

Model updating of real structures with ambient vibration data

K. A. T. L. Kodikara¹ · T. H. T. Chan¹ · T. Nguyen¹ · D. P. Thambiratnam¹

Received: 18 September 2015/Revised: 24 May 2016/Accepted: 25 May 2016/Published online: 3 June 2016
© Springer-Verlag Berlin Heidelberg 2016

Abstract It is important to develop reliable finite element models (FEMs) for real structures not only in the design-phase but also for the structural health monitoring and life-cycle management purposes. To do so, model updating is often carried out to minimise the discrepancies between FEMs and real structures. Among existing model updating approaches, sensitivity based model updating methods which can be either manual or automated, have proven to be very effective in the application of real structures and have been widely used on flexible bridge structures. However, very few studies were reported on buildings especially those with medium-rise characteristics which are often associated with complicated initial modelling and different degrees of parameter uncertainties. In addition, even-though a handful of studies has been done on manual model updating for bridge structures, not much research has taken into account the influence of external structural components on manual model updating process. To address these issues, two case studies with real structures are established in this research. One is conducted with a 10-story concrete building to demonstrate the importance of having sufficiently detailed initial FEMs in automated model updating of medium-rise buildings and effective use of boundary limits and parameter groups to maintain the physical relevance of the updated FEMs. Other is an investigation with a single span inflexible foot bridge to highlight the necessity to consider external structural components in manual model updating of inflexible structures. Both studies employ actual ambient vibration

monitoring data obtained from the test structures for the model updating processes.

Keywords Model updating · Finite element modelling · Sensitivity analysis · Ambient vibration

1 Introduction

Model updating is the process of correcting the modelling errors of an analytical 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 [1]. In recent times, there has been much attention in the area of structural dynamics towards the derivation of accurate models of structures. These accurate models are useful in many civil engineering applications such as structural health monitoring, damage detection, structural evaluation and maintenance. 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 structures it is 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 [2]. The purpose of model updating is to adjust the mechanical and material properties as well as geometrical properties of structural elements to obtain a better agreement between numerical and experimental results.

Among many model updating methods available, sensitivity based model updating has been very popular in real structure applications for the last two decades. Such methods can be either manual where the tuning parameters are changed manually to improve the initial FEMs or

✉ K. A. T. L. Kodikara
tharindu.kodikara@qut.edu.au

¹ School of Civil Engineering and Built Environment,
Queensland University of Technology, Brisbane, Australia

automated in which case it is often conducted in an iterative manner. Several successful studies had been reported in using sensitivity based model updating, mostly on flexible bridge structures such as long span cable stayed bridges [3–10]. However, very few studies have been carried out on automated model updating of building structures [11, 12] especially those with medium-rise characteristics. These types of structures are often associated with complicated initial modelling and different degrees of parameter uncertainties leading to real challenges for the users to establish satisfactory initial FEMs as well as appropriate updating parameters and ranges. The importance of addressing the aforementioned challenges of medium-rise buildings to develop reliable FEMs using sensitivity based automated model updating techniques have not been highlighted in the previous studies. Another issue arising from previous studies is that even though several case studies have been carried out with manual model updating, they were mostly concerned about flexible-type bridge structures such as cable-stayed bridges and choosing internal structural elements for model tuning [4, 7, 10]. As a result, there has been a shortage of studies on inflexible bridge structures (such as short- and mid-span concrete bridges) and assessing the influence of external structural components on manual model updating processes.

To address some of the aforementioned issues, two case studies of model updating with real structures are established in this research. The first case study considers a 10-storey building located at Queensland University of Technology (QUT) premises. Due to its low height/width ratio, the structure is considered to be non-slender and quite challenging to be calibrated by means of ambient vibration measurements. Further, the structure is rather complex in terms of internal structural variation such as slab thicknesses and elemental orientations which are often found in medium-rise buildings. The aim of this case study is, firstly, to demonstrate the importance of having sufficiently detailed initial FEMs of complex medium-rise buildings in automated model updating. Secondly, it is intended to show how boundary limits and parameter groups based on element types can be defined for tuning parameters for such types of building structures to maintain the physical relevance of the updated FEM. To expedite the updating process, FEM tools which is a multi-functional computer-aided engineering program for FEM updating will be used in conducting the automated model updating [13].

The second case study treats a single span foot bridge which is considered to be an in-flexible planar structure with challenging boundary conditions at one of its supports (see Sect. 3.2 for more details). Manual model updating coupled with systematic sensitivity analysis is used in this study to obtain the high sensitivity elements for each response of

every parameter. This case study highlights the importance of taking into account the external structural components (located in the vicinity of the support of the structure under consideration) in the manual model updating process.

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. The experimental output-only modal analysis (OMA) procedure and modal properties obtained for the two case studies are described in the previous research work at QUT [14, 15]. 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 [16, 17]. The details of the two case studies are discussed in the next two succeeding sections before conclusions along with summary of the findings are made.

2 Case study 1: QUT-SHM benchmark building

The first case study concerns the 10-story P block of the Science and Engineering Centre complex at Gardens Point Campus of QUT. This is a concrete frame structure with post tensioned slabs and reinforced concrete columns. Overall, the building has a rather common level configuration with four semi-underground bases consisting of lowest four levels with horizontal dimensions of approximately 75×65 m. The upper floor levels possess a smaller floor area with dimensions of 65×45 m. The total height of the building is 42 m from the formation level of the building while the floor height of the building varies in the range 2.7–4.5 m. Even though the structure has an overall common configuration, for structural detailing a number of variations in slab thicknesses, slab openings, column sizes and orientations will need to be considered. 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 and level 4 layout which can be considered as a typical floor level are presented in Fig. 1 and Fig. 2 respectively.

The P block contains a vibration sensing system employing a software-based synchronization method and operating in a continuous monitoring manner. As illustrated in Fig. 1, there are six analog tri-axial accelerometers and two single-axis accelerometers installed to capture the vibration responses of the structure. The sensors were located on the upper part of the building which is globally more sensitive to the ambient excitation sources such as wind loads and human activities. Acceleration data of the sensors were sampled at a frequency of 2000 Hz and then

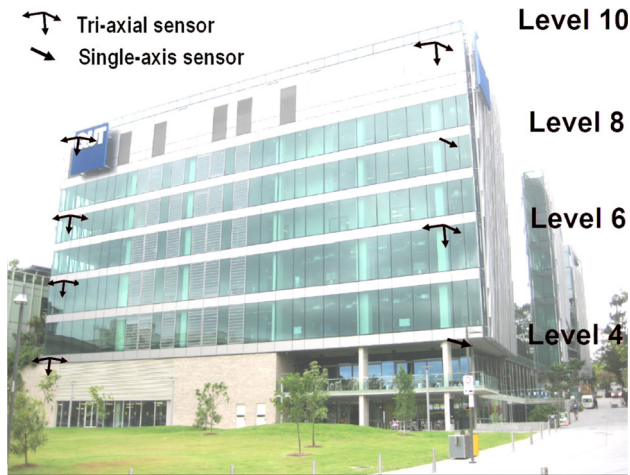
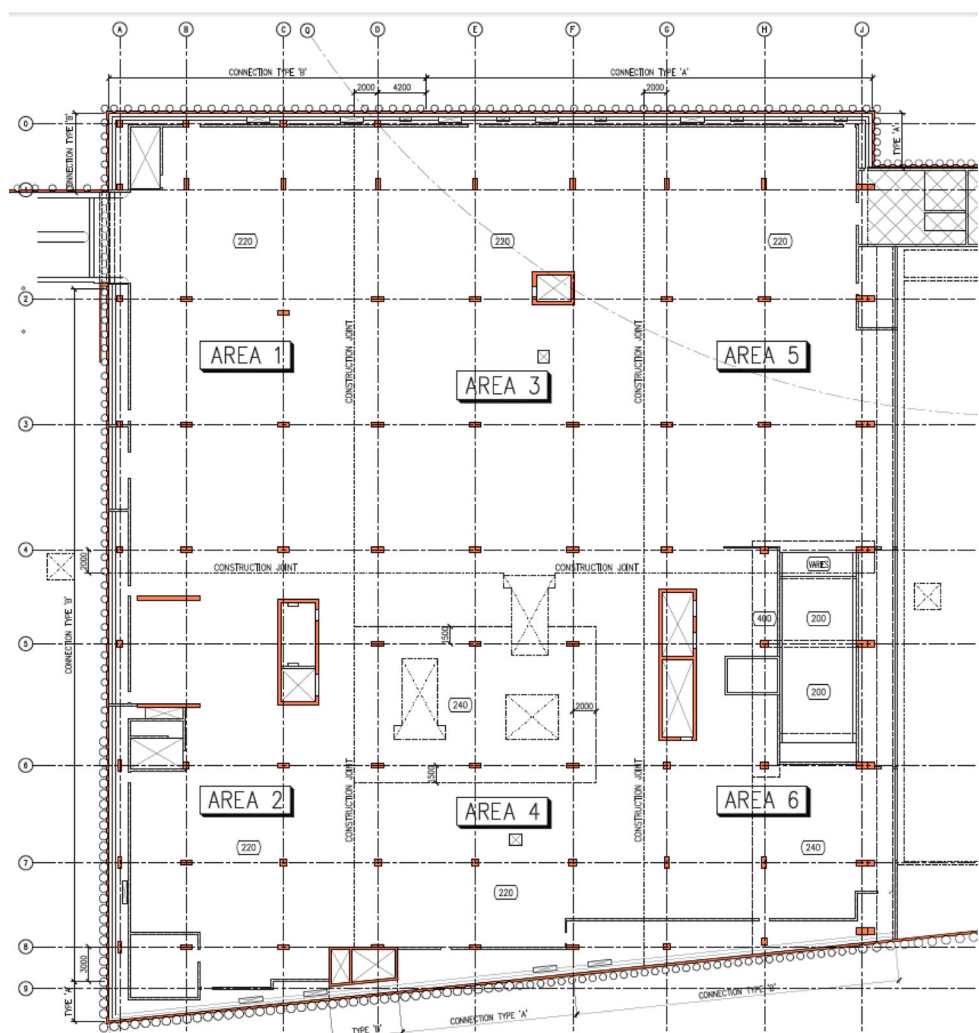


Fig. 1 View of P block sensor arrangement

split into 30-min subsets to allow sufficient uninterrupted data acquisition length and total number of 64 such data sets obtained in various days were used for the modal analysis purposes. Data driven Stochastic Subspace

Fig. 2 Level 4 layout of the building



Identification (SSI-data) with unweighted principal component estimator was selected as the main OMA technique for this case study. For illustration purposes, a typical SSI-data stabilization diagram for OMA of the building is shown in Fig. 3 (upper diagram). Even though only a limited number of sensors were available to capture the ambient vibration responses, six frequently excited modes of the building were extracted with high confidence [14]. First five global modes extracted from OMA are illustrated in Fig. 3 (lower diagram) (Table 2 in Sect. 2.1.2 provides more detailed description about the mode shapes). Further details regarding the vibration sensors and data synchronization solutions of P block can be found in Nguyen et al. [15].

2.1 Model updating procedure

2.1.1 Initial finite element modelling

To study the importance of the initial finite element modelling in medium-rise inflexible building structures, a

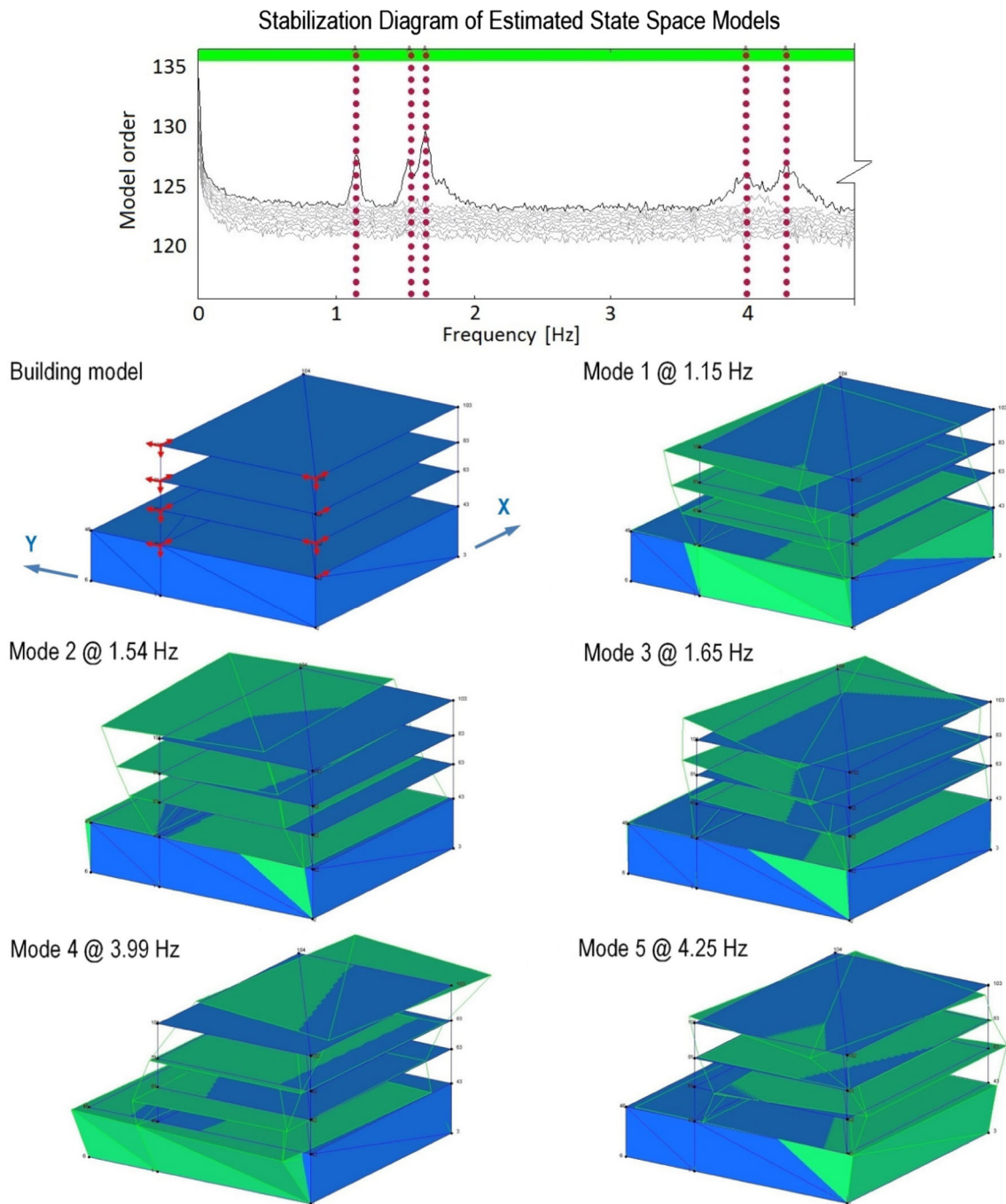


Fig. 3 Stabilization diagram and typical animation views of first five modes

simple FEM developed during the design process was trailed for the model updating. In this model, the level of detailing is low in-terms of modelling shear cores and columns. The results were not satisfactory as the original error for the frequencies of first three global modes was close to 50 %. The model updating resulted in over 100 %

change to the selected updating parameters, which caused losing the physical relevance of the updated FEM.

Hence, a more detailed FEM was developed using the commercially available software package SAP2000 non-linear version 15.2.0 [18]. Maximum error of the frequencies for first five global modes was reduced to 17 %

which highlights the importance of initial finite element modelling in relatively inflexible structures for model updating purposes (See Table 1 for more details). The particular considerations taken during the development of initial FEM are summarized below.

- Detailed modelling is considered when modelling the shear cores taking into account major and minor openings and internal thin walls to enable the torsional behaviour of the structure to be as close as possible to the real structure.
- The spandrel beams are modelled as shell elements instead of frame elements.
- Floor diaphragms are assigned to each floor level to maintain rigid behaviour of floor levels.
- Since the building cladding was fully glazed and all the partitions are light-weight initial investigations revealed that the effect of mass and stiffness of non-structural elements was negligible. Hence this was not included in the FEM.
- The building consists of complex interior slab configurations which makes it impossible to model the floor slabs in detail. Therefore average slab thicknesses are considered in the initial FEM. This can be justified since in the automated model updating floor slab thickness can be used as an updating parameter to account for the simplifying assumption used in initial FEM.

The developed initial FEM consists of 9400 local elements (1400 frame elements and 8000 shell elements). Since the floor system of the building consists of only post-tensioned slabs, all the frame elements represent the columns in the building. Amongst 8000 shell elements 2320 are shear walls and 5680 shell elements are floor slabs.

2.1.2 Correlation analysis

To correlate the results between initial FEM and OMA results, the FEM data generated in SAP2000 and test data were imported into the updating software FEMtools. The Modal Assurance Criterion (MAC) which is a correlation criterion in statistics used for this purpose.

$$MAC(\Psi_a, \Psi_e) = \frac{|(\{\Psi_a\}^T \{\Psi_e\})|^2}{(\{\Psi_a\}^T \{\Psi_a\})(\{\Psi_e\}^T \{\Psi_e\})} \tag{1}$$

where Ψ_a and Ψ_e are analytical and experimental mode shape vectors, respectively. The correlations of dynamic properties for the first five global modes are tabulated in Table 1. Table 1 shows that the correlation was good in-terms of frequency except for the 1st and 5th mode where the error exceeds 10 %. The correlation of mode shapes expressed in-terms of MAC values was not good except for the 1st mode.

2.1.3 Model updating

Even though the initial FEM developed produce good correlation compared to the model used by the designers for static analysis, the correlation is not satisfactory for dynamic analysis purposes. Hence, model updating was used to improve the FEM.

According to Brownjohn and Xia [19], successful model updating depends on choosing correct number of responses, appropriate selection of updating parameters. Initial studies carried out on response selection revealed that selection of OMA frequencies and OMA mode shape ordinates for the first five modes produce good results in model updating. Hence, the frequencies and associated mode shape pairs of first five modes were selected for the model updating.

As stated earlier, selection of appropriate updating parameters is vital for a successful model updating. The selected updating parameters should be physically realisable; hence the chosen parameters should be uncertain in the FEM. Otherwise, the updated model will produce physically meaningless updated parameters. Further, it is necessary to select the updating parameters that are most sensitive to the selected responses [3]. Sensitivity analysis is carried out to choose the appropriate parameters for the model updating.

Since the parameters chosen are of different types, normalized relative sensitivities have been used for the sensitivity analysis.

Table 1 Correlation between initial FE model and OMA results

Mode	OMA frequency (Hz)	Initial FE model (Hz)	Error (%)	MAC (%)	Mode shape
1	1.147	0.990	−13.69	89.9	1st translational—X direction
2	1.544	1.452	−5.96	50.5	1st translational—Y direction
3	1.653	1.678	1.51	42.5	1st torsional
4	3.989	3.680	−7.75	63.2	2nd translational
5	4.254	4.972	16.88	68.4	2nd torsional

Table 2 Parameters selected for the model updating and the implemented limits

Parameter	Group	Minimum limit (%)	Maximum limit (%)
Young's modulus (E)	Element-shell type	-15	+15
Mass density (ρ)	Element-shell type	-15	+15
Cross sectional area (AX)	Element type	-15	+15
Torsional stiffness (IX)	Element type	-15	+15
Bending moment of inertia about Y (IY)	Element type	-15	+15
Bending moment of inertia about Z (IZ)	Element type	-15	+15
Shell thickness (H)	Individual shell elements	-30	+30

$$[S_r] = \left[\frac{\delta R_j}{\delta P_j} \right] [P_j] \quad (2)$$

$[S_r]$ = Relative sensitivity matrix;

$[P_j]$ = A diagonal, square matrix holding parameter values

The sensitivity matrix is obtained by finite difference method. Then the relative sensitivities have been normalized with respect to the response values.

$$[S_n] = [S_r][R_i]^{-1} = [R_i]^{-1} \left[\frac{\delta R_j}{\delta P_j} \right] [P_j] \quad (3)$$

$[S_n]$ = Normalized relative sensitivity matrix; $[R_i]$ = A diagonal, square matrix holding the response values

When selecting the local elements for the model updating, initially all the possible uncertain parameters can be used, but through sensitive analysis low sensitivity parameters should be eliminated for more effective updating process. In structural modelling there are always uncertainties 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 with in automated model updating of large civil engineering structures. Hence in this case study only the parameters that can be systematically coped are considered for sensitivity analysis and later for automated model updating.

The uncertain parameters included in the sensitivity analysis are Young's modulus, mass density of all local elements (9400 local elements each), cross sectional area, torsional stiffness, bending moment of inertia about Y direction and Z direction of all columns (1400 local elements each) and shell thickness of floor slabs (5680 local elements). Hence, the total parameter space used for the sensitivity analysis was 30,080 local parameters.

Then through normalized sensitivity analysis, sensitive local elements for each response are identified and selected for the automated model updating. The parameter sets are defined to make the model updating more realistic and meaningful. For an example, for the selected parameters

for columns (frame elements), sets are defined based on individual columns, except for the shell thickness. No sets are used for the shell elements and in automated model updating variations in local shell elements are allowed. As stated in Sect. 2.1.1, since the actual internal variation of slab thickness is impossible to model, in most cases average slab thicknesses are used in the initial FEM. Hence, it is justifiable to allow variation of slab thickness in shell element level. Summary of all the sets defined for the identified high sensitive elements are presented in Table 2.

After selection of responses and parameters, automated model updating is carried out. The selected parameters are estimated by an iterative process in the updating procedure. Sensitivity-based parameter estimation coupled with pseudo-inverse parameter estimation is used as the updating algorithm. The functional relationship between the modal characteristics and the structural parameters can be expressed in terms of a Taylor series expansion limited to linear terms.

$$\{R_e\} = C + [S](\{P_u\} - \{P_0\}) \quad (4)$$

$$\{\Delta R\} = [S]\{\Delta P\} \quad (5)$$

$\{R_e\}$ = Experimental data;

$\{R_a\}$ = Predicted system responses for a given state $\{P_0\}$ of the parameter values;

$\{P_u\}$ = Updated parameter values

Since the Taylor's expansion is truncated after the first term, the neglected higher order terms necessitate several iterations, especially when $\{\Delta R\}$ contains large values.

Pseudo-inverse of the sensitivity matrix is calculated to determine the desired parameter variation.

$$\{\Delta P\} = ([S]^t[S])^{-1}[S]^t\{\Delta R\} \quad (6)$$

The least squares solutions obtained from the above equation will minimize the residue:

$$\{\text{residue}\} = [S]\{\Delta P\} - \{\Delta R\} \quad (7)$$

To obtain physically realisable and meaningful values for updating parameters upper and lower bounds are used

in the updating procedure. If a parameter reaches its allowable maximum/minimum value during any iteration, the parameter will be made inactive for the rest of the model updating. Upper and lower bounds used for all the parameters are tabulated in Table 2. Higher upper and lower bounds are used for the shell thickness of floor slabs to account for the use of average slab thicknesses (instead of actual thicknesses) in the initial FEM.

The automated updating process will be stopped when a given residue value is achieved, or a given minimum improvement between two consecutive iterations is achieved or maximum number of iterations achieved. In this case study the above mentioned values have been chosen considering convergence of the results and computational efficiency.

- Minimum residue value is 0.1 %.
- Minimum improvement between two consecutive iterations 0.01 %.
- Maximum number of iterations 100.

2.2 Model updating results

The automated procedure stops after 39 iterations due to the minimum improvement between two consecutive improvements falls below the established value of 0.01 %. The updated model results are summarized in Table 3. 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.

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 Fig. 4. From Table 4 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 5 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 ρ value can be allowed for certain elements of a structure from the design values due to various reasons such as changes of concrete batches and different compaction levels. Considering the maximum and minimum changes to the above mentioned parameters, the results are physically realisable. In the updated model there are two aspects to justify for the shell thickness of the floor slab elements which are the variation limit for the thickness and the choice of no grouping for shell elements. The rationale of no grouping for shell element thicknesses is that according to the as built drawings the slab thicknesses vary significantly in small portions so this type of grouping is impractical and the reason for choosing 30 % variation limit is that in some areas actual thickness is 30 % higher or lower from the average values used in the initial FEM.

To highlight the importance of the model updating procedure adopted in this research, it is worth comparing the results of this study with the results of similar cases reported in literature. Previously mentioned (In Sect. 1) case study [11, 12] on sensitivity based model updating on a 15 story building used basic initial FEMs developed with design drawings to correlate the frequencies and associated mode shapes of first six global modes. The largest error in terms of frequency and maximum MAC value for the mode shape pairs is 13.3 and 85 % respectively as opposed to the 4.6 and 89.4 % in this case study. Further, in the aforementioned case study most tuning parameters achieved higher variation from the initial values such as E values of floor slabs 70 % and I values of columns 50 % which tend to cause the loss in physical relevance of the updated FEMs. However, in this research most of the parameter variations were limited to 15 % (including E values of floor slabs and I values of columns) except the shell thickness of the slabs a higher variation (30 %) is used for legitimate reasons.

Table 3 Comparison of first five natural frequencies of the P block before and after model updating

Mode number	OMA frequency (Hz)	FEM before		FEM after	
		frequency (Hz)	Error (%)	Frequency (Hz)	Error (%)
1	1.147	0.990	−13.69	1.094	−4.62
2	1.544	1.452	−5.96	1.555	0.71
3	1.653	1.678	1.51	1.657	0.24
4	3.989	3.680	−7.75	3.988	−0.03
5	4.254	4.972	16.88	4.258	0.09

Fig. 4 Comparison of FEM mode shapes of updated model and OMA mode shapes of P block

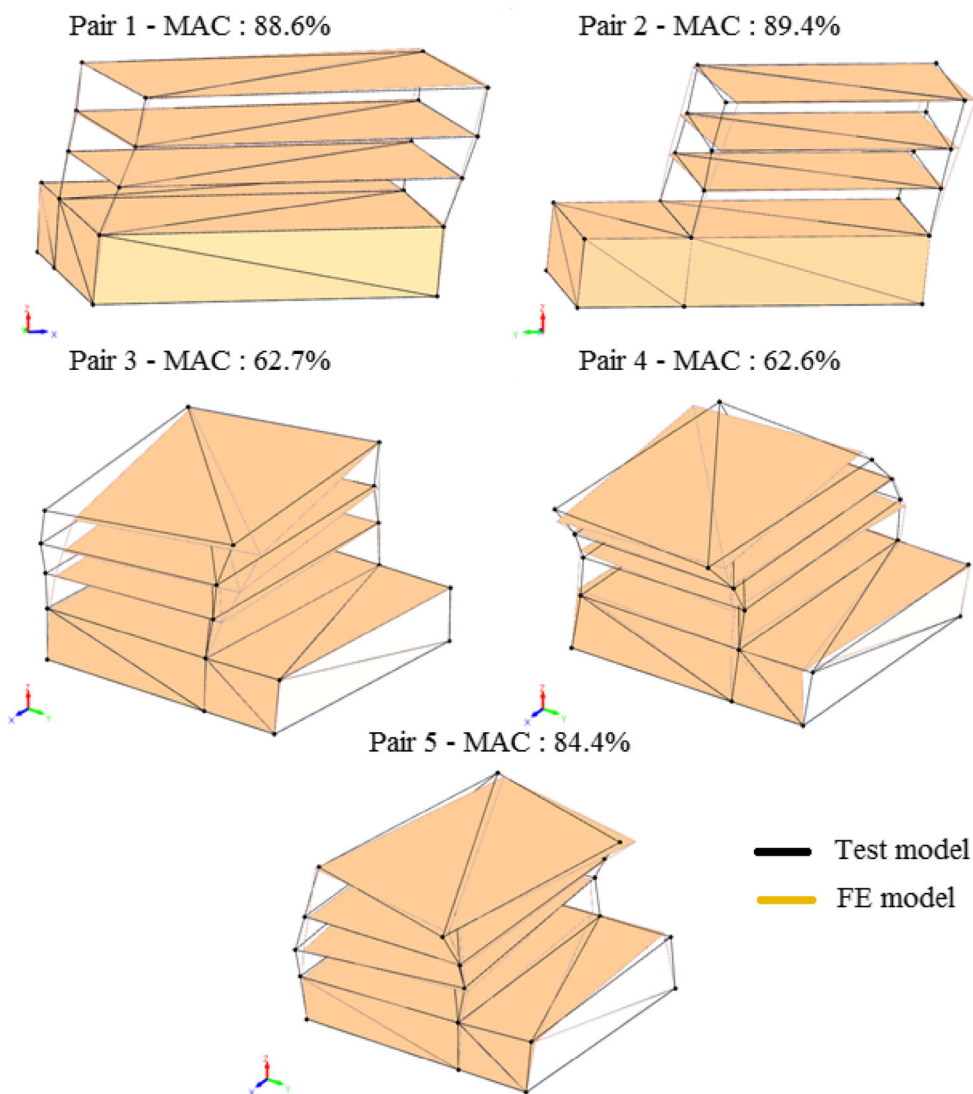


Table 4 Comparison of MAC values for mode shape pairs before and after model updating

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

3 Case study 2: QUT-SHM benchmark foot bridge

The foot bridge is a concrete overpass located at the fourth floor of the P block. It is a concrete slab of 375 mm thickness, simply supported at two ends and has

the span of approximately 8.5 m. The support at one end is an extension of the main building floor slab, while at the other end, the structure is roller supported on a reinforced concrete beam. Figure 5 shows an overview (left) and a layout (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 Fig. 5. Additionally two single axis accelerometers were placed at quarter and three quarter spans to measure the vertical motion.

Even though the structure is inflexible, the number of sensors is limited and the ambient vibration conditions are quite challenging, the first two modes of the footbridge are identified [20] which serves the purpose of model updating application presented in this paper. As illustrated in Fig. 6, the first mode is a first order bending mode while the second one is a first order torsional mode.

Table 5 Maximum and minimum changes to the parameters after model updating

Parameter	Initial value	Max. value	% Difference	Min. value	% Difference
E	$3.5E + 07 \text{ kN/m}^3$	$4.26E + 07 \text{ kN/m}^3$	+15	$2.98E + 07 \text{ kN/m}^3$	-15
ρ	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

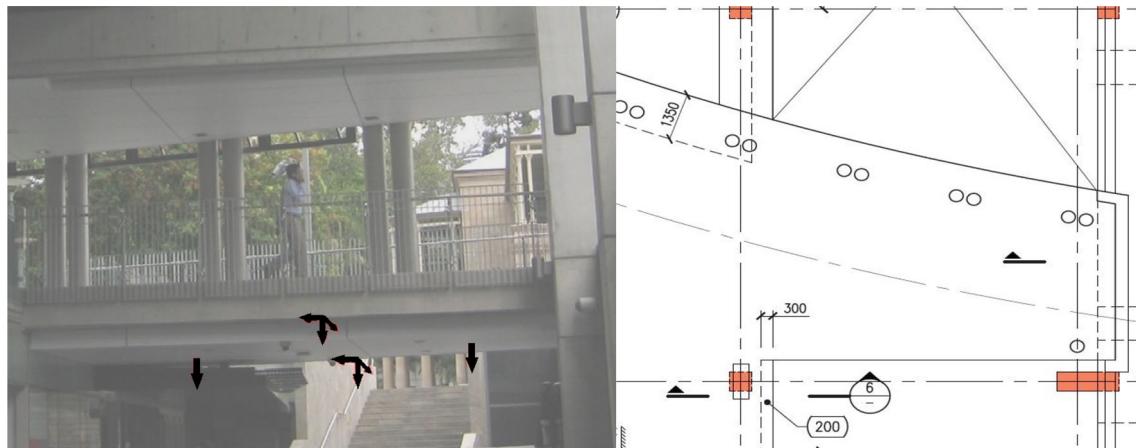
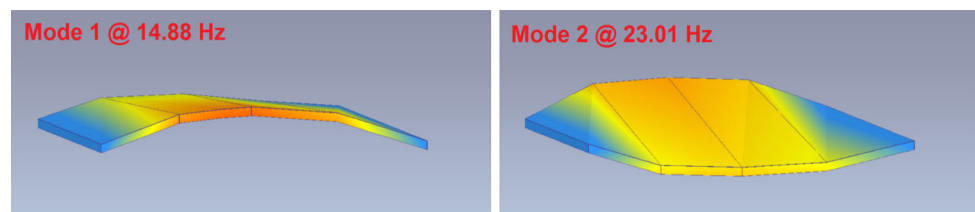


Fig. 5 Overview (left) and layout (right) of the foot bridge

Fig. 6 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 to represent the real structure as accurately as possible.

For this structure, unlike in the previous case study, a manual model updating procedure is used. The model developed by SAP2000 is exported to FEMtools. The FEM consists of 361 local elements used to model the concrete deck and 26 spring elements used to idealise the support boundaries. Then a sensitivity analysis is performed for the parameters that are likely to change during the model updating procedure. The same process used for the P block structure is used for the sensitivity analysis of the footbridge. The total local element count for the sensitivity analysis is 1239, which consists of

translational stiffness of spring elements in X, Y and Z directions ($26 \times 3 = 78$), rotational stiffness of spring elements in X, Y and Z directions ($26 \times 3 = 78$), Young’s modulus of concrete deck shell elements (361), mass density of concrete deck shell elements (361) and shell thickness of concrete deck elements (361). 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. They 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).

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

3.2 Model updating results

Figures 7, 8, 9, 10 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 of the foot bridge that is connected to the main building floor.

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 6 summarises the frequencies and MAC values for the first two modes before and after performing several trial and error processes.

Table 7 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 five local elements and 300 % increase for ten local elements. However, to match with the findings of the manual model updating, in the vicinity of the strip of local elements considered for model updating in the real structure there is a beam with a 1000 mm depth for 1/3rd of the span and 1500 mm depth for remaining 2/3rd of the span. Since the beam is not part of the original foot bridge, this was not considered in the initial FEM. However, by using the sensitivity analysis of the structure it is found that such an adjacent structural component is crucial for the FEM to represent the actual structure in terms of modal behaviours and that the model updating process has successfully

Fig. 7 Normalized sensitivities vs. uncertain parameters (Response 1)

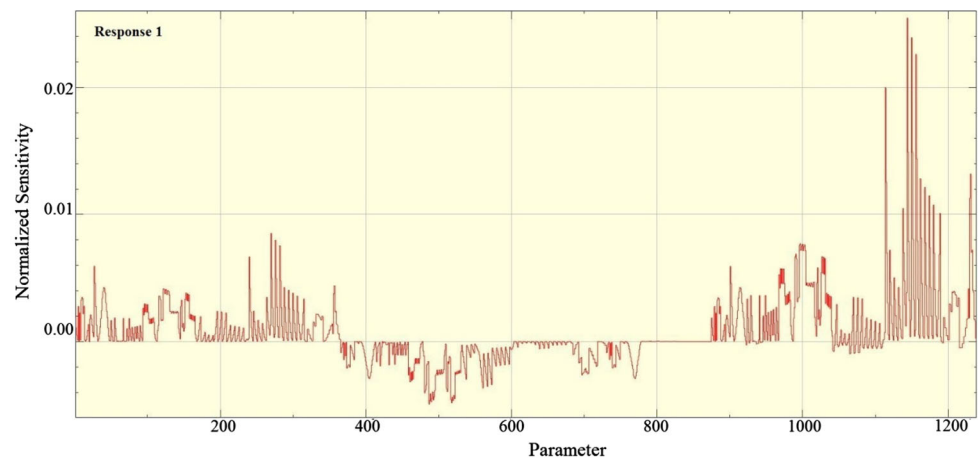


Fig. 8 Normalized sensitivities vs. uncertain parameters (Response 2)

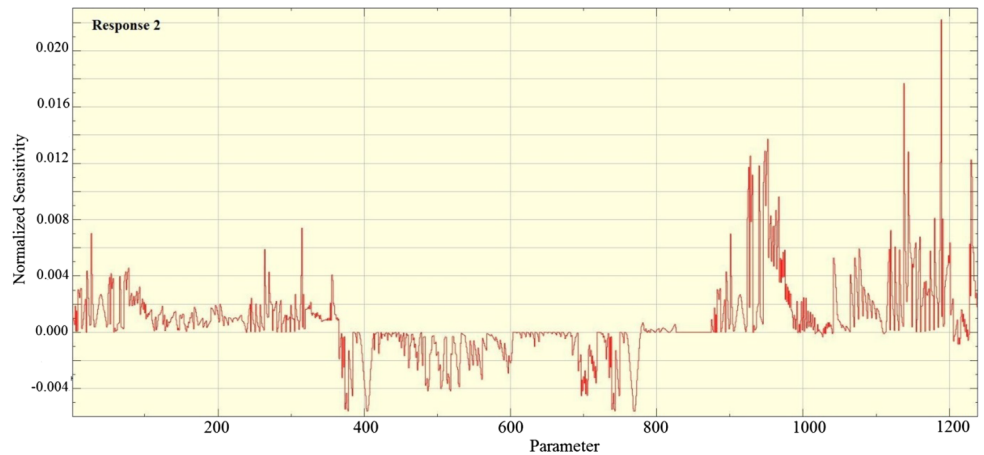


Fig. 9 Normalized sensitivities vs. uncertain parameters (Response 3)

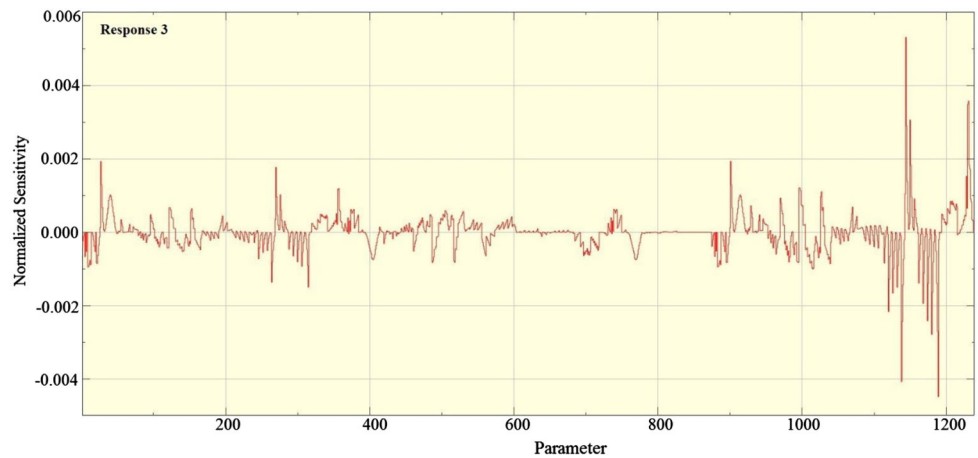


Fig. 10 Normalized sensitivities vs. uncertain parameters (Response 4)

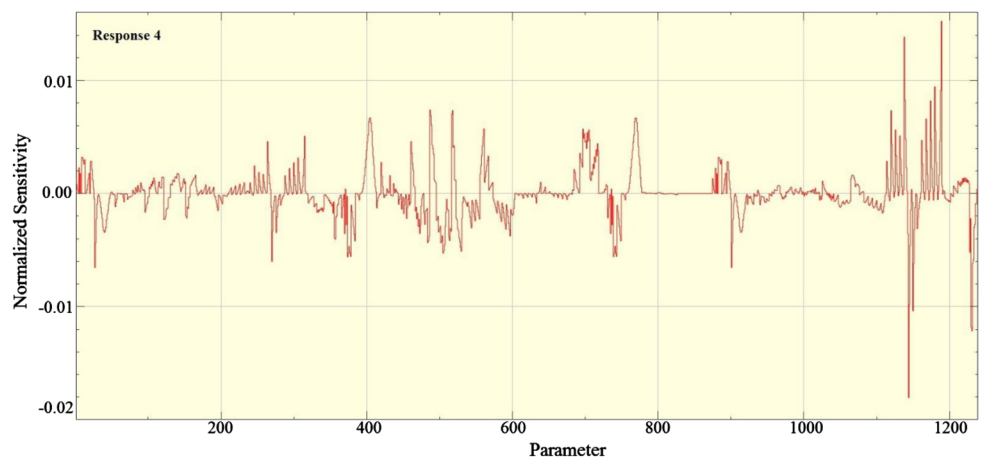


Table 6 Comparison of the first two natural frequencies before and after model updating

Mode number	OMA frequency (Hz)	FEM before		FEM after		MAC before (%)	MAC after (%)
		Frequency (Hz)	Error (%)	Frequency (Hz)	Error (%)		
1	14.88	13.1	-11.96	14.30	-3.90	86.4	83.4
2	23.01	21.86	-4.99	23.25	1.04	74	74

resolved this. For illustration purposes, the view at the particular boundary is shown in Fig. 11(left) while Fig. 11 (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 can be seen as acceptable considering the complexities of the structure’s boundary conditions and the limited number of sensors used for measurement. A reason for the lack of 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 (refer Fig. 9 and Fig. 10) for the mode shapes. The results can be further improved by conducting automated model updating after successful manual model tuning of the initial FEM [4, 7, 10]. However, since the main purpose of this case is to focus only on some aspects of manual model updating, further improvement of the FEM through automated model updating is beyond the scope of the case study.

Fig. 11 View at the boundary and the extruded view of the updated SAP model

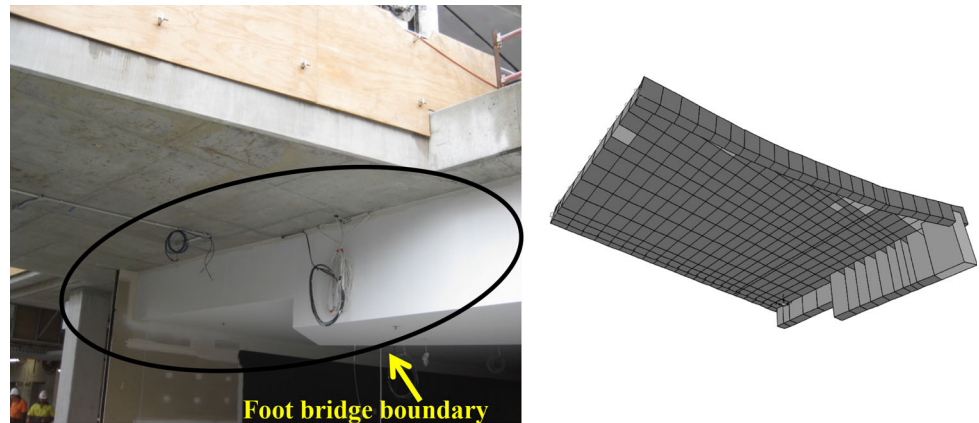


Table 7 Parameter changes before and after model updating

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	1500	300
349	375	1500	300
343	375	1500	300
337	375	1500	300
283	375	1500	300
331	375	1500	300
325	375	1500	300
319	375	1500	300
406	375	1500	300
405	375	1500	300

4 Conclusions

The model updating procedure has been successfully carried out for two case studies which treated relatively inflexible structures, the P block and the foot bridge at the Queensland University of Technology, Brisbane. These case studies show that it is possible to accomplish effective model updating techniques for real civil engineering structures but greater care needs to be taken when dealing with complex concrete structures not only in automated model updating but also in manual model updating applications. On one hand, even though automated model updating is efficient in real civil structure applications, the first case study herein showed that it is necessary to develop sufficiently detailed initial FEMs to obtain satisfactory correlation using automated model updating of

medium-rise inflexible building structures. In addition, it was shown that how parameter groups based on element types (such as columns) and reasonable upper/lower limits based on engineering judgement (such as 30 % for slab thickness and 15 % for other tuning factors herein) should be introduced onto the tuning parameters to maintain the physical relevance of the updated FEMs. On the other hand, the second case study highlighted the importance of considering the external structural components in the vicinity of the main structure when conducting manual model updating of inflexible structures such as short-span concrete bridges. The advantage of manual model updating is that a significant change can be made for certain elements if it is physically meaningful and justifiable, which is very useful in dealing with complex local conditions as demonstrated in the second case study.

References

- Liu Y, Li Y, Wang D, Zhang S (2014) Model updating of complex structures using the combination of component mode synthesis and Kriging predictor. *Sci World J* 2014:476219
- Jaishi B, Ren WX (2005) Structural finite element model updating using ambient vibration test results. *J Struct Eng* 131(4):617–628
- Brownjohn JM, Xia PQ (2000) Dynamic assessment of curved cable-stayed bridge by model updating. *J Struct Eng* 126(2):252–260
- Živanović S, Pavić A, Reynolds P (2007) Finite element modelling and updating of a lively footbridge: the complete process. *J Sound Vib* 301(1):126–145
- Zhang Q, Chang T, Chang C (2001) Finite-element model updating for the Kap Shui Mun cable-stayed bridge. *J Bridge Eng* 6(4):285–293
- Brownjohn JMW, Moyo P, Omenzetter P, Lu Y (2003) Assessment of highway bridge upgrading by dynamic testing and finite-element model updating. *J Bridge Eng* 8(3):162–172
- Park W, Kim HK, Jongchil P (2012) Finite element model updating for a cable-stayed bridge using manual tuning and sensitivity-based optimization. *Struct Eng Int* 22(1):14–19

8. Kim JT, Ho DD, Nguyen KD, Hong DS, Shin SW, Yun CB, Shinozuka M (2013) System identification of a cable-stayed bridge using vibration responses measured by a wireless sensor network. *Smart Struct Syst* 11(5):533–553
9. Cismaşiu C, Narciso AC, Amarante dos Santos FP (2015) Experimental dynamic characterization and finite-element updating of a footbridge structure. *J Perform Constr Facil* 29(4):04014116. doi:10.1061/(asce)cf.1943-5509.0000615
10. Daniell WE, Macdonald JH (2007) Improved finite element modelling of a cable-stayed bridge through systematic manual tuning. *Eng Struct* 29(3):358–371
11. Lord JF (2003) Model Updating of a 48-storey Building in Vancouver Using Ambient Vibration Measurements. Doctoral dissertation, University of British Columbia
12. Ventura C, Lord J, Turek M, Brincker R, Andersen P, Dascotte E FEM updating of tall buildings using ambient vibration data. In: *Proceedings of the Sixth European Conference on Structural Dynamics (EURODYN)*, 2005, pp 4–7
13. FEMtools UM (2012) FEMtools Dynamic Design Solutions N.V. (DDS)
14. Nguyen T, Chan THT, Thambiratnam DP (2014) Field validation of controlled Monte Carlo data generation for statistical damage identification employing Mahalanobis squared distance. *Struct Health Monit* 13(4):473–488
15. Nguyen T, Chan THT, Thambiratnam DP, King L (2015) Development of a cost-effective and flexible vibration DAQ system for long-term continuous structural health monitoring. *Mech Syst Signal Process* 64–65:313–324
16. Nguyen T, Chan THT, Thambiratnam DP (2014) Effects of wireless sensor network uncertainties on output-only modal-based damage identification. *Aust J Struct Eng* 15(1):15
17. Nguyen T, Chan THT, Thambiratnam DP (2014) Effects of wireless sensor network uncertainties on output-only modal analysis employing merged data of multiple tests. *Adv Struct Eng* 17(3):319–330
18. Computers & structures Inc. (2014) Integrated software for structural analysis & design, computers & structures, Inc., Berkeley, California, USA, V. 15.2.0
19. Brownjohn JM, Xia P (1999) Finite element model updating of a damaged structure. In: *Society for experimental mechanics, Inc., 17th international modal analysis conference*, pp 457–462
20. Structural Vibration Solutions A/S (2011) SVS-ARTEMIS Extractor-Release 5.3, User's manual. Aalborg-Denmark