EFFECTIVE USE OF AMBIENT VIBRATION MEASUREMENTS FOR MODAL UPDATING OF A 48 STOREY BUILDING IN VANCOUVER, CANADA

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SUMMARY: This paper presents an overview of the experimental and analytical studies performed on the One Wall Centre tower in Vancouver, Canada. This 48-storey reinforced concrete shear core structure is the highest building in Vancouver. Its oval-shaped floor plan and tuned liquid column dampers located on the roof of the building make the Wall Centre a challenge to model analytically. Ambient vibration testing was conducted on the building in order to determine its dynamic characteristics. Such parameters include the fundamental lateral and torsional natural frequencies of the building, as well as the corresponding damping ratios. Those parameters were determined using a commercially available computer program. Two finite element models of the structure were developed using a finite element computer program. One model of the building was updated manually so to match the modal parameters obtained experimentally. The experimental results as well as the analytical results are presented in this paper. The analytical modal updating procedure is described as well.

KEYWORDS: Ambient vibration tests, manual modal updating, finite element models, natural frequencies, mode shapes.

INTRODUCTION

Ambient vibration testing is generally preferred to non-destructive forced vibration measurement techniques for obtaining the modal parameters of large structures for many reasons. A structure can be adequately excited by wind, traffic, and human activities and the resulting motions can be readily measured with highly sensitive instruments. Expensive and cumbersome devices to excite the structure are therefore not needed. Consequently, the overall cost of the measurements conducted on a large structure is reduced [1].

The study described in this paper was performed in order to obtain the modal parameters of a high-rise building in Vancouver, British Columbia, Canada, using ambient vibration testing techniques. The building is of interest to structural engineers for many reasons: a) it is the highest building in Vancouver; b) it makes use of tuned liquid column dampers to reduce its vibrations due to wind; and c) its oval shaped plan view is fairly unusual. The building is of interest also because of its reinforced concrete shear core, which concentrates most lateral and torsional resisting elements at the centre of the building. The torsional response of a shear core building of such shape is of great interest to structural engineers dealing with earthquake excitations.

A series of ambient vibration tests was conducted on April 10, 2001 by a group of researchers from The University of British Columbia. Testing procedures are described below. The modal parameters of interest were the fundamental lateral and torsional natural frequencies as well as their corresponding mode shapes. Damping ratios were also estimated using two different techniques.

Two finite element models of the building were developed, and some details about the computer program used for the modelling are given in the following sections. Results from the analysis of the vibration measurements, such as fundamental frequencies and mode shapes, are tabulated and discussed. The finite element models were updated manually based on the modal parameters obtained experimentally. The updated results are also presented.

DESCRIPTION OF THE BUILDING

The 48-storey One Wall Centre is the highest building in Vancouver, B.C., Canada (Figs. 1 & 2). The 137 m high building has a 7:1 height-to-width ratio, which makes it a very slender structure. In plan, the building is 23.4 m by 48.8 m and is oval shaped with pointed ends (Fig. 3).

Fig. 1: North face of the One Wall Centre

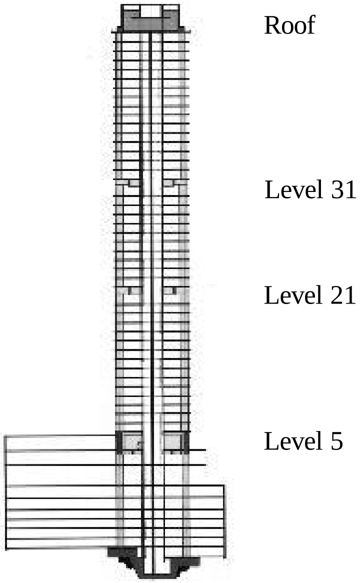


Fig. 2: Cross section of the One Wall Centre

The building is made up of a central reinforced concrete core whose walls are up to 900 mm thick at the base. The core contains six elevator shafts and two stairways. The floor slabs are typically 175 mm thick.

At level 5, a 6.4 m deep outrigger beam transfers the loads to the outrigger columns. More outrigger beams are found at levels 21 and 31 and are 2.1 m deep. The concrete water tanks on the roof of the building also act as outriggers (Fig. 2).

Two 183-m^3 tuned liquid column dampers are located on the roof of the structure. Each damper contains two water columns connected by a sluice gate to regulate the water flow. The system is calibrated to the natural frequency of the building by monitoring the water level in the tank and the opening of the sluice gate. The movement of the structure and the water tanks are out of phase in order to reduce the motion of the building due to wind loads [2].

EXPERIMENTAL STUDY

Instrumentation

The instruments used for the dynamic measurements of the building were force balanced accelerometers (Kinemetrics, Model FBA-11, and EpiSensor, Model FBA ES-T), cables, a 16-channel data acquisition system, signal conditioner and A/D converter (Kinemetrics, VSS3000), and a laptop computer for the data acquisition and data storage.

The data was recorded for a period of 12 minutes per set-up at 2000 samples per second (sps) and decimated to 250 sps. One day was needed to complete the totality of the ambient vibration measurements.

Sensor Locations

In order to capture the translational modes in the North-South (NS) and East-West (EW) directions, and the torsional modes of the building, two uni-directional accelerometers were positioned in the NS direction, and one uni-directional accelerometer was placed in the EW direction (Fig. 3) Two reference sensors were placed on the 45th floor (one in each direction). The sensors were placed close to the reinforced concrete core. In order to simplify the analysis of the measurements, the oval-shaped structure was idealized as a diamond. The motion of the apexes of the diamond was generated assuming that the floor slab behaved as a rigid diaphragm.

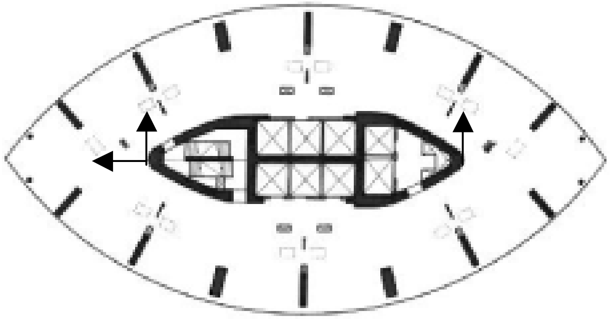


Fig. 3: Typical floor plan and sensor arrangement

Almost every other floor of the building was measured. In total, 7 set-ups were needed to complete the measurements and 3 floors were measured per set -up.

Spectral Analysis of Ambient Vibration Data

The idea behind modal identification is to identify the modal parameters of a structure using experimental data. The building is subjected to ambient vibrations generated by wind, occupants, ventilation, etc. These “unknown” loads are assumed to be produced by a virtual system loaded by white noise. The white noise is assumed to drive the total system and not only the structural system. Therefore, structural modes are identified as well as what are called operational modes. The “art” of output-only modal identification is to be able to distinguish the structural modes from the operational modes.

The computer program ARTeMIS Extractor, release 3.1, was used to perform the modal identification of the structure [3]. Two techniques were used to perform the modal identification: the Frequency Domain Decomposition (FDD) and the Stochastic Subspace Identification (SSI).

The FDD technique consists on performing an approximate decomposition of the system response into a set of independent single degree of freedom (SDOF) systems for each mode. The singular values are estimates of the spectral density of the SDOF systems, and the singular vectors are estimates of the mode shapes.

The Enhanced Frequency Domain Decomposition (EFDD) feature offered by ARTeMIS adds a modal estimation layer to the FDD editor. When the FDD analysis is completed and the mode shapes are identified, the EFDD identifies the SDOF Bell functions and from these SDOF Spectral Bells, all modal parameters are estimated. The damping ratios can be obtained from the EFDD but not the FDD.

The SSI technique consists of fitting a parametric model to the raw times series data collected by the sensors. Using a specific representation of the transfer function, all the modal parameters are exposed. Therefore, the natural frequencies, damping ratios, and mode shapes can be extracted. The Unweighted Principal Component (UPC) algorithm was used to analyse the data.

The objective of using two modal identification techniques is to cross-validate the results. If the same mode is identified by the two different techniques, it can be treated as a good structural mode rather than an operational mode.

EXPERIMENTAL RESULTS

The ARTeMIS EFDD Peak Picking editor displays singular values of the spectral density matrices (Fig. 4). The peaks represent either structural modes or operational modes. It is up to the user to judge if the peak corresponds to one or the other as described previously.

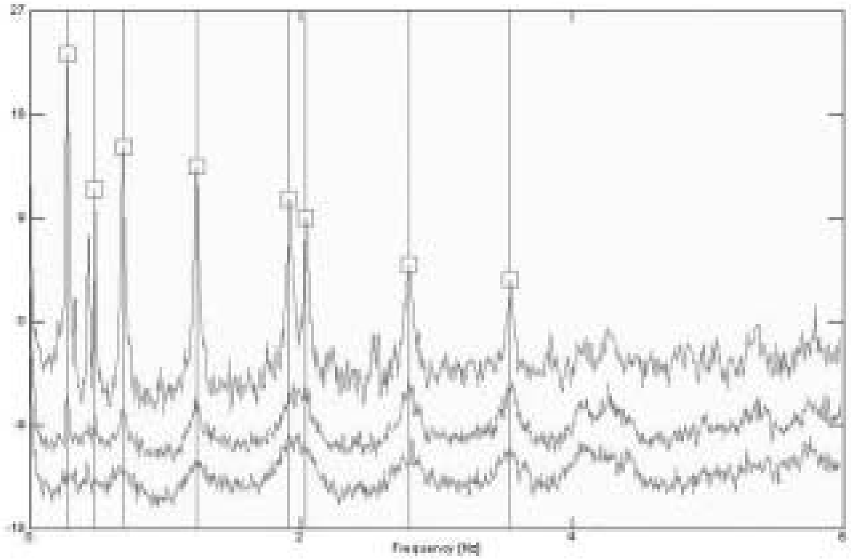


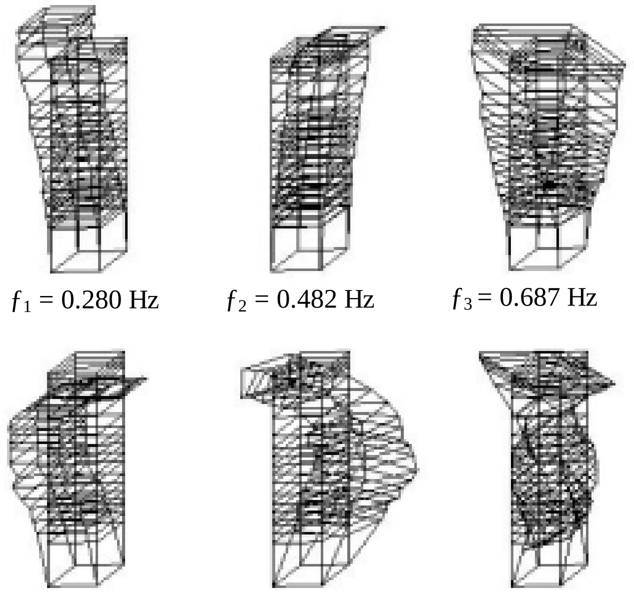
Fig. 4: Singular values of the spectral density matrices

The values of the structural mode peaks are displayed in Table 1 [4]. They represent the natural frequencies of the building. The Modal Assurance Criterion (MAC) is calculated for the same structural mode found using the EFDD technique and the SSI technique. The MAC value for each mode can also be found in Table 1.

The first six structural modes of the building are well defined graphically in both directions (NS and EW) as well as in torsion. Isometric views of the mode shapes are presented in Fig. 5. The damping ratios obtained using the EFDD and the SSI are tabulated in Table 2. They represent the amount of damping in the building at the ambient vibration level, hence the small damping values. The values obtained are similar to values obtained in other studies using similar techniques [5]. The only suspect value of damping is for the 1st NS mode generated by the SSI analysis. This is due to a poor definition of the first mode in the time domain. This explains the poor correlation between the frequency obtained from the EFDD and SSI techniques as shown in Table 1. These damping values have to be interpreted correctly and should not be used directly for the seismic analysis of the building. They can be used to update a finite element model of the building, from which the level of damping under seismic loads can be estimated.

Table 1: Fundamental frequencies and standard deviations

No.	Mode shape description	f_i (Hz)				MAC
		EFDD	σ_{EFDD}	SSI	σ_{SSI}	
1	1st NS	0.280	± 3.32 x 10^{-3}	0.284	± 43.5 x 10^{-3}	0.65
2	1st EW	0.482	± 551 x 10^{-6}	0.481	± 43.2 x 10^{-3}	0.71
3	1st torsion	0.687	± 1.05 x 10^{-3}	0.691	± 31.7 x 10^{-3}	0.98
4	2nd NS	1.23	± 2.27 x 10^{-3}	1.24	± 10.2 x 10^{-3}	0.87
5	2nd EW	1.92	± 2.22 x 10^{-3}	1.92	± 3.39 x 10^{-3}	0.99
6	2nd torsion	2.04	± 4.06 x 10^{-3}	2.04	± 9.94 x 10^{-3}	0.99
7	3rd NS	2.80	± 4.21 x 10^{-3}	2.81	± 18.1 x 10^{-3}	0.36
8	3rd torsion	3.54	± 10.9 x 10^{-3}	3.54	± 18.8 x 10^{-3}	0.92



f_1 = 0.280 Hz f_2 = 0.482 Hz f_3 = 0.687 Hz

f_4 = 1.23 Hz f_5 = 1.92 Hz f_6 = 2.04 Hz

Fig. 5: Mode shapes identified by ARTeMIS EFDD

Table 2: Damping ratios and standard deviations

No.	Damping (%)			
	EFDD	σ_{EFDD}	SSI	σ_{SSI}
1	1.94	± 0.521	14.2	± 14.5
2	0.935	± 0.194	5.71	± 4.78
3	0.817	± 0.191	1.99	± 1.29
4	0.621	± 0.185	0.545	± 0.350
5	0.714	± 0.214	0.440	± 0.218
6	0.606	± 0.217	0.849	± 0.712
7	0.656	± 0.267	1.61	± 0.883
8	0.423	± 0.197	1.09	± 0.716

ANALYTICAL STUDY

The computer program ETABS version 7.1 was used for the analysis of two finite element models of the One Wall Centre [6]. ETABS is a program developed specifically for building systems. This finite element program can be used for linear and non-linear, static and dynamic analysis of a tri-dimensional computer model of a structure. Three-dimensional mode shapes and frequencies, P-delta effects, response spectrum analysis and linear time history analysis are all options available in ETABS. In this study, the program was used to compute the fundamental frequencies and corresponding mode shapes of the model.

A partial model, called here Model #1, was used for the wind and seismic analyses of the One Wall Centre, as it is common practice in the industry in order to save time and money associated with the time required to develop a very detailed computer model of the structure. The reinforced concrete shear core, the outrigger beams, and the outrigger columns were included in the model as the main structural elements (Fig. 6). Since the program can estimate the self-mass of the structure, additional point masses of 410,000 kg were added in the X and Y global horizontal directions at the geometrical centre of the model located inside the reinforced concrete core in order to model the masses of the reinforced concrete slab, columns, and partitions. The floor mass moment of inertia in the vertical (Z) direction was set to 62×10^6 kg*m^2.

Since the ambient vibration results were obtained from low levels of excitation, it could be argued that not only the main structural elements, but the so-called non-structural elements contribute to the overall stiffness of the structure and need to be modelled in order to get a good correlation between the experimental and analytical results. Model #2 was developed for this purpose (Fig. 7). The gravity load columns and the exterior cladding were added to Model #1 to form Model #2. The water tanks were modeled but not “filled with water” since the ambient vibration test was conducted with the water tanks empty. The mass moment of inertia of the slab was calculated to be 68×10^6 kg*m^2. Masses of 450,000 kg were added in the X and Y global direction to replicate the mass of the slab and other appurtenances and partitions. The outside window façade was also modelled since it plays an important role in the order of the mode shapes of the building, as it will be shown below.

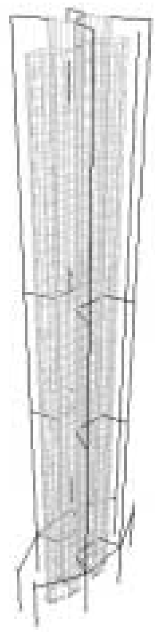


Fig. 6: ETABS Model #1

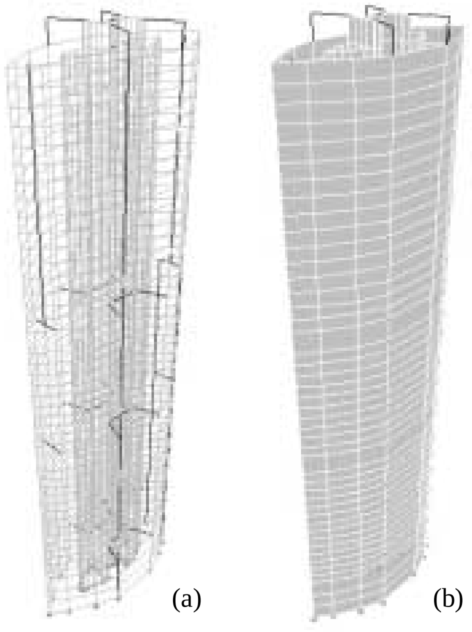


Fig. 7: ETABS Model #2: (a) wire frame, (b) full model

ANALYTICAL RESULTS

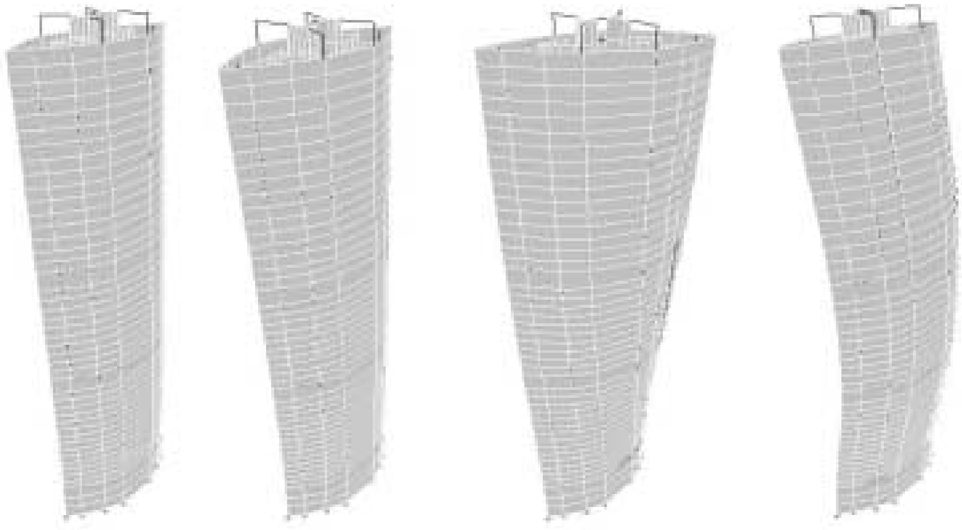
The fundamental frequencies and corresponding mode shapes of the One Wall Centre were obtained using the finite element models developed. The results from both models are presented in Table 3 and the ambient vibration results are repeated again for comparison sake.

The fundamental frequencies estimated by ETABS Model #1 are about 15% lower than the frequencies estimated by ARTeMIS. One interesting aspect is that the computer model predicts the 2nd torsional mode to have a lower order than the 2nd EW mode. The ambient vibration results show that the order of these two modes should be reversed. Clearly, Model #1 is not suitable for representing the building behaviour at low levels of excitation and that a more detailed finite element model should be developed for calibration with the ambient vibration test results.

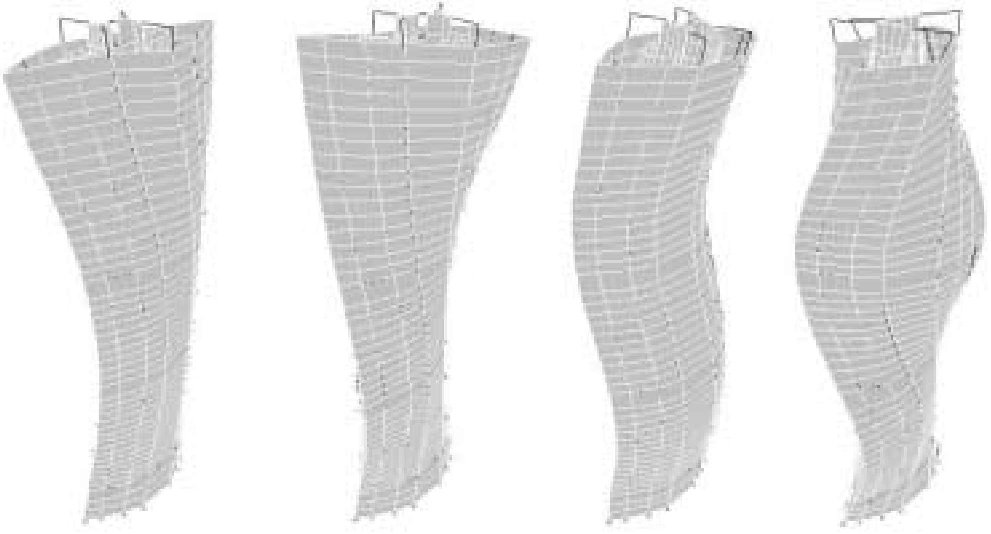
Table 3: Comparison between ambient vibration and finite element model results

No.	Ambient Vibration Test		FE Model #1			FE Model #2		
	Mode Shape	f_{i} (Hz)	Mode Shape	f_{i} (Hz)	% Diff.	Mode Shape	f_{i} (Hz)	% Diff.
1	1st NS	0.280	1st NS	0.242	13.6	1st NS	0.284	1.43
2	1st EW	0.482	1st EW	0.435	9.75	1st EW	0.527	9.34
3	1st torsion	0.687	1st torsion	0.582	15.3	1st torsion	0.707	2.91
4	2nd NS	1.23	2nd NS	1.00	18.7	2nd NS	1.13	-8.13
5	2nd EW	1.92	2nd torsion	1.72	N/A	2nd EW	2.04	6.25
6	2nd torsion	2.04	2nd EW	1.87	N/A	2nd torsion	2.09	2.45
7	3rd NS	2.80	3rd NS	2.46	12.1	3rd NS	2.59	-7.50
8	3rd torsion	3.54	3rd torsion	2.89	18.4	3rd torsion	3.48	-1.69

To increase the fundamental frequencies and to reverse the order of the 2nd torsional and 2nd EW modes, Model #1 needed to be stiffened. To do so, the gravity load columns were modelled following the structural drawings and the outside façade was modelled and given a low stiffness value. Without any other adjustments, the order of the 2nd torsional and 2nd EW modes was reversed (Fig. 8). The fundamental frequencies were matched by adjusting the modulus of elasticity (E = 35 GPa) and the thickness (t = 0.0125 m) of the cladding. As shown in Table 3, the fundamental frequencies are now all within an acceptable 10% difference margin.



$f_1 = 0.284$ Hz $f_2 = 0.527$ Hz $f_3 = 0.707$ Hz $f_4 = 1.13$ Hz



f_5 = 2.04 Hz f_6 = 2.09 Hz f_7 = 2.59 Hz f_8 = 3.48 Hz

Fig. 8: Modes shapes identified from the updated ETABS finite element model

CONCLUSION

The results of the ambient response of the One Wall Centre were presented and the computer program ARTeMIS identified 8 fundamental frequencies and clear mode shapes using the Enhanced Frequency Domain Decomposition (EFDD) and the Stochastic Subspace Iteration (SSI). A MAC index was used to correlate the results obtained from the two techniques and showed with confidence that the mode shapes found were the actual structural mode shapes of the structure. Also, the damping ratios were estimated by the two same techniques and these results were also presented and found to be comparable to other studies performed.

ETABS was used to develop two finite element models of the One Wall Centre. Model #1 is a reflection of common practice in the industry. Only a partial model of the building was done due to tight schedule and budget constraints. The fundamental frequencies and mode shapes were obtained and compared to the ambient vibration results. The frequencies were off by about 15% and the order of the 2nd torsional and EW transverse modes needed to be reversed.

ETABS Model #2 was a more detailed model of the building and proved to be better for modal updating. By adding the cladding, the order of the 2nd torsional and 2nd EW modes was immediately reversed and the fundamental frequencies were now within a more reasonable 10% difference.

Many other factors could be, and should be, considered when updating a finite element model. Manual updating is only one solution and it can be time consuming and sometimes even frustrating. Computer programs such as FEMtools are available to help the analyst to validate, refine, and inspect his/her finite element model [7]. Although a good correlation was achieved between the ambient vibration data and the finite element model in this study, further investigation using special-purpose software, like FEMtools, is needed in order to get an even better match between the experimental results and the finite element model.

Now that a calibrated finite element model of the One Wall Centre is completed, it will be used in the future for the health monitoring of the building. After a seismic event, a similar study could be performed and the results obtained compared to the present results. The “health” of the building can then be determined. Remote damage detection techniques are now being developed and should make the health monitoring of structures an easier task.

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