Automated Model Updating Using Ambient Vibration Data from a 48-storey Building in Vancouver

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ABSTRACT

This paper describes the results of an automated 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.

1 INTRODUCTION

The modal characteristics of a structure can be determined in a few different ways. During the design stages of a building, a finite element model (FEM) can be generated, 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 FEM. Various model-updating techniques are available but the basic concept of model updating is to vary certain parameters in the FEM until the modal response predicted by the FEM 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 modal characteristics of the One Wall Centre, a 48-storey reinforced concrete shear core building located in the heart of downtown Vancouver, British Columbia, Canada, were first obtained from ambient vibration data using state-of-the-art modal identification techniques. A FEM of the building was then generated using the structural drawings of the structure. Then, an automated model updating technique was used to "tune-up" the FEM so that the analytical modal parameters correspond to the experimental ones.

The experimental results are briefly revisited and the automated model updating technique is described in details and results from the updated FEM are compared to the original ones. The results are explained and discussed.

2 EXPERIMENTAL STUDY

The structural system of the One Wall Centre is fully described in reference [1]. Details about the experimental study, such as sensor location, instrumentation used for data collection, and spectral analysis results of the ambient vibration data, can also be found in reference [1].

The output-only modal identification results were obtained using the computer program ARTeMIS Extractor (Version 3.1) [2]. The experimental modal analysis (EMA) results are presented in Table 1. More information about the modal identification techniques used in this study can be found in reference [1].

3 AUTOMATED FEM UPDATING STUDY

An attempt to manually update a FEM of the One Wall Centre using the experimental results obtained with ARTeMIS is described in reference [3]. Although an acceptable match was obtained between the analytical and experimental dynamic response of the building, this technique showed limitations, mainly with 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 results with the experimental ones. The computer program FEMtools (Version 2.2) 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 [4].

3.1 FEM of the Building

A FEM was generated in FEMtools from the geometry and material properties indicated on the structural drawings of the One Wall Centre. 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. The natural periods of the FEM before updating can be found in Table 2.

3.2 Sensitivity Analysis

Performing a sensitivity analysis is an integral step in the automated model updating process in FEMtools. Therefore, the concepts of relative sensitivity and normalized sensitivity will be explained herein.

If the model sensitivities to various parameters are to be compared simultaneously (as it is the case in this study), the use of relative sensitivities is advised [4]. The relative sensitivity matrix, $[S_r]$, is obtained (Equation 1) as follows:

$$[S_r] = \left[\frac{\delta R_i}{\delta P_j}\right] * [P_{jj}] \tag{1}$$

where R_i represents all the selected responses, P_j represents all the selected parameters, $\delta R_i / \delta P_i$ is the differential sensitivity coefficient, and $[P_{jj}]$ is a diagonal square matrix holding the parameter values. (Note that the differential sensitivity coefficient is equal to the sensitivity matrix when computed for all selected responses with respect to all selected parameters)

The relative sensitivity can either be positive or negative, as a result of a positive or negative differential sensitivity coefficient. A positive $\delta R_i / \delta P_i$ means that an increase of the parameter "j" will also result in an increase in the value of the response "i". Conversely, a negative $\delta R_i / \delta P_i$ means that an increase of the parameter "j" will result in a decrease in the value of the response "i".

The relative sensitivity can also be normalized with respect to the response value (Equation 2) as follows:

$$[S_n] = [S_r] * [R_i]^{-1} \tag{2}$$

where $[S_n]$ is the normalized relative sensitivity matrix, and $[R_i]$ is a diagonal square matrix holding the response values. The normalized sensitivity is used in this study to compare the effect of changing parameters on the dynamic response of the FEM.

A sensitivity analysis of the dynamic response of the FEM of the building to a change in element properties was first conducted on a large number of parameters [5]. 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 FEM was sensitive to a change in E (for the shear walls, floor slabs and cladding), in ñ (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 normalized sensitivity for the 161 parameters can be found in Figure 1. The normalized sensitivity of selected parameters can also be found in Table 3.

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 FEM 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.

3.3 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 FEM. It can be seen in Figure 2 that the MAC value of the experimental and analytical mode shapes are well correlated.

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.

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 FEM. The large change in cladding thickness can be justified since an accurate initial value for such a parameter is difficult to estimate.

3.4 Importance Index

An Importance Index (IS) was also developed to rank the significance of each parameter change and the IS of each selected parameter is listed in Table 3. The *importance index* is defined as the absolute value of the product of the variation and the normalized sensitivity of the model. The higher the IS, the more influential the required parameter change is on the model updating. For example, a large variation between an initial and actual property may not have a great effect on the response of the model if the normalized sensitivity of the parameter is low. The same is true for a parameter with a high normalized sensitivity but a small variation between the initial and actual property. This is why the IS a useful tool for targeting which parameters of the original model have the greatest effect on the updated model.

For example, the thickness, H, of the cladding has a very high importance index. Some variation associated with the cladding element was not unexpected, as this element was introduced to the model to represent the contribution of all non-structural components (windows, interior walls, partitions, etc.) to the overall stiffness of the structure. Therefore, the large decrease in the value of the cladding thickness reflects the fact that an accurate initial value for this parameter was difficult to predict. It can be noted, however, that the actual value of the parameter returned by the computer program is comparable to findings from a similar study by Ventura et al. [6].

Refer to [7] for more details concerning the automated model updating results.

4 CONCLUSION

The natural periods and corresponding mode shapes of the One Wall Centre were determined both experimentally and analytically. Automated updating of the FEM 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 FEM 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. An Importance Index was developed so that each parameter could be ranked based on their influence on the FEM.

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.

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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

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

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

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

Property	*Element*	*Initial Value (kN, m, kg)*	*Updated Value (kN, m, kg)*	*Variation (%)*	*Normalized Sensitivity*	*Importance Index (IS)*
E	Shear walls (Levels 1-20)	3.65E+07	1.49E+07	-59	0.51	30
E	Shear walls (Levels 20-31)	3.52E+07	5.76E+07	64	0.18	11
E	Shear walls (Levels 31-Roof)	3.38E+07	1.25E+07	-63	0.29	18
E	Floor slabs	3.65E+07	6.74E+07	84	0.36	31
E	Cladding	3.25E+07	2.74E+07	-16	0.34	5
ρ	Shear walls (Levels 1-20)	2400	1590	-34	-0.08	3
ρ	Shear walls (Levels 20-31)	2400	1220	-49	-0.09	4
ρ	Shear walls (Levels 31-Roof)	2400	4470	86	-0.69	60
ρ	Floor slabs	2400	2280	-28	-0.89	25
ρ	Cladding	2200	2210	1	-0.03	0
H	Cladding	0.0125	0.00731	-42	0.99	41

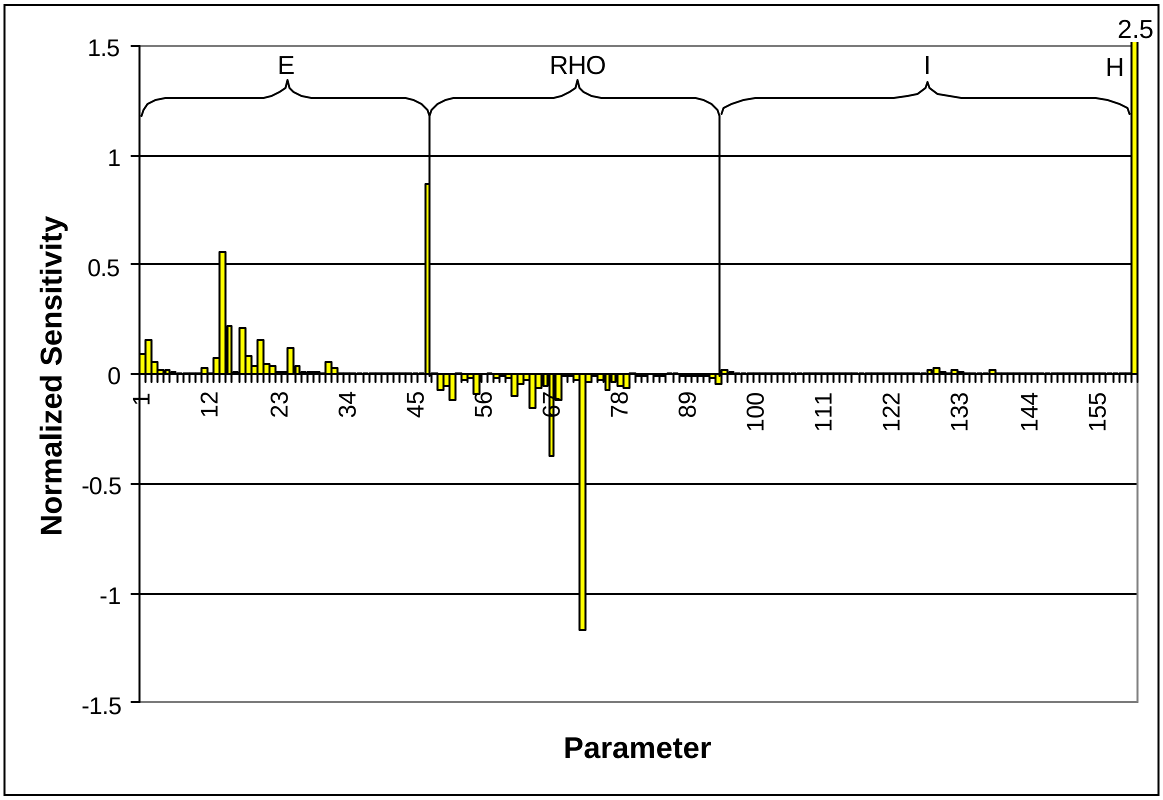

Figure 1. FEM normalized sensitivity to selected parameters.

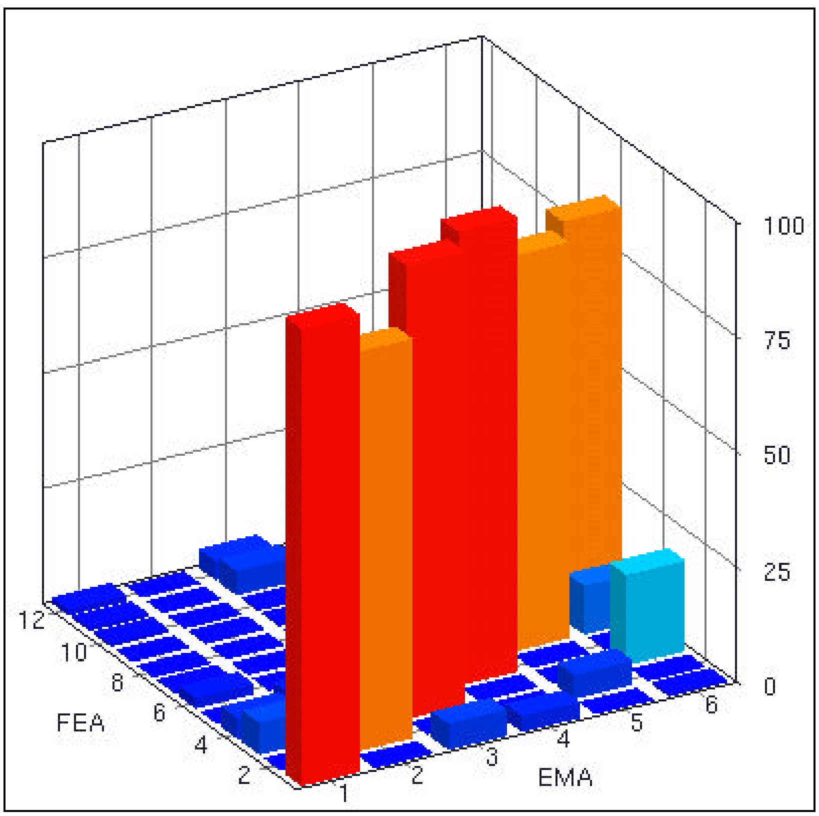

Figure 2. MAC values of the FEA and EMA mode shapes after updating.

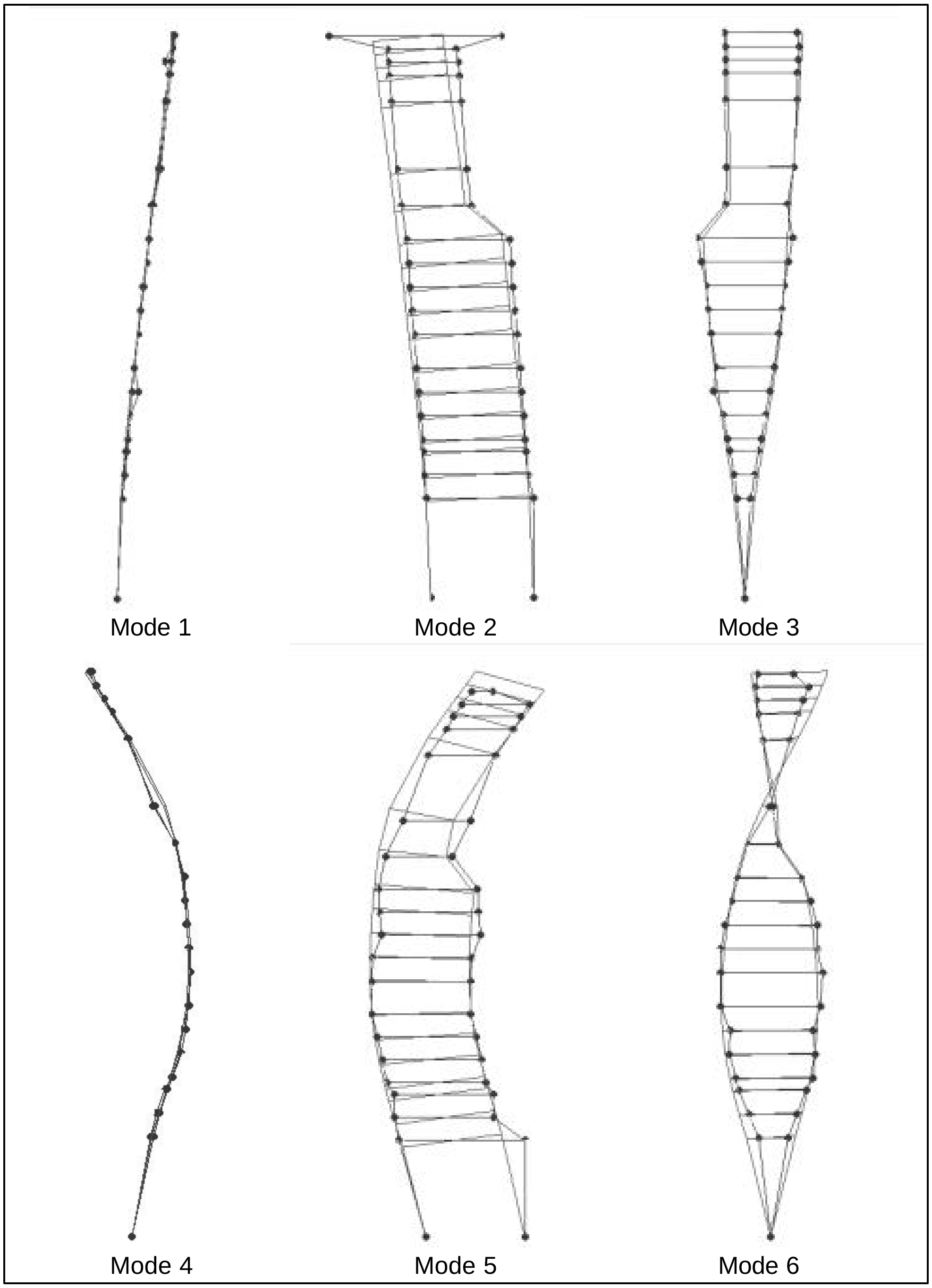

Figure 3. EMA and FEM mode shapes after updating.