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[N1026] FEM Updating Using Ambient Vibration Data from a 48-storey Building in Vancouver, British Columbia, Canada

Jean-François Lord and Carlos E. Ventura
Department of Civil Engineering
The University of British Columbia, Vancouver, BC, Canada
ventura@civil.ubc.ca

Eddy Dascotte
Dynamic Design Solutions n.v.
Interleuvenlaan 64, B-3001 Leuven, Belgium

Rune Brincker
Department of Building Technology and Structural Engineering
Aalborg University, Aalborg, Denmark

Palle Andersen
Structural Vibration Solutions ApS
NOVI Science Park, Niels Jernes Vej, DK 9220, Aalborg East, Denmark

ABSTRACT

This paper describes results of a model updating study conducted on a 48-storey reinforced concrete shear core building. The output-only modal identification results obtained from ambient vibration measurements of the building were used to update a finite element model of the structure. The starting model of the structure was developed from the information provided in the design documentation of the building. Different parameters of the model were then modified using an automated procedure to improve the correlation between measured and calculated modal parameters. Careful attention was placed to the selection of the parameters to be modified by the updating software in order to ensure that the necessary

changes to the model were realistic and physically realisable and meaningful. The paper highlights the model updating process and provides an assessment of the usefulness of using an automatic model updating procedure combined with results from an output-only modal identification.

INTRODUCTION

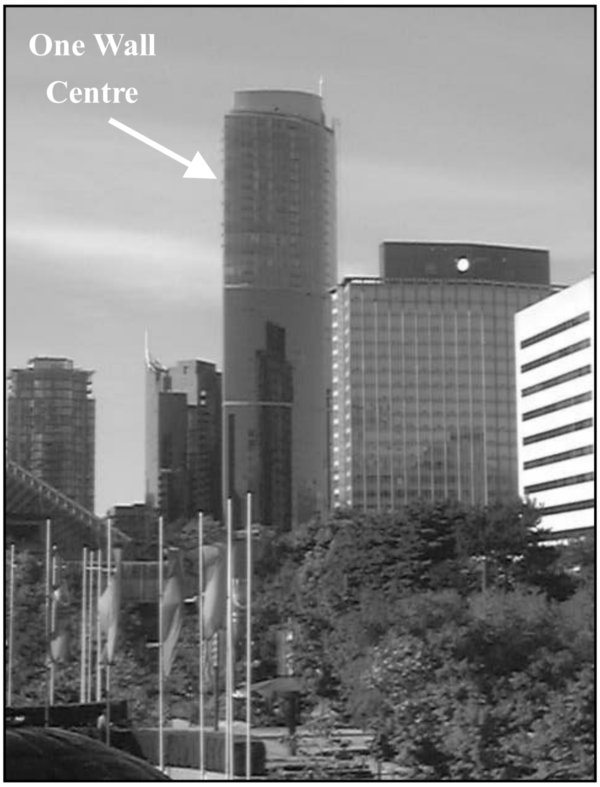

Figure 1. The One Wall Centre, looking South.

The study presented in this paper focuses on the One Wall Centre, a 48-storey building located in downtown Vancouver, British Columbia (Figure 1) [1]. The response of this building is of interest to structural engineers for a number of reasons. The structure is currently the highest building in Vancouver, and it is the only building in the region that makes use of tuned liquid column dampers to reduce vibrations due to wind. The main lateral load resisting system for the One Wall Centre is a reinforced concrete shear core with a unique shape, which makes the study of the dynamic response of the building very interesting. In addition, a good understanding of the seismic response of the building is important since Vancouver is located in one of the most active seismic regions of Canada.

The modal characteristics of a structure can be determined in a few different ways. During the design stage of a building, a finite element (FE) model can be constructed, using the specified building geometry, material properties and section properties. The modal characteristics can then be predicted analytically. After construction of the building, the actual response of the structure can be measured using ambient vibration testing techniques. The data collected at these low levels of excitation can be used to perform output-only modal identification to obtain the natural periods and mode shapes of the structure. By gaining insight into the “true” response of the structure, one can use this information to update an existing FE model. Various model-updating techniques are available but the basic concept of model updating is to vary certain parameters in the FE model until the modal response predicted by the FE model corresponds to the experimental results. An updated model provides a better analytical representation of the dynamic response of the building and a calibrated tool for the prediction of seismic response.

The One Wall Centre was a perfect candidate for this type of ambient vibration testing and model updating study because of the unique characteristics of the building and the motivations for understanding its dynamic response described above.

DESCRIPTION OF THE BUILDING

The One Wall Centre is part of a three building complex located in the heart of downtown Vancouver, British Columbia, Canada, and is the home of the Sheraton Hotel. The building is 48 storeys high and includes 6 additional levels of underground parking. The bottom two thirds of the building are used for hotel operations and the top third is for privately owned luxury suites.

At the time of its completion, the One Wall Centre was the highest building in Vancouver, standing 207 m above sea level. The building is 137 m tall, which also makes it one of the tallest structures in the city. The parking levels and elevator shafts extend an additional 23 m into the ground. The floor heights are typically 2.615 m. The building has a 7:1 height-to-width ratio, which makes it a very slender structure, susceptible to vibrations due to wind. In plan, the building is 23.4 m by 48.8 m and is shaped like an ellipse with pointed ends (Figure 2).

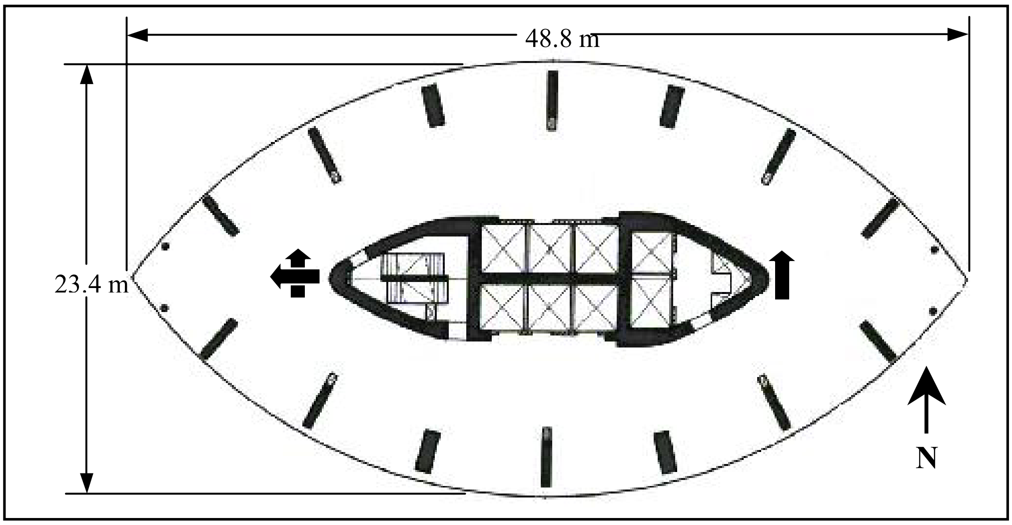

Figure 2. Typical floor plan and sensor location.

A structure of the type of the One Wall Centre is prone to excessive deformations due to wind because of its lightness and slenderness. Thus, failure may occur at a serviceability level long before structural failure. In order to prevent undesirable sensations for the occupants of the upper floors, the roof of the One Wall Centre was fitted with two 183-m^3 tuned liquid column dampers (TLCD) to reduce vibrations due to wind.

EXPERIMENTAL STUDY

In order to capture the translational modes (in the transverse (North-South (NS)) and longitudinal (East-West (EW)) directions) and torsional modes of the building, two uni-directional accelerometers were positioned in the transverse (NS) direction, and one uni-directional accelerometer was positioned in the longitudinal (EW) direction. The sensor locations and orientations are indicated by the arrows in Figure 2. The sensors were placed as close as possible to the outside perimeter of the concrete core. Since the lateral motion of the building was the only motion of interest in this study, no vertical sensors were mounted.

The modal identification results for the One Wall Centre were determined using the computer program ARTeMIS Extractor (Version 3.1) [2]. The experimental modal analysis (EMA) results presented in Table 1 were evaluated using a state-of-the-art modal identification techniques available in ARTeMIS called the Enhanced Frequency Domain Decomposition (EFDD) technique. The results were confirmed using a Stochastic Subspace Iteration (SSI) technique (due to space limitation the SSI results are not presented here) [3].

Table 1 First six mode shapes of the One Wall Centre determined experimentally.

Mode No.	*Mode Type*	*EMA Period (s)*	*Std.Dev*
1	1st NS	3.57	± 0.042
2	1st EW	2.07	± 0.002
3	1st torsion	1.46	± 0.002
4	2nd NS	0.81	± 0.001
5	2nd EW	0.52	± 0.001
6	2nd torsion	0.49	± 0.001

AUTOMATED FEM UPDATING STUDY

An attempt to manually update a FE model of the building using the experimental results obtained with ARTeMIS is described in reference [4]. Although an acceptable match was obtained between the analytical and experimental dynamic response of the building, this technique showed limitations, mainly the number of parameters that one can vary concurrently in order to obtain such a match. In light of this, it was decided to use an automated model updating technique to match the analytical with the experimental results. The computer program FEMtools was selected for this work. This program is a multi-functional computer-aided engineering (CAE) program that includes various tools for true integration of finite element analysis and static or dynamic testing, automation of CAE processes and development of data pre- and post-processing tools [5].

FEM of the Building

A FE model was generated in FEMtools from to the geometry and material properties indicated on the structural drawings. Beams and columns were modelled as 3D beam-column elements, and shear walls were modelled as 4-node plate elements. In addition, every floor slab was modelled, to avoid developing local modes in the columns, using 4-node and 3-node plate elements. At the base of the structure in the model, the ends of every element were fixed against translation and rotation for the 6-DOF. The elements of the underground floor levels were not modelled. In total, the model consisted of 616 beam-column elements, 2,916 4-node plate elements, 66 3-node plate elements, 2,862 nodes, four different material properties, 144 different element geometry sets, and 17,172 degrees of freedom.

Selection of Parameters for Automated FEM Updating

A sensitivity analysis of the dynamic response of the FE model of the building to a change in element properties was first conducted on a large number of parameters [6]. A *parameter* refers to a selected *property* of a given *element*. For instance, the mass density (a *property*) of the shear walls of the upper floors (an *element*) will constitute a *parameter*. The selected parameters for the sensitivity analysis were the following:

- The Young's modulus, E, of the beams, columns, shear wall, floor slabs and cladding
- The material mass density, ρ, of the beams, columns, shear wall, floor slabs and cladding
- The second moment of inertia, I, of the beams and columns in both principal directions
- The thickness, H, of the cladding.

This resulted in 161 different parameters that the program computed the sensitivity for. The analysis showed that the dynamic response of the FE model was sensitive to a change in E (for the shear walls, floor slabs and cladding), in ρ (for the same elements) and in H for the cladding. The dynamic response of the model was not sensitive in a change in E, ρ and I for the beams and columns.

The number of parameters used for model updating was reduced to 29 based on the sensitivity analysis results:

- The Young's modulus, E, of the shear wall, floor slabs and cladding
- The material mass density, ρ, of the shear wall, floor slabs and cladding
- The thickness, H, of the cladding.

A variation in E should be interpreted as a required increase/decrease in the overall stiffness of the selected elements (EI), not as an increase/decrease in the physical property itself. A variation in ρ should give insight into how sensitive is the FE model to mass distribution of the structural and non-structural elements. The stiffness contribution of the windows and the non-structural elements was modeled by the inclusion of the cladding. A variation of H was necessary since a starting value for such a parameter is difficult to predict.

Automated FEM Updating Results

The computer program converged to a solution after five iterations. The results are summarized in Table 2. The FEM natural periods before and after model updating are compared and the EMA natural periods are repeated for comparison. The updated FEM natural periods are now equal to the EMA natural periods. The last column of the table shows the MAC values of the updated FE model. It can be seen that the experimental and analytical mode shapes are well correlated.

Table 2 First six mode shapes of the One Wall Centre before and after model updating.

Mode No.	*EMA Period (s)*	*FEM Period Before (s)*	*FEM Updated*	
			Period (s)	*MAC (%)*
1	3.57	3.01	3.57	99
2	2.07	1.52	2.07	87
3	1.46	1.05	1.46	99
4	0.81	0.76	0.81	99
5	0.52	0.40	0.52	86
6	0.49	0.36	0.49	87

The resulting FEM mode shapes after updating are compared to the EMA mode shapes in Figure 3. The dots in Figure 3 represent the EMA mode shapes and the wire frame represents the FEM mode shapes. The computer program was successful in matching both analytical and experimental mode shapes.

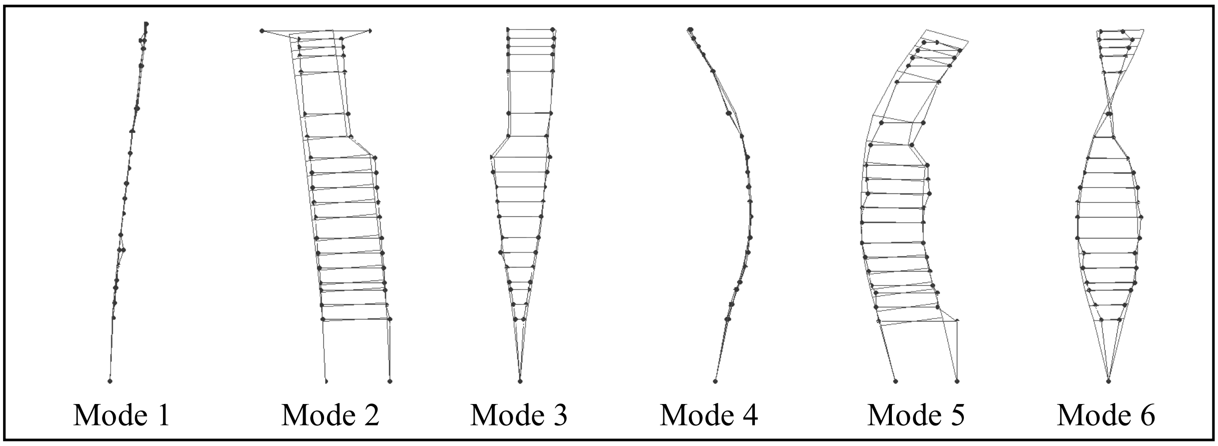

Figure 3. EMA and FEM shapes after updating.

A summary of the changes performed by FEMtools in order to match the FEM results to the EMA results is presented in Table 3. The Young's modulus of the shear walls was overestimated for most cases. This decrease in E should be thought as a variation of the overall stiffness of the selected elements (EI) as mentioned before. This variation is justified since the full cross-section of the elements was used to calculate the effective moment of inertia (i.e. I_{gross}) in the FE model. The large change in cladding thickness can be justified since an accurate initial value for such a parameter is difficult to estimate. Lack of space in this paper prevents from additional discussions on the subject. Refer to [1] for more details concerning the automated model updating results.

CONCLUSIONS

The natural periods and corresponding mode shapes of the One Wall Centre were determined experimentally and analytically. Automated updating of the FE model by a computer program made possible to achieve a good correlation between the analytical and experimental natural periods and mode shapes. It was found that the FE model needed to be more flexible and that a reduction in the Young's modulus of the reinforced concrete of the shear walls was necessary in order for the FEM to match the EMA. Finally, it must be emphasized that it remains the responsibility of the user to accept or reject the changes proposed by the computer program. The user should be able to justify any significant changes to the model by using past experience or sound engineering judgment.

Table 3 FEMtools parameter comparison before and after FE model updating.

Property	*Element*	*Initial Value* *(kN, m, kg)*	*Updated Value* *(kN, m, kg)*	*Variation* *(%)*
E	Shear walls (Levels 1-20)	3.65E+07	1.49E+07	-59
E	Shear walls (Levels 20-31)	3.52E+07	5.76E+07	64
E	Shear walls (Levels 31-Roof)	3.38E+07	1.25E+07	-63
E	Floor slabs	3.65E+07	6.74E+07	84
E	Cladding	3.25E+07	2.74E+07	-16
ρ	Shear walls (Levels 1-20)	2400	1590	-34
ρ	Shear walls (Levels 20-31)	2400	1220	-49
ρ	Shear walls (Levels 31-Roof)	2400	4470	86
ρ	Floor slabs	2400	2280	-28
ρ	Cladding	2200	2210	1
H	Cladding	0.0125	0.00731	-42

ACKNOWLEDGMENTS

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