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Finite Element Model Updating of Civil Engineering Infrastructures: A review literature

H. Moravej[1], S. Jamali[2], T.H.T. Chan[3], A. Nguyen[4]

[1,2,3,4] *School of Civil Engineering & Built Environment, Queensland University of Technology – Australia, Email: h.moravej@qut.edu.au*

Abstract

There are many civil engineering structures in Australia that have experienced different functional deficiencies during their service lives due to the harsh environment, fatigue effect, extreme loads and aging. The current practice of for assessment of structures relies mostly on design conditions. According to a comprehensive review of the literature, current practice in Australian lacks effective techniques to investigate the performance of structures systematically. Assessment of structures is usually performed using simplified methods and design conditions. Besides, code of practice requires revisions such as those made to AS5100.7 to include an additional section for evaluation of existing structures using structural health monitoring (SHM) techniques. Therefore, there is a need to assess the integrity of structures through a holistic approach to satisfy the structural safety. One of the reliable methods to investigate the performance of structures is Finite Element Model Updating (FE model updating) which aims to generate the accurate finite element models (FEM)s of real structures. Availability of reliable FEMs of structures is beneficial in many aspects such as their applications in SHM, evaluation of load carrying capacity, damage detection and performance monitoring of structures in extreme conditions like an earthquake. This paper comprehensively reviewed the previous application of FE model updating in civil structural engineering in Australia and worldwide, clarified the main existing gaps and presented how to make the method more applicable in practice according to the recent advancement in the technology. It is recommended to address further two significant factors, as convergence accuracy and computational intensity mitigation, without sacrificing each other in the future studies. Also, it is proposed to include more of SHM techniques including FE model updating in the assessment of existing structures, and provide a systematic procedure for application of FE model updating in codified approach.

1. Introduction

Australia, as a wide land surrounded by oceans, encounters harsh environment every year especially along the coastal line with the highly urbanised district and numerous infrastructures. Natural hazards such as Cyclone Debbie in Queensland recently or overwhelming Sydney tornado in 2015 cause inevitable damages on structures every year. So after such disasters, are buildings still safe to be reoccupied or bridges are at the same load carrying capacity as before to be still operational? These questions must be addressed.

Thus there is a significant need to evaluate the performance of existing structures during their lifetime. There are a variety of approaches for structural assessment such as visual inspection (Estes 2003), Non-destructive testing (Huston *et al.* 2011), bridge testing using acoustic emissions (Nair 2010), but one increasingly popular approach is the vibration analysis with the aim of assessment and modifying the structural properties with the use of several factors like natural frequencies, mode shape, mode shape curvature, damping ratios, Frequency Response Functions and etc. The vibration analysis would be applied by means of either experimental test on the real structures or by

using analytical approaches to simulate structures to obtain the real structural properties. Among all analytical methods, FE modelling method is possibly the most favorable approach, especially for large and complex structures. Nevertheless, the use of this method is not always easy especially when it comes to the application to assess capacity of existing structures. The inherent deficiencies in FEM in this context could be attributed to false assumptions, simplifications, improper modelling techniques (Jamali *et al.* 2017a) and errors in an approximation of input parameters such as material properties. So in advance of applying FEM in structural assessment, it is essential to adjust its defined parameters with real cases. The most reliable approach to reconciling FEM with real structures is FE model updating with an efficient impression in a wide range of structural fields such as Structural Damage Detection and Health Monitoring (Ng 2014; Chan *et al.* 2009) structural dynamic design functions, Fatigue Analysis and Damage Prognosis, Structural Performance Monitoring (Zanardo *et al.* 2006), Structural Control, Retrofitting & Rehabilitation, nuclear power plants and aeronautic. In light of SHM, bridge assessment is directed recently through FE model updating with the aim of minimizing the discrepancy between analytical and experimental measurements (Jamali *et al.* 2017b; Ding *et al.* 2012)
Recent SHM development at QUT is an example of the innovative application of FE model updating for long-term performance monitoring and assessment of structures in Australia. This SHM system was developed using 8 accelerometers that were synchronised via a cost-effective DAQ system which enables the extraction of modal parameters from ambient excitation (Nguyen *et al.* 2015). Furthermore, modal data of the building are continuously recorded and checked for any anomaly using unsupervised statistical learning methods and application of FE model updating (Nguyen *et al.* 2014; Kodikara *et al*. 2016a; Kodikara *et al.* 2016b). In this study, the model updating process is revisited with application of this framework for the purpose of assessment and monitoring of civil engineering infrastructure. First, the techniques commonly used as auxiliary steps prior to the main model updating task are reviewed, then two main FE model updating approaches as Direct and Iterative are briefly explored before the latter as the most applicable and reliable one for civil engineering applications is discussed in more detail. In the end, the current gaps and the future directions are presented.

2. Initial Comparison between experimental and FEM data

Prior to using any FE model updating method, the consistency of the experimental work should be confirmed which is satisfied by available procedures such as choosing the types, locations and the number of sensors to be used, the sampling rate at which the data to be collected and which size of the data storage should be selected. Also, other aspects as normalization of measured data, information condensation, feature extraction, and data fusion should be considered as well (Sohn *et al.* 2003). Next, the test data and FE counterpart should be compared to be ensured about the existence of some correlation between their data before conducting the main model updating task.

2.1 Correlation techniques

Correlation indices show how close the experimental data are with FEM's counterpart. These methods comprise assessment of Frequency Response Functions (FRFs), mode shapes and natural frequencies of experimental data and FE data to check the level of agreement.

2.1.1 FRF matching

Generally, a frequency response function is a mathematical representation of the relationship between the input and the output of a system and it is basically obtained from the Eq. (1) (Friswell & Mottershead 2013).

$$H(f)=\frac{Y(f)}{X(f)} \tag{1}$$

In this equation, H(f) is the frequency response function. *Y*(f) and *X*(f) are the output and input of the system respectively in the frequency domain.

To compare the results from FE and experimental test, one simple technique would be plotting FRFs for both in one diagram as illustrated in Figure. 1 In this diagram, the vertical axis and horizontal axis stand for magnitude of FRF and Frequency respectively (Chang & Park 1998; D'Ambrogio & Fregolent 1998). As it can be seen, a proper correlation between the FE and experimental FRF results is figured out in Figure. 1(a), on the other hand, Figure 1(b) shows a kind of mismatching between these two counterparts. In such condition, a better matched FEM is required before the main model updating phase can take place.

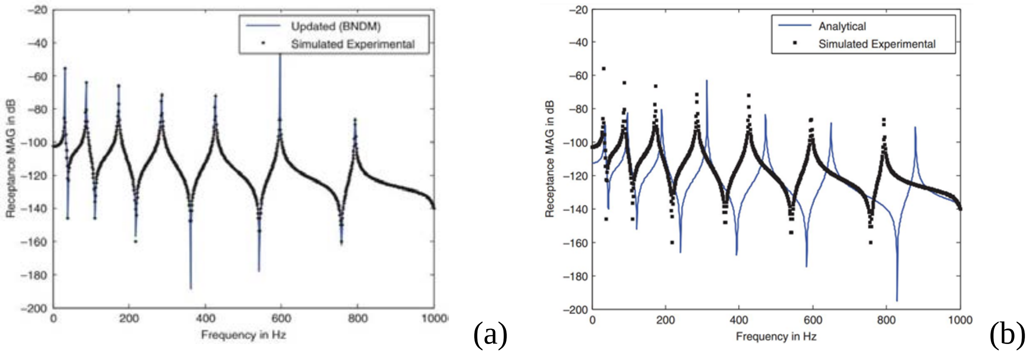

Figure 1 FRF plots matching. (a) good matching (b) mismatching (Sehgal & Kumar 2016)

2.1.2 Natural frequencies matching

Natural Frequency is another feature which should be considered in comparison between experimental and FE data before updating. In cases the error has a significant percentage, beyond 50%, it is recommended to adjust the current FEM (e.g. by manual tuning) or generate a new FEM before carrying out model updating (Živanović *et al.* 2007; Ewins 1984).

2.1.3 Mode shapes matching

Mode shape as one of the intrinsic dynamic properties of structure that signify the displacement of the structure in each natural frequency. Mode shape depends on material properties and boundary conditions of structures. Overlaying technique is a simple method to compare mode shapes (Sampaio *et al.* 1999). In this method, the divergence between FE and experimental mode shape is visually depicted in a diagram. The significant drawback of this methods is that they are not suitable for automated correlating. Another approach for correlation of mode shape is Modal Scale Factor (MSF) technique which is proper for automated correlating since this method presents a quantitative fitting between two corresponding data. MSF result is transferred on one x–y diagram with mode shape from the experimental test on one axis and FE mode shape on another (Adhikari & Friswell 2010). Perfect correlation between both mode shapes is presented by unity in MSF. In MSF method, the scatter of the x–y graph is not presented, so to overcome the dispersion of data in MSF plot, Modal Assurance Criterion (MAC) is often used which was also defined as mode shape correlation coefficient (Allemang & Brown 1982). MAC can be calculated using Eq. (2).

$$\text{MAC} = \frac{\left| \{\phi_x\}_i^T \{\phi_A\}_j \right|^2}{\left(\{\phi_x\}_i^T \{\phi_A\}_i\right) \cdot \left(\{\phi_A\}_j^T \{\phi_A\}_j\right)} \tag{2}$$

In this equation, $\{\varnothing_X\}_i$ and $\{\varnothing_A\}_j$ represent the i^{th} experimental and j^{th} analytical mode shape respectively; while superscript '*T*' denotes the transpose of the corresponding vector. MAC value would find the perfect matching state between experimental and analytical data when it reaches to unity, and once a MAC value is close to zero explains misfit between two modes (Pandey *et al.* 1991). Figure 2 shows a MAC plot between experimental and FE modes.

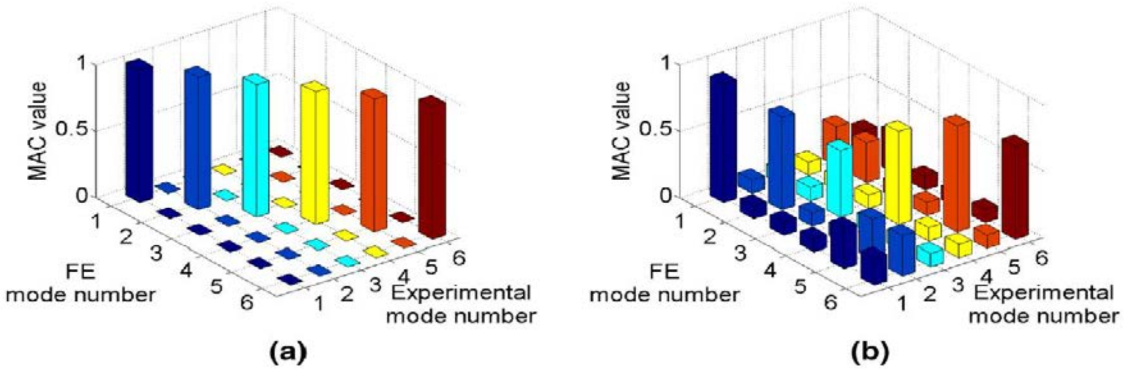

Figure 2 Modes correlation using MAC. (a) Good correlation, (b) poor correlation (Sehgal & Kumar 2016)

It is shown that the diagonal components are equal to one and the others are zero, which demonstrates ideal fitting between two different sets of data. On the other hand, in Figure 2b, a mismatching is illustrated since neither diagonal components are equal to 1, nor off-diagonal ones are equal to zero. Having said that, perfect correlation is not always feasible due to testing condition, corrupted data, and faulty equipment. MAC value has weaknesses in identification of systematic deviances as well as being poor in checking orthogonality due to lack of mass or stiffness matrix in the function. The latter drawback can be overcome by applying normalised MAC (NMAC) (Arora *et al.* 2009a). NMAC comprises a weighting matrix [W], which can be substituted by either mass or stiffness matrix. NMAC also has a shortcoming in defining the spatial scattering of correlation, which can be satisfied by using Coordinate MAC (COMAC). COMAC is applicable when number of the correlated mode pairs is found via MAC or NMAC. COMAC value equal to '1' presents excellent correlation at a particular coordinate (Lieven & Ewins 1988).

2.2 Dimension Compatibility Methods

It is common that the degrees of freedom (DOF) measured in an experimental test are generally much smaller than FE's (DOF) as a reason for the lack of a sufficient number of sensors. Also, some DOFs are so challenging to be recognised such as the fixity of support, lateral movement of foundation, local vibration of connecting parts. Accordingly, the dimension of FEM is typically not consistent with their experimental counterparts, whereas in Model Updating, between the two data sets, one point-to-point correlation is necessary. This aim could be satisfied via increasing the experimental data or by decreasing the FEM.

2.2.1 Coordinate Expansion

One approach to achieving the dimension compatibility could be an expansion of measured data sets to reach the same degree of FE's size which is named "coordinate expansion". A simple technique is to replace the unknown components with their FE counterparts. This method is cost-effective in computation, despite sometimes it causes incorrect results in model updating. To conquer such drawback, couple transformation matrix based coordinate expansion should be generated (Arora *et al.* 2009b; Arora *et al.* 2009c). There are several different methods in this category such as System equivalent reduction and expansion processes (SEREP) (Adhikari & Friswell 2010), FE eigenvectors combining with MAC matrix (Arora 2011), Curve fitting (Atalla & Inman 1998) and a method which is made on the assumption that unknown eigenvectors could be considered as a linear combination of measured eigenvectors (Bais *et al.* 2004).

2.2.2 Model Minimization

This approach is mainly on the contrary with the previous method with the aim to reduce the analytical model's size and make its Degree Of Freedom (DOF) close the experimental model counterpart. A basic technique is to cut those unavailable experimental degrees of freedom. So a reduced model is provided. The main lack of this method is that some of mass and stiffness parameters related to the removed DOFs are totally missed and their effects would not be available anywhere (Baruch 1978). Another technique in this area is an approximate method which tries to generate a compact model of a whole structure entirely but approximately through converting the original model. One method of gaining a condensed model is static reduction proposed by Baruch & Bar Itzhack (1978) which is mostly known as Guyan reduction method (Guyan 1965). The significant disadvantage of this method is that it would not reflect any of the Eigen parameters of the original full FEM. Improved reduced system (IRS) method is another scheme of model minimization with the aim to reproduce the eigenvalues and eigenvectors closely to the original FEM (Baruch 1978; Bayraktar *et al.* 2011). If the reduced model is required to have eigenvalues and eigenvectors exactly the same as that of original FEM then SEREP should be used (Beattie & Smith 1992; Berman 1979).

3. Finite Element Model Updating main frameworks (Direct and Iterative)

The FE model updating methods can be generally categorised into two main groups as Direct and Iterative techniques.

Direct approach is computationally effective since the result would be prepared only in one step with easy converging results. One aspect of this technique is that they reproduce the measured data exactly. The experimental data and their analytical counterpart are rarely to be the same as a result of measurement noise and model deficiency. Updating is fulfilled in one step to optimise the parameters in the model but not with the aim of exactly reproducing the noise. If the updated model exactly reproduces defective measured data, any consequent analysis may be faulty. So, this method requires reliable modal testing and analysis procedures. Direct approach applies matrix methods to calculate the result with performing equation of motion. A major shortcoming of this approach is that the updated stiffness and mass matrices may not be physically sensible. In the other words, while it satisfies the mathematical problem, it is not capable of reflecting the real changes in structural properties (Friswell & Mottershead 2013). This technique is also referred as the technique of reference since one of the three parameters (damping, stiffness and mass matrices) is supposed to be the reference and the other two quantities are adjusted (Baruch & Bar Itzhack 1978; Baruch 1978; Berman 1979). Recently a vibro-acoustic FE model updating technique was offered by Modak (2014). Such method could apply to update the vibro-acoustic FEM of elastic systems. In this technique, stiffness and mass matrix from the structural together with the acoustic components of the model can be updated. Another direct FE model updating method was developed by Bucher and Barun (1993) which was able to handle incomplete known eigensolutions that were tested numerically on a fixed beam and a sequential spring-mass system. In 2007, a new method named cross-model-cross mode (CMCM) was established by Hu et al (2007). This method aimed to simultaneously update the physical properties of the system matrices as well as the mass and stiffness matrices. Further, substructure energy direct FE model updating method based on the physical property modification was generated by Fang et al. (2011). The advantage of this technique was that it could deal with insufficient experimental data. Also in this method, the whole structure is separated into several substructures. Thus, just the crucial subsystems are detected and adjusted rather than updating the whole system. Dynamic behaviour of the FEM of structures relies on different parameters, as mentioned before.

In iterative methods, one objective function is generated between input structural parameters and structural responses. Iterative approach aims to update the parameters iteratively in such a way that between FEM's response and the corresponding experimental response minimal difference exists. The cycle of iterations is finished once the responses from FEM and experimental data no longer change in subsequent iterations. Despite being computationally expensive, iterative techniques represent the realistic behaviour of the structure (Berman & Nagy 1983). Since the Iterative method can achieve more reliable results, this technique has further applications in structural engineering by far and many investigations have been conducted to develop the technique which will be addressed in the next part.

4. Finite Element Model Updating based on iterative frameworks

In the iterative approach, one objective function is made and it is reduced iteratively to reach the adjusted parameters. These techniques initially started with the development of an iterative eigendata sensitivity technique called inverse eigensensitivity method (IESM) (Collins *et al.* 1974). Lin et al. enhanced the convergence of this technique through applying the FE data together with the experimental responses for assessing sensitivity coefficients (Urn & Du 1995). In IESM, eigen data and damping ratios are performed to construct an objective function. Modal data is provided by modal analysis, so the accuracy in applying the modal analysis has a significant effect on the validity of extracted modal data which is conducted to the model updating results. To circumvent this issue, obtained signal data can directly be transferred for model updating using Response Function Method (RFM) (Lin & Ewins 1990). Since in RFM there is no need for modal extraction to apply to measured data, the chance of errors during modal analysis process decreases. According to a comparative report by Modak et al. (2002), RFM has a better performance than IESM in cases of insufficient experimental data without noise, while IESM is more efficient in the updating cases with the existence of noise; especially when the updating region includes higher number of modes. Furthermore, in RFM, the sensors' positions and sample rate of experimental have significant effects on the convergence of the method. Modak et al. (2005) established a constrained optimization FE model updating method. The method was applied to a fixed-fixed beam and an F-shape frame structure. Despite the technique is computationally more intense than IESM, it can alleviate the effect of variance between the sensitivities of mode shapes and natural frequencies. Atalla and Inman (1998) employed Neural Network (NN) technique in the FE model updating of a flexible frame with training an NN and verified it via a constructed sample of the structure, testing it and comparing the experimental and analytical responses. Such an NN could be exploited to find updated physical parameters by setting experimental responses as inputs. Provided NN model has trained appropriately, its calculation process is rather faster than conventional optimization approaches. Furthermore, NN method is also reliable in the presence of noise (Levin & Lieven 1998a). The main drawback of this technique is that a great amount of training data is necessary.

4.1 Objective function definition in FE model updating

Application of FE model updating in real structures faces a variety of complexities such as errors in measurement, the existence of nonlinearity, damping effect and a large number of updating parameters. Due to such issues, the conventional model updating methods may be unable to converge and minimise the objective functions properly in a global scale. So the application of optimization approaches with the capability to obtain the global optimum is indeed required, such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO) and Simulated Annealing (SA) (Sehgal & Kumar 2016). According to a comparative research by Levin and Lieven (1998) FE model updating by applying SA leads to a better performance than GA approach. Having said that, the efficiency of FE model updating based on both methods relies on accurately selecting the updating parameters. Marwala (2010) concluded that the application of PSO in FE model updating is so effective in cases with many updating parameters. Further, Mthembu *et al.* (2011) employed PSO in multi-model FE model updating to select the most accurate structural model in the presence of many updated models. For the purpose of damage detection, the residuals should be sensitive to even slight local structural changes. In a research, a sensitivity-based FE model updating is carried out for the purpose of damage detection. The objective function consisting of the modal flexibility residual is formulated and its gradient is derived. The proposed procedure is illustrated with a simulated beam and a laboratory-tested beam with damage. Despite all the elements in the FEM are used as the updating parameters, which is considered as the extreme adverse condition in the FE model updating, the identified damage pattern is comparable. It is demonstrated that the proposed FE updating using the modal flexibility residual is promising for the detection of damaged elements (Jaishi & Ren 2006). In many optimization concepts, single-objective optimization techniques propose reliable algorithms to optimise a single criterion. But this framework is disabled to cope with the optimization cases when different criteria at the same time are considered. In such situations, a multi-objective optimization problem would be evolved (Kim & Park 2004). Perera and Ruiz (2008) proposed a multistage algorithm for damage detection in large-size structures with the application of modal data obtained from experimental tests together with the FE model updating methods applied on simple FEMs. In this method, a multi-objective technique was employed to optimise the objective function. Optimization procedure is formulated in a multi-objective context solved by using evolutionary algorithms. The multistage algorithm for damage detection was applied to the I-40 Bridge in New Mexico and it was found that the offered approach is robust, fast and easy to perform. Generally, the results of the several tests on an identical structure would not be same in all cases due to various operational and environmental factors. Consequently, every parameter has an approximate value of a variance and a mean value. Mares *et al.* (2006) included an approximate concept of parameters into FE model updating by applying it to a simulated three degree-of-freedom mass–spring structure and reach the reliable result. The center of the distribution would be defined as the mean value and the size is identified by the variance of test data. Same work was then extended by Mottershead *et al.* (2011) who developed a stochastic FE model updating technique. The framework was constructed based on statistical models with a large database. A Bayesian framework was presented by Wan and Ren (2014) to a Stochastic Model Updating method for measurement of parameters uncertainty which could not be reduced. Bayesian method overcomes the issues of inverse uncertainty quantification in a direct mode, which evades the problems of gradient computation and ill-conditionedness that is related to the optimization process. Some researchers used Bayesian implication to achieve structural reliability updates and to analyse the likelihoods of diverse damage circumstances (Papadimitriou *et al.* 2001; Sohn & Law 2000)

Sun & Betti (2015) developed a hybrid optimization approach for the stochastic model updating of structures. The method is originated as an inverse problem, conducted through a Bayesian framework, and is calculated via a hybrid optimization algorithm. The offered hybrid approach comprises of a global and local assessment operator named Modified Artificial Bee Colony (MABC) and Broyden-Fletcher-Goldfarb-Shanno (BFGS) respectively. Parametric studies and numerical optimization of mathematical functions show the efficiency of the offered method is demonstrated through the numerical and the experimental data sets.

4.2 Reduced Order Techniques in FE model updating

Because of the iterative nature of the FE model updating, this approach would be computationally intensive, especially when it deals with large-scale structures. Guo and Zhang (2004) developed a method to perform the Response Surface methodology (RSM) in FE model updating. The significance of this method is that there is no need to calculate the FE response at each iteration because the FEM is swapped with an approximated mathematical equation, thus the amount of computation is significantly reduced. In this technique, by considering updating parameters as inputs together with the FE responses as outputs, n-dimensional response surfaces are generated. Through applying the response surfaces along with the experimental responses, the model parameters are updated by optimizing the objective function. This type of FE model updating is reliable as the sensitivity-based method, more efficient in computational aspect and faster in convergence aspect (Sehgal & Kumar 2016). Shahidi and Pakzad (2013) applied a time-domain technique in RSM based FE model updating. Since in traditional techniques, measured signals should be converted to response parameters such as mode shape, resources for the training data to generate response surface models are declined. Hence, time-domain results were performed to compensate this issue. One of the significant factors in the FE model updating framework is parameters selection, particularly in the case of large structures. It is obvious that the real structures include so many parameters and considering all of them are updated, the model updating procedure becomes complicated and time-consuming undoubtedly. Moreover, it is likely that the updating problems lead to ill-conditioning as well (Friswell & Mottershead 2013). Recently one parameter selection technique was developed by Kim and Park (2008) which comprises two steps. In the first step, each updating parameter is considered incorrect. Next two adjacent parameters are combined if they have the same sensitivity signs i.e. both are positive or negative. Thus the number updating parameters is considerably reduced in this way. Such process is continued until all nearby parameters find different sensitivity signs. If the number of updating parameters is less than a limit point, the process will stop; otherwise, the technique is transferred to the second step. In this step, a comparative analysis is applied to the opposite sign sensitivity neighboring groups of the updating parameters, and those two groups are selected to be merged which cause the least decrease in entire sensitivity. Weng et al. (2012) offered a novel substructure model updating approach. In this method, the experimental flexibility matrix for the whole structure is divided into the several substructural matrices. All these substructures matrices are applied as references to update the independent substructures' models. Application of this method is computationally efficient since just the concerned substructure is modified. Furthermore, in this framework, only the measurement of the local area of the focused substructures is needed. The proficiency of the substructure based model updating is numerically illustrated on a large-scale real structure. This method was applied to Guangzhou New TV Tower. and, it was proved that substructure-based procedure is much faster than the traditional global-based procedure.

5. Concluding Remarks and Future Research Directions

From the reviewed literature, it is found that structural damping is not considered in the majority of the works, while damping effect significantly affects the structural responses. So it is recommended to investigate the damping effect in the future research to enhance the reliability of the FE model updating as suggested by Friswell & Mottershead (2013). In most of FE model updating cases, the structures are assumed to behave linearly. This assumption could affect the accuracy of FE model updating methods, especially when dealing with assessment of old infrastructures. Response of structures such as buildings and bridges changes over time and in order to reflect these changes, as-is condition of the structure needs to be reflected in the FEM. Material nonlinearity is common in many structures and geometrical nonlinearity to some extent. Such nonlinearities are time-dependent and are affected by various environmental and operational factors. Hence, for assessment purpose, nonlinearity aspect of the structure shall be considered even though the past performance of the structure was satisfactory (Asgarieh *et al.* 2017). Reserved capacity, redundancy, ductility, life cycle and load-distribution are some of the essential information that daily can evaluate when nonlinearity is considered into the modelling. Generally, the nature of FE model updating is the calculation of an inverse problem. It is found that too many updating parameters can lead to an ill-conditioned problem or become computationally costly. So more development in numerical concept is still necessary to converge the inverse problem accurately and with less computation. Major sources of inaccuracy in the FEM are due to physical errors, geometrical errors and modelling error. A systematic comparison with experimental and analytical data using MAC and other modal comparison methods can be effective in alleviating the occurrence of the error. Accurate parameter selection is the most pivotal step in FE model updating which still needs to be improved. Despite a number of techniques have been proposed in this aspect, the parameter selection mostly relies on the engineering judgment and structural response. It is suggested to have a systematic guideline for model updating parameter selection of different structures based on hierarchy level of structural importance. In addition, a generalised process can be formulated to include the application of FE model updating in the routine practices. This includes for buildings, bridges, and any other civil structures that need assessment or retrofitting. The newly released version of AS 5100 Bridge design set (Australian Standards, 2017) is a good example, in which its Part 7 includes the application of SHM for bridge assessment. Such combination of codified approaches with advanced SHM and FE model updating technique would significantly improve the accuracy of the assessment. In turn, the full functionality of the structure is utilised with more confidence in the assessment. Further experimental investigations on benchmark studies such as QUT-SHM benchmark (Nguyen *et al.* 2015) building are needed, which can definitely be helpful in two aspects; to further develop the applicability and accuracy of FE model updating for real structures, and to bridge the gap between the research and the industry.

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