Model Updating of Real Structures with Ambient Vibration Data

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Abstract

It is important to develop reliable finite element models for real structures not only in the design phase but also for the structural health monitoring and structural maintenance purposes. This paper describes the experience of the authors in using ambient vibration model identification techniques together with model updating tools to develop reliable finite element models of real civil engineering structures. Case studies of two real structures are presented in this paper. One is a 10 storey concrete building which is considered as a non-slender structure with complex boundary conditions. The other is a single span concrete foot bridge which is also a relatively inflexible planar structure with complex boundary conditions. Both structures are located at the Queensland University of Technology (QUT) and equipped with continuous structural health monitoring systems.

1. Introduction

Model updating is the process of correcting the modelling errors of an analytical finite element model (FEM) by using measured data and this technique is applied to generate a refined baseline FEM that accurately predicts the dynamic or static behaviour of a structure (Liu et al., 2014). Nowadays in structural dynamics much attention has been paid to the derivation of accurate models of the structures. These accurate models are used in many civil engineering applications such as structural health monitoring, damage detection, structural evaluation and assessment. During the development of the FEMs there are several assumptions and structural idealizations taken into consideration. When the experimental modal identification is carried out for the real structure it is hence inevitable to experience differences with the developed FEMs. These differences originate from the uncertainties in the simplifying assumptions of structural geometry, materials and inaccurate boundary conditions in the FEM (Jaishi and Ren, 2005). The purpose of model updating is to adjust the mechanical and materials properties as well as geometrical properties of structural elements in order to obtain a better agreement between numerical and experimental results.

The aim of this paper is to demonstrate how ambient vibration model identification techniques can be used together with model updating tools to develop reliable baseline FEMs of real civil engineering structures. Two real case studies of model updating are presented in this paper. The first case study considers a 10 storey building located at QUT premises. This structure is a medium rise building with common floor configuration. Due to its low height/width ratios, the structure is considered to be non-slender and demanding to excite with ambient sources of vibration. Also there are several adjacent structures (such as semi-detached patios and external stair cases) connected to the main building which results in rather complex boundary conditions at certain areas. The second case study treats a single span foot bridge which is considered to be an in-flexible planar structure also with challenging boundary conditions at one of its supports (see details later).

The dynamic characteristics of interest for the model updating are the first few natural frequencies and the corresponding mode shapes. The experimental modal analysis results obtained from the ambient vibration measurements are used to update the FEMs of these two structures. Automated model updating procedure has been used for the updating of the 10 storey building structure. FEM tools which is a multi-functional computer-aided engineering program for FEM updating has been used in this work (FEMtools, 2012). Upper limits and lower limits are implemented for the changes of the updating parameters in order to make the changes realistic and physically meaningful. For the foot bridge, a manual model updating procedure is carried out by manually updating the parameters for high sensitive elements of the structure. Sensitivity analysis is performed to identify the high sensitivity elements for each response of every parameter. The experimental output-only modal analysis (OMA) procedure and modal properties obtained by analysing ambient excitation responses for the two case studies are described in the previous research work at QUT [(Nguyen et al., 2014c, Nguyen, 2014)]. It is worth noting that OMA has gained more popularity in comparison to the input-output counterpart in recent years as it is more applicable for monitoring in-service civil structures [(Nguyen et al., 2014a, Nguyen et al., 2014b)] The OMA software package ARTeMIS (Structural Vibration Solutions A/S, 2011) is used for this work. The details of the two case studies are discussed under two separate sections. An introduction, model updating procedure and model updating results are included for each case study.

2. Case Study: QUT-SHM Benchmark Building

One of the cases considered in this study is the 10 storied Science and Engineering Centre complex at Queensland University of Technology premises in Gardens Point Campus Brisbane (P Block). It is a concrete frame structure with post tensioned slabs and reinforced concrete columns. The building has a rather common level configuration with four semi-underground bases consisting of lowest four levels. Dimensions for the first four levels are approximately 75m x 65m. In the upper floor levels it has a smaller floor area with approximate dimensions of 65m x 45m. The total height of the building is 42m from the formation level of the building. The floor height of the building varies in the range 2.7m to 4.5m. Even though the structure has an overall common configuration when it comes to structural detailing it has a number of variations in terms of slab thicknesses, slab openings, column sizes and orientations (not to mention the local boundary condition issues as previously mentioned). The three main shear walls are placed in the middle of the building, two to the east and other to the west to resist the lateral loads due to potential wind, lateral seismic loads and torsional forces. An overview of the P block (right) and floor level 1 layout (left) are presented in Figure 1.

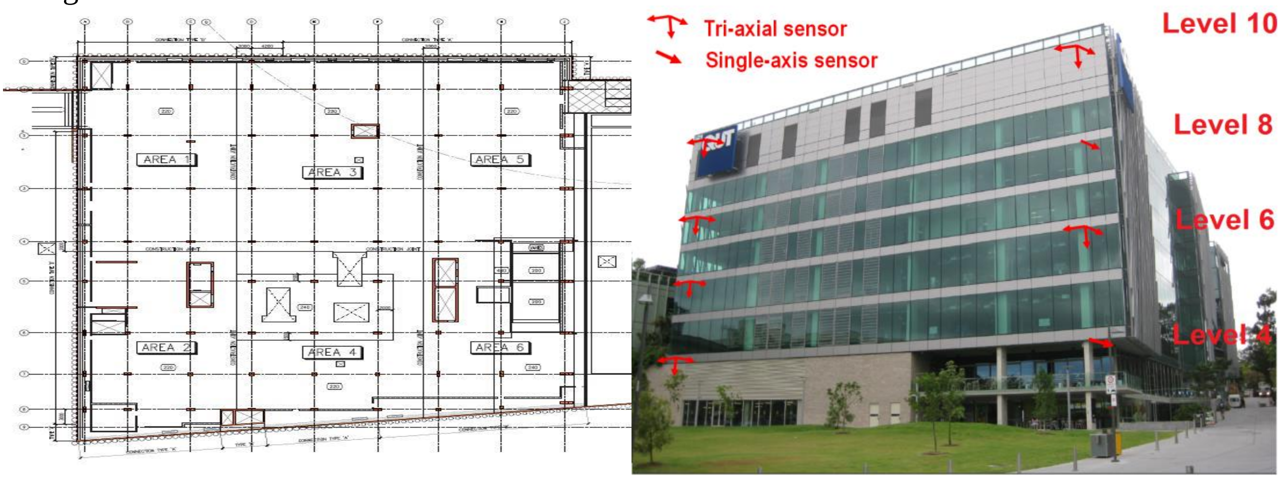

Figure 1. View of P block sensor arrangement and level 1 floor layout.

The P block contains a vibration sensing system employing a software-based synchronization method. As illustrated in Figure 1, there are six analog tri-axial accelerometers and two single-axis accelerometers installed to capture the vibration responses of the structure. The sensors are located on the upper part of the building because the upper part of the building is globally more sensitive to the ambient excitation sources such as wind loads and human activities. Acceleration data of the sensors are sampled at a frequency of 2000Hz and then split into 30-minute subsets for modal analysis purposes. Even though only limited number of sensors are available to capture the ambient vibration responses six frequently excited modes of the building were extracted with high confidence (Nguyen et al., 2014c). Three of such modes extracted from OMA are illustrated in Figure 2. Further details regarding the vibration sensor and data synchronization solutions of P block are presented in Nguyen (2014).

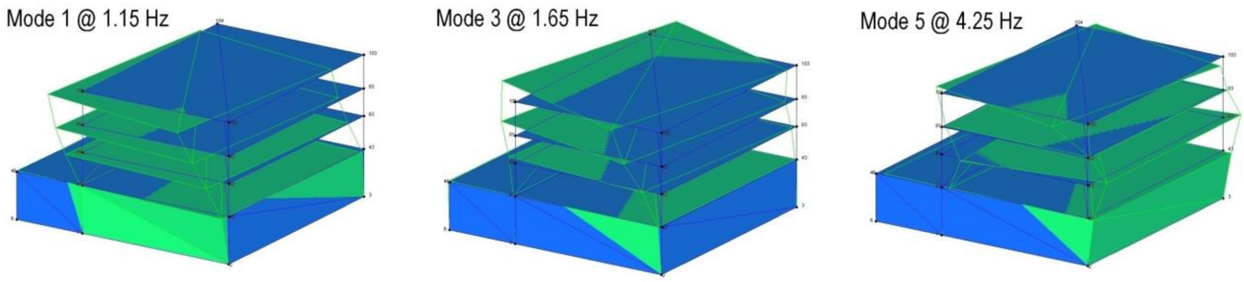

Figure 2. Mode Shapes of P block for OMA- Mode 1, Mode 3 & Mode 5

2.1 Model Updating Procedure

Initially a FEM was developed using the commercially available software package SAP2000 nonlinear version 15.2.0 (Computers & structures Inc., 2014). The as-built drawings have been used for the finite element modelling to represent the actual structure as close as possible. Detailed modelling is considered when modelling the shear cores taking into account major and minor openings and internal thin walls. The shear cores are considered to have a strong influence on the torsional behaviour of multi-storey buildings (Brownjohn et al., 2000).
The results obtained from the finite element modal analysis are used against the OMA results to update the FEM. Automatic model updating procedure using FEMtools is carried out to update the FEM. Initially a sensitivity analysis is performed to select the most sensitive parameters for the model updating procedure. Then maximum and minimum limits are introduced for the parameter changes in order to make the model updating results more meaningful. Table 1 shows the selected parameters and the implemented maximum and minimum limits for each selected parameter. The first five modes are used for the automatic updating procedure.

Table 1. Parameters selected for the model updating and the implemented limits

Parameter	Level	Minimum Limit	Maximum Limit
Young’s Modulus (E)	Local	-15%	+15%
Mass Density (RHO)	Local	-15%	+15%
Cross Sectional Area (AX)	Local	-15%	+15%
Torsional Siffness (IX)	Local	-15%	+15%

Bending Moment of Inertia about Y (IY)	Local	-15%	+15%
Bending Moment of Inertia about Z (IZ)	Local	-15%	+15%
Shell Thickness (H)	Local	-30%	+30%

2.2 Model Updating Results

The updated model results after 39 iterations are summarized in Table 2. The table shows the OMA frequencies and the FEM frequencies for both before and after updating for the first five natural modes. From the table it can be seen that four FEM modes match the corresponding OMA modes with 1.3% or less error which is considered to be an excellent match. The largest error is 4.6% for the first mode which is still a very good match for practical purposes considering the scale of the structure.

Table 2. Comparison of first five natural frequencies of the P block before and after model updating

Mode Number	OMA Frequency	FEM Before		FEM After	
		Frequency	Error	Frequency	Error
1	1.147 Hz	0.990 Hz	-13.69%	1.094 Hz	-4.62%
2	1.544 Hz	1.452 Hz	-5.96%	1.555 Hz	0.71%
3	1.653 Hz	1.678 Hz	1.51%	1.657 Hz	0.24%
4	3.989 Hz	3.680 Hz	-7.75%	3.988 Hz	-0.03%
5	4.254 Hz	4.972 Hz	16.88%	4.258 Hz	0.09%

The Modal Assurance Criterion (MAC) values for the mode shapes are also considered in the model updating. Table 3 shows the MAC values for each mode shape pair before and after updating the model. A graphical comparison of mode shapes of FEM and OMA is shown in Figure 3.
From Table 3 it can be seen that there are three pairs matching with 84% or higher MAC values. The other two modes also have a reasonable match with over 60% MAC values. This can be considered as an acceptable result considering the complexities of the structure's details and boundary conditions as previously mentioned as well as the limited number of sensors used for measurement.

Table 3. Comparison of MAC values for mode shape pairs before and after model updating

Mode Shape Pair	MAC Before Model Updating	MAC After Model Updating
1	89.9%	88.6%
2	50.5%	89.4%
3	42.5%	62.7%
4	63.2%	62.6%
5	68.4%	84.4%

When it comes to structural modelling there is always uncertainty associated with the cross sectional areas of elements, stiffness of elements and boundary conditions of the structure. However the uncertainties in boundary conditions such as arbitrary structural configurations and variations at the boundary are difficult to deal within automatic model updating of large civil engineering structures. Hence in this case study only the parameters that can be systematically coped are considered for automatic model updating.

Table 4 summarises the parameter changes after updating the FEM. Since the upper and lower limits are introduced to each parameter the outcomes are realistic and meaningful. A variation of 15% for material properties such as the E value and RHO value can be allowed for certain elements of a structure from the design values due to various reasons such as changes of concrete batches etc. Considering the maximum and minimum changes to the above mentioned parameters, the results are physically realisable. The reason for the use of the higher limits for shell thicknesses is that in the initial model several simplifying assumptions had been made for the slab geometry. As it was impossible to model the slab panels accurately due to the amount of variation considered in the interior structural detailing, the average values had been used in the initial model in most cases. Higher limits are used for shell thicknesses in order to account for this.

Table 4. Maximum and minimum changes to the parameters after model updating

Parameter	Initial Value	Max. Value	% Difference	Min. Value	% Difference
E	3.5E+07 kN/m^3	4.26E+07 kN/m^3	+15	2.98E+07 kN/m^3	-15
RHO	2.4 kN/m^3	2.76 kN/m^3	+15	2.04 kN/m^3	-15
AX	Varies	Varies	+8.34	Varies	-9.61
IX	Varies	Varies	+1.31	Varies	-1.51
IY	Varies	Varies	+14.3	Varies	-15
IZ	Varies	Varies	+10.7	Varies	-4.35
H	Varies	Varies	+30	Varies	-30

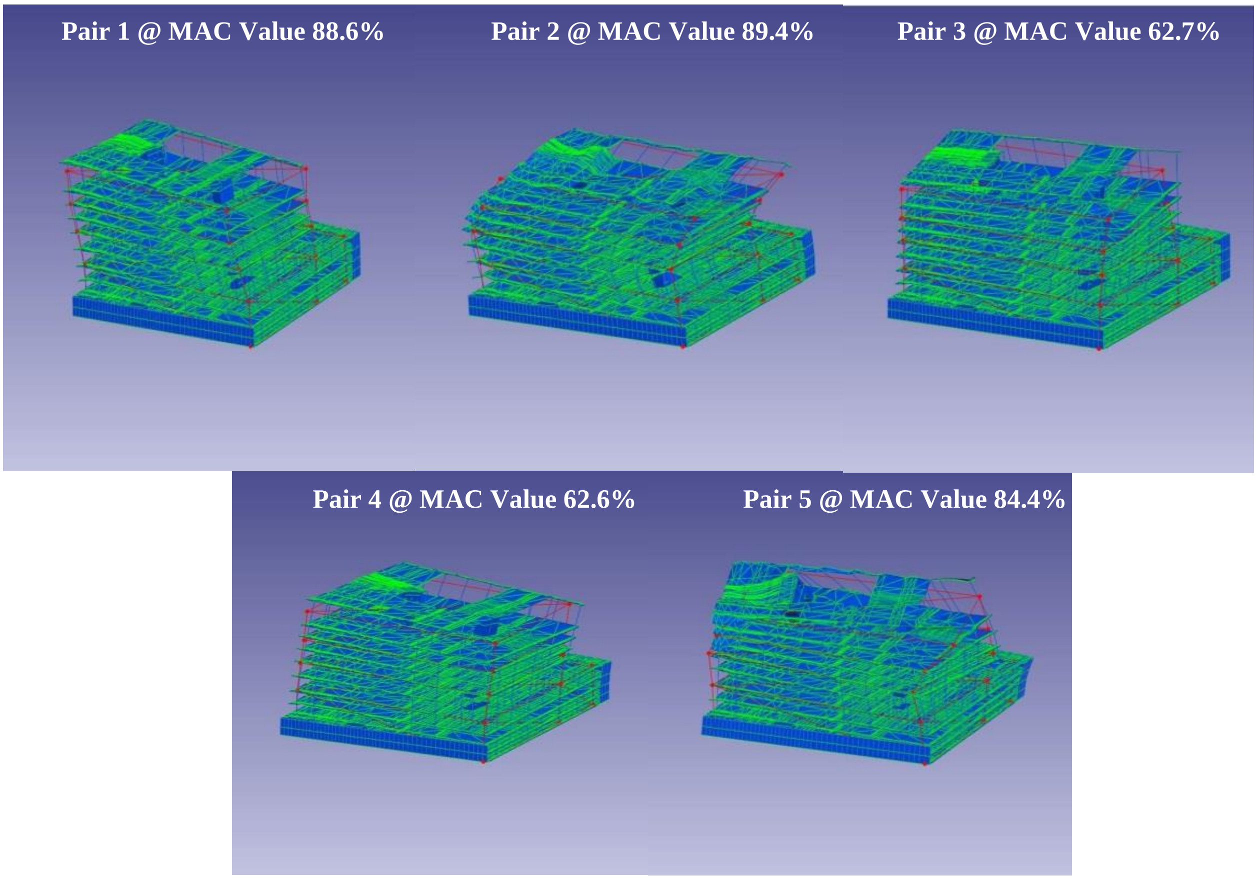

Figure 3. Comparison of FE mode shapes of updated model and OMA mode shapes of P Block

3. Case Study: QUT-SHM Benchmark Foot Bridge

The footbridge is a concrete overpass located at the fourth floor of the P block. It is a concrete slab of 375mm thickness and the span is approximately 8.5m. The bridge is supported at the two ends. At one end it is an extension of the main building floor slab, while at the other end it is roller supported on a reinforced concrete beam. The Figure 4 shows a layout (left) and an overview (right) of the foot bridge. The foot bridge has two tri-axial analog accelerometers positioned in the middle of the two unsupported edges as shown in Figure 4. Additionally two single axis accelerometers were placed at a quarter and three quarters of the span to measure the vertical motion. Even though the structure is inflexible and the ambient vibration conditions are quite challenging, the first two modes of the footbridge are identified with the computer program ARTeMIS. However it is difficult to identify the other natural frequencies due to the complexities of the structure's boundary conditions and difficulties in exciting the structure with ambient sources because of its inflexible nature (Nguyen, 2014).

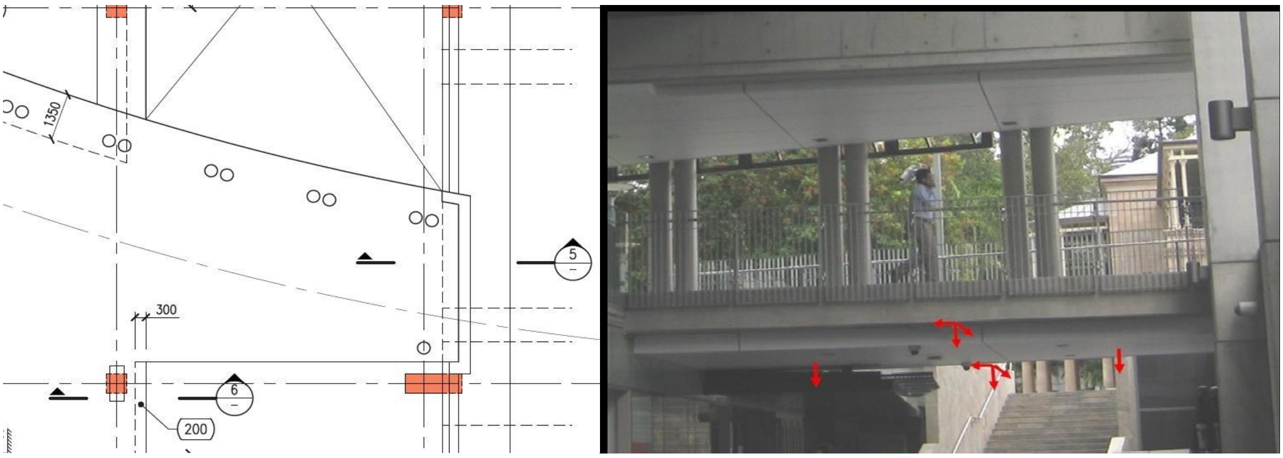

Figure 4. Layout and Overview of the Foot Bridge

The two mode shapes derived from OMA for the footbridge are illustrated in Figure 5. The first mode is a first order bending mode and the second mode is a first order torsional mode. Further details for the OMA procedure and results of the foot bridge can be found in (Nguyen (2014)).

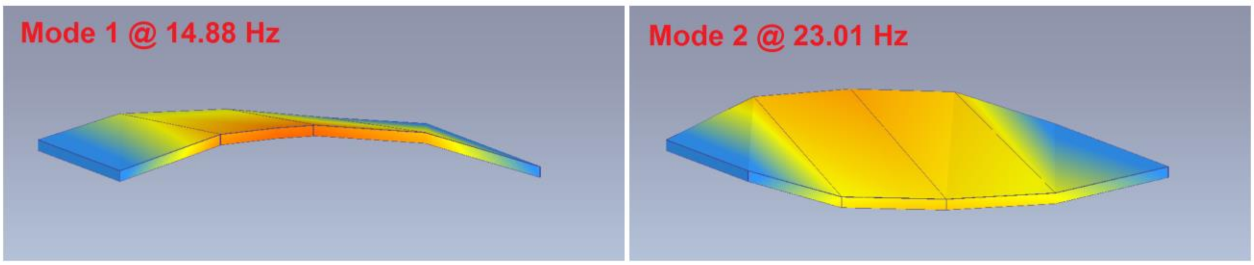

Figure 5. First two mode shapes of the foot bridge

3.1 Model Updating Procedure

As with the case study of the benchmark building structure, a FEM was developed using SAP2000. The as-built drawings have been used in order to represent the real structure as accurately as possible.

For this benchmark structure, unlike the previous case study, a manual model updating procedure is used. The model developed by SAP2000 is exported to FEMtools. Then a sensitivity analysis is performed for the parameters that are likely to change during the model updating procedure. The same parameters used for the model updating of P block structure are used for the sensitivity analysis of the foot-bridge. The total local element count for the sensitivity analysis is 1239. The sensitivity of each local element for each local parameter is tested against the target responses. Since only the first two natural frequencies and the associated mode shapes are available for model updating only four target responses are chosen for the sensitivity analysis purpose. Those are;

- Frequency of mode number 1 (Response 1)
- Frequency of mode number 2 (Response 2)
- Mode shape of mode 1 (Response 3)
- Mode shape of mode 2 (Response 4)

After that for each parameter the highest sensitive elements are figured out and tabulated. Then the outcomes of the sensitivity analysis are analysed against the likelihood of the occurrence. Finally the respective parameters of the selected elements are changed and the response of the FEM is observed. This procedure is repeated until the occurrence of a good match between the FEM and OMA results.

3.2 Model Updating Results

Figure 6 shows the normalized sensitivities for each local parameter of each local element. It is clear from the figure that the normalized sensitivities are high towards the end of the graph. This means that the local parameter shell thickness is the highest sensitive parameter for all responses, especially for the first two responses. The individual elements with highest sensitivities are identified. Interestingly the highest sensitive elements for the parameter shell thickness are in a 0.5 strip of meshed slab elements at the end the foot bridge that is connected to the main building floor.

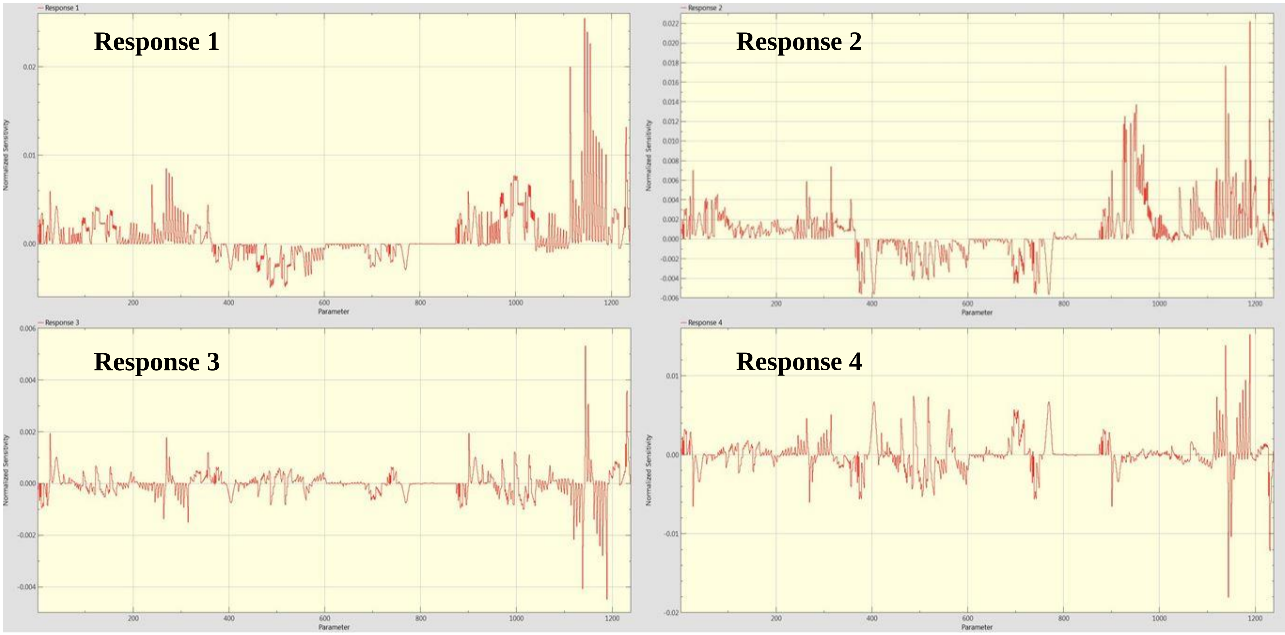

Figure 6. Normalized sensitivities vs. each parameter of each local element

A trial and error process is then carried out by changing the slab thicknesses of those local elements and observing the changes to the responses. Table 5 summarises the frequencies and MAC values for the first two modes before and after performing several trial and error processes.

Table 5. Comparison of the first two natural frequencies before and after model updating

Mode Number	OMA Frequency	FEM Before		FEM After		MAC Before	MAC After
		Frequency	Error	Frequency	Error		
1	14.88 Hz	13.1 Hz	-11.96 %	14.30 Hz	-3.90 %	86.4 %	83.4 %
2	23.01 Hz	21.86 Hz	-4.99 %	23.25 Hz	1.04 %	74 %	74 %

Table 6 provides the resultant change for the shell thickness of each local element considered in the model updating of the foot bridge. The table shows a significant change with an increase in shell thickness of 166.67% for 10 local elements and 300% increase for 5 local elements. However, interestingly in the real structure very close to the strip of local elements considered for model updating there is a beam at the boundary of the footbridge with a 1000mm depth for 2/3rd of the span and 1500mm depth for remaining 1/3rd of the span. Initially for the FEM this was not considered for the sake of simplicity but from the sensitivity analysis of the structure it is found that the beam at the boundary is crucial for FEM to represent the actual structure and that the model updating process has successfully resolved this. For illustration purposes, the view at the particular boundary is shown in Figure 7 (left) while Figure 7 (right) shows an extruded view of SAP2000 model after updating the foot bridge. It is also noted that there is no improvement to the MAC values for both the modes. As discussed in the previous case study the MAC values are acceptable considering the complexities of the structure's boundary conditions and the limited number of sensors used for measurement. One reason for no improvement of MAC values is that even though the shell thickness has a higher sensitivity for the first 2 natural frequencies, some of the local elements have a positive correlation and some elements have a negative correlation (Figure 5) for the mode shapes. It can be identified as one of the drawbacks of manual model updating that it is difficult and time consuming to update number of parameters at the same time for a particular structure.

Table 6. Parameter changes before and after model updating

Local Element Number	Initial Shell Thickness mm	Final Shell Thickness mm	Percentage Difference %
367	375	1000	166.67
307	375	1000	166.67
301	375	1000	166.67
295	375	1000	166.67
289	375	1000	166.67
355	375	1000	166.67
349	375	1000	166.67
343	375	1000	166.67
337	375	1000	166.67
283	375	1000	166.67
331	375	1500	300
325	375	1500	300

319	375	1500	300
406	375	1500	300
405	375	1500	300

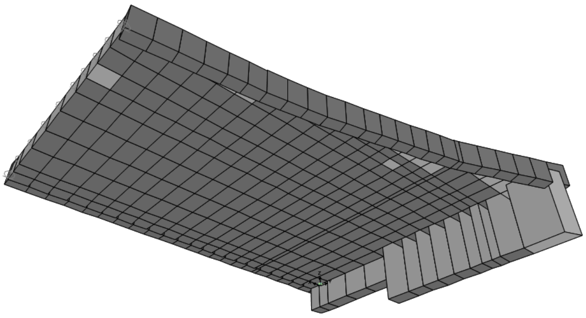

Figure 7. View at the boundary and the extruded view of the updated SAP model

4. Conclusions

The model updating procedure is successfully carried out for two case studies, the P block and the foot bridge. These case studies show that it is possible to accomplish effective model updating techniques for real civil engineering structures. The use of an automatic model updating tool is highly efficient in updating large civil engineering structures as demonstrated in the P block case study. However careful attention should be paid when selecting parameters and implementing limits in order to make the updated model realistic. Also in the automatic model updating it can be difficult to systematically deal with the local boundary condition variations. On the other hand, manual model updating is effective for small structures as shown in the foot bridge example. However, in manual updating it can be time consuming and difficult to update number of parameters at the same time. The advantage of manual model updating is that a significant change can be made for certain elements if it is physically meaningful and justifiable.

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