computed, with the same initial conditions, for 2854 and 2861 windows, respectively. The mean value  $\pm$  one standard deviation is shown with black dotted line. With red solid line, the analytical result is shown for a system having the corresponding fundamental frequency and damping. The values that best correlate with the recorded signals represent the solution of the algorithm.

The results for the IFA building show a frequency of 1.56 Hz (0.64 s) on the longitudinal (L) direction, and 1.59 Hz (0.63 s) on the transversal (T) direction. This is a consequence of the similar stiffnesses that the building has on both directions. The computed damping ratio is 2 % on the longitudinal direction and 1.9 % on the transversal direction, which represent typical values for this type of building [27].

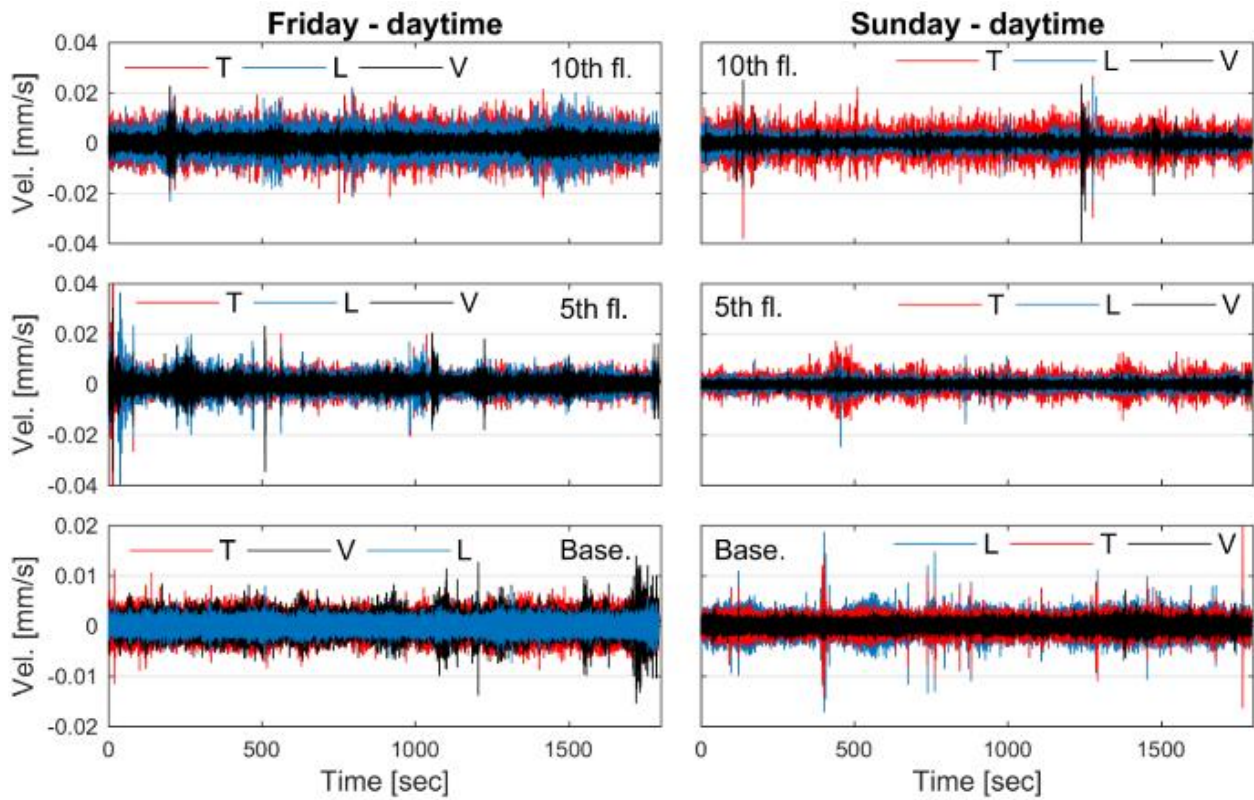


Figure 6. 30 minutes-long records of velocities on 3 components: longitudinal (L, blue line), transversal (T, red line) and vertical (V, black line) obtained on the Rotar building during a working day (Friday) and during the weekend (Sunday)

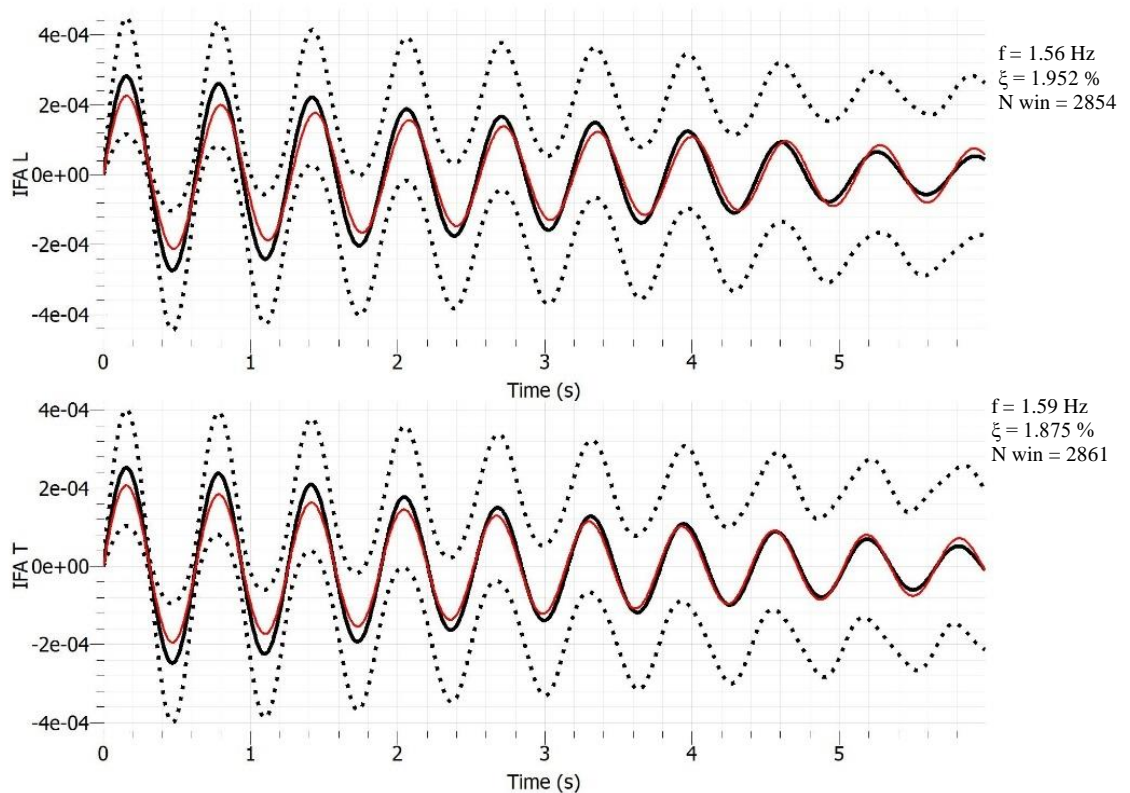


Figure 7. Random Decrement Technique (RDT) applied to records made on the IFA building

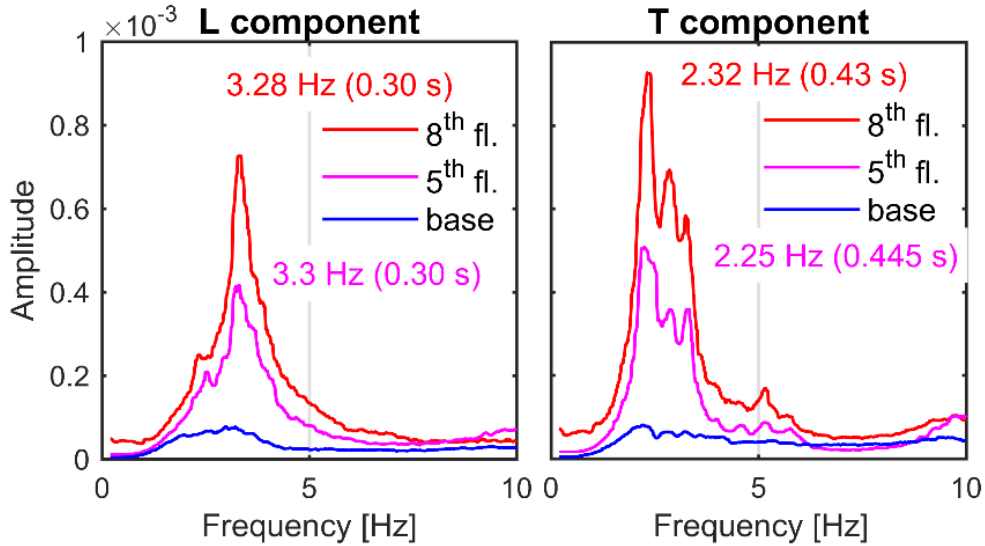
The IFA building was also instrumented within the URS project [28], during a three-month period (from May to August 2004). The authors reported a fundamental frequency of the building in the range 1.40...1.60 Hz, which is consistent with the results of the present study.



In two other studies, the fundamental frequency of the building, computed from earthquake recordings by deconvolution, was 1.59 Hz according to [29] and 1.67 Hz according to [30]. The values are close to those extracted from ambient vibration measurements.

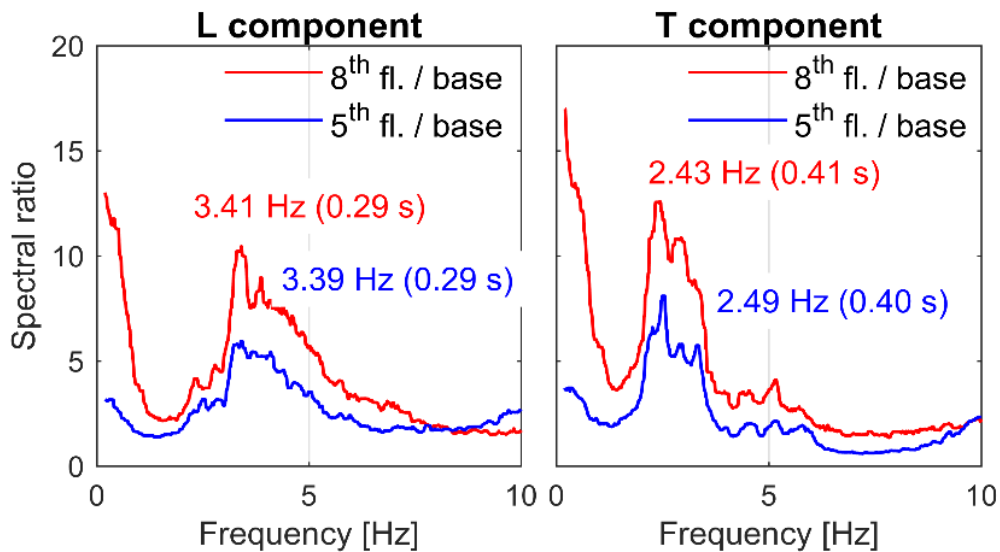
**4.2. Analysis in Frequency Domain**

In what concerns the analyses in the frequency domain, an example of Fourier spectra for the 13 September building is presented in Figure 8, while a transfer function example is presented in Figure 9. Since this building is not symmetrical, the fundamental period on transverse direction (T), from the top recording, is 0.43 seconds (2.32 Hz), and on longitudinal direction (L) the period is 0.30 seconds (3.28 Hz).



**Figure 8. Fourier spectra of signals recorded on the 13 September building, and the corresponding fundamental frequency (period) on both directions**

This means that the building is stiffer in the longitudinal direction. The same observation is valid also for the transfer function, where the spectral ratios were computed on both directions and the resulting peaks are at 0.41 seconds (2.43 Hz) and 0.29 seconds (3.41 Hz), for the top over base spectral ratio. However, the effect of soil-structure interaction is not fully removed by using the transfer function instead of the spectra recorded on top of the building, due to the fact that the structure is not perfectly clamped to the ground. The fundamental periods were obtained, for each building, also by using the empirical Equations 7 to 10 from the corresponding design regulations. For the seismic code P100-81, the fundamental period was computed on both directions, longitudinal and transversal, as the formulas are different for each direction.



**Figure 9. Transfer function of signals recorded on the 13 September building, and the corresponding fundamental frequencies (periods) on both directions**

Table 2 summarizes all the results, for each building, obtained by using different methods for estimating the fundamental period. The corresponding damping ratio values are given in the last column.

The first observation is the consistency of results that involved signal processing (FS, RDT and TF). The differences between the results obtained using Fourier spectra and RDT are very small (0.01 s), since both methods use just recordings from the top of the building. For the transfer function, in all the cases, the values are equal or lower than the ones computed from FS and RDT. A possible explanation of this trend could be the use of top and basement recordings, thus reducing the period-elongation effect of the soil.

Regarding the fundamental period computed using empirical formulas from the seismic design code, the resulting values were higher than the experimental ones, for the 13 September and Rotar buildings. This shows an apparent overestimation of the fundamental period by the empirical formulas in the P100-81 and P100-1/2013 codes, respectively, for this type of structures.

**Table 2. The dynamic parameters computed using four methods: Fourier Spectra (FS), Random Decrement Technique (RDT), Transfer Function (TF) and empirical formulas from design codes**

| Building     | Day      | Direction | Fundamental period (seconds) |      |      |             | Damping RDT (%) |
|--------------|----------|-----------|------------------------------|------|------|-------------|-----------------|
|              |          |           | FS                           | RDT  | TF   | Design code |                 |
| IFA          | Thursday | L         | 0,64                         | 0.64 | 0.60 | 0.46        | 2.0             |
|              |          | T         | 0,63                         | 0.63 | 0.62 |             | 1.9             |
| Rotar        | Friday   | L         | 0.39                         | 0.38 | 0.37 | 0.70        | 3.8             |
|              |          | T         | 0.53                         | 0.52 | 0.50 |             | 2.7             |
|              | Sunday   | L         | 0.39                         | 0.40 | 0.37 |             | 5.4             |
|              |          | T         | 0.53                         | 0.52 | 0.50 |             | 2.8             |
| 13 September | Thursday | L         | 0.31                         | 0.30 | 0.30 | 0.40        | 4.2             |
|              |          | T         | 0.44                         | 0.43 | 0.42 | 0.49        | 4.2             |
|              | Sunday   | L         | 0.30                         | 0.30 | 0.29 | 0.40        | 2.8             |
|              |          | T         | 0.43                         | 0.42 | 0.41 | 0.49        | 3.9             |

Given the aspects presented in Section 2 of the paper, this could be interpreted also as an underestimation by the above codes of the overall building stiffness. Nevertheless, the observed difference could also come from other factors, as additional dimensioning requirements, specific to each code. On the other hand, an opposite result was obtained for the IFA building, for which the value resulted from the empirical formulas in the P13-70 code was lower than the period computed from ambient vibration data. One should keep in mind that the building was subjected to the strong 1977 earthquake and, afterwards, it was damaged and retrofitted twice, first after this earthquake and later in the early 1990's. In the absence of more detailed information on the retrofitting, a primary conclusion is that, at present, the stiffness is smaller than estimated at design time, according to the P13-70 design code. Further investigation on applied retrofitting solutions and on effective material characteristics will provide information for more in-depth analyses.

For the two residential buildings (13 September and Rotar), where the data were recorded during working days and weekends, similar or very close values of the fundamental period were obtained, regardless of the day. As for the damping ratio, the variation was larger, ranging from 3.8 % (Friday) to 5.4 % (Sunday), on the longitudinal direction of the Rotar building. Following the same tendency, for the 13 September building, on the longitudinal direction, the damping ratio computed on Sunday was 2.8 %, while for Thursday it was 4.2 %.

Such relatively small variations were reported also in other studies aimed to monitor and track the dynamic characteristics of buildings; they were related mostly to the atmospheric conditions that can slightly modify the building's dynamic parameters [9, 11, 12, 23, 31].

From the soil-structure interaction perspective, the most important aspect is that the fundamental period of the building differs significantly from the period of the soil layers beneath.

For Bucharest area, the fundamental period of the sedimentary subsurface layers down to Fratesti complex, considered herein as bedrock (average depth of 140 – 150 m) was estimated in two studies conducted by Zaharia et al. [32], using the H/V technique, and by Bala et al. [33], from borehole data. These values were compared to the fundamental period of the analyzed buildings. The results show that the IFA building is founded on a soil having a fundamental period of vibration of approximately 1.3 seconds, double than the fundamental period of the building

(0.64 s). Based on this comparison, it can be concluded that the resonance of soil and structure, for the first mode of vibration, in the elastic range, is avoided. The same conclusion applies also for the other two buildings (13 September and Rotar), with fundamental periods of 0.53 and 0.43 seconds, and which are located in areas where the soil has fundamental periods of about 1.4 – 1.5 seconds, according to the above references.

## 5. Conclusion

A study on ambient vibration measurements performed on three multistory buildings in Bucharest area was presented, in which values of dynamic characteristics obtained by three different methods (Fourier spectra, transfer function and random decrement technique) were compared and analyzed in correlation with various factors, as measurement time and retrofitting history, whenever applicable. Each building is representative for a construction period/design code and/or a structural system used in Romania. Based on data available in the literature about site predominant periods on building locations, the possibility of site-soil resonance was also assessed. The study revealed consistent values for both the fundamental period and the damping ratio of the buildings, for all methods used. Some small diurnal and weekly variations were identified for the two parameters, which can be explained by differences in atmospheric conditions and building occupancy at the moment of data acquisition. The results, in terms of validated data on the dynamic characteristics of buildings representative for the Romanian building stock and of assessment of methods performance, add up to the prerequisites needed for the development of a countrywide pre- and post-earthquake assisted decision platform.

## 6. Funding

Most of this work was carried out within Nucleu Program, supported by the Ministry of Research and Innovation, project number: PN18150203 and by the Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe (SERA) project - EU Horizon 2020 Programme, Grant No. 730900.

## 7. Acknowledgement

The software suites Geopsy ([www.geopsy.org](http://www.geopsy.org), last accessed 27.07.2018) and Holisurface ([www.holiSurface.com](http://www.holiSurface.com), last accessed 13.08.2018) have been used for this study.

## 8. Conflicts of Interest

The authors declare no conflict of interest.

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