FEM Updating of Tall Buildings Using Ambient Vibration Data

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ABSTRACT: Ambient vibration testing is the most economical non-destructive testing method to acquire vibration data from large civil engineering structures. The purpose of this paper is to demonstrate how ambient vibration Modal Identification techniques can be effectively used with Model Updating tools to develop reliable finite element models of large civil engineering structures. A fifteen story and a forty-eight story reinforced concrete buildings are used as case studies for this purpose. The dynamic characteristics of interest for this study were the first few lateral and torsional natural frequencies and the corresponding mode shapes. The degree of torsional coupling between the modes was also investigated. The modal identification results obtained from ambient vibration measurements of each building were used to update a finite element model of the structure. The starting model of each 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 ambient vibration modal identification.

1 INTRODUCTION

From the viewpoint of structural engineering design practice, there are several reasons for conducting vibration measurements in existing buildings. For instance, the owner of a building located in a seismically active zone may be interested in determining whether the structure complies with current earthquake engineering design practice. If the structure is found to be at risk during a severe earthquake, then remedial structural modifications may have to be implemented in different parts of the structure. In order to accomplish this, the structural engineer responsible for this structural retrofit would aim to provide a design that satisfies the safety and serviceability requirements of the local building code in the most economical way. The structural engineer would not only need information of the actual conditions of the building, including its dynamic characteristics, but would also be required to develop a realistic finite element computer model of the structure, which can be used to evaluate possible retrofit scenarios. In such situations it is not only desirable to have economical and effective ways of determining experimentally the dynamic properties of large civil engineering structures, but also have effective ways to have a high degree of confidence that the structure's finite element model is a realistic representation of the physical structure.

The aim of this paper is to demonstrate how Natural-Input Modal Analysis (NIMA) techniques can be effectively used with Model Updating tools to develop reliable finite element models of large civil engineering structures. A fifteen story and a forty-four story reinforced concrete buildings are used as a case studies for this purpose.

The dynamic characteristics of interest for this study were the first few lateral and torsional natural frequencies and the corresponding mode shapes. The degree of torsional coupling between the modes was also investigated. The NIMA results obtained from ambient vibration measurements of each building were used to update a finite element model of the structure. 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 a natural - input modal identification.

2 FEM UPDATING

One of the purposes of conducting ambient vibrations tests on large Civil Engineering structures is to use the modal information obtained from these tests to improve the finite element model of the structure being investigated. The nature of any of the NIMA methods permits only the determination of the natural frequencies, associated mode shapes, and to a certain extent, the modal damping values. Information to modal participation factors and modal mass participation can not be obtained with the current vibration testing techniques and analysis tools. Nevertheless, it is still possible to update a fine element model (FEM) using results from ambient vibration tests by making use of natural frequencies and mode shapes only.

An attempt to correlate experimental and analytical modal properties of a high-rise building using a manual updating process is described by Ventura and Horyna (2000). That study clearly showed the limitations and difficulties in trying to obtain a good general correlation between experimental and analytical modal properties for a large civil engineering structure. 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.

During the last four years the authors have been collaborating to develop and implement practical ways to perform automated FEM model updating using ambient vibration data. Computer programs ARTeMIS and FEMtools have been used for this work. ARTeMIS (SVS, 2004) is a NIMA special purpose program, while FEMtools (DDS, 2004) is a multi-functional computer-aided engineering (CAE) program for FEM updating. Two case studies are described below to illustrate how ambient vibration data results can be used for FEM model updating using the programs described above. A discussion of the engineering interpretation of the results is included for each case study.

3 CASE STUDY: 15-STOREY REINFORCED-CONCRETE BUILDING

The building considered in this study is called Heritage Court Tower (HCT) and it is located in downtown Vancouver, British Columbia in Canada. It is a relatively regular 15-story reinforced concrete shear core building. In plan, the building is essentially rectangular in shape with only small projections and setbacks. Typical floor dimensions of the upper floors are about 25 m by 31 m, while the dimensions of the lower three levels are about 36 m by 30 m. The footprint of the building below ground level is about 42 m by 36 m. Typical story heights are 2.70 m, while the first story height is 4.70 m. The elevator and stairs are concentrated at the center core of the building and form the main lateral resisting elements against potential wind and seismic lateral and torsional forces.

The tower structure sits on top of four levels of reinforced concrete underground parking. The parking structure extends approximately 14 meters beyond the tower in the south direction forming an L-shaped podium. The parking structure and first floors of the tower are basically flush on the remaining three sides. The parking structure extends approximately 14 m beyond the tower in the south direction but is essentially flush with the first floor walls on the remaining three sides. The building tower is stocky in elevation having a height to width aspect ratio of approximately 1.7 in the east-west direction and 1.3 in the north-south direction. An overview of the building and a typical floor plan diagram are presented in Fig. 1.

Figure 1. View of HCT building and typical floor plan dimensions (m).

A series of ambient vibration tests was conducted on April 28, 1998 by researchers from the University of British Columbia to obtain modal characteristics of this building. It was of practical interest to test this building because of its shear core, which concentrates most of lateral and torsional resisting elements at the center core of the building. Additional structural walls are located close to the perimeter of the building but are arranged in such a way that they offer no additional torsional restraint. Shear core buildings may exhibit increased torsional response when subjected to strong earthquake motion depending on the uncoupled lateral to torsional frequency ratio and of the amount of static eccentricity in the building plan. The dynamic characteristics of interest for this study were the first few lateral and torsional natural frequencies and the corresponding mode shapes. The degree of torsional coupling between the modes was also investigated. The modal identification for the HCT building was performed using computer program ARTeMIS Extractor.

3.1 *Selection of parameters for model updating.*

The following parameters were selected for the model updating:

- The Young's modulus of Elasticity, E, of the beams, columns, shear walls, floor slabs and cladding panels.
- The mass density, ρ, of the same elements.
- The moment of inertia, I, of the columns.
- The thickness, H, of the cladding panels.

This resulted in 13 different parameters that the program could use for updating the model. By permitting independent variations of E for the different groups of structural elements it is possible to have a sense of the sensitivity of the model to material properties and how these affect the overall stiffness of the structure. There is always a degree of uncertainty about the actual material properties of the elements as well as what is the most realistic representation of the element stiffness when developing a FE model of a building. A variation of the mass density, ρ, of each group of elements helps to determine how sensitive is the building model to the mass distribution of the structural and some non-structural elements attached to the structural system. The moment of inertia and as consequence the lateral stiffness, of the columns is one of the most uncertain parameters to model in concrete frame structures. The value of I is highly sensitive to the choice of the concrete section to be used (cracked or uncracked), and to how the composite action of the steel reinforcement with the concrete is included in the model. In addition to this, the column stiffness can vary significantly as a function of its effective length, so variations in the values if I can also be interpreted as needed changes of the model to better represent the effective length of the columns. Finally, the thickness of the cladding plates was allowed to change since these elements were included in the model to account for the additional mass and somewhat additional stiffness that the external cladding provides to the whole structure. In practical structural analysis of buildings, very seldom the influence of cladding is taken into account in the structural model. However, preliminary studies of the FE model without the cladding elements showed that these do have an influence on the dynamic properties of the structure and should be included in the model. Their greatest influence is on the value of the rotational mass moment of inertia of each floor.

The correlation of responses and computation of MAC values between the experimental and analytical models was done at 40 points (4 points per floor, at ten different levels).

3.2 *Model updating results.*

The resulting modal frequencies after thirteen iterations of parameters' updating are presented in Table 2. The table includes the experimental frequencies (EMA values), as well as the FEM frequencies before and after updating. The last column of the table shows the MAC values of the updated model. From this table it can be seen that some of the frequencies of the updated model are for all practical purposes the same as the experimental ones. The largest difference is about 12% for the third mode, but this is still acceptable for practical purposes. The MAC values are also very acceptable.

A 3D plot of the MAC matrix before and after the model updating is presented in Fig. 2, and a graphical comparison of mode shapes is presented in Fig. 3. The MAC matrix comparison clearly shows how the automatic updating process accomplished a good matching of experimental and analytical modes and how the modes of the initial model changed to match the experimental modes. Lack of space for this paper prevents additional discussion of this further refinement.

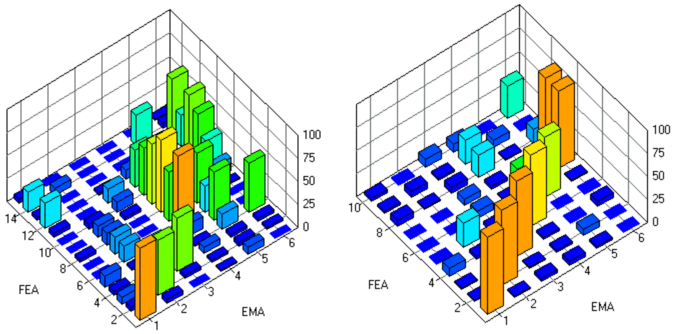
Table 1. Comparison of first six natural frequencies of the HCT Building (Hz) before and after model updating.

Mode No.	EMA freq.	FEM before	FEM updated freq.	FEM updated MAC
1	1.23	1.33	1.20	83%
2	1.27	1.74	1.40	82%
3	1.44	2.07	1.63	85%
4	3.87	4.08	3.88	84%
5	4.25	4.38	4.25	73%
6	5.35	5.66	5.62	81%

Table 2 provides a summary of the changes that FEMtools made to the FE model in order to achieve the correlation values presented in the table above. The units of the quantities in this table are meters, newtons and kilograms. Although it appears that some of the changes are very significant, a sensitivity analysis of the model to changes in some of these parameters showed that their overall influence is not that great. One such case is the change of the moment of inertia along the weak axis of the columns. However, other parameters such as the mass density and stiffness parameters (E and H) of the cladding changed significantly. The initial cladding mass was underestimated but the stiffness was overestimated. The initial stiffness of the floor slabs was also underestimated.

Table 2. Comparison of initial and final values of parameters.

Type	Element	Initial value	Actual Value	% diff.
E	Columns	2.5E+010	1.3E+010	-50
E	Beams	2.5E+010	3.8E+010	50
E	Floor Slabs	3.0E+011	5.1E+011	70
E	Shear Walls	2.5E+010	1.7E+010	-32
E	Cladding	3.0E+010	1.4E+010	-54
ρ	Columns	2.4E+003	2.9E+003	20
ρ	Beams	2.4E+003	1.9E+003	-20
ρ	Floor Slabs	3.0E+003	2.2E+003	-25
ρ	Shear Walls	2.4E+003	1.9E+003	-20
ρ	Cladding	3.0E+003	4.5E+003	50
I_{max}	Columns	varies	varies	50
I_{min}	Columns	varies	varies	-50
H	Cladding	0.02	0.006	-69



a) MAC matrix before updating b) MAC matrix after updating

Figure 2. MAC matrices for six mode shapes of HCT building.

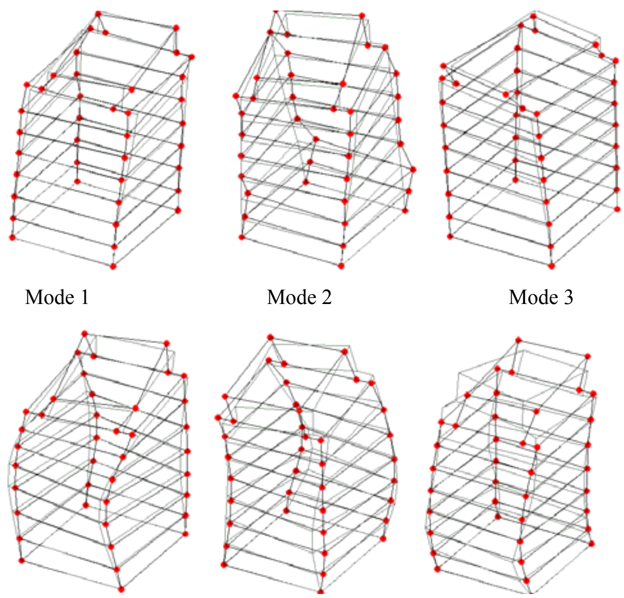


Figure 3. Comparison of reduced FE mode shapes of updated model and "experimental" mode shapes of HCT building.

4 CASE STUDY: 48-STOREY REINFORCED-CONCRETE BUILDING

The One Wall Centre (Fig. 3) 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 is used for hotel operations and the top third is for privately owned luxury suites.

At the time of its completion in March of 2001, 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 (Fig. 4).

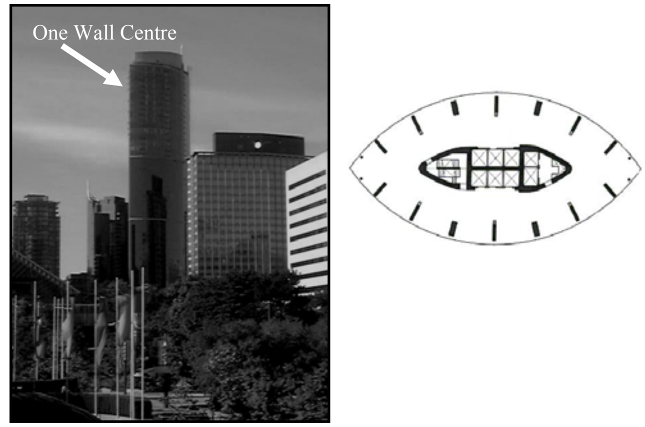


Figure 4. View of One Wall Centre building and typical floor plan.

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.

The ambient vibration tests were conducted to capture the translational modes (in the transverse (North-South (NS)) and longitudinal (East-West (EW)) directions) and torsional modes of the building. The modal identification for the One Wall Centre was performed using computer program ARTeMIS Extractor (Lord and Ventura, 2002).

4.1 *Selection of parameters for model updating.*

Similar to the HCT, the parameters discussed in 3.1 were selected for the model updating. 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 very 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 that sensitive to a change in E, ρ and I for the beams and columns. In view of this, the number of parameters used for model updating was reduced to 29 (E values of the shear walls, floor slabs and cladding; ρ values of the shear walls, floor slabs and cladding; and H value of the cladding).

A variation in E was 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 was considered to give insight into how sensitive was 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 was difficult to predict.

4.2 *Model updating results.*

The computer program converged to a solution after five iterations. The results are summarized in Table 3. 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.

A summary of the changes performed by FEMtools in order to match the FEM results to the EMA results is presented in Table 4. 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.

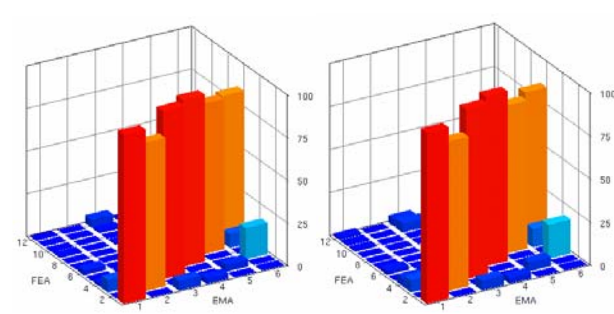
Table 3. First six mode shapes of the One Wall Centre before and after model updating.

Mode No.	**EMA Period (s)**	**FEM Period Before (s)**	**FEM Updated Period (s)**	**FEM Updated 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

A 3D plot of the MAC matrix before and after the model updating is presented in Fig. 5, and a graphical comparison of mode shapes is presented in Fig. 6. The MAC matrix comparison shows that in this case the automatic updating process just helped refine the matching of experimental and analytical modes and how the modes of the initial model changed to match the experimental modes. Lack of space for this paper prevents additional discussion of this further refinement. For more details see Lord, 2003.

Table 4. Parameters before and after model updating.

Type	Element	Initial Value (kN, m, kg)	Updated Value (kN, m, kg)	Diff. (%)
E	Shear Walls (Levels 1-20)	3.65E+07	1.49E+07	-59
E	Shear walls (20-31)	3.52E+07	5.76E+07	64
E	Shear walls (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 (1-20)	2400	1590	-34
ρ	Shear walls (20-31)	2400	1220	-49
ρ	Shear walls (31-Roof)	2400	4470	86
ρ	Floor slabs	2400	2280	-28
ρ	Cladding	2200	2210	1
H	Cladding	0.0125	0.00731	-42



a) MAC matrix before updating b) MAC matrix after updating

Figure 5. One Wall Centre - MAC matrices for 6 mode shapes

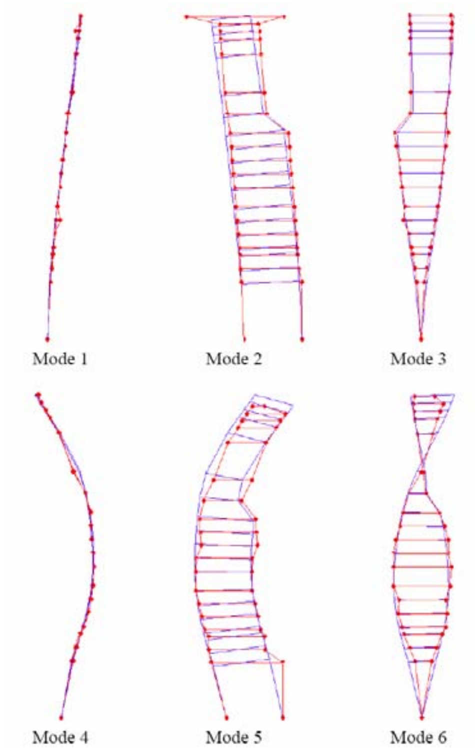


Figure 6. Comparison of reduced FE mode shapes of updated model and "experimental" mode shapes of One Wall Centre

5 CONCLUSIONS

Natural frequencies and modes of vibrations of the Heritage Tower Building and the One Wall Centre were determined experimentally and analytically. These case studies show that is it possible to accomplish an effective model updating of a large civil engineering structure using the results from an Natural-Input Modal Identification analysis. The use of an automatic model-updating tool greatly facilitates determining, which are the model parameters that can be modified in order to achieve a good correlation between experimental and analytical results. But at the end of a model updating exercise it is up to the analyst to accept the changes suggested by the modal updating program and to justify how realistic are the changes to be done.

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7 REFERENCES

DDS, Dynamic Design Solutions N.V.,2004. FEMtools for Windows Version 3.0 Leuven, Belgium, www.femtools.com

Lord, J.F. 2003. Model Updating of a 48-storey Building in Vancouver Using Ambient Vibration Measurements. M.A.Sc. Thesis, Department of Civil Engineering, the University of British Columbia, Vancouver, Canada

Lord, J.F and Ventura,C.E, 2002. "*Measured and Calculated Modal Characteristics of a 48-Story Tuned Mass System Building in Vancouver*", International Modal Analysis Conference-XX: A Conference on Structural Dynamics, Society for Experimental Mechanics, Los Angeles, CA, USA, 2, 1210-1215.

SVS, Structural Vibration Solutions ApS, ARTeMIS Extractor (Release 3.4) User's Manual (Aalborg, Denmark, 2004) www.svibs.com

Ventura, C.E. and Horyna, T., 2000. "*Measured and Calculated Modal Characteristics of HCT Building.*" Proc. of the XVIII IMAC, San Antonio, Texas, 2000, pp. 1070-1074.