Modal parameters of a RC frame structure identified from ambient vibration measurements

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SUMMARY:
The paper presents the results of ambient vibration measurements and analysis performed for the identification of the modal parameters of a building in Bucharest, Romania. The 5 storey building built in the '70s has a reinforced-concrete frame structure with infill masonry-walls, with 16.85x42.30m plane dimensions and 19m height. Ambient vibration measurements were performed with equipments from National Center for Seismic Risk Reduction, Bucharest (donated by Japan International Cooperation Agency). The paper presents the analysis of 4 sets of velocity records obtained in 2 sensor configurations, having as result the first three modal parameters (corresponding to transverse, longitudinal and torsion vibrations). The possible soil-structure interaction effects are also addressed. A numerical model of the structure is used for the comparison of computed modal characteristics with the experimental ones. The obtained results characterize the dynamic building behaviour in the small amplitude vibration range.

Keywords: modal parameters, ambient vibrations

1. INTRODUCTION

Modal identification of existing buildings through the analysis of in-situ vibration measurements became a classic procedure for providing a "witness" of modal characteristics of a building, for studying the seismic response of buildings and even for damage detection. Modal characteristics are often identified from ambient vibration measurements (Midorikawa, 1990, Dunand et al., 2003, Negulescu et al., 2004 a, b, Michel et al., 2008, etc.) and from seismic records (Celebi et al., 1993, Ventura et al., 1995, Celebi 2000, Demetriu, 2001, Demetriu and Aldea, 2006, etc.). The results are generally used for studying their evolution in time, for comparison with new characteristics after a seismic rehabilitation, for calibration of computer models, etc. In some cases the studies are targeting the soil-structure interaction effects (Trifunac and Moslem, 1986, Dunand et al., 2004, Aldea et al., 2007, etc.). The paper presents the results of ambient vibration measurements and analysis performed for the identification of the modal parameters of an existing building in Bucharest, Romania.

1.1. Building description

The building of the Faculty of Civil, Industrial and Agricultural Buildings (FCCIA) of the Technical University of Civil Engineering Bucharest (UTCB) is located in the central NE area of Bucharest. The entire building consists of 4 different independent units, separated by seismic joints. The paper focuses on the main and larger unit of FCCIA building, shown in Figure 1.1. Built in the '70s, the main building has semi-basement, ground floor and 3 stories. The shape is rectangular (16.85m x 42.30m) and the total height is ~19m (Lozinca, 2009). A central corridor along the longitudinal direction separates the functional areas that are located on both sides. The hall divides the interior space in 2 unequal spans of 6.25 m and 7.25 m. The building has a reinforced concrete frame structure consisting of 4 longitudinal and 10 transverse frames (Fig.1.1). There are 3 unequal spans of 6.25m, 3.35m and 7.25m on the longitudinal direction, and 9 equal spans of 4.70m on the transverse direction, Fig.1.2.

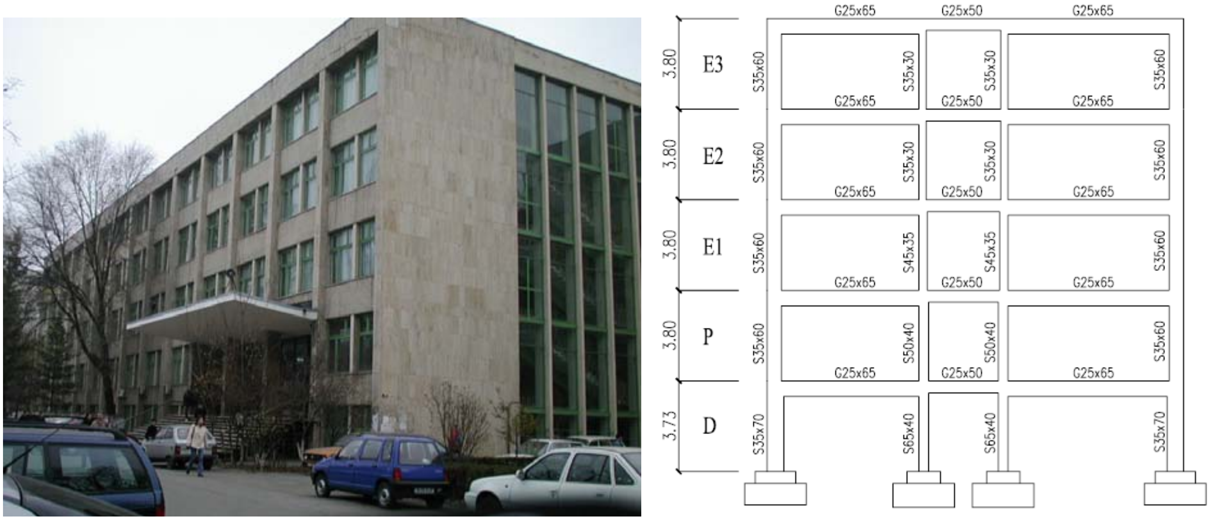

Figure 1.1. FCCIA building. Example of transverse frame (Lozinca, 2009)

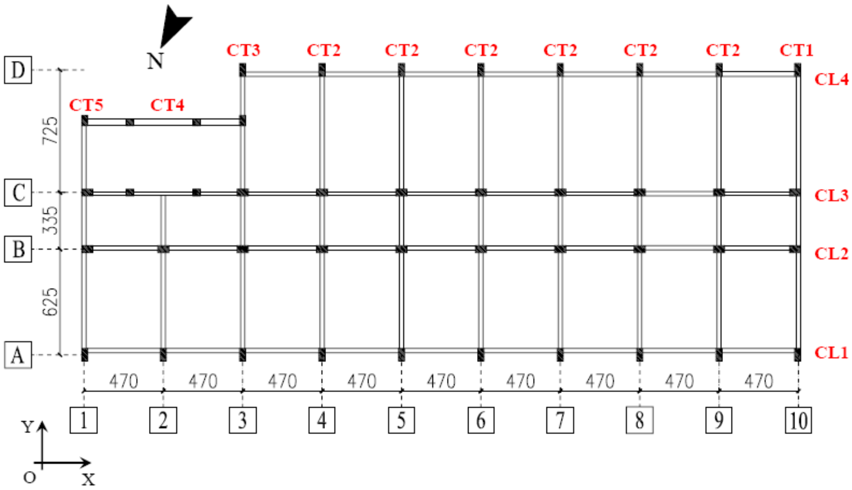

Figure 1.2. FCCIA building. Plane view of current storey (Lozinca, 2009)

From the structural point of view, there are 5 different types of transverse frames and 4 types of longitudinal frames. The slabs are made of reinforced concrete with 12cm thick in the marginal spans and 10cm in the central span. The columns on the north-western and south-eastern fronts have a constant section of 35x60cm along the whole height of the building, except the semi-basement where the section becomes 35x70cm. The interior columns present 3 steps of variation. The non-structural walls are made of solid brick masonry, with light self weight, with low mechanical and deformation properties. The foundation consists of isolated footings (reinforced bush and simple concrete block) under the frames columns and a rectangular network of foundation beams.

1.2. Ambient vibration measurements

In 2003 ambient vibration measurements were performed (by staff from National Centre for Seismic Risk Reduction NCSRR and UTCB together with Japanese experts from Building Research Institute, Tsukuba) using Japanese Geodas portable station and 1 second velocity sensors. The equipment was donated to NCSRR by Japan International Cooperation Agency (JICA) within the Project Reduction of Seismic Risk for Existing Buildings and Structures (JICA, 2002).

Several sets of recordings of 5 minutes each were acquired. The sampling frequency was 200 Hz. Two sensor configurations (setups) were used during measurements.

In the first setup, the sensors (with simultaneous recording on 11 channels) were installed on the central corridor as follows: (i) at the basement floor: two vertical measuring sensors at both extremities of the structure on the building longitudinal direction and two horizontal measuring sensors in the centre of the structure, following the transverse and longitudinal directions of the building; (ii) at the 1st and 3rd floors: two horizontal sensors at each floor following the transverse and longitudinal directions of the building; (iii) in free field: three horizontal sensors following the transverse, longitudinal and the vertical directions. In the second setup (with simultaneous recordings on 9 channels), the sensors from basement and free field were kept at the same location, and at the 3rd floor were installed two horizontal sensors in order to investigate torsional vibration. The sensors setups and numbering are shown in Fig. 1.3.

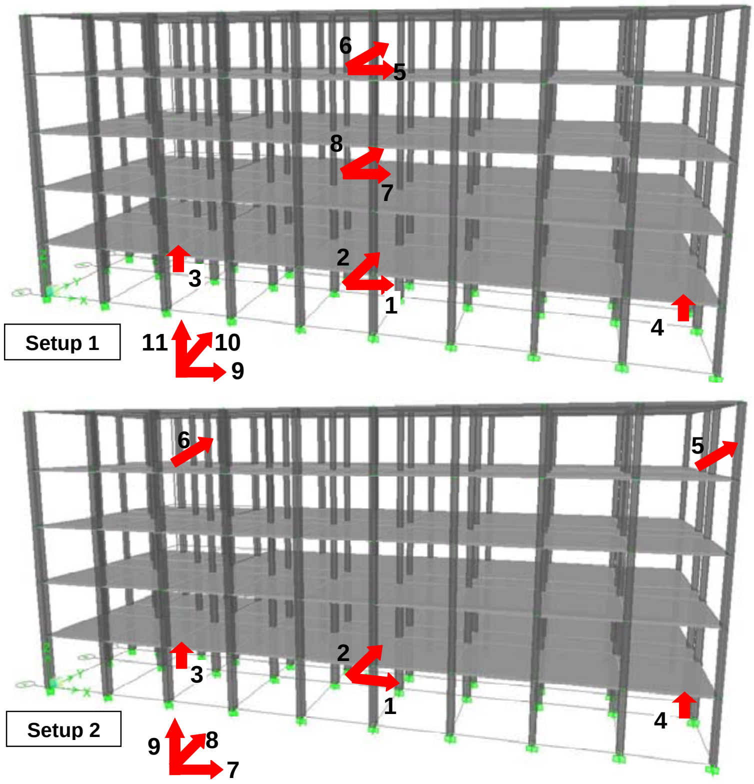

Fig. 1.3. Sensors configurations for ambient vibration measurements at the FCCIA-UTCB building

2. ANALYSIS OF AMBIENT VIBRATION RECORDS

2.1. First sensor setup

The following results were obtained using the first setup of sensors, and the whole length of velocity ambient vibration records (Udrea et al., 2011). In Figure 2.1 are shown examples of the records at the top of the building (3rd floor) and in the free field, and the evolution of the Fourier amplitude spectra from the free field record to the first and third floors, on transverse and longitudinal directions. The Fourier amplitude spectra clearly indicate the first frequencies of vibration on each direction of the building. The average values of the first two modal frequencies (and the corresponding periods) identified from the analysis of the Fourier spectra and of the Fourier spectral ratios (top/free field) from all the sets of records from Setup 1 are given in Table 2.1.

2.2. Second sensor setup

In the second setup the sensors recorded the transverse vibration at the top of the building. The average Fourier spectra and average Fourier spectral ratios are shown in Figure 2.3.

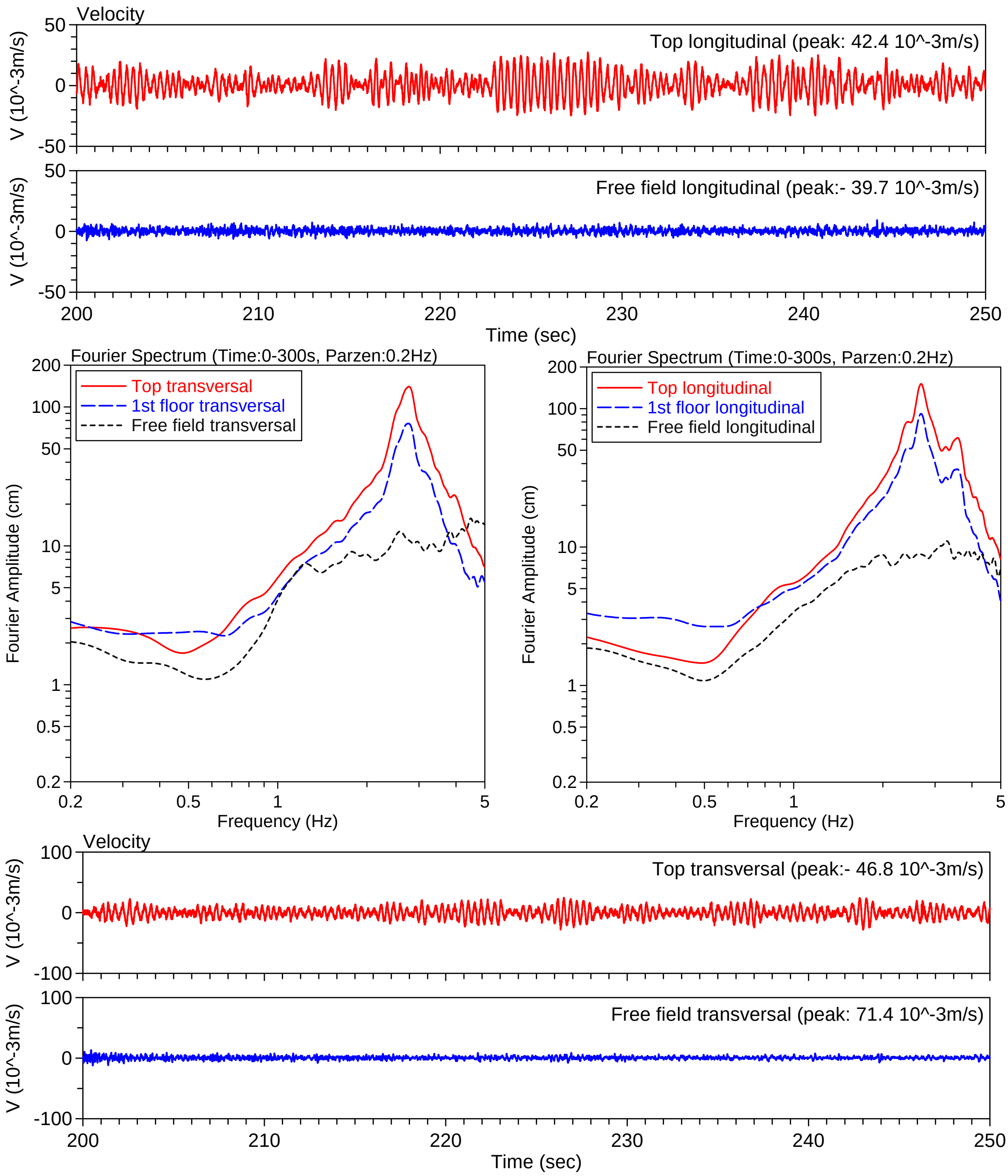

Fig. 2.1. Examples of ambient vibration records and Fourier amplitude spectra (Setup 1)

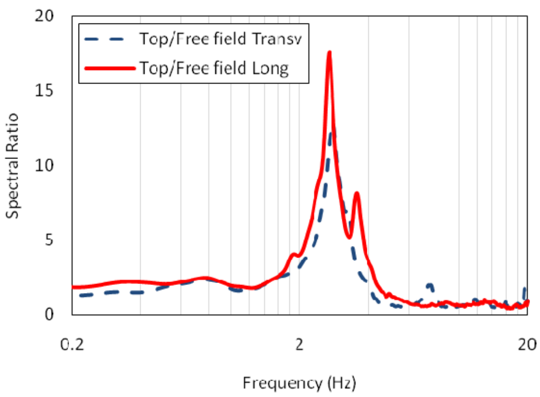

Fig. 2.2. Average Fourier spectral ratios (Setup 1)

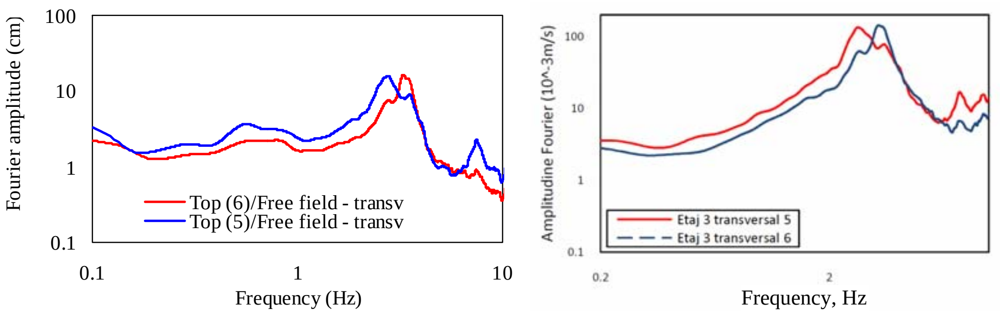

Fig. 2.3. Average Fourier amplitude spectra and Fourier spectral ratios (Setup 2)

The difference between the records from sensors 5 and 6 in the second setup allows the identification of the frequency of torsional vibration mode, Figure 2.4.

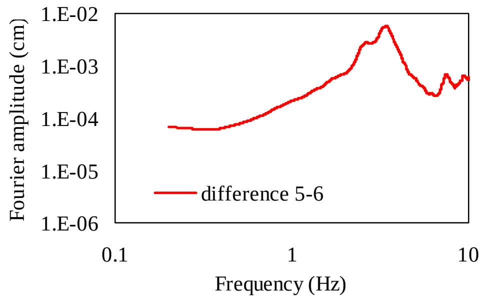

Fig. 2.3. Average Fourier amplitude spectra of the difference between sensors 5 and 6 (Setup 2)

2.3. Modal identification results

A synthesis of the average values of the first frequencies of translational modes (and corresponding periods) obtained from the spectral analysis of data recorded in the setup 1 is given in Table 2.1.

Table 2.1. First modal frequencies (and corresponding) periods identified through the analysis of ambient vibrations for the UTCB-FCCIA building (Setup 1)

Setup 1	Fourier Amplitude								Fourier Spectral Ratio							
	Transverse				Longitudinal				Transverse				Longitudinal			
	f_1 (Hz)	T_1 (s)	f_2 (Hz)	T_2 (s)	f_1 (Hz)	T_1 (s)	f_2 (Hz)	T_2 (s)	f_1 (Hz)	T_1 (s)	f_2 (Hz)	T_2 (s)	f_1 (Hz)	T_1 (s)	f_2 (Hz)	T_2 (s)
Measurement 1	2.77	0.36	7.44	0.13	2.69	0.37	3.58	0.28	2.79	0.36	7.42	0.13	2.70	0.37	3.49	0.29
Measurement 2	2.76	0.36	7.52	0.13	2.70	0.37	3.53	0.28	2.76	0.36	7.44	0.13	2.70	0.37	3.50	0.29
Measurement 3	2.69	0.37	7.29	0.14	2.66	0.38	3.55	0.28	2.78	0.36	7.30	0.14	2.66	0.38	3.55	0.28
Measurement 4	2.73	0.37	7.32	0.14	2.66	0.38	3.53	0.28	2.77	0.36	7.26	0.14	2.63	0.38	3.54	0.28
Average	*2.74*	*0.37*	*7.39*	*0.14*	*2.68*	*0.37*	*3.54*	*0.28*	*2.78*	*0.36*	*7.36*	*0.14*	*2.67*	*0.37*	*3.52*	*0.28*

In 2003-2004 two independent analyses were performed with slightly different approaches. The results are herein briefly summarized for comparison. The first analysis (Negulescu et al., 2004a) included: (i) Fourier spectra, (ii) Power spectra and (iii) Spectral ratios, and used the whole length of the records. Data obtained from both setups of sensors were used and the results are presented in Table 2.2.

In the second analysis (Negulescu et al., 2004b), all the waveforms from setup 1 were displayed, divided into data windows of 4096 values, and the segments identified with abnormal amplitudes were eliminated (the number of data windows used for the analysis was different for every recording and varies from 7 to 10). The first periods of translation are given in Table 2.3.

Table 2.2 First modal frequencies of the FCCIA building (2004a results)

	Fourier amplitude			Power spectral density			Spectral ratios		
	Trans.	Long.	Tors.	Trans.	Long.	Tors.	Trans.	Long.	Tors.
Setup 1 Measurement 1	2.81	2.67	3.47	2.77	2.68	3.58	2.81	2.71	3.49
Measurement 2	2.78	2.67	3.45	2.76	2.69	3.56	2.77	2.72	3.52
Measurement 3	2.73	2.66	3.53	2.73	2.66	3.56	2.79	2.72	3.54
Measurement 4	2.84	2.68	3.52	2.72	2.66	3.51	2.78	2.72	3.56
Setup 2 Measurement 1	2.8	2.63	3.51	-	2.66	3.48	2.74	2.64	3.28
Measurement 2	2.73	2.62	3.41	2.79		3.42	2.76	2.66	3.54
Measurement 3	2.74	2.6	3.35	-	2.66	3.31	2.78	2.66	3.54
Measurement 4	2.8	2.66	3.3	2.81	2.68	3.28	2.76	2.65	3.47
Average value ±st. dev. (Hz)	*2.78 ±0.04*	*2.65 ±0.03*	*3.44 ±0.08*	*2.76 ±0.03*	*2.67 ±0.01*	*3.46 ±0.11*	*2.77 ±0.02*	*2.68 ±0.03*	*3.49 ±0.09*

Table 2.3 First modal periods of the FCCIA building (setup 1, 2004b results)

Method	*Setup 1*- measurement no.	1	2	3	4	*Average*
Fourier amplitude spectra	T_1 – Longitudinal (s)	0.37	0.37	0.37	0.38	*0.37*
	T_1 – Transverse (s)	0.35	0.36	0.35	0.35	*0.35*
Fourier spectral ratios	T_1 – Longitudinal (s)	0.37	0.37	0.39	0.37	*0.37*
	T_1 – Transverse (s)	0.35	0.35	-	-	*0.35*

One can observe the good match of the results in Tables 2.1-2.3. By taking into consideration all the results from the two setups, the following modal periods were identified for the FCCIA building:

- translation on longitudinal direction: T_{1L}= 0.37s T_{2L}= 0.28s
- translation on transverse direction: T_{1T} = 0.36s T_{2T}= 0.14s
- torsion: T_T = 0.30s.

3. INVESTIGATION OF SOIL-STRUCTURE INTERACTION EFFECTS

Since ambient vibration records were simultaneously obtained in free field and at the base of the building and top of the building, the possible soil structure interaction SSI effects can be evaluated. In Figure 3.1 are comparatively presented the spectral ratios top/free field and top/base. The characteristics of the top/free field spectral ratios include all soil structure interaction effects. Due to SSI inertial effects, the peak frequencies from the top/free field spectral ratio should be smaller than the peak frequencies from the top/base spectral ratios. The comparison of the identified peak frequencies is presented in Table 3.1.

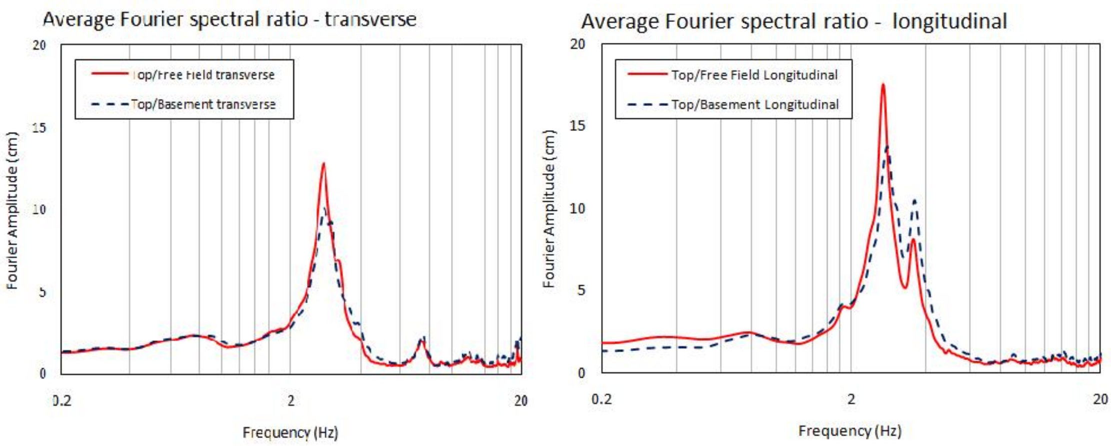

Fig. 3.1 Comparison between the average of the spectral ratio Top/Free field and Top/Base on transverse (left) and longitudinal direction (right)

Table 3.1 First modal frequencies of the FCCIA building from spectral ratios Top/Free field (T/FF) and Top/Base (T/B)

Setup 1	Modal frequencies (Hz)							
	Transverse direction				Longitudinal direction			
	f_1 (T/FF)	f_1 (T/B)	f_2 (T/FF)	f_2 (T/B)	f_1 (T/FF)	f_1 (T/B)	f_2 (T/FF)	f_2 (T/B)
Measurement 1	2.79	2.87	7.42	7.42	2.70	2.83	3.49	3.67
Measurement 2	2.76	2.77	7.44	7.48	2.70	2.77	3.50	3.64
Measurement 3	2.78	2.87	7.30	7.58	2.66	2.70	3.55	3.58
Measurement 4	2.77	2.88	7.26	7.46	2.63	2.75	3.54	3.56
Average	*2.78*	*2.85*	*7.36*	*7.48*	*2.67*	*2.76*	*3.52*	*3.61*

Results in Table 3.1 show a constant slight reduction of the modal frequencies in case of the top/free-field spectral ration, and thus confirm the existence of a slight soil-structure interaction inertial effect.

The kinematic soil structure interaction effect is associated to the modification of the signal at the base of the structure in comparison to the free field signal. The base/free field spectral ratios are used for investigating this effect, Figure 3.2. The spectral ratios from all the records from setups 1 and 2 are shown, and the averages of all ratios are also displayed.

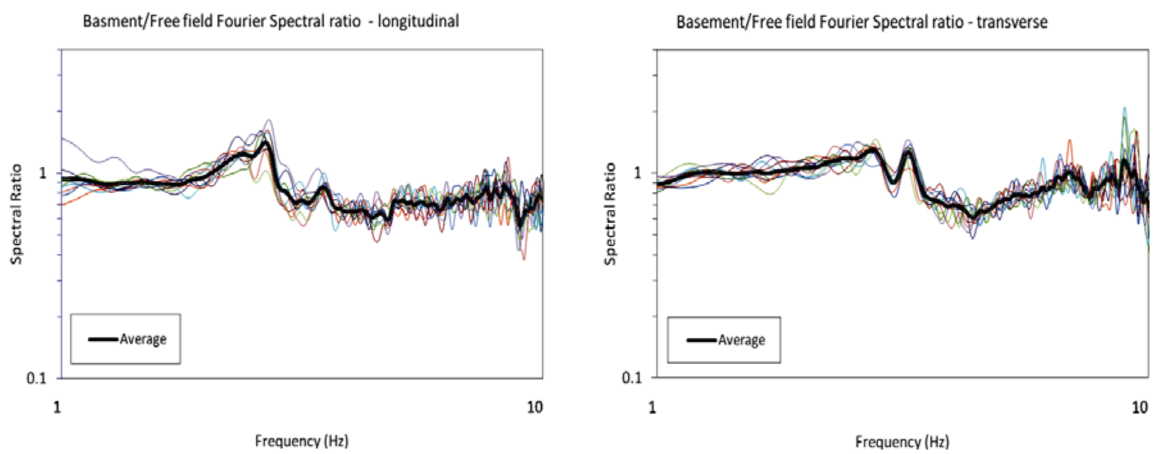

Fig. 3.2 Basement over free field spectral ratios

It can be noticed that after the peak corresponding to the peak frequency of the building, spectral ratio values decrease under unit value, due to high frequencies filtering, indicating a slight soil-structure interaction kinematic effect.

The vertical sensors located at the basement level at the extremities of the building (Figure 1.3) allowed the study of the rocking frequency. The results were not very clear, but a rocking frequency candidate of 10.72 Hz was selected (corresponding rocking period 0.09s).

The study allowed the identification of slight soil structure interaction effects, with no significant numerical effect, as one could expect in this case of a mid-rise building, not very rigid, with no basement and with isolated foundations lying on a Eurocode 8 class C ground (the 30m weighted average shear wave velocity at UTCB site is 309m/s).

4. ANALITYCAL STUDY

A three-dimensional structural model (model 1) for seismic evaluation was constructed by Lozinca (2009), in ETABS software. The model only included the horizontal and vertical structural elements.

The modal periods obtained with this structural model 1 are significantly different from those obtained from the analysis of ambient vibration records (Table 4.1).

Since the results from ambient vibration analysis correspond to low amplitude vibrations, it can be considered that not only the structural elements but also the non-structural ones contribute to the overall building stiffness. Consequently the non-structural elements should also be considered in the analytical computer model in order to obtain a reasonable comparison between analytical and experimental results (Ventura et al., 2002).

A new three-dimensional structural model (model 2) was constructed and it includes all the partition and closing walls and windows (with their actual disposal and with consideration of the actual position and dimension of doors and windows openings), after an on-site investigation of the building.

In Figure 4.1 are shown the three-dimensional structural models of main FCCIA building.

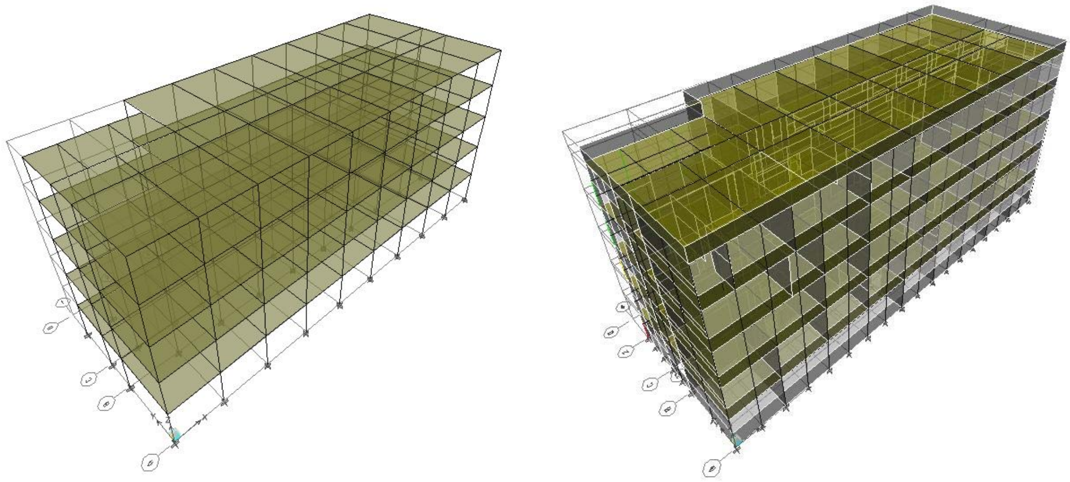

Figure 4.1. FCCIA building – model 1 (left, only structural elements) and model 2 (right, complete model)

In Figure 4.2 are presented the first three vibration mode shapes of the complete model of building.

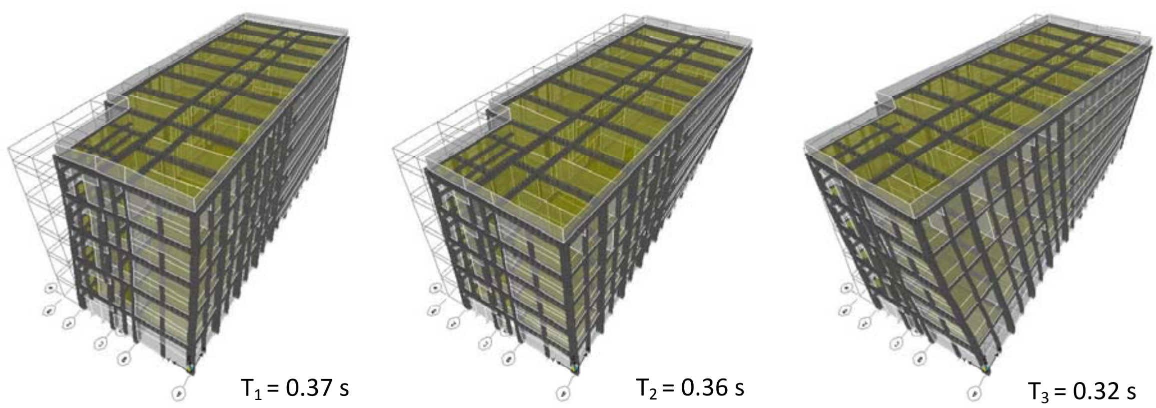

Figure 4.2. FCCIA building –the first three-dimensional mode shapes - model 2 (complete model)

In Table 4.1 are comparatively presented the first modal periods of the FCCIA main building from the analysis of the ambient vibration measurements, and from the computer analysis of the two building models above described.

Table 4.1 Comparison of the first modal frequencies of the FCCIA building

Vibration mode	Fourier amplitude	Fourier spectral ratio (top/free-field)	Fourier spectral ratio (top/basement)	Model 1	Model 2
	T (s)	T (s)	T (s)	T (s)	T (s)
longitudinal	0.37	0.37	0.36	0.90	0.37
transverse	0.37	0.36	0.35	0.89	0.36
torsion	0.30	-	-	0.83	0.32
longitudinal	0.28	0.28	0.28	0.32	0.13
transverse	0.14	0.14	0.13	0.30	0.12

As one can observe, the differences between the two building models are significant and they reflect the underestimation of the overall building stiffness in model 1. By including in the model the non-structural elements, the results are getting closer to the experimental results, and the order of the vibration modes is the same.

5. FINAL REMARKS

The results characterize the building's behaviour in the small amplitude vibration domain , and include the contribution of non-structural elements and of the partial embedment of the semi-basement to the global rigidity of the building.

The analysis of ambient vibration measurements also allowed the identification of slight soil-structure interaction effects, with no significant numerical effect, as one could expect in this case of a mid-rise building, not very rigid, with no basement and with isolated foundations lying on a Eurocode 8 class C ground.

The results from the analysis of ambient vibration measurements allowed the development of a calibrated computer model that can be used in future for building's monitoring. These results can also be useful as a witness of the present state of the building in case of future comparisons with results after a strong earthquake or after seismic rehabilitation.

AKCNOWLEDGEMENT

Authors would like to acknowledge JICA for the portable ambient vibration measurement equipments donated within the Seismic Risk Reduction Project, and for supporting the working periods of Romanian researchers in Japan and of Japanese researchers in Romania. Special thanks to the staff of Building Research Institute, Tsukuba, Japan.

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