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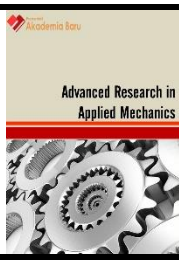

Structural Damage Identification Using Model Updating Approach: A Review

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ABSTRACT

There have been countless studies to investigate structural damage identification. This field of study is sometimes referred to as structural health monitoring. Model updating approach is a non-destructive testing method that uses characteristic values related to structural models such as natural frequencies and mode shapes to identify the damage. Researchers over the last decade have focused on several model updating techniques for structural damage detection and identification. However, various methods can be used for model updating, and it can sometimes be quite confusing to choose which method to use for each case. Since this can have serious consequences, it is imperative to understand model updating better. This paper gives an introduction to structural damage identification, while brief information on finite element model updating is described and reviewed in terms of available methods and types of measured data. Here, the performance of different model updating methods utilized in structural damage identification is compared. This study has found that researchers in the iterative method extensively use modal data-based methods and frequency-based methods. The insights gained from this study may assist those who want a brief idea about model updating and its application in structural damage identification.

Keywords:
Structural damage identification; finite element model updating

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1. Introduction

Structural damage is a long-standing challenge for the engineering community because deterioration of the structure will badly affect its safety and reliability. Damage can be described as any difference in the structural physical properties or material properties that may cause unwanted stresses, displacements, or vibrations on the structure due to several factors such as corrosion, fatigue and cracks [1]. Hence, different types of damages affect different structural properties [2].

Over the past few decades, there has been sustained research activity in structural damage. Researchers all over the world have been examined various defects in different types of materials. For instance, Cha *et al.* [3] focused on structural surface damage such as steel delamination, steel corrosion, bolt corrosion and concrete cracks in steel, bolt and concrete. Meanwhile, Xu *et al.* [4] studied the corrosion, fatigue crack, rebar exposure and coating failure in steel. They also studied the

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rebar exposure, salt petering, water leakage, crack, spalling, honeycomb and pockmark in concrete. Kralovec and Schagerl [5] focused on matrix crack, fiber crack, delamination and notch in composites. Meanwhile, a significant amount of research is concerned with investigating the causes of defects. For example, previous research by Gholizadeh [6] identified that, material defects are the major sources of composite failures. However, different causes of defects is found in industrial equipment by Dubov *et al.* [2] where the main source of failure is the stress concentration zones.

There are numerous studies to investigate the identification of structural damage. The model updating approach is a non-destructive testing method that uses characteristic values related to structural models such as natural frequencies and mode shapes to identify the damage. Researchers over the past decade have focused on various model updating techniques for detecting and identifying structural damage. However, various methods can be used to update the model, and it can be quite confusing at times to choose which method to use for each case. Since this can have serious consequences, it is imperative to understand the model updating better.

This article aims to give a comprehensive overview of model updating techniques and types of measured data. After the introduction, the structure of this paper can be listed as follows: Section 2 brief description of the methods used to identify structural damage. Section 3 describes the model updating methods and the comparison of performance between different methods and the structural response. Finally, Section 4 summarizes trends in the model updating method and structural response.

2. Structural Damage Identification

Structural damage detection plays a vital role in the early damage stage [7]. There has been an increased recognition that more attention needs to be paid to structural damage identification. This field of study is occasionally referred to as structural health monitoring. Damage identification is one of the main components of structural health monitoring. The purposes of damage identification are to identify, locate and distinguish the structural damage [8].

There have been numerous studies to investigate structural damage identification. A recent study by Song *et al.* [8] highlights about research progress on structural damage identification in civil engineering. Hou and Xia [7], Das *et al.* [9] presented a complete review on the vibration-based damage identification used for structural health monitoring. In more advanced and multidiscipline, Avci *et al.* [10], Noel *et al.* [11] studied structural health monitoring using wireless sensor networks.

Song *et al.* [8] classified the methods of structural damage identification into local methods and integrated methods. The local method is a non-destructive testing (NDT), while the integrated damage identification methods are based on structural vibrations. To better understand NDT methods, Gholizadeh [6] categorized it into contact methods and non-contact methods, as shown in Table 1. Song *et al.* [8] divided integrated damage identification methods into model-based and non-model-based methods; where model-based methods use characteristic values related to structural models, including the natural frequencies, mode shapes, modal curvature, dynamic flexibility and dynamic stiffness, and the finite element method to identify the damage and non-model-based methods use characteristic values derived from the vibration time history, frequency spectrum or time region instead of features of the structural model. Table 2 shows the list of model-based methods and non-model-based methods.

Table 1
NDT methods [6]

Contact Methods	Non-Contact Methods
Traditional ultrasonic testing [12]	Through transmission Ultrasonic
Eddy current testing [13]	Radiography testing
Magnetic testing [14]	Thermography [15]
Electromagnetic [16]	Infrared Testing
Penetrant testing [14]	Holography [17]
Liquid penetrant [14]	Shearography [18]
	Visual inspection

Table 2
Integrated damage identification methods

Model-based Methods	Non-model-based Methods
Model updating method	Dynamic fingerprint analysis
Genetic algorithms	Wavelet transformation
Neural networks	Hilbert-Huang Transform
Support vector machine	

As for the model-based methods, Kim *et al.* [19] presented the methodology to locate and estimate the size of damage in beam-type structures for which a few natural frequencies or mode shapes are available. Likewise, [20-25] investigated the effectiveness and applicability of the model-based damage detection for offshore structures. Besides, a number of researchers implemented genetic algorithms to detect damage in structures [26-29]. Meanwhile, [30-36] focused on the use of neural networks to detect structural damages and [37-40] studied the support vector machine approach for damage detection. For non-model-based methods, [41, 42] proposed structural health monitoring based on dynamic fingerprints, which are functions of the structural physical properties and modal parameters. Other approaches are wavelet transformation [43-47] and Hilbert-Huang transform [48-51].

Researchers over the last decade have studied various model updating techniques for structural damage detection. Model updating technique can be loosely described as model calibration, where this technique is basically about updating a finite element model of a structure to reduce the errors between numerical and experimental results [52-54]. Model updating techniques can be categorized into the direct (non-iterative) method and iterative method. The iterative method consists of sensitivity-based method, probabilistic/statistical method, optimized algorithm method and evolutionary algorithm method [55].

3. Finite Element Model Updating

Finite element (FE) model updating is an important tool in the field of structural health monitoring. Numerous techniques for FE model updating have been developed over the past decades. FE model updating using experimental data to refine a mathematical model of a structure [56]. The direct method, also known as non-iterative, requires complete modification of the system matrices or substructures [8, 57, 58]. The benefits of using this method are computationally cheaper, and it shows precise results [53]. However, Alkayem *et al.* [55] stated that the direct method might not give a reasonable physical explanation of the changes in structural characteristics. Some examples of direct methods are error matrix methods, matrix-update methods, optimal matrix methods and the eigenstructure assignment method [55].

Meanwhile, the iterative method, also called as sensitivity method, overcomes the limitations of the direct methods [53] but requires a sensitivity matrix concerning all updating parameters, leading to expensive computation [11]. A tutorial for the sensitivity method in finite element model updating written by Mottershead *et al.* [59] stated that the sensitivity method is based upon linearization of the generally non-linear relationship between measurable outputs, such as natural frequencies, mode shapes or displacement responses and the parameters of the model in need of correction. This method may not apply to structures with considerable damage [8], but it is applied successfully to large-scale industrial problems [53]. Researchers in the iterative method extensively use modal data-based methods and frequency-based methods.

Model updating can also be done by using statistical and probability-based approaches [55]. Simoen *et al.* [54] emphasized that this method provides detailed information about the uncertainty of the quantities of interest. Notably, this method is computationally demanding and challenging because one needs to understand the distribution of all variables [54, 55]. Bayesian framework-based method, Taguchi-based method and Tikhonov regularization method are examples of statistical/probability-based approach.

Aside from the methods mentioned above, researchers have examined various optimization algorithms to solve the FE model updating problem. The optimization algorithm can be used directly or combined with the sensitivity-based method, depending on the ability of the optimization algorithm to handle complex and highly nonlinear FE model updating [55]. However, despite the success of the optimization algorithm in certain aspects, it still suffers from low efficiency and failure to solve optimization problems [55].

There is a vast literature on the evolutionary algorithm method for solving the disadvantages of the optimization algorithms method. The evolutionary algorithm is a computational intelligence technique used to solve complex optimization problems. For instance, Dey *et al.* [60] employed Bees algorithm to update the model of cracked and uncracked concrete beams. Alkayem *et al.* [55] provides an extremely useful detailed review of critical aspects of structural damage identification using evolutionary algorithm-based FE model updating. A summary of advantages and limitations for model updating methods is shown in Table 3.

Table 3
Summary of advantages and limitation for model updating methods

Method	Example	Advantages	Limitation
Direct (non-iterative)	• Matrix-update methods [61] • Optimal Matrix methods • Error Matrix methods • The Eigen Structure Assignment methods [62]	• The direct method shows precise results[53] • Computationally cheaper[53]	• Might not give a reasonable physical explanation of the changes in structural characteristics[55]
Sensitivity (iterative)	• Modal data-based methods [63]	• Provides wider choice of	• Requires a sensitivity matrix with respect to all

	• Frequency response data-based methods [64]	parameters for updating[53] • Applied successfully to large-scale industrial problems[53, 59] • Overcoming the limitations of the direct methods[53]	updating parameters[65], leading to expensive computation[55] • May not be applicable to structures which contain a considerable amount of damage[55]
Probabilistic/Statistical	• Taguchi-based methods [66] • Bayesian framework-based methods [67-69] • Tikhonov regularization methods [70, 71] • Markov Chain Monte Carlo sampling technique[57, 72]	• Provide detailed information regarding the resulting uncertainty of the quantities of interest[54] • When detailed information is required regarding the resolution and interaction of the parameters, the Bayesian approach is most suited[54]	• Requirement to solve complex integrals[55] • Need to understand the distribution of all variables[55] • High computational cost[55]
Optimization Algorithm	• Nelder-Mead [73] • Couple Local Minimizers, Trust Region Newton [74] • Penalty Function [75] • Sequential Quadratic Programming [76]	• Minimize residuals between the dynamic characteristics of the FE model and damage structure[55]	• Low efficiency and failure to solve optimization problems[55]
Evolutionary Algorithm	• Tug-of-war optimization [77] • Cyclical parthenogenesis algorithm [78]	• Can solve complex optimization problems of high nonlinearity,	• The application to structural damage identification is not yet well resolved[55]

	• Bees algorithm[60]	multimodal interactions[55]

Several studies have examined the structural response for model updating, especially the modal-based and frequency response functions (FRF)-based [79]. The modal-based model updating methods depend on the modal characteristics data such as natural frequencies and mode shapes extracted directly from the measured FRF data [79, 80]. Meanwhile, the FRF-based updating methods directly employ the measured FRF data to update the structural parameters [80]. However, Pedram *et al.* [81] reported that the FE model updating using Power Spectral Density (PSD) has recently been studied. Pedram *et al.* [82] explained that PSD is a second-order transfer function, where excitation at a certain degree of freedoms (DOFs) at each frequency point will lead to the auto-spectral and cross-spectral density of the responses. Table 4 shows the advantages and limitations of each measured data in solving model updating problems.

Table 5 summarizes the measured parameter used in recent research studies, complete with the model updating method used for each case study. Using principal components of FRF, Esfandiari *et al.* [83] derived the sensitivity relation by including principal components analysis data obtained from the incomplete measured structural responses in a mathematical formulation. On the other hand, [57, 60, 84-92] employed modal data for their case study. For concrete-encased composite column-beam connections, Nasery *et al.* [84] applied an improved frequency domain decomposition method for modal extraction for concrete-encased composite column-beam connections. Grip *et al.* [85] used modal data as structural response and updating by the classical iterative sensitivity-based method for a reinforced concrete plate. Sotoudehnia *et al.* [86] extracted incomplete noisy modal data and constructed the finite element model using the classical finite element technique and Sander's thin shell theory for the cylindrical shell. Oh *et al.* [87] updated the model using natural frequencies measured in an impact hammer test for a beam structure.

Likewise, Dey *et al.* [60] performed a laboratory test on a simply supported beam with a smartphone to get the natural frequencies of both damaged and undamaged beams using the accelerometer application software. The model was updated with the Bees algorithm to get more accurate results. Recent work by Lee [91] proposed a modal-based damage identification method applied to portal beam structures. Chen *et al.* [88] used the incomplete modal quantities extracted from measurements such as the acceleration time histories to update a parameterized baseline model for a 10-story shear-type building and a 33-bar truss structure. Meanwhile, for the 31-bar planar truss structure, Chen and Yu [92] established an objective function using frequencies and mode shapes. Das and Debnath [57] utilized modal data for FE model updating of a reasonably complex structure in the form of a cantilever plate. For the hybrid bolted joint structure, Adel *et al.* [90] computed the natural frequencies and compared them to the modal test results to evaluate and verify the new model predictions.

Table 4
Advantages and limitation of each type of measured data

Data	Advantages	Limitation
Modal data	• Better convergence in the presence of measurement noise when more vibration modes are considered [82]	• Numerical extraction process cause additional errors and inaccuracies [79] • Less measured data than unknowns [80]

FRF data	• The amount of available test data is not limited to a few identified eigenvalues and eigenvectors only [79] • The redundancy of information can be used to reduce the effects of noise [79] • Avoiding modal analysis errors, especially when the extracted structural modes are close to each other [80] • Provide more deformation data in a wide range of frequencies [93]	• The spatial DOF incompleteness of FRF. The incompleteness makes the FRF-based methods converge more slowly [79] • The magnitude values of FRF data near natural frequencies can change very quickly and cause the updating process to converge to a local meaningless minimum [79]
PSD data	• Embraces the data on structural behaviour at wide frequency ranges [81] • More sensitive to damage [81] • Include both auto and cross spectral terms, making more data available for model updating [81]	• Highly sensitive function of structural parameters [81, 82] • Computing a reliable linear equation that traces the changes in PSD back to the variation in structural parameters is challenging [81]

Table 5
Modal parameter used in recent research study

Method	Modal parameter	Material used	Researchers
Sensitivity	Principal components of FRF	A 2D steel truss and a steel frame model	[83]
	Modal data	Concrete-encased composite column-beam connections	[84]
	Modal data	A reinforced concrete plate	[85]
	Modal data	Cylindrical shell	[86]
	FRF	2D Truss structure	[80]
	FRF	A scale 2D fixed platform	[94]
	FRF	2D truss model and a concrete beam	[95]
	PSD	Concrete beam	[82]
	PSD	Plate and shell models	[81]
	Modal Strain Energy	Beam-like structure	[96]
Probabilistic/ Statistical	Time-invariant model parameters	A bridge pier and a moment resisting steel frame	[97]
	Modal data	Beam structure	[87]
	Modal data	A 10-story shear-type building and a 33-bar truss structure	[88]

	Modal data	Cantilever plate	[57]
	Modal data and temperature	Frame structure	[89]
Optimization Algorithm	Modal data	Portal beam structure	[91]
	Modal data	31-bar planar truss structure	[92]
	FRF	A composite structure of honeycomb sandwich beam	[98]
Evolutionary Algorithm	Modal Strain Energy	Beam and concrete portal frame	[77]
	Modal data	Simply supported beam	[60]
	Modal data	Hybrid composite/aluminum bolted joints	[90]

In contrast, [80, 94, 95] have further developed FRF data for 2D structure. Shadan *et al.* [80] applied FRF data to identify unknown structural parameters using a sensitivity-based model updating approach. Fathi *et al.* [94] utilized incomplete noisy FRF data for damage detection in an offshore platform. Rahai *et al.* [95] introduced a sensitivity-based finite element model updating method using singular value decomposition of the frequency response function. On the contrary, Wang *et al.* [98] performed an acceleration FRF based model updating method with Kriging model as metamodel in optimization process on a composite structure of honeycomb sandwich beam.

Meanwhile, [81, 82] developed a sensitivity based damage detection method using power spectral density. This approach had been tested for concrete beam, plate and shell models. Instead, Yang *et al.* [96] proposed a modal strain energy-based model updating method for damage assessment of beam-like structure. Kaveh and Zolghadr [77] established a new guided structural damage identification approach by using the change in the amount of modal strain energy of a damage structural element of beam and concrete portal frame. Besides the modal parameter above, Ebrahimian *et al.* [97] performed a series of experiments using time-invariant model parameters to a bridge pier and a moment resisting steel frame. On the other hand, Hou *et al.* [89] considers the uncertainties and varying temperature conditions to locate and quantify the sparse damage.

4. Conclusion

This paper has listed the numerous techniques for finite element model updating and the advantages and limitations of each method. This study showed that researchers in the iterative method extensively use modal data-based methods and frequency-based methods. However, there is an increasing need and scope for the evolutionary algorithm as their application to identify structural damage is not yet well resolved. The insights gained from this study may be helpful for those who want a brief idea of the model updating.

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