Finite element model updating of tall buildings with a computer-aided model updating system (CAMUS)

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SUMMARY

Dynamic behaviour is one of the most important design considerations for tall buildings; natural frequencies and corresponding mode shapes are basic data for seismic and wind response analyses. The results of the analysis and design depend very much on the quality of the three-dimensional (3-D) finite element model developed. Comparison of natural modes of the mathematical analysis with those of field measurements is the most widely used approach to assess the credibility of the mathematical model. Finite element model updating of tall buildings, a very time consuming procedure to achieve the credible model, has rarely been studied before.

Different from the most popular model updating approaches which are based on sensitivity analysis techniques, this paper presents an attempt of finite element model updating of tall buildings with a computer aided model updating system (CAMUS). After investigating knowledge and experiences of model updating techniques and finite element modelling of tall buildings, a knowledge-based system was developed to implement finite element model updating of tall buildings. Based on the correlation analysis results of natural frequency that are stored in the knowledge base, the system searches the most likely modelling error in the model over the knowledge base of possible problems (experience on model updating) and guides the user to update the model. The performance of the algorithm was demonstrated with an application of finite element model updating of a 66-storey frame-core wall office tower.

KEY WORDS: structural dynamics; tall building; finite element modelling; model updating; structural analysis; knowledge-based system

1 INTRODUCTION

Three-dimensional (3-D) finite element (FE) modelling is widely accepted technique to carry out structural dynamic analysis and design of tall buildings. The accuracy of finite element analysis (FEA) results is strongly dependent on the accuracy of a 3-D FE model developed by analysts.

FE modelling is so powerful that its limitations are often ignored by users. It should be remembered that the assumptions and theory of FE method are not universally applicable [1]. User errors, such as supplying the program with the wrong data, are far more likely causes of incorrect FEA results. Ellis and Littler [2] used a number of experimental measurements to check the accuracy of methods for predicting natural frequencies and damping in buildings. Their general conclusion was that theoretical predictions were likely to involve considerable errors. Ewins and Imregun [3] presented a comparison of FE results produced by 12 analysts working independently with six commercial FE packages. The results from the independent analysts were identified to differ significantly from each other and from the experimental modal data. It was suggested that, for major structures, the design calculation should be verified using experimental measurements when the structure was complete.

Such experimental validation is easiest to perform using data provided by 'ambient vibration survey' and recent years have seen rapid development in technology of 'output only' modal analysis [4] which should lead to more applications for correlating test data with analysis. In the last decade, a few researchers [5, 6, 7] have studied the correlation analysis between experimental data and finite element model analysis of several high-rise buildings. Recently, a similar work on investigation of the dynamic characteristics of a 79 storeys super-tall building was presented by Li and Wu [8].One of the typical studies on correlating dynamic characteristics between FEA and EMA was given by Brownjohn et al. [11]. Using the concept of lumped masses and rigid floor slabs, six mathematical models were built using a popular PC based FE program to model a frame-core wall structural system These models were analyzed to obtain the first nine mode shapes and their natural frequencies which were compared with those from field measurements, using numerical correlation indicators. Several factors important to correctly model the structural system of a tall building were presented and discussed. It was indicated that comparison or correlation analysis of dynamic properties such as modal frequency and mode shapes between FEA and experimental modal analysis (EMA) is essential to judge the structural performance of the developed model. At the mean time, the study for a knowledge-based system on finite element model updating of tall buildings was proposed. A rare case on finite element model updating of buildings was described by Ventural et al. [12]. The output-only modal identification results obtained from ambient vibration measurements of a 15-storey reinforced concrete shear core building were used to update a finite element model of the structure.

Previous researches on model updating are mainly limited to mechanical engineering systems or small-scale building structures. However, FE model updating of tall buildings is different from traditional model updating.

From 1960s to 1970s, many researchers conducted theoretical research on system identification. The relationship between the modal characteristics and the structural parameters was studied using eigenvalue and eigenvector partial derivative matrices. The statistical identification method was utilized by Collins et al. (1974) [13] to modify stiffness and mass characteristics of a FE model of the Saturn 5 space vehicle, systematically using experimental measurements of the natural frequencies and mode shapes of a structure.

Synthesizing the research work on sensitivity analysis [14], correlation analysis [15,16], measurement selection and parameter uncertainties [17], an automatic mathematical model updating program SYSTUNE was developed by Dascotte et al. (1989) [18]. The general procedure of this program was described and several applications of FE model updating with experimental data were introduced by Dascotte (1991) [19]. This program was developed into FEMtools, a practical commercial software package by Dynamic Design Solutions in Leuven, Belgium (1997) [20]. In this package, exchanges of analytical and experimental data with external database are accomplished by interface programs and a neutral file system. The whole procedure for FE model updating is divided into four modules: pretest analysis, correlation analysis and error localization, sensitivity analysis, and model updating.

Wright Laboratory is another major research centre contributing to FE model updating research. Using vector optimization techniques and a weighted performance ranking system, the updating process was applied to a T-38 horizontal stabilizer [21]. This vector optimization technique was combined with sensitivity analysis [22] so that an automated structural optimization system (ASTROS) was developed in 1990 to implement FE model updating. Then the work was extended by Gibson [23] and Cobb et al. (1996) [24].

The common feature of the above three major approaches is based on sensitivity analysis to carry out the adjustment of structural parameters, such as elemental material or geometrical properties and nodal properties like spring stiffness, boundary conditions and lumped mass values. These approaches were called by the author as methods of micro model updating [25]. Practically, it is well known that an engineer with rich knowledge on structural concepts and many years of experience on FE model updating can finish the work more efficiently and quickly than a junior engineer can. The investigation indicates that the procedure of model updating is normally conducted by adding crucial structural members or removing secondary ones from the model. This kind of procedure is complicated and crucial to the success of FE model updating. It depends very much on the engineer's knowledge and experience of the model and task domain that is a knowledge-based system and unable to be expressed in mathematical formulations. In contrast to the traditional model updating approaches, methods of micro model updating, such model updating approaches are called as methods of macro model updating that require the assistance of a computer aided model updating system. Unfortunately, no work has been reported about the macro model updating of FE models at the present except the one described here.

In the areas of economics and finance, Freedman and Stuzin [26] describe such a methodology, called knowledge-based tuning, that allows a human analyst and a knowledge-based system to collaborate in adjusting an analytic model. In knowledge-based tuning, subjective judgements about missing factors are specified by the analyst in terms of linguistic variables. These linguistic variables and knowledge of the model error history are used by the tuning system to infer a specific model adjustment. A logic programming system was developed that illustrates the tuning methodology for a macro-econometric forecasting model that empirically demonstrates how the predictability of the model can be improved.

Deng (2001) [27] investigated the knowledge and experience on finite element modelling of tall buildings and developed a computer-aided model updating system (CAMUS) to implement finite element model updating of tall buildings. The paper reported here presents part of the work that has been done by Deng and Brownjohn.

2 METHODS OF FINITE ELEMENT MODEL UPDATING

2.1 Overview

Finite element model updating has emerged in the 1990s as a subject of immense importance for the design, construction, and maintenance of mechanical systems and civil engineering structures. However, this subject has rarely been applied in tall buildings. The aim of model updating in structural dynamics is to generate improved numerical models, which may be applied in order to obtain predictions for alternative loading arrangements and modified structural configurations.

The last few years have seen considerable growth in the various techniques available for correlation and model updating. A comprehensive survey on model updating has been conducted by Mottershead and Friswell [28], who also provide detailed procedures [29]. All methods developed during the past thirty years are categorised by them into two methods. One is called 'direct' method. This method is capable of replicating the measured natural frequencies and mode shapes at one step, but the major drawback is that the changes to the mass and stiffness matrices brought about by updating are seldom physically meaningful. The other one is based on eigenvalue and eigenvector sensitivities. This method allows a wide choice of parameters to be updated and both the measured data and the initial analytical parameter estimates may be weighted.

There are two problems to be considered for the present techniques of model updating.

(1) In many cases, the success of the updating procedure will strongly depend on the judgement of possible error localisation and the selection of design parameters to be updated. How to make the choice needs intelligent considerations and practical experiences. For existing methods of model updating, the most important choices can only be achieved by experienced researchers and not by numerical analysts. The need to collect and utilise these experiences has been recognised for a few years, but no such research has been reported at the time of working. This is one objective for the system to be developed.

On the other hand, there have been some commercially available software tools, such as FEMtools, which provide a semi-automatic updating capability. These tools program the procedures of model updating and do provide a significant saving in computational and man time over the traditional manual techniques. However, the crucial process of error localisation and parameter selection can no more be resolved than with traditional techniques.

(2) With current techniques, it is impossible to improve the model with respect to uncertain data, which are not included in the model [30]. Such uncertain data are caused by erroneous model parameters and errors due to physical effects [31]. These errors can only be recognised by experimental investigation of the real structure.

It was pointed out that [28] the problem of identifying a parametric model involves first determining the most appropriate specific mathematical structure, and guidance needs to be provided in the preparation of finite elements meshes for updating. It is assumed that the initial model is fixed with respect to the mesh configuration, boundary conditions and type of element during the whole procedures of model updating. However, for large models with tens of thousands of degrees of freedom, for example a tall building, the initial model is frequently updated by adding, removing, or refining mesh elements according to physical insight and engineering judgements.

In order to explain the lack of correlation between numerical analysis and field measurements, it is necessary to consider the likely causes of inaccuracy in numerical models. It should be mentioned that while experimental measurements are not taken without error, it is assumed here that the measured data are correct. There are three commonly encountered forms of model errors which may lead to inaccuracy in the model predictions:

(1) Model structure errors, which are liable to occur when there is uncertainty concerning the governing physical equations—such errors might occur typically in the modelling of strongly non-linear behaviour in certain engineering systems.

(2) Model order errors, which arise in the discretizations of complex systems and can result in a model of insufficient order—the model order may be considered to be a part of the model structure.

(3) Model parameter errors, which would typically include the application of inappropriate boundary conditions and inaccurate assumptions used in order to simplify the model.

Table 1 Relationship between model errors and model problems

	Model Errors	**Model Problems**
1	Model structural errors	The governing physical equations
2	Model order errors	The discretizations of complex systems
3	Model parameter errors	Boundary conditions, assumptions used

Table 1 summarises the model errors and corresponding model problems when finite element analysis results are not consistent with experiment mode analysis results. The traditional model updating approaches based on sensitivity analysis techniques can be applied to locate the model parameter errors and solve the model problems by updating the model parameters selected, such as elastic modulus and structural mass. However, a computer-aided model updating system, or a knowledge- based system (KBS), is possible to locate both the model order errors and the model parameter errors by providing physical insight and engineering judgements on model updating.

The general model updating procedures are illustrated in Figure 1 as shown below. In this figure, the model updating procedures are divided into two phases. The model updating approaches based on KBS is termed as macro model updating and the other one based on sensitivity analysis techniques is termed as micro model updating. The major differences between these two model updating approaches are listed. For finite element model updating of tall buildings, most of the model problems can be resolved by the KBS based macro model updating approaches.

Figure 1 Comparison between KBS based model updating and sensitivity analysis based model updating

2.2 Methods of micro model updating

The validations of FE models are usually performed by comparing numerical eigendata with natural frequencies and mode shapes obtained from experimental measurements. A general procedure for FE model updating, using experimental modal data, consists of four steps: (1) mode pairing, (2) error localization, (3) correlation analysis and (4) model updating.

The purpose of model updating is to modify the mass, stiffness and damping parameters of the numerical model in order to obtain better agreement between numerical results and test data. The aim is to generate improved numerical models that may be applied to obtain predictions for alternative loading arrangements and modified structural configurations. Model updating based on sensitivity analysis is one of the most popular approaches over the past thirty years.

Sensitivity analysis

Sensitivity coefficients are defined as the rate of change of a particular response quantity *R* with respect to a change in an analysis model property *P*, also referred to as parameter. They are evaluated at a particular state of the parameters. Parameters can be element material or geometrical properties and nodal properties like spring stiffness, boundary conditions and lumped mass properties. Responses can be resonance frequencies and mode shapes.

Two major approaches for the computation of sensitivity coefficients are differential sensitivity analysis method and finite difference sensitivity analysis method.

Differential sensitivities require the derivatives of the element matrices while finite difference sensitivity analysis uses the difference between two states of the element matrices. The type of sensitivity analysis that is available is also depending on the parameter type because, due to increasing computational difficulties, not all parameter types permit differential sensitivity analysis.

A differential sensitivity coefficient is the slope of the response R_i with respect to parameter P_j, computed at a given state of the parameter. When this differential is computed for all selected responses with respect to all selected parameters, the sensitivity matrix [S] is obtained:

$$[S] = S_{ij} = \left[\frac{\delta R_i}{\delta P_j} \right] \tag{1}$$

where:

i : *1* ... *N* Responses

j : *1* ... *M* Parameters

Each row of the sensitivity matrix corresponds with a response R_i, each column with a parameter P_j. The sensitivity matrix is usually a rectangular matrix.

Instead of using differential sensitivities, derivatives can be approximated with a forward finite difference approach. This is done using two finite element analysis (FEA) results for two states of the parameter P_j:

$$\frac{\Delta R_i}{\Delta P_j} = \frac{R_i\left(P_j + \Delta P_j\right) - R_i\left(P_j\right)}{\Delta P_j} \tag{2}$$

Model updating based on sensitivity analysis

The functional relationship between the modal characteristics and the structural parameters can be expressed in terms of a Taylor series expansion limited to the linear term. This relationship can be written as:

$$\{R_e\}=\{R_a\}+[S](\{P_u\}-\{P_o\}) \tag{3}$$

or

$$\{\Delta R\}=[S]\{\Delta P\} \tag{4}$$

Where:

$\{R_e\}$	Vector containing the reference system responses (experimental data).
$\{R_a\}$	Vector containing the predicted system responses for a given state.
$\{P_o\}$	Vector containing the original parameter values.
$\{P_u\}$	Vector containing the updated parameter values.
$[S]$	Sensitivity matrix.

It is to be noted that Eq. (3) implies that responses occur in pairs, i.e. if experimental response is used as reference, then the corresponding analytical response must exist. When resonance frequencies are selected as reference response, this pairing can be done using a mode shape pairing criterion.

Eq. (3) is usually underdetermined and can be solved using a pseudo-inverse (least squares), weighted least squares or Bayesian technique, depending on whether weighting coefficients are added or not. 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.

2.3 Methods of macro model updating

The aim of model updating is to generate improved numerical models that are able to reproduce reliable structural behaviours and able to be applied for static and dynamic structural analysis. Different from the methods of micro model updating that are based on sensitivity analysis techniques, the procedure of the methods of macro model updating that are based on KBS is to match the most likely model problems from the knowledge base according to the identified model order errors and model parameter errors, and then update the model.

As shown in Figure 2, the model errors may be identified by assessing the difference error of structural responses, e.g. natural frequencies and mode shapes, between finite element analysis and experimental modal analysis results. The mode error index is introduced here to assess the model error significance along three mode directions, X, Y and T. The model problems are the collection of likely problems that can be used to improve the model error of structural responses. The mode improvement index is introduced here to explain how a model problem may improve the modelling of structural mass and stiffness along X, Y and T mode directions, and then improve the structural responses.

Figure 2 Pairing criterion between model errors and model problems

Mode error index of structural responses

After mode pairing, it is widely accepted to check the model errors of the finite element model by comparing the structural responses between experimental modes and analytical modes, such as mode shapes and natural frequencies. Therefore, the mode error index is defined as a numerical index showing the difference error of mode responses between finite element analysis and experimental mode analysis, which implies the likely problems of the mass modelling and stiffness modelling.

Table 2 gives a general definition of a three-level mode error index of any structural responses. Similarly, a five-level or seven-level mode error index can also be defined when it is necessary.

Table 2 Definition of mode error index of structural responses

Difference Error of Structural Responses (Δ%)	(-∞, -10]	(-10, 10)	[10, +∞)
Mode Error Index (NumDiff)	-1	0	+1

When tall buildings are studied, the aim is normally to investigate the mode responses via three mode directions, two translation directions (X, Y) and one torsional direction (T). This means that mode error index can be categorized as three types as shown in Table 3. According to the value of mode error index, researchers are guided to search the most likely model problems in the finite element model, which are expected to be able to improve the FE mode analysis results and limit the mode error index within the acceptable level for engineering use.

Table 3 Examples of mode error index definition

Mode Error Index (NumDiff)		
X- direction mode	Y- direction mode	T- direction mode
ModeX.NumDiff	ModeY.NumDiff	ModeT.NumDiff
(-1, 0, +1)	(-1, 0, +1)	(-1, 0, +1)

Mode improvement index of a model problem

The difference error of mode responses shows the numerical variation of the finite element analysis compared with experimental mode analysis and the mode error index indicates the mode improvement direction of the next procedure. Many solutions can be utilized to improve the model and researchers may locate the likely model problem and update the finite element model. The structural responses, e.g. natural frequencies and mode shapes, are direction functions of the stiffness and mass distribution of the structure. Results of the frequency and mode shape calculations may vary significantly depending upon the mass modelling and stiffness modelling. It can be concluded that the model error of a structure modelling is originated from incorrect mass modelling and stiffness modelling.

Identifying the incorrect mass modelling or stiffness modelling in the structure and updating them is the approach commonly used by experienced analysts to improve performance of the structural response. Among the model updating procedure, there are numerous solutions may be applied to improve the structural responses of a structure. Studies indicate that some solutions are applied to update either structural mass or structural stiffness, others applied to update both structural mass and structural stiffness together.

Table 4 Definition of mode improvement index of model problems

Mode Improvement Index					
Problems on structural mass			Problems on structural stiffness		
X- direction	Y- direction	T- direction	X- direction	Y- direction	T- direction
NumMx	NumMy	NumMt	NumIx	NumIy	NumIt
(-1, 0, +1)	(-1, 0, +1)	(-1, 0, +1)	(-1, 0, +1)	(-1, 0, +1)	(-1, 0, +1)

Where:

NumMx, MumMy, NumMt

-1	reduce the structural mass of the model significantly
0	minor effection to the structural mass of the model
+1	increase the structural mass of the model significantly

NumIx, NumIy, NumIt

-1	increase the structural stiffness of the model significantly
0	minor effection to the structural stiffness of the model
+1	reduce the structural stiffness of the model significantly

In this study, the mode improvement index was defined to justify how a solution changes the structural mass and stiffness modelling along X, Y and T mode directions. As a result, for each likely model problem, there are six mode improvement indices which are given in Table 4. The stiffness indices *NumIx*, *NumIy* and *NumIt* are the indices indicating the influence of the problem to the stiffness of the model along X-, Y- and T-direction, respectively. The mass indices *NumMx, NumMy*, and *NumMt* are the indices indicating the influence of the problem to the translational mass along X- and Y-direction, and the torsional mass (or mass moments of inertia), respectively. It can be seen that the mode improvement index is defined as three-level values similar to the definition of mode error index.

Pairing criterion between model error index and mode improvement index

Many solutions may exist in the model updating procedure. The first solution is the one that can improve all modes (X, Y, and T) together. Once such a solution, which may not exist in the model, is identified, a FE model can be updated most efficiently. The second solution is the one that can improve some modes (XY, YT or XT) together. If both the first and the second solution cannot be obtained in the model updating procedure, the last option is to identify the one that can improve one mode (X, Y, or T) at one time.

Model updating experience shows that it is unusual to consider improving all modes simultaneously. Instead, the practical model updating procedure is most likely to consider three mode directions, X, Y and T, separately. Among the modes in each direction of X, Y and T, the mode with the maximum absolute difference error of natural frequency could be focused for improvement first. These three modes with the maximum absolute difference error of natural frequency can be named as *ModeMaxDiffX*, *ModeMaxDiffY*, and *ModeMaxDiffT*. In another words, it is possible to identify the solution that can improve *ModeMaxDiffX*, *ModeMaxDiffY*, and *ModeMaxDiffT* at the same time, two of them, or any one of them.

Table 5 gives the relationship between model error index of structural responses and mode improvement index of model problems. From this table, it can be seen that the first solution is to search and collect ProblemsXYT; the second solution is to search and collect any one from ProblemsXY, ProblemsYT, and ProblemsXT; the last solution is to search and collect any one from ProblemsX, ProblemsY, and ProblemsT.

Table 5 Conditions of collecting problems of three focusing modes

OBJECT	Conditions of Collecting Problems
ProblemsX	ConditionX
ProblemsY	ConditionY
ProblemsT	ConditionT
ProblemsXY	(ConditionX AND ConditionY)
ProblemsYT	(ConditionY AND ConditionT)
ProblemsTX	(ConditionT AND ConditionX)
ProblemsXYT	(ConditionX AND ConditionY AND ConditionT)

ConditionX	*(ModeMaxDiffX.NumDiff = (Problem.NumIx OR Problem.NumMx))*
ConditionY	*(ModeMaxDiffY.NumDiff = (Problem.NumIy OR Problem.NumMy))*
ConditionT	*(ModeMaxDiffT.NumDiff = (Problem.NumIt OR Problem.NumMt))*

3 IMPLEMENTATION OF CAMUS

A knowledge-based system involves techniques of representing human knowledge, and methods of reasoning toward the solution of problems. Each knowledge-based system consists of two principal parts: the knowledge representation and the knowledge inference. In this study, the knowledge-based system was developed on the platform of *the Intelligent Rules Element* [32], a general purpose knowledge-based application development tool. *The Intelligent Rules Elements* provides a friendly graphical user interface to create a knowledge-based application, a rich set of data structures to represent the domain knowledge and a powerful inference engine to complete tasks in the domain. *The Rules Element* is also a hybrid tool, which means it integrates *rules* and *objects* as well as many additional features.

In this system, the domain knowledge (knowledge base) of the finite element model, natural frequency, and experiences on model updating is represented with *Objects*. The procedure of problems locating and model updating is represented with *Rules*, which reason over the domain knowledge.

Based on the correlation analysis results of natural frequency that are stored in the knowledge base, the system searches the most likely problem over the knowledge base of possible problems and guides the user to update the model. Some external applications, such as finite element analysis program (SAP2000), modal assurance criterion (MAC) analysis and mode pairing program, etc., are embedded in the system. As the result, a graphical user interface was developed to make this system easier to use. Figure 3 shows the algorithm of macro model updating with a knowledge-based system.

Figure 3 Algorithm of computer-aided model updating system (CAMUS)

Starting from an original model file or an updated model file, eigenvector analysis determines the undamped free-vibration mode shapes and frequencies of the system. The modal assurance criterion (MAC) analysis between FEA and EMA is implemented by analyzing two output files of mode shapes, which are extracted from for FEA and EMA results. Based on the results of MAC analysis and confirmed with the visual mode shape inspection results, two groups of mode shape are auto-matched and so are two groups of natural frequencies.

A FE model is the assembly of mass matrices and stiffness matrices. The nodal elements, frame elements and shell elements are extracted from the source file of the model and stored into the knowledge base of a FE model. Paired mode shapes and natural frequencies are retrieved to form the knowledge base of natural frequency. Experts with years of modelling experience not only know how to represent structural components with suitable finite elements, but also know how to locate possible modelling problems. Engineering judgements show that lower fundamental natural frequencies indicate structural stiffness underestimated or structural mass overestimated; higher natural frequencies indicated that structural stiffness overestimated or structural mass underestimated. Modelling experience and engineering judgements are translated and stored into the knowledge base of possible problems.

In the module of correlation analysis of natural frequency, the difference errors of natural frequency (D_f) for all paired modes between FEA and EMA are calculated. All paired modes are ranked by their absolute difference errors ($AbsD_f$) and grouped by mode directions X, Y and T. As the result, the model error indices of three modes with the maximum absolute difference errors along X, Y, and T directions are determined.

Searching for possible problems is the key part of utilizing the knowledge bases and inferring the best solutions. By pairing the mode error index of structural responses, natural frequency, with the mode improvement index (stiffness and mass index) of problems, the system identify the most likely problem in a FE model and provide suggestions on finite element model updating of tall buildings.

Finally, the update criteria are tested and the feasibility of the updating method is verified. When a FE model needs updating and the updating method is feasible, users go back to external FEA programs and implement the model updating, or update the model parameters stored in the KB of a FE model which may be output and transferred into the source codes recognized by FEA programs..

4 APPLICATION TO THE MODEL UPDATING OF A TALL BUILDING

4.1 Structural systems of republic plaza

The structural system presented here is the 280m, sixty-six storey Republic Plaza tower, one of the three tallest buildings in Singapore. The tower has a frame-tube structural system with an internal core wall connected to a ring of external columns by horizontal steel framing system at every floor. The reinforced concrete (RC) central core wall has a plan area of 21.5m by 22.65m and extends almost the full height of the building. Except for the top few levels, the core wall varies in thickness from 600mm to 400mm and contains a RC core slab at every level. Figure 4 shows the layout of the typical floor plan at level 18, and a perspective view of this building is shown in Figure 5.

Figure 4 Typical cross section at level 18

Figure 5 Perspective view of completed building

Much of the core is taken up by the numerous lift shafts. Note that a set of low rise (LR) lifts reaches only to the 35th floor, above which the core is open at that side from 37th floor upwards, while other lifts extend to the highest floors.

The perimeter of the building comprises eight large steel tube columns with diameters up to 1.22m diameter and eight smaller columns, up to 1.02m diameter. These columns reduce in diameter at higher floors and up to the 49th level are filled with concrete. Up to level 62 the perimeter lies in a square with dimension 45m and has two tapering sections between levels 20 and 27 and between levels 44 and 46. Two mechanical equipment floors are located at levels 28 and 47 above the tapering sections and have twice the normal storey height of 3.95m. Outriggers were installed on these two levels to enhance the rigidity of the building frame under lateral loads. The connections of the outrigger systems were not made until the building was completed to avoid introducing dead loads into the bracing.

The horizontal framing system has moment resisting connections at the beam-column joints while the beam to core connections are simply pinned. The column bases are bolted to the foundation at basement level B1 where they sit on a deep and very stiff foundation system. The foundation system comprises six inner caissons founded up to 62m deep in boulder clay and connected by a 5.5m thick concrete mat, and eight exterior caissons founded up to 40m deep and linked by deep transfer beams. All caissons are 5m in diameter.

Experimental modal analysis

An ambient vibration test (AVT) of Republic Plaza was conducted in late 1995 just after the structural system of the building was completed but before fitting out for tenants and installation of various non-structural elements [33].

The twelve natural frequencies (in Hz) averaged over all the measurements are summarised in Table 6. It should be noted that for modes X1-X4, they are the mixture modes of X-direction and torsion but dominated by translation in X-direction. For modes T1-T4, they are the mixture modes of X-direction and torsion too, but dominated by torsional direction.

Table 6 Translational and torsional mode frequencies for unoccupied building

	Frequency/Hz

Mode	X-direction		Y-direction		Torsion	
1	X1	0.191	Y1	0.199	T1	0.566
2	X2	0.703	Y2	0.746	T2	1.340
3	X3	1.550	Y3	1.730	T3	2.310
4	X4	2.483	Y4	3.011	T4	3.330

Smoothed vertical plane mode shapes for modes Xl, X2, X3, Y1, Y2 and Y3 are shown together in Figure 6. For X direction modes the ordinates are components of building motion measured in the X direction ($\theta = 90^\circ$) at the same position with respect to the core wall (location 1, Figure 4) on various levels in the building. For Y direction modes the ordinates are for components at $\theta = 0^\circ$.

Figure 6 (a) Translational mode shapes from field measurements (b) Torsional modes determined from AVT.

Torsional mode shapes are shown in Figure 6b. These are the components of translation ϕ_X, ϕ_Y measured in the X- and Y-directions at location 1 in Figure 4 with respect to the building centreline. .

4.2 Finite element models and updated results

Background of the original model

FE models were based on the structural drawings and other information that was provided by the architect and the contractor. In addition, the contractor provided a detailed record of the actual masses of core wall, columns, core slab, office slab, curtain wall, and several water tanks at each storey during the construction period.

The original model was developed by two final year students [34]. By lumping masses at a FE model nodes and assuming rigid floor slabs, the personal computer based finite element (FE) code SAP2000 was used to model the frame-core wall system of the building. Masses of the n^{th} node/floor were determined as the sum of masses of core slab, office slab, and large water tanks at the n^{th} floor, and the averaged mass of core wall, columns and curtain wall between the $(n-1)^{th}$ and n^{th} storey. The mass moments of inertia about the z-axes were determined as the sum of those separate mass moments of inertia about the z-axis. At basement level the core is assumed to be fully fixed to the foundation, but the columns are assumed to be pinned.

A sequence of five cumulatively changing FE models are presented in the remainder of this section and they are described one by one to illustrate the significance of the methods of macro model updating with a computer-aided model updating system.

RP1 -Model with closed core wall and frames

Figure 7a shows the original model with a closed core wall and framing system. The core walls as shown in Figure 7b are modelled as shell elements without considering any openings, taking the Young's modulus *E* as $34 KN/mm^2$ for the grade 50 concrete used. From level 1 to level 39, the thickness of the shell elements is set as 600mm and at higher levels the thickness is taken as 400mm. All columns and main beams are modelled as steel frames. As secondary horizontal floor beams are believed to contribute little to the stiffness of the entire structural system, they are omitted from the framing system in order to simplify the model.

Figure 7 (a) RP1 with the closed core wall and framing system (b) the core wall component of RP1

In the numerical modal analysis, eighteen modes of FEA were produced to pair nine modes of EMA. The correlation analysis results and pairing of natural frequencies between nine paired modes of RP1 and EMA are shown in Table 7. Three modes with the maximum absolute difference error along directions X, Y, and T and their mode error indices are listed in Table 8. The three values in the 5th column of Table 8 are positive one (+1) meaning that the stiffness of RP1 along all three directions X, Y and T are stronger than expected and need to be reduced.

Table 7 Pair of frequencies between RP1 and EMA

Mode	Direction	f_{EMA} (Hz)	f_{FEA} (Hz)	MAC (%)	D_f (%)	AbsD_f (%)	Rank
1	X1	0.191	0.184	99.9	-4	4	9
2	Y1	0.199	0.192	99.7	-4	4	8
5	T1	0.566	1.182	99.4	109	109	3
3	X2	0.703	0.864	98.3	23	23	6
4	Y2	0.746	0.899	99.0	21	21	7
8	T2	1.340	3.026	95.3	126	126	1
6	X3	1.550	2.080	87.8	34	34	4
7	Y3	1.730	2.163	99.1	25	25	5
11	T3	2.310	4.988	83.3	116	116	2

Table 8 Three modes being focused in RP1

ModeMaxDiff	Mode	Direction	D_f	NumDiff
ModeMaxDiffX	6	X3	34%	+1
ModeMaxDiffY	7	Y3	25%	+1
ModeMaxDiffT	8	T2	126%	+1

In the Module of searching for problems, about thirty problems were correlated from the KB of possible problems and the most likely problem with the maximum weighting was *OWOpenXYL*. The definition of *OWOpenXYL* is the openings on outside walls along X- and Y- directions should be fewer or smaller than those in the current model. The model improvement indices of the problem *OWOpenXYL* are listed in Table 9. Three stiffness indices are positive one (+1) and it means the problem *OWOpenXYL* can reduce the modal stiffness of the model along X-, Y- and T-direction at the same time.

Table 9 Mode improvement index of the problem OWOpenXYL

Problem	NumIx	NumIy	NumIt	NumMx	NumMy	NumMt

OWOpenXYL	+1	+1	+1	0	0	0

A close inspection of the values in Table 8 and Table 9 may verify the pairing criterion between model error index and mode improvement index that is given in Table 5. The message file *OWOpenXYL.txt* of the problem explained that some major openings and secondary openings along X- and Y-directions were missing or not large enough. The major opening and vertical rows of secondary openings on the core wall might significantly weaken the torsional rigidity of the closed core wall. Under this guidance, it was found that the major opening along X direction from 38th to the top was not represented in the original model. Hence, the major opening was removed from RP1 to form RP2.

It should be noted that the difference error of *ModeMaxDiffT* in Table 8 is 126% which has the physical meaning of too high torsional rigidity in RP1. However, in order to start from simple experiences, three-level indices (-1,0,+1) are applied in this system. All difference errors of natural frequency above 10% are indexed as positive one (+1). The advantage of such definition is to shorten the study periods and the disadvantage is losing the difference between higher error and lower error. Setting five-level or seven level indices can improve the system and fewer problems will be correlated while searching for problems.

RP2 -Model with major openings and frames

RP2 is developed from RP1 by removing material for the major openings (10.9 m wide) from level 38 upwards as shown in the core wall, Figure 8. All the shell elements between the openings on the different levels with major openings are removed.

Figure 8 The core wall component with major openings of RP2

Since the structure is symmetric in the Y-direction, EMA modes Y1, Y2, and Y3 are almost translational, while the remaining modes X1, T1, X2, T2, X3, and T3 are neither purely translational nor purely torsional. Modes X1, X2 and X3 are mainly lateral motion with a degree of torsion that increases with mode number, while modes T1, T2, and T3 are mainly torsional motion. This feature makes it very difficult to implement model pairing between FEA modes and EMA modes. However, this problem was solved in this knowledge-based system by introducing the module of MAC analysis and mode pairing.

The correlation analysis results and pairing of natural frequencies between nine paired modes of RP2 and EMA are shown in Table 10.

Table 10 Pair of frequencies between RP2 and EMA

Mode	**Direction**	**f_{EMA} (Hz)**	**f_{FEA} (Hz)**	**MAC (%)**	**D_f (%)**	**AbsD_f (%)**	**Rank**
1	X1	0.191	0.179	99.8	-6	6	7
2	Y1	0.199	0.191	99.7	-4	4	8
3	T1	0.566	0.550	69.2	-3	3	9
5	X2	0.703	0.980	96.2	39	39	1
4	Y2	0.746	0.852	98.2	14	14	4
6	T2	1.340	1.459	48.6	9	9	6
7	X3	1.550	1.864	81.2	20	20	2
8	Y3	1.730	2.029	97.3	17	17	3
9	T3	2.310	2.606	68.3	13	13	5

Three modes with the maximum absolute difference error along directions X, Y, and T and their indices of difference error are listed in Table 11. Comparing the difference error values of the natural frequencies in the 4th column of Table 11 against those in Table 8, it clearly shows the mode improvement by locating the problem of OWOpenXYL and updating the model from RP1 to RP2. On the other hand, all of the three mode error indices in Table 11 are still positive one (+1), which means the stiffness of RP2 along X-, Y- and T-directions are still higher than expected and need to be reduced further.

Table 11 Three modes being focused in RP2

ModeMaxDiff	Mode	Direction	D_f	NumDiff
ModeMaxDiffX	5	X2	39%	+1
ModeMaxDiffY	8	Y3	17%	+1
ModeMaxDiffT	9	T3	13%	+1

In the Module of searching problems, the most likely problem identified with the maximum weighting was *OWOpenXYL* again. The KB of possible problems shows its mode improvement index as same as that listed in Table 9. The meanings of three stiffness and mass indices are the same as those explained in RP1. It can be explained that this problem can be used to reduce translational stiffness of the model along X- and Y-directions, and torsional stiffness of the model as well, with little contribution to translational mass (X- and Y-directions) and torsional mass.

Note that the aim of identifying such a problem is not to locate a specific parameter to be updated in a 3-D FE model, but to give subjective and clear guidance on likely problems. This is the concept of macro model updating of tall buildings with engineering judgements and experiences.

Different from missing major openings in the RP1, in this iteration, five columns of secondary openings along X- and Y-directions were identified in the real building but not modelled in RP2. The five columns of secondary openings were removed from RP2 to form RP3.

RP3 -Model with major openings and secondary openings

In the real building, the core walls are usually perforated by the vertical lines of secondary openings that are required for doors and corridors, and which result in coupled shear walls. In model RP3 the coupled core walls are modelled by incorporating vertical lines of secondary openings as shown in Figure 9.

For every level, a standard opening 3.2m wide and 3.25m high is located in the middle of north side of each storey. In the north-west and north-east corners of the core wall, two smaller openings are used to approximate door spaces at each storey. In the south-west and south-east corners of the core wall, there are two additional standard openings from level 1 through level 37. For the convenience of modelling, and due to location of nodal points, these openings are all set as 2.65m wide and 3.25m high and the shell elements located at these locations are removed. Triangular and trapezoidal shell elements are used as transitions to rectangular shell elements.

Figure 9 The core wall component with major opening and secondary openings of RP3

Table 12 shows the correlation analysis results and pairing of natural frequencies between nine paired modes of RP3 and EMA. Three modes with the maximum absolute difference error along directions X, Y, and T and their mode error indices are listed in Table 13. All difference errors of natural frequency in the table are below negative 10%. Hence, three values in the 5th column of Table 13 are negative one (-1) meaning that the stiffness of RP3 along three directions X, Y and T are softer than expected and need to be enhanced.

Table 12 Pair of frequencies between RP3 and EMA

Mode	Direction	f_{EMA} (Hz)	f_{FEA} (Hz)	MAC (%)	D_f (%)	AbsD_f (%)	Rank
1	X1	0.191	0.161	99.9	-16	16	3
2	Y1	0.199	0.179	99.8	-10	10	6
3	T1	0.566	0.464	84.5	-18	18	2
5	X2	0.703	0.782	97.0	11	11	5
4	Y2	0.746	0.774	99.0	4	4	8
6	T2	1.340	1.005	81.4	-25	25	1
7	X3	1.550	1.524	91.2	-2	2	9
8	Y3	1.730	1.798	99.0	4	4	7
9	T3	2.310	1.990	89.0	-14	14	4

Table 13 Three modes being focused in RP3

ModeMaxDiff	Mode	Direction	D_f	NumDiff
ModeMaxDiffX	1	X1	-16%	-1
ModeMaxDiffY	2	Y1	-10%	-1
ModeMaxDiffT	6	T2	-25%	-1

In the Module of searching problems, many problems were matched in the KB of possible problems by the system, but they were not identified in RP3 before the problem *ORXYMiss* was identified in RP3. The problem *ORXYMiss* means outriggers along X- and Y-directions in the model may be missing.

The KB of possible problems shows its mode improvement index as listed in Table 14. The stiffness indices *NumIx* and *NumIy* are (-1) which means adding outriggers can lead to enhance translational stiffness of the model along X- and Y-directions. The stiffness index NumIt is (0) indicating this problem has little influence to the torsional rigidity of the model. The other three mass indices *NumMx*, *NumMy* and *NumMt* are (0) means the mass of outriggers have little contribution to translational mass along X- and Y-direction, and torsional mass.

Table 14 Mode improvement index of the problem ORXYMiss

Problem	NumIx	NumIy	NumIt	NumMx	NumMy	NumMt
ORXYMiss	-1	-1	0	0	0	0

The message file *ORXYMiss.txt* of the problem indicated that some outriggers or bracings along X and Y-directions were missing or not enough. Experiences show that outriggers connecting the framing system with the core wall can make them work together, particularly for simplest translational modes. It also can be seen that the model problem of *ORXY-Miss* is belong to the collection of ProblemXY and ConditionX and ConditionY are as applied in Table 5. At the end of this iteration, sixteen steel frame outriggers were added from RP3 to form RP4.

RP4 -Model with outriggers

As shown in Figure 10 (for the RP4 model with core wall and framing system), sixteen steel beams are employed as outriggers at the two mechanical equipment floors to limit storey drift. In the dynamic response, these outriggers are expected to enhance the lateral stiffness and torsional rigidity. After checking the drawings, it was confirmed that these outriggers physically exist in the real building. Therefore, the sixteen outrigger frame elements are added from RP3 to form RP4.

Figure 10 Plan view of RP4 showing outriggers

Inspection of the MAC values of nine paired modes shows a slight improvement between RP4 and RP3. However, the difference errors of natural frequency of three fundamental modes X1, Y1 and T1 became nearly perfect (–1%, 6% and –14% respectively) in Table 15.

Table 15 Pair of frequencies between RP4 and EMA

Mode	Direction	f_{EMA} (Hz)	f_{FEA} (Hz)	MAC (%)	D_f (%)	AbsD_f (%)	Rank
1	X1	0.191	0.190	99.9	-1	1	8
2	Y1	0.199	0.212	99.9	6	6	7
3	T1	0.566	0.489	86.1	-14	14	2
4	X2	0.703	0.794	97.2	13	13	3
5	Y2	0.746	0.810	99.4	9	9	5
6	T2	1.340	1.032	82.5	-23	23	1
7	X3	1.550	1.553	92.0	0	0	9
8	Y3	1.730	1.846	99.0	7	7	6
9	T3	2.310	2.052	90.5	-11	11	4

Three modes with the maximum absolute difference error along directions X, Y, and T and their indices of difference error are listed in Table 16. The *NumDiff* (+1) of *ModeMaxDiffX* indicates a requirement to reduce the translational stiffness of the model along X-direction. The *NumDiff* (0) of *ModeMaxDiffY* indicates no special requirement to the translational stiffness of the model along Y-direction. The *NumDiff* (-1) of *ModeMaxDiffT* indicates a requirement to enhance the torsional rigidity of the model.

Table 16Three modes being focused in RP4

ModeMaxDiff	Mode	Direction	D_f	NumDiff
ModeMaxDiffX	4	X2	13%	+1
ModeMaxDiffY	5	Y2	9%	0

ModeMaxDiffT	6	T2	-23%	-1

In the Module of searching problems, the most likely problem identified in RP4 was *IWXYMiss*. The problem *IWXYMiss* means some inside walls along X- and Y-direction were missing or not enough in the model. The KB of possible problems shows its mode improvement index as listed in Table 17. Except the stiffness index *NumIt* is (-1), all other stiffness indices and mass indices are (0). This means that this problem, adding inside walls into the model, may enhance the torsional rigidity of the model and have little effect on translational stiffness of the model along X- and Y-directions. It also means solving this problem does not have obvious contribution to translational mass and torsional mass of the model.

Table 17 Mode improvement index of the problem IWXYMiss

Problem	NumIx	NumIy	NumIt	NumMx	NumMy	NumMt
IWXYMiss	0	0	-1	0	0	0

The message file *IWXYMiss.txt* of this problem suggested that some inside thin walls along X- and Y-directions were missing or not enough. From the points of experienced engineers, these inside thin walls may connect the outside walls with openings and make them closed. Thin internal walls within the core should be carefully modelled to enclose part of the open section, which can increase the torsional rigidity of the opened core wall noticeably. Usually inside walls are thin and close to the centroid of the floor plan, so they contribute little to translational stiffness, translational mass and torsional mass of the model.

Based on above information, inside thin walls not represented in RP4 were put into the model RP5.

RP5 -Model with major openings, secondary openings and internal thin walls

Figure 4 shows some of many thin (200mm) internal walls located within the core wall. These walls have relatively small translational stiffness due to their thickness and proximity to the neutral axis; so it seems that they could be omitted in the structural analysis. However, the torsional rigidity of a closed cross section is much larger than that of a similar section with a partial opening.

In this building, the core wall can be assumed to be partially opened at the lines of secondary openings in addition to the major openings. However, when the internal thin walls are added, the core walls become partially closed. These thin walls could be useful for enhancing the torsional rigidity of the whole structural system.

Due to the complexity of modelling, the four panels, approximating the internal thin walls, as shown in Figure 11 are added to RP4 to form RP5.

Figure 11 Plan view of RP5 showing outriggers and thin internal walls

Table 18 shows the correlation analysis results and pairing of natural frequencies between nine paired modes of RP1 and EMA. In this figure, except mode X2 (17%) and Y2 (11%), difference errors of all other modes are within a satisfactory 10 per cent. This model reproduces the basic structural dynamic behaviours including mode shapes and natural frequencies, which are correlated very well with those modal parameters from EMA. Therefore, the model RP5 can be accepted as the final 3-D FE model for further loading and structural dynamic analysis, and there is no need to continue the updating procedure.

Table 18 Pair of frequencies between RP5 and EMA

Mode	Direction	f_{EMA} (Hz)	f_{FEA} (Hz)	MAC (%)	D_f (%)	AbsD_f (%)	Rank
1	X1	0.191	0.194	99.9	2	2	9
2	Y1	0.199	0.214	99.9	8	8	5
3	T1	0.566	0.602	97.6	6	6	6
4	X2	0.703	0.820	95.5	17	17	1
5	Y2	0.746	0.830	99.4	11	11	2
6	T2	1.340	1.283	95.6	-4	4	7
7	X3	1.550	1.690	96.0	9	9	4
8	Y3	1.730	1.897	99.1	10	10	3
9	T3	2.310	2.260	92.8	-2	2	8

One question may arise is that there is no need to add inside walls in RP5 if there is no removal of secondary openings in RP3. In another words, one may suspect/argue that secondary openings in RP3 should not be removed or more openings were removed than expected.

This can be explained in two points:

1) The secondary openings removed are based on the construction drawings of the real building on which EMA was performed and other smaller openings were ignored in the model. .
2) The MAC values of torsional modes (T1, T2 and T3) are improved considerably from 0.692, 0.486 and 0.683 in RP2 to 0.845, 0.814 and 0.890 in RP3. The changes from RP2 to RP3 demonstrate the contribution of secondary openings to torsional modes of the model. On the other hand, the MAC value of torsional modes (T1, T2) are improved obviously from 0.861, 0.825 in RP4 to 0.976, 0.956 and in RP5. The changes from RP4 to RP5 reveal the significance of inside walls to torsional modes of the model.

The numerical simulations from RP1 to RP5 presented in this application show that a computer-aided model updating system is able to identify model problems based on model errors step by step. All of the four mode problems which were identified from RP1 to RP4 are due to model order errors not model parameter errors. These model problems cannot be solved with methods of micro model updating but solved with methods of macro model updating. The model updating procedure shows that the model problems were identified by pairing mode improvement index of model problems with mode error index of structural responses.

5 CONCLUSIONS

The relationship between model errors and model problems of finite element model updating of tall buildings was established by defining mode error index of structural responses and mode improvement index of model problems. The performance of the algorithm, which was verified with the application of model updating of a 66-storey frame-core wall office tower, shows that the computer-aided model updating system presented in this paper is able to implement finite element model updating of tall buildings, especially those with model order errors.

The main advantage of the proposed system is the rapid identification of likely problems in the finite element model and the explanation of the physical meaning of the model problem. Like experienced engineers, based on the correlation analysis results of paired modes between finite element analysis and experimental modal analysis, the system searches and identifies the most likely problem from the knowledge base of possible problems. The knowledge and experience applied in the KB of possible problems give the physical meaning of the updated parameters and make the updating procedure understandable and the user confident with the updated results.

This is the first time, in the field of model updating, to implement the finite element model updating of tall buildings with a developed knowledge-based system. Three-level index (-1, 0, +1) was applied to evaluate the difference error of natural frequencies as well as mass and stiffness index of each problem. To define five- or seven-level indices may make the system more efficient and accurate. How to utilise the correlation analysis results of mode shapes for problem searching could be a significant topic for further research. Finally, research on the relationship between natural frequencies of higher modes and the distribution of structural mass and stiffness of tall buildings is expected to enhance the ability of problem searching with the proposed system.

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