FEM UPDATING OF THE HERITAGE COURT BUILDING STRUCTURE

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ABSTRACT

This paper describes results of a model updating study conducted on a 15-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 meaningfull. 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

Of the various methods to obtain vibration data for Output-Only Modal Identification, ambient vibration testing is the most economical nondestructive testing method to acquire vibration data from large civil engineering structures. The main advantage of this method is that no special, artificial-type of excitation has to be applied to the structure of interest in order to determine its dynamic characteristics. Wind, traffic, micro-tremors and human activity are continuously dynamically exciting a large civil engineering structure, and one can take advantage of these natural excitation "loads" to evaluate its dynamic properties with an adequate instrumentation and data analysis system.

From the viewpoint of structural engineering design practice there are several reasons for conducting vibration measurements in an existing building. For instance, the owner of a building located in a seismically active zone may be interested in determining whether or not 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 engineering 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 require having a good assessment of the actual conditions of the building, including its dynamic characteristics, but would also require 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 develop full confidence that the finite element model of such structure is a realistic representation of the physical structure. The aim of this paper is to demonstrate how Output-Only Modal Identification techniques can be effectively used with Model Updating tools to develop reliable finite element models of large civil engineering structures. A fifteen, concrete story building is used as a case study for this purpose.

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 a high rise building in Vancouver [1]. 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 [2].

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.

2. DESCRIPTION OF THE 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 is presented in Figure 1 and a typical floor plan diagram is presented in Figure 2. Because the building sits to the north side of the underground parking structure, coupling of the torsional and lateral modes of vibration was expected primarily in the EW direction.

3. EXPERIMENTAL STUDY

The vibration measurements were conducted using an eight-channel (with force-balanced accelerometers) system. The accelerometers were typically located in the northwest and northeast corners of the building on every other floor starting from the roof down to the ground floor. Details of the field testing of this structure are given in reference [1]. The tower model was simplified to a rectangle with nodes aligned vertically. The motions of the corners of this rectangle were computed from the measured motions by assuming rigid body motion of the floor slabs. Program ARTeMIS [3] was used to conduct the experimental modal analysis (**EMA**) and determine the modal properties of the building. The first six identified natural frequencies of vibration are listed in Table 1 and the corresponding wire-frame spatial views of the mode shapes are shown in Figures 2. In this figure only the part of the building above the ground level is physically represented. Additional modal identification studies conducted by other researchers and summarized in reference [4] confirm the values of the frequencies and mode shapes presented here.

Mode No.	EMA freq.	Mode type
1	1.23	1st NS mode
2	1.27	1st Torsional
3	1.44	1st EW mode
4	3.87	2nd Torsional (coupled)
5	4.25	2nd NS mode
6	5.35	2nd EW mode (coupled)

Table 1. First six experimentally determined natural Frequencies of the HCT Building (Hz).

4. FEM UPDATING STUDY

An attempt to correlate experimental and analytical modal properties of the building using a manual updating process is described in reference [5]. That study clearly shows the limitations and difficulties in trying to obtain a good general correlation between experimental and analytical modal properties for a large civil engineering structure. In view of this it was decided to use a more efficient platform for updating the initial FE model of the structure. Program FEMtools [6] was selected for this work because it is a CAE analysis program that includes various tools that permit a fast and effective integration of test and FE analysis data. The analytical work involved comparing the natural frequencies and mode shapes of the EMA and FEM models until an acceptable correlation was achieved. Details of the FE model used for this study and of the parameters selected for the model updating are given in the following sections.

4.1. FE model of the building

The FE modeling analysis capabilities of FEMtools were used to create a "starting" model of the structure. The information presented in the design drawings of the building was used to formulate the geometry and material properties of the model. Since the experimental results indicated that the motions at the ground floor level of the building were negligible compared with the motions at the upper floors, it was decided to model only the superstructure of the building and assume a "fixed base" condition at the ground level. The main structural elements (concrete core shear walls, gravity load columns, header beams and load transfer beams at the second floor) were all included in the model. Beams and columns were modeled as 3D beam-column elements and shear walls were modeled as 4-node plate elements. Flat slab floors were modeled mostly as 4-node plate elements. The exterior cladding of the building was also modeled as simplified 4-node thin plates placed near the perimeter of the structure. All setbacks and structural section changes throughout the height of the building were taken into account.

The concrete material properties were determined form the design specifications included in the drawings. In total the model consisted of 348 beam-column elements and 818 plate elements, it contained 1456 nodes, 7 different material properties, and 184 different element geometries. This resulted in a FE model with 8736 degrees of freedom. Two views of the FE model of the building are presented in Figure 4: a 3D view of the complete model and a wire-frame representation emphasizing the core shear walls distribution.

4.2 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 as above.
- The moment of inertia, I, of the columns.
- The thickness, H, of the simulated cladding panels.

This resulted in 13 different parameters that the program could use for updating the models. 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).

4.3 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.

The resulting mode shapes of the updated model are shown in Figure 5 and a comparison of modes from the reduced FE model and the experimental model is shown in Figure 6. A 3D plot of the MAC matrix before and after the model updating is presented in Figure 7. 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.

Since not all the floors of the building were measured, the spatial representation of the higher modes of vibration might not be very accurate and the reliability of the experimental model may not be as high for the higher modes as for the lower modes of vibration. This is why only 6 modes of vibration were selected for the updating study. However, once a good correlation between experimental and analytical results was obtained, four more experimental modes were added to the analysis and a further refinement to the model was accomplished. Lack of space for this paper prevents additional discussion of this further refinement.

Mode No.	EMA freq.	FEM before	FEM updated freq.	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. Comparison of first six natural frequencies of the HCT Building (Hz) before and after model updating.

Table 3 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.

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

Table 3. Comparison of initial and final values of parameters selected for model updating.

6. CONCLUSIONS

Natural frequencies and modes of vibrations of the Heritage Tower Building were determined experimentally and analytically. This case study shows that is it possible to accomplish an effective model updating of a large civil engineering structure using the results from an Output-Only 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.

ACKNOWLEDGEMENTS

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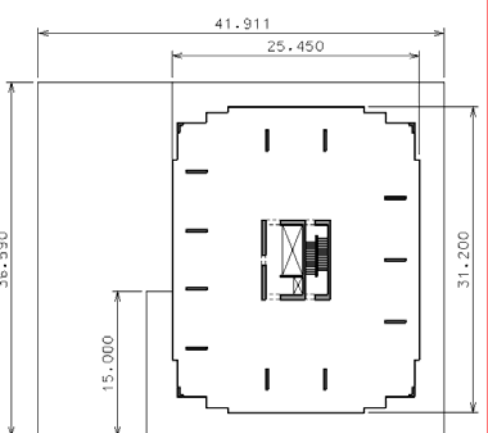
Figure 1. View of HCT building.

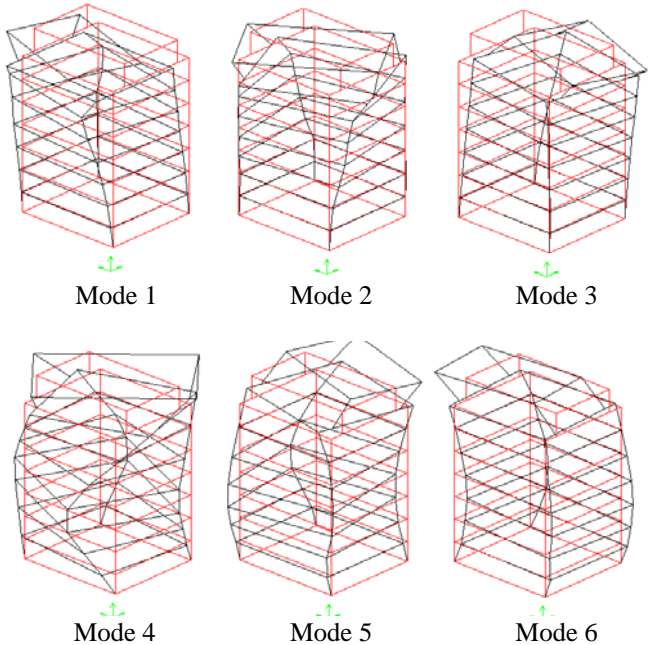
Figure 2. Schematic typical floor plan of the HCT building.

Mode 1   Mode 2   Mode 3

Mode 4   Mode 5   Mode 6

Figure 3. First six experimental determined mode shapes of HCT building.

a) Complete Model   b) Details of Model
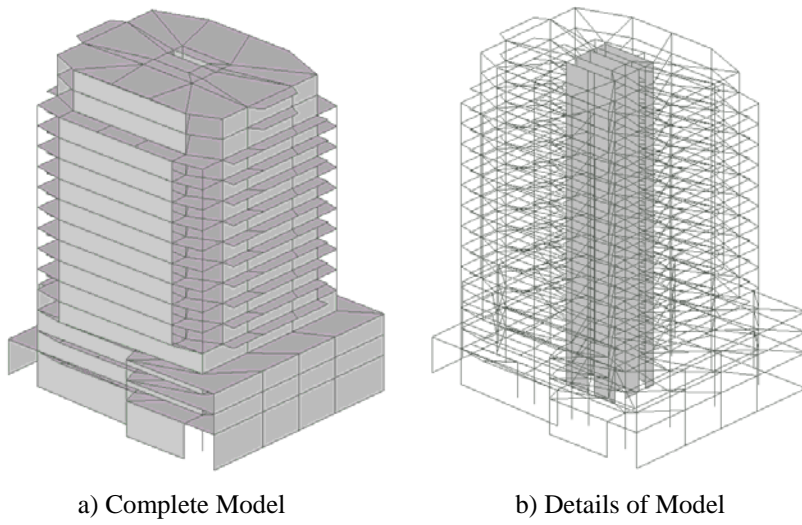
Figure 4. FE model of HCT building.

Mode 1   Mode 2   Mode 3

Mode 4   Mode 5   Mode 6
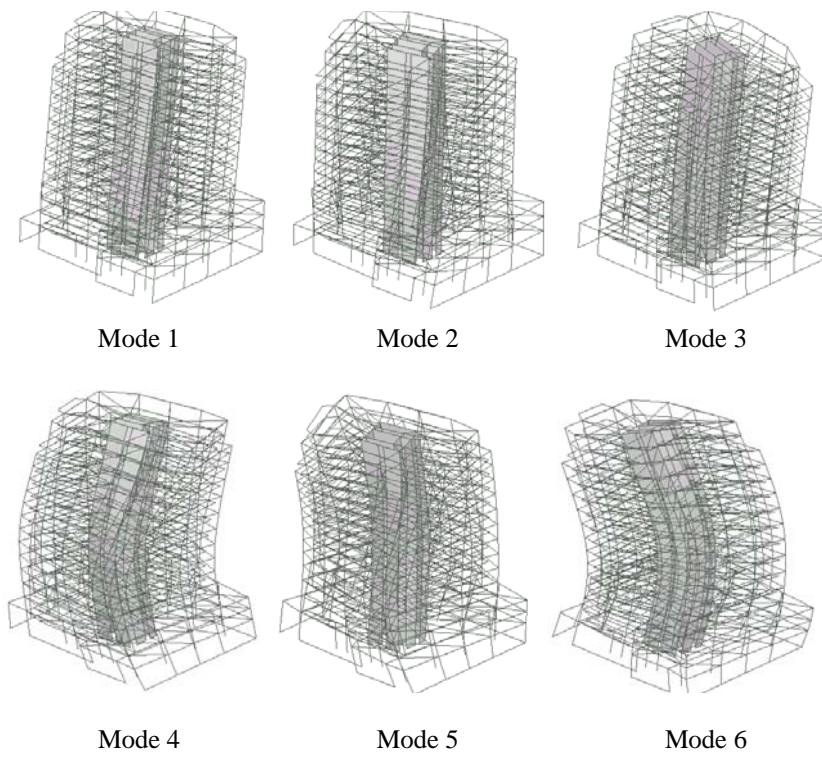
Figure 5. First six mode shapes of updated FE model of HCT building.

Mode 1   Mode 2   Mode 3
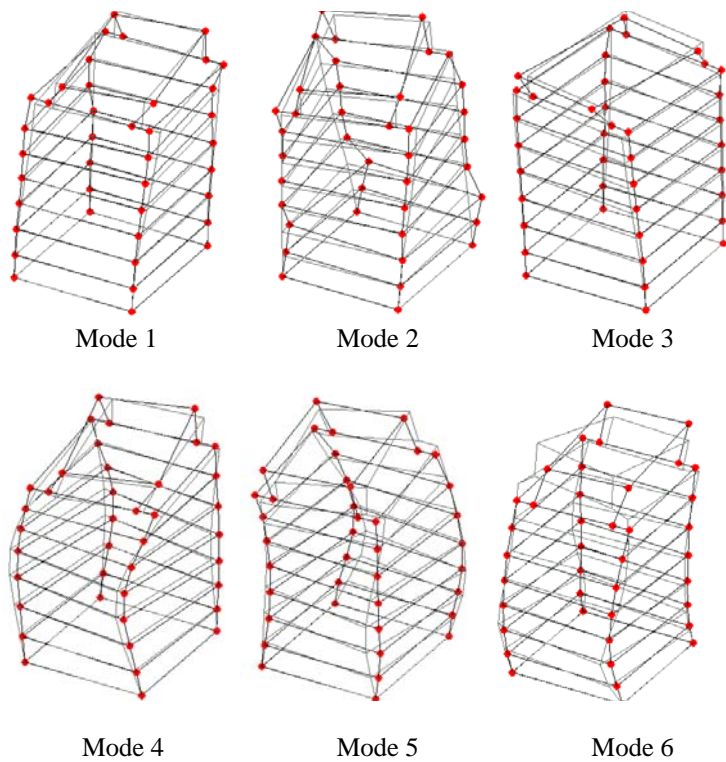
Mode 4   Mode 5   Mode 6

Figure 6. Comparison of reduced FE mode shapes of updated model and experimental determined mode shapes of HCT building.

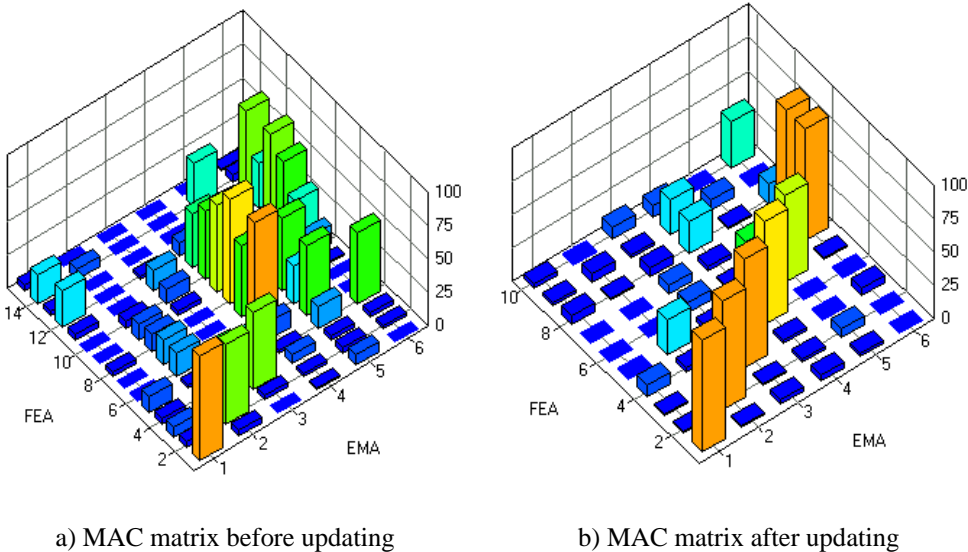a) MAC matrix before updating   b) MAC matrix after updating

Figure 7. Comparison of 3D plots of MAC matrices for first six mode shapes of HCT building.