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EFFECT OF NON-STRUCTURAL COMPONENTS ON THE MODAL PROPERTIES OF BUILDINGS USING AMBIENT VIBRATION TESTING

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ABSTRACT

This paper illustrates the effect of non-structural components on the variation of dynamic properties of buildings in the elastic range using ambient vibration testing. A six-storey reinforced concrete building that forms part of the École de Technologie Supérieure campus was studied. Ambient vibration tests were conducted on this building during its construction and once finished. Measured records at different floor levels served to extract the natural frequencies, mode shapes and damping ratios of the building. Values obtained for the studied building, both at bare frame and finished phases were then compared. Calculated differences in the natural frequencies of the building range between 1.6 % and 21.7 %. Results highlight the importance of considering the contribution of non-structural components such as glass, facades and partition walls in the process of structural analysis and modeling of buildings.

Keywords: Dynamic modal properties, ambient vibration testing, signal analysis, non-structural components, system identification

1. INTRODUCTION

A building is mainly made up of structural components and non-structural components (NSCs) or systems known in Canada as operational and functional components (OFCs). According to CSA S832-14 (CSA 2014), OFCs are those systems or elements housed in or attached to the floors but are not part of the main load-bearing structural system. They can generally be divided into three categories of sub-components:

1. **Architectural components:** *internal* like interior partition walls, ceilings and lighting fixtures and *external* like cladding and parapets;
2. **Building or operational services:** including *plumbing systems* (like piping and sprinklers), *mechanical systems* (like heating, ventilation and air conditioning systems, and elevators), *electrical systems* (like electric generators, transformers, and battery racks), *information technology and telecommunications* (like telephone system, communication system, and cable trays);
3. **Building contents:** *common* like supplies, computer systems, record storage, and *specialized* like fine arts, medical equipment and hazardous laboratory or medical materials.

The first two categories are built-in NSCs that form part of the building, while the third category includes all pieces of furniture found inside the building.

When a building is subject to seismic excitation, most international design practices consider that its lateral load resisting system is an assembly of structural components such as the structural frames, shear walls, concrete cores, etc.; they neglect the contribution of NSCs and treat them as independent from the structural system. For instance, most designers of partitions and facades assume that these components are completely detached from the structure and thus do not contribute to its lateral stiffness. In practice, this would rarely be the case even when gaps are specified. Therefore, the role played by the NSCs is not incorporated in either the national building code of Canada (NRC 2010) or the CSA S832 standard (CSA 2014).

Although they lack in structural abilities, increased evidence indicates that the role of NSCs in resisting lateral loads, can be very significant, and the interaction between the NSCs and the structural skeleton may lead to distress, loss of serviceability and occasional failure of the NSCs even after moderate wind or earthquake events. The contribution of NSCs to the lateral stiffness of buildings was recently pointed out by many researchers (Asgarian and McClure 2012; Devin and Fanning 2012; Li et al. 2011; Sofi et al. 2014; Sugiyama et al. 2000). Moreover, the actual performance of real buildings during earthquakes differs significantly from the one based on idealized structural models as highlighted in Lucchini et al. (2014), Sofi et al. (2015) and Sofi et al. (2013).

In the last decade, in situ ambient vibration tests (AVT) have been widely used to complement and improve seismic vulnerability evaluation of existing buildings (Boutin et al. 2005; Gilles 2011; Michel et al. 2008a; Ventura and Horyna 1997). AVT provide information about the dynamic characteristics of a structure in real conditions in the elastic range, as sensitivity of available equipment can detect any level of physical changes in the building characteristics.

In order to gain an insight into the effect of NSCs on the estimation of modal properties of buildings, a series of AVT were conducted on a six storey building that was recently constructed on the École de technologie supérieure (ÉTS) campus. Experimental modal parameters such as the frequency of vibration, the damping ratios and the mode shapes for this case-study building were identified at the completion of the bare frame and finished phases before the addition of building content. Results were compared in order to assess the expected variation in the building modal properties due to the addition of architectural components and heavy mechanical equipment. It is known that modal parameters depend on the materials, the stiffness, the mass and the geometry of the structure. Results obtained at both construction phases are shown and confirm that NSCs affect the modal properties of buildings.

2. DESCRIPTION OF THE TEST STRUCTURE

The “Maison des étudiants” (MDE) located on the ÉTS campus in Montreal is a six-storey reinforced concrete office building (see Figure 1.a). The lateral force resisting structural system is made up of reinforced concrete moment resisting frames, a central concrete core wall and shear walls located at the Western and Eastern boundaries. This 29.3 m building has two basement levels and consists mainly of offices and open spaces at the lowest four floors while the fifth floor consist of offices and teaching rooms (see Figure 2). The top floor consists of a mechanical room, and an extension of elevators and stairs. This building has a square shape in plan with dimensions 59m x 59m.

The particularity of architectural design of the MDE structure stems from the fact that it has many innovative structural subsystems and non-structural components. Indeed, a complex steel structure that supports a ten-meter cantilever slab is an example of the harmonious integration of steel while enhancing the visual appearance of the entire building (see Figure 1b). As recognition, the building won the Award of excellence in steel construction from the Canadian Institute of Steel Construction (CISC), in the category of Commercial and Institutional Projects. In addition, 2760 square meters of curtain walls entirely enclose the building. Vertical and diagonal perimeter columns that support glass panels amplify the height effect of the entrance. The west and east facades are composed of precast concrete panels at the ground level of the building. Finally, the outside of the east facade will be completed with a 790 square meters green roof in an inclined plane structure.



Figure 1: General 3-D views of the MDE Building in the finished phase a) North view reproduced from drawings, b) South-East facade with steel cantilever (Reproduced from Carignan (2015))

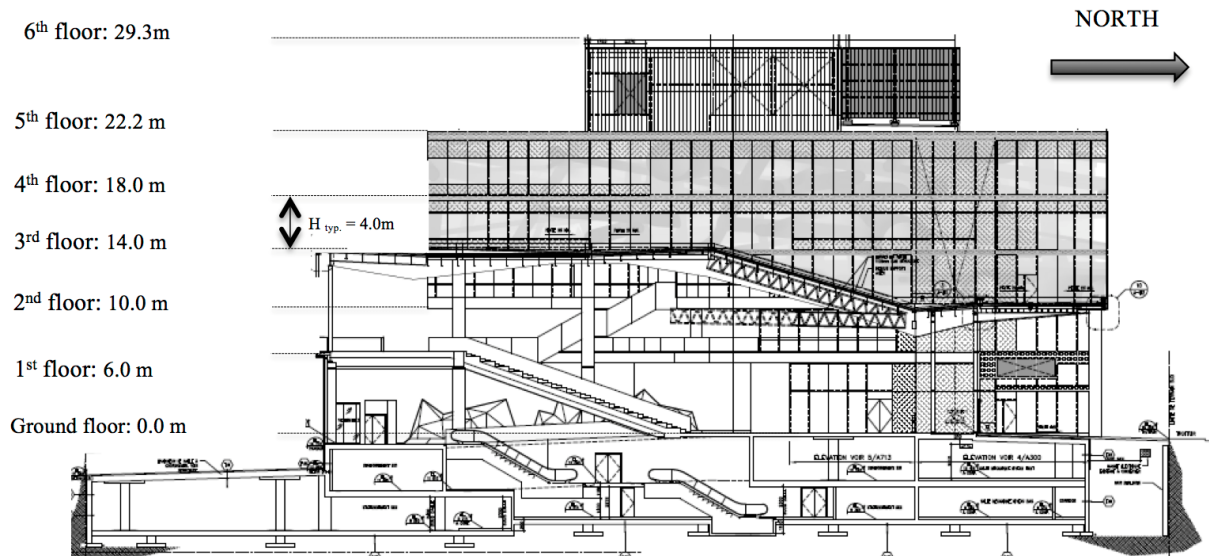


Figure 2: North south elevation view of the MDE building

3. AMBIENT VIBRATION TESTING AND DATA PROCESSING

3.1 Test setups

High-resolution digital tromographs for passive and active seismic surveys and vibration monitoring were used to measure the vibration response of the structure due to prevailing environmental conditions (wind, anthropic activities, noise). The Tromino® sensor works in the acquisition frequency range of 0.1 to 1024 Hz in which all natural frequencies of buildings are included (Micromed S.p.A 2011). Both velocities and accelerations induced by ambient vibrations were measured in three orthogonal directions: two in the horizontal plane (x, y) and one along the vertical axis (z). It should be noted that only the output modal parameters and velocity motions in the horizontal plane are discussed in this paper.

AVT were carried out for two different phases of construction (Figure 3):

- a) Bare frame phase: reinforced concrete frames and walls completed and some cladding elements in place, mainly the precast concrete panels and some window panels at the ground level ;

- b) Finished phase: the elevators in place, the mechanical room housing all main mechanical, electrical systems as HVAC, fire protection and water treatment added. The windows and gypsum panels were gradually added in the period between the two measures.



Figure 3: Construction sequence a) bare frame phase - September 2014, b) finished phase - July 2015 (Reproduced from (ÉTS 2015))

Many architectural NSCs (partitions, both wood and suspended ceilings) and building contents were added since the official opening of the building in October 2015. Therefore, a third AVT will be carried out in 2016 in order to assess the effect of internal architectural components and building content on the dynamic properties of the building.

The spatial distribution of measurement points is selected in such a way to better catch the dominant modes of vibration of the building and the rotational component of the floors. Selected measurement points are divided into groups, so-called setups. Multiple setup configurations (a total of 3 and 6 respectively for the two phases) were done using two reference sensors remaining in the same place to normalize components of the modal shapes, and four roving sensors moving to the measurements points. Five or six sensors per floor measuring along the “y” direction (matching the building y-axis) were positioned as shown in Figure 4.

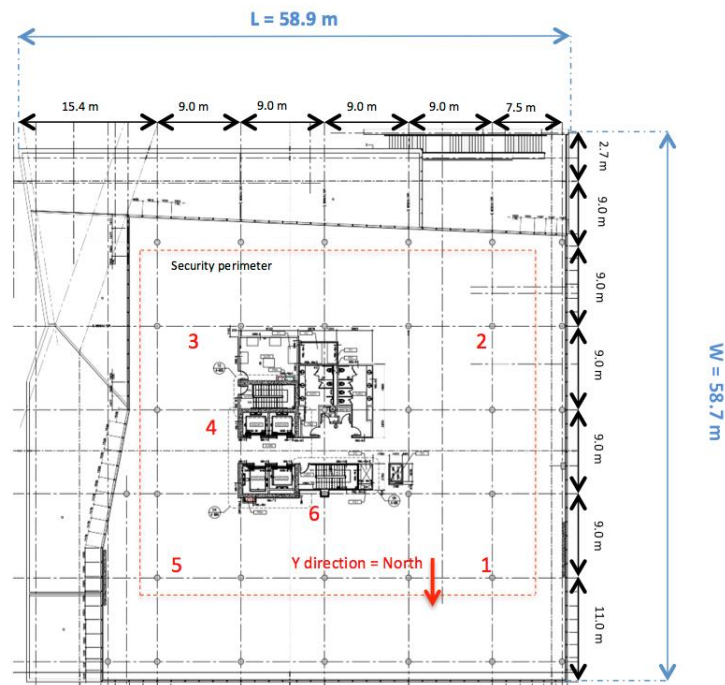


Figure 4: Horizontal measurements points at different floor levels

For instance, Figure 4 shows also the schematic layout of the first setup for the finished phase of the building with all six sensors at the fifth floor. For the second setup, two roving sensors will be moved to the sixth floor (points labeled 31 and 32) housing the mechanical room (see Figure 5). Only these two setups are included in this analysis as the frequency of vibration is easily captured from recordings at the top level of the structure. In this case, sensors labeled 1, 4, 5 and 6 are considered as reference sensors. The remaining setups (with sensors 1 and 6 as reference) will be studied and will serve to calibrate the finite element model of the building in an ongoing research project.

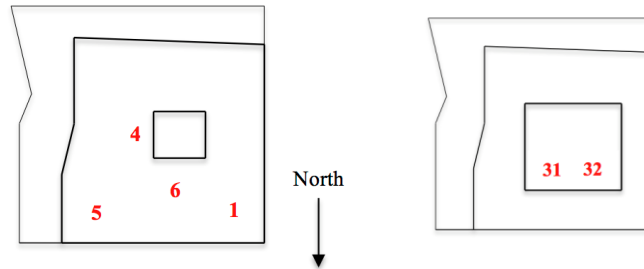


Figure 5: Horizontal Setup 2: a) four sensors on 5th floor b) two on 6th floor

Due to construction constraints, the different testing locations were taken within a security perimeter. The ground floor was not monitored since it was not accessible during the construction works. The ambient motions of the structure were recorded for 8 minutes at a sampling rate of 128 Hz. Setups with such characteristics are considered adequate for the studied building (Micromed S.p.A 2011). The sensors were synchronized using built-in radio facilitating communication at longer distance up to 400m.

3.2 Response analysis

The recorded signals were processed by means of standard signal pre-processing techniques implemented in a Matlab routine in order to clean the signal, select the two horizontal (x, y) measurements required for the analysis and regroup recorded signals of each setup. This routine has been developed specifically to analyse data acquired with Tromino sensors, so a compatible file was developed. Then, the modal analysis was carried out using the commercial software Artemis Extractor® once a model has been built based on the different measurements points, with a total of 20 points for the bare frame and 26 points for the finished building (Figure 6). (Note that points at ground floor are not measurements points.)

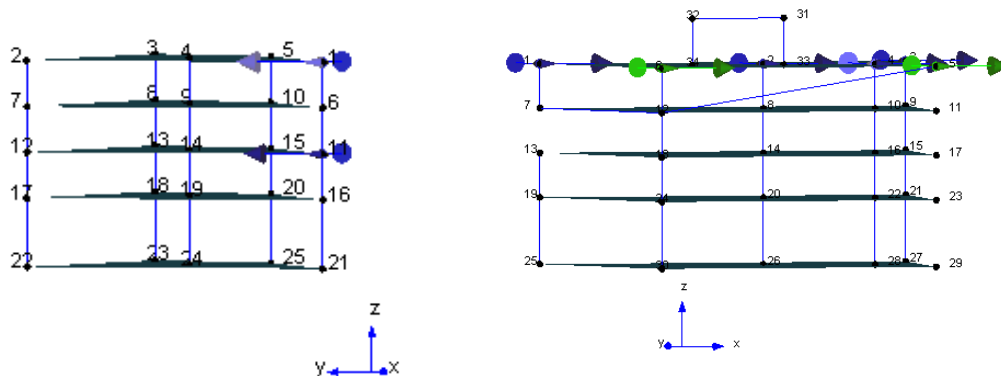


Figure 6: Uploaded model in Artemis extractor for setup 1: a) bare frame, b) finished phase

Two peak picking techniques can be used to identify the modal parameters of the structure: Frequency Domain Decomposition (FDD) and Enhanced Frequency Domain Decomposition (EFDD) (SVIBS 2011). The Fourier transform is the basic tool of frequency analysis. Peak picking techniques use the singular value decomposition (SVD), which leads to the rejection of the effect of noise to identify the building's dominant frequencies and corresponding mode shapes (Cremona et al. 2003). It consists of decomposing the power spectral density matrices into single-degrees-of-freedom systems by singular value decomposition.

Compared to the basic FDD version, the EFFD method provides an improved estimate of both the natural frequencies and the mode shapes and includes damping also. An adjustment is necessary using Modal Assurance Criterion (MAC) for comparing experimental and analytical eigenvectors, with the results presented in the form of a matrix. When the coefficient is close to 1, the mode shapes are close and it is then possible to select frequencies with good correlation (Michel et al. 2008b; Ventura 2012).

Figure 7 illustrates the process, considering one set of signals (gray curves) integrated in the Artemis Extractor software. The amplitude of the input signals is given in decibels (dB) or power spectral density (PSD) representing in fact the energy in each frequency that characterizes a mode. The Artemis software automatically identifies some peaks corresponding to vibrational frequencies; it is also possible to complete the identification of other important peaks manually.

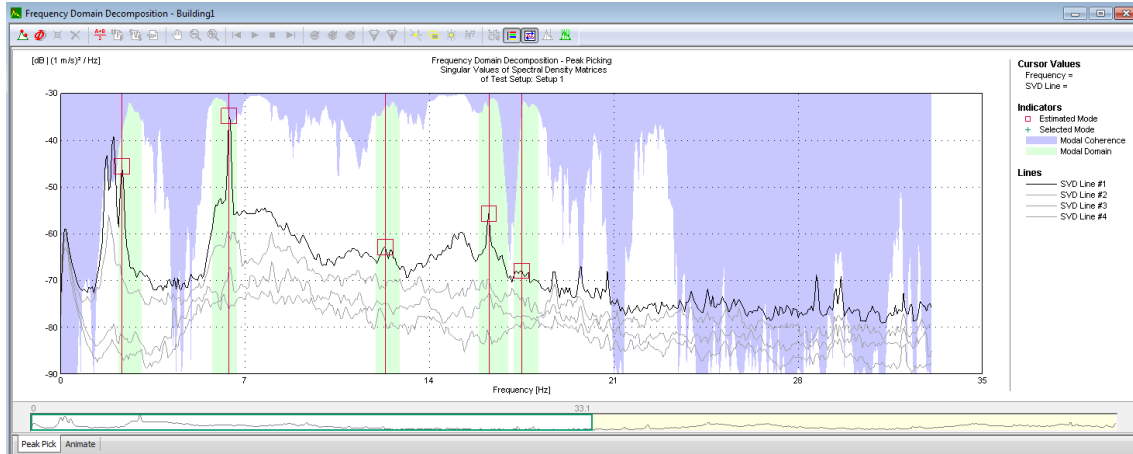


Figure 7: Signal analysis and processing using the FDD method with automatic peaks identification

4. IDENTIFICATION OF MODAL PARAMETERS

4.1 Natural Frequencies and mode shapes

The natural frequencies for the first three modes of vibration corresponding to two construction phases of the studied building were extracted as summarized in Table 1. Only results obtained with EFFD method are presented since they are close to values obtained from the FDD method, and values of damping ratios can only be obtained by the former technique.

Table 1: Estimated natural frequencies and mode shapes using the EFDD method

Modes	Bare frame phase		Finished phase		Difference (%)
	Frequency (Hz)	Mode shape	Frequency (Hz)	Mode shape	
Mode 1	2.3	Transverse	1.8	Transverse	21.7
Mode 2	6.4	Longitudinal	6.3	Longitudinal	1.6
Mode 3	12.4	Torsional	11.9	Torsional	4.0

4.1.1 Natural Frequencies

For the computed frequencies (Table 1), a general decrease in values can be observed between the two construction phases. The difference in terms of percentage ranges from 1.6 to 21.7 %. It is an indication of the effect of the additional mass in the building. This result was expected since the effect of variation in stiffness is very small as the main rigid components (some window panels and concrete panels) have already been in place at the bare frame phase.

4.1.2 Comparison of computed fundamental period with the NBCC value

The fundamental period of a building is an important design parameter, especially for the calculation of seismic design base shear forces and for the evaluation of spectral accelerations. According to the current edition of NBCC (NRC 2010), the fundamental period T for shear walls and other structures is calculated by the empirical formula as given in Equation 1.

$$[1] \quad T = 0.05(h_n)^{3/4}$$

Where h_n is the total height of the building.

A comparison of periods extracted from AVT and calculated according to NBCC equation is summarized in Table 2.

Table 2: Comparison of building periods extracted from or AVT and calculated according to NBCC equation

	T (s)	
	Bare frame	Finished phase
AVT	0.44	0.56
NBCC		0.63
Difference (%)	30.0	11.0

We can conclude that extracted fundamental periods for the finished phase are close to the value given in the NBCC for this type of building, and an increase in the building mass leads to an increase of the period of vibration, therefore a decrease in the seismic force. The AVT results highlight the fact that the contribution of the mass of NSCs is not negligible and may counteract the effect of increased rigidity.

4.1.3 Mode shapes

Mode shapes typically were obtained from the modal analysis; they remained the same in both phases. Figure 8 illustrates mode shape obtained for the bare frame phase using the EFDD analysis technique. We can note a torsional component in modes 1 and 2

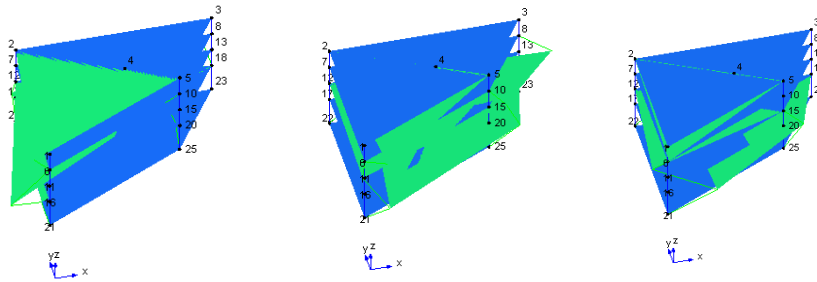


Figure 8: Mode shapes from EFDD method (Bare frame)

4.2 Damping

As for the estimated damping ratios (Table 3), values corresponding to the considered modes of vibration vary between 0.5 and 1.8% for the bare frame phase while they vary between 1.2 and 2.5% for the finished phase. It is worth mentioning that values of damping ratios extracted from AVT present significant scatter and sometimes are deemed not reliable (Tamura 2011). Tischer (2012) noted that the variability in computed damping ratios extracted from measurements taken at different periods for the same existing building is attributed to a variation in ambient conditions like the temperature and the time of measurement. Tamura (2011) and Cremona et al. (2003) also found a variability in damping ratios associated with different parameters such as the structural materials, architectural finishing, types

of non-structural components, variation of damping evaluation techniques (proportional to the vibration amplitude) and the non-stationary of excitations.

Table 3. Damping ratio estimation by EFDD

	Bare frame phase	Finished phase
Modes	(%)	(%)
Mode 1	1.8	2.5
Mode 2	0.5	1.5
Mode 3	1.4	1.2

Within this study, the results obtained for the finished phase (first mode) are in the range of expected values:

- 1) A value close to 3% is widely used in common practice for the linear analysis of new constructions, and
- 2) According to the relationship between frequency and damping ratio proposed by Tamura (2011) in Equation 2, the expected damping ratio associated to the first frequency is equal to 2.6%.

$$[2] \zeta = 0.0143f_1$$

Therefore, the results obtained in this study can be considered as reliable.

5. CONCLUSIONS

In this paper, the changes in the modal properties at the bare frame and the finished phases of a case study building were identified by performing a series of ambient vibration tests. Modal analyses of the building in both phases were carried out using both FDD and EFDD techniques. Obtained results show a decrease in the natural frequencies of the building in the finished phase, which indicates that the NSCs play an important role in the evolution of the modal parameters. Results in the finished states are close to values obtained according to NBCC recommendations.

This difference in frequencies between the two phases can be explained by the fact that additional masses of facades, glass panels and mechanical and electrical equipment outweighs the increase in lateral stiffness due to the presence of these NSCs. Therefore, it is worth to study separately the effect of different types of NSCs on the building modal properties, especially the increase in stiffness due to addition of external architectural components before having additional masses due to mechanical and electrical components, internal architectural components and building content. Therefore, we could assess and compare the relative contribution on different types of NSCs on modifying the dynamic properties of buildings.

Despite some limitation in the reliability of damping ratios extracted from AVT, obtained values are very close to general values used in common practice.

The third AVT that will be undertaken shortly will serve to study the effect of building content on the dynamic properties of the buildings and the soil-structure interaction.

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