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Assessment of sensitivity-based FE model updating technique for damage detection in large space structures

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Abstract. Civil structures may experience progressive deterioration and damage under environmental and operational conditions over their service life. Finite element (FE) model updating method is one of the most important approaches for damage identification in structures due to its capabilities in structural health monitoring. Although various damage detection approaches have been investigated on structures, there are limited studies on large-sized space structures. Thus, this paper aims to investigate the applicability and efficiency of sensitivity-based FE model updating framework for damage identification in large space structures from a distinct point of view. This framework facilitates modeling and model updating in large and geometric complicated space structures. Considering sensitivity-based FE model updating and vibration measurements, the discrepancy between acceleration response data in real damaged structure and hypothetical damaged structure have been minimized through adjusting the updating parameters. The feasibility and efficiency of the above-mentioned approach for damage identification has finally been demonstrated with two numerical examples: a flat double layer grid and a double layer diamatic dome. According to the results, this method can detect, localize, and quantify damages in large-scaled space structures very accurately which is robust to noisy data. Also, requiring a remarkably small number of iterations to converge, typically less than four, demonstrates the computational efficiency of this method.

Keywords: model updating; damage detection; structural health monitoring; space structures; sensitivity analysis; vibration measurements

1. Introduction

Civil structures may experience progressive deterioration and damage under environmental and operational conditions over their service life. The aim of structural health monitoring (SHM) is to identify the presence, location, and extent of damage in civil infrastructures before the damage leads to a catastrophic failure. In general, damage in structures can be defined as any changes to the material and geometric properties such as modulus of elasticity, cross-sectional area, boundary conditions, and system integrity.

FE model updating technique is one of the most important approaches of damage identification in structures because of its capabilities in damage recognition. The fundamental basis of model updating relies on the fact that in practical engineering problems there is always a discrepancy

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between analytical and experimental measured data. In the process of model updating, a problem is considered as an optimization problem while the errors between analytical and experimental measured data is appointed as an objective function where this objective function is minimized by tuning some preselected design parameters (Friswell and Mottershead 2013, Marwala 2010b, Zhang *et al*. 2008). Thus, by comparing the original FE model and updated model, damage in the structure can be detected, localized, and quantified.

In recent decades, a wide range of model updating methods have been developed based on the nature of excitation, measured data, and analysis. In general, model updating parameters can be expressed as either deterministic or probabilistic. Least square-based methods, sensitivity-based methods, and optimization algorithm-based methods are classified as deterministic methods for model updating (Bakir *et al*. 2007, Mottershead *et al*. 2011, Nguyen *et al*. 2018, Savadkoohi *et al*. 2011, Weber and Paultre 2009, Yang and Lin 2005). A tutorial study has been performed on the sensitivity method in FE model updating to provide a basic introduction to this method and its capability for damage detection especially in large-scale structures (Mottershead *et al*. 2011). In recent years, Bayesian probabilistic approach (Sun and Büyüköztürk 2016, Wan and Ni 2018) and optimization algorithms methods (Cha and Buyukozturk 2015, Chou and Ghaboussi 2001, Ghaffarzadeh and Raeisi 2016, Gomes and Silva 2008, Malekzehtab *et al*. 2011, Meruane Naranjo and Heylen 2008, Park *et al*. 2006, Sun *et al*. 2013) have been applied for damage identification of structures.

Several approaches have been established for damage detection in large space structures. (Ghiasi *et al*. 2019)) introduced a three-stage damage detection method for large space structures by implementing improved bat optimization. (Saberi and Kaveh 2015) proposed a method based on charged system searched algorithm and residual force method for detection of damage in space structures. (Gholizad and Safari 2017) offered a two-stage damage detection in large space structures based on continuous wavelet transform and experimental modal analysis. (Kim and Bartkowicz 1993) developed a method for damage detection and health monitoring for large space structures using on-orbit modal identification. A novel four-step method of damage detection was proposed based on strain mode under ambient excitation for space truss structures by (Xu and Wu 2012), which is called the environmental excitation incomplete strain mode method.

Generally, the data measured in FE model updating procedure may be expressed in time, frequency, as well as modal and time-frequency domains. Many authors have researched the model updating in time domain (Cattarius and Inman 1997, Choi and Stubbs 2004, Jaishi and Ren 2005, Lopez and Zimmerman 2002, Majumder and Manohar 2003, Marwala 2010a, Shahidi and Pakzad 2013, Trickey *et al*. 2002, Zimin and Zimmerman 2009).

The research presented in this paper aims to investigate the applicability and efficiency of sensitivity-based iterative FE model updating method using time domain data for structural damage identification in large-sized space structures. To this end, two large space structures have been utilized to validate the accuracy and efficiency of this method. Furthermore, different damage scenarios and sensor placements were considered in the damage identification procedure. Also, in order to study the influence of noise, contaminated recorded acceleration data were included in the analyses. The results revealed the high accuracy and efficiency of this method in damage detection of large space structures.

Section 2 presents the fundamentals of the sensitivity-based FE model updating framework using vibration measurements. Section 3 demonstrate the damage detection framework. Section 4 discusses numerical examples consisting of a flat double layer grid and a double layer diamatic dome. Finally, section 5 concludes the paper.

2. Sensitivity-based iterative model updating

2.1 Theoretical background

The sensitivity method is one of the most powerful FE model updating methods in damage detection of engineering structures. In general, any correlation between measured outputs such as displacement, acceleration, strain, and frequency, as well as the updating parameters including modulus of elasticity, the mass density, and the moment of inertia of elements in structures are non-linear. The sensitivity method is developed based on linearization of this nonlinear relationship using truncated Taylor series expansion (Mottershead *et al.* 2011), which is defined as follows

$$\boldsymbol{\varepsilon}_Z = \boldsymbol{Z}_m - \boldsymbol{Z}(\boldsymbol{\theta}) \approx \boldsymbol{r}_i - \boldsymbol{S}_i(\boldsymbol{\theta} - \boldsymbol{\theta}_i) \tag{1}$$

The error, $\boldsymbol{\varepsilon}_Z$, which is obtained from the differences between the measured output vector ($\boldsymbol{Z}_m$) and the predicted output vector ($\boldsymbol{Z}(\theta)$) is assumed to be small for updating parameters vector ($\boldsymbol{\theta}$) in the vicinity of $\boldsymbol{\theta}_i$, hence

$$\boldsymbol{r}_i \approx \boldsymbol{S}_i \Delta\boldsymbol{\theta} \tag{2}$$

Where, $\boldsymbol{r}_i$ is the residual vector, i.e., the differences between the measured and analytically predicted responses, and is defined as

$$\boldsymbol{r}_i = \boldsymbol{Z}_m - \boldsymbol{Z}_i \tag{3}$$

And $\boldsymbol{S}_i$ is the sensitivity matrix and is given by

$$\boldsymbol{S}_i = \left[\frac{\partial Z_j}{\partial \theta_k}\right]_{\theta=\theta_i} \tag{4}$$

$\Delta\boldsymbol{\theta}$ represents the changes in the updating parameters vector. The subscript *i* indicates the iteration number while subscripts *j* and *k* denote the output data points and the parameter indices, respectively. In each iteration, Eq. (2) is solved for

$$\Delta\boldsymbol{\theta} = \boldsymbol{\theta} - \boldsymbol{\theta}_i \tag{5}$$

And the model is then updated to give

$$\boldsymbol{\theta}_{i+1} = \boldsymbol{\theta}_i + \Delta\boldsymbol{\theta} \tag{6}$$

The updated parameters are then used for updating FE model of the structure. This iterative procedure continues until adequate convergence is attained. Finally, the changes in the updating parameters ($\Delta\boldsymbol{\theta}$) could be regarded as a damage vector. In order to solve Eq. (2), the equation system must be overdetermined meaning that the number of parameters should always be smaller than the number of measurements (Mottershead *et al*. 2011).

Essentially, model updating is an optimization problem. Solving the optimization problem by minimizing the objective function, will yield the updated parameters. In this paper, the objective function is established based on the differences of the acceleration response data between the measured output data and the analytical prediction. The objective function here is defined as

$$J(\boldsymbol{\theta}) = \boldsymbol{\varepsilon}_Z^T \boldsymbol{W}_\varepsilon \boldsymbol{\varepsilon}_Z \tag{7}$$

Where, $\mathbf{W}_{\varepsilon}$ is the symmetric weighting matrix. This matrix is included to account the importance of each term in the residual vector. Accordingly, this study set weighting matrix equal to identity matrix, i.e., $\mathbf{W}_{\varepsilon} = \mathrm{I}$. For overdetermined system of equation objective function are minimized with respect to $\Delta\boldsymbol{\theta}_{\mathbf{i}}$ to give parameter estimation as

$$\Delta\boldsymbol{\theta}_i = [\boldsymbol{S}^T\boldsymbol{W}_{\varepsilon}\boldsymbol{S}]^{-1}\boldsymbol{S}^T\boldsymbol{W}_{\varepsilon}\boldsymbol{r}_i \tag{8}$$

Which is a least square solution to the optimization problem.

2.2 Updating parameters and measured data

The updating parameters are the unknown physical features of the model. Different types of updating parameters are used in FE model updating such as Young's Modulus, mass density of materials, moment of inertia, thickness, and boundary conditions of elements. Parameter selection plays a key role in FE model updating (Wan & Ren, 2014). In the model updating process, the measured outputs must be sensitive to any small changes in updating parameters. In this study, modulus of elasticity (E) is considered as the updating parameter. The updating parameter vector ($\boldsymbol{\theta}$) is shown in Eq. (9), where subscript n denotes the number of elements.

Time-domain response data extracted from impact tests contain high-frequency information and are sensitive to damage. Unlike frequency domain methods which generally rely on analytical models, time domain methods are independent of modal parameters and analytical models (Cattarius & Inman, 1997). Hence, the recorded acceleration response data are extracted at some certain nodes of structures via the vibration test procedure which is implemented as the response data measured in the process of model updating. The measured data vector ($\mathbf{Z}$) is defined according to Eq. (10), where subscript m refers to the number of sensors times the number of recorded time points of acceleration.

$$\boldsymbol{\theta} = [E_1 \quad E_2 \quad \cdots \quad E_n]^{-1} \tag{9}$$

$$\boldsymbol{Z} = [a_1 \quad a_2 \quad \cdots \quad a_m]^{-1} \tag{10}$$

2.3 Sensitivity matrix

The sensitivity or Jacobian matrix is a first-order derivative of residuals with respect to updating parameters as defined in Eq. (4). Two different approaches can be employed to establish the sensitivity matrix including analytical and numerical methods. Numerical method is usually utilized where there is no precise relationship between the measured outputs and physical parameters; as such, this method is used in this paper. Each term in the sensitivity matrix represents the partial derivative of acceleration response with respect to modulus of elasticity. The formulation takes the following form

$$\boldsymbol{S}_i = \begin{bmatrix} \frac{\partial a_1}{\partial E_1} & \frac{\partial a_1}{\partial E_2} & \cdots & \frac{\partial a_1}{\partial E_n} \\ \frac{\partial a_2}{\partial E_1} & \frac{\partial a_2}{\partial E_2} & \cdots & \frac{\partial a_2}{\partial E_n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial a_m}{\partial E_1} & \frac{\partial a_m}{\partial E_2} & \cdots & \frac{\partial a_m}{\partial E_n} \end{bmatrix} \tag{11}$$

2.4 Noise modeling

In practice, several factors such as ambient vibration or instrument errors influence the response accuracy of a real structure in a laboratory or in field measurements. Note that noisy data have adverse effects on results. To capture this, Gaussian White Noise (GWN) has been considered in the analyses. In signal processing, white noise is a random signal with equal intensity at different frequencies whose components have a normal distribution with a zero mean and unit standard deviation. In this paper, noise is applied according to the following equation

$$\boldsymbol{Z}_{mo} = \boldsymbol{Z}_{po} + NL \times \boldsymbol{GWN} \times \boldsymbol{Z}_{po} \tag{12}$$

Where, $\boldsymbol{Z}_{mo}$ is the measured output vector, $\boldsymbol{Z}_{po}$ denotes the predicted output, NL shows the noise level, and $\boldsymbol{GWN}$ represents the gaussian white noise vector.

2.5 Damage formulation

Recently, various damage indices have been introduced by many researchers. Damage in structures could be considered as corrosion or chemical degradation, material softening due to cyclic loading, loss of members and loosening connections between members, cracks under overloading, etc. All the above-mentioned phenomena will affect the stiffness of structures. The stiffness matrix of truss structures depends on modulus of elasticity and cross-sectional area of its elements. Thus, any changes in these parameters could be supposed as a damage in the FE model updating process. In this study, the damage state has been simulated by reducing the modulus of elasticity of elements, which is expressed as follows

$$E_i^d = \frac{(100 - DR_i)}{100} \times E_i^u \tag{13}$$

Where, DR_i is the damage ratio of the ith member in percent which varies from 0 to 100, with 0 and 100 indicating undamaged and fully damaged states, respectively, E_i^d and E_i^u represent the modulus of elasticity of the ith member for damaged and undamaged states, respectively.

2.6 Damage detection

In FE model updating, the difference between experimental and numerical data should be considered as an objective function. In this paper, experimental output data have been extracted from FE models of the structures via simulated experimental data procedure. The model updating for damage detection goes through the following eight steps:

1. Selecting the updating parameter vector
2. Establishing the simulated experimental model and extracting the measured output data
3. Establishing the FE model of the structure and extracting the predicted output data
4. Sensitivity analysis and computing the sensitivity matrix
5. Solving penalty function and obtaining the updated design parameters
6. Updating the FE model in step 3 to better reflect the measured data in step 2.
7. Further updating the updated model identified in step 6 to minimize the discrepancy between measured data and predicted data
8. If proper convergence is achieved, existence, location, and extent of damage can be recognized

To sum up, the whole flowchart of the damage detection procedure is shown in Fig. 1.

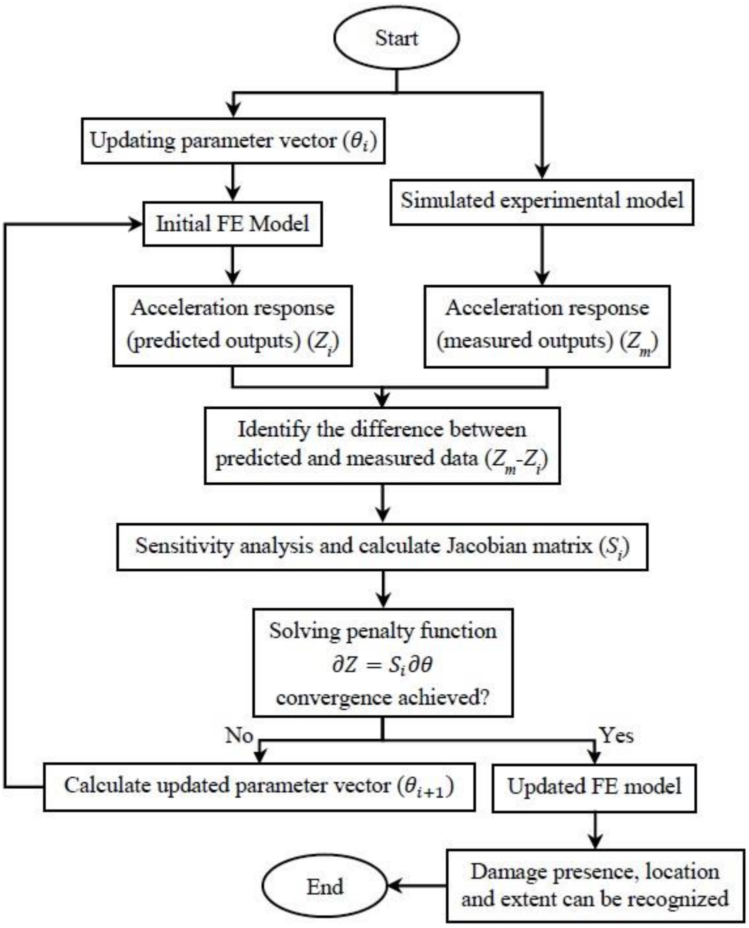


Fig. 1 Flowchart for the model updating procedure

3. Framework of damage detection procedure

Several approaches have been developed for damage detection in space structures. Meanwhile, FE model updating has been rarely studied due to its difficulties in modeling and model updating process. To overcome this, a novel method is presented in this article. This method is classified in two phases including modeling and model updating process. The entire procedure is organized in Fig. 2. The modeling of large complicated space structures in MATLAB® (The MathWorks, Inc., MA, USA) software is a computationally expensive operation and very time-consuming. This method in phase 1 facilitates this problem. Any space structure in shape and size can be easily modeled in Formian software as an initial model. In the next stage, the initial model is transferred to AutoCAD software and then to SAP2000 software. The date required for phase 2 such as node coordinates, number of nodes, geometric and mechanical properties of members, seismic nodal mass,

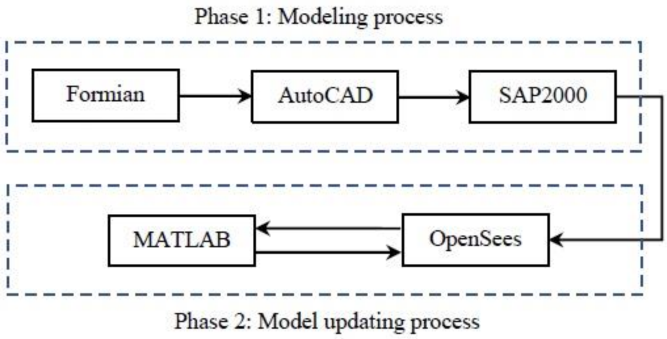


Fig. 2 Flowchart of the damage detection procedure

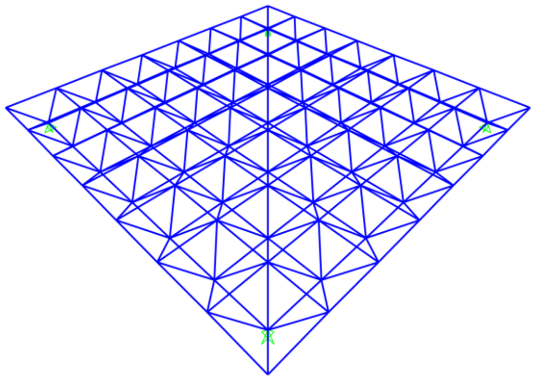
etc. could be extracted accurately from SAP2000. Model updating process in phase 2 is performed through linking MATLAB and OpenSees software framework. The detailed process has been illustrated in Fig. 1. In each iteration, FE analysis is performed in OpenSees with the analysis results including acceleration in sensor placements transferred to MATLAB to solve the penalty function and update design parameters. The updated parameters are then transferred to OpenSees to analyze the updated model. This process continues until convergency is achieved and residual vector becomes ignorable. Based on the changes in the updating parameters, damage in the model can be identified. Implementing this method in damage detection process has three important benefits: i) applicability for modeling and analyzing space structures at any size and shape, ii) eliminating any error in the modeling and model updating process, iii) being straightforward and timesaving.

4. Numerical examples

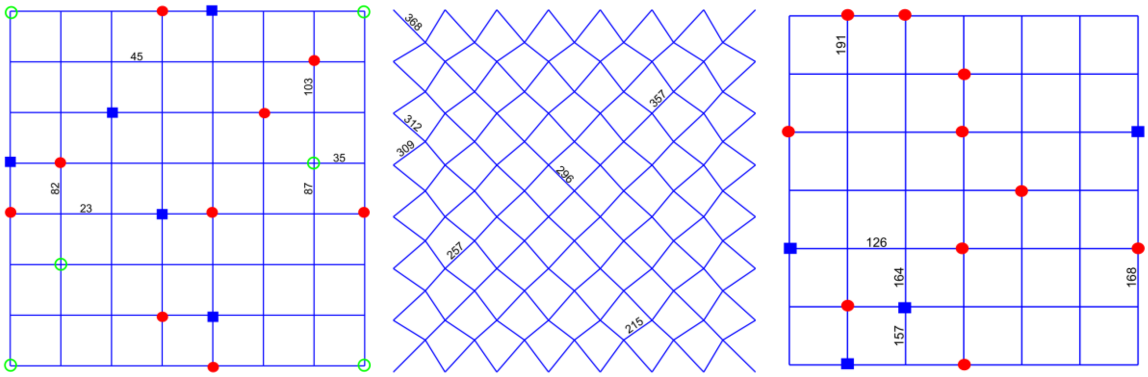
In this section, applicability of the above-mentioned model updating method to damage identification in large-scaled space structures is demonstrated with two numerical examples. To model the energy dissipation characteristics of the structure, a proportional damping model called Rayleigh damping is used. The deadweight of the members is treated as lumped mass concentrated at the nodes. Acceleration response data are measured in sensor placements due to impulsive loads on certain points on the structure. All analysis is performed on a standard Intel® Core™ i7-7500U 3.5GHz PC with 8GB RAM.

4.1 Flat double layer grid

The first example represents a flat double layer grid consisting of 392 truss elements and 113 nodes. Fig. 3 displays the perspective and plan views of this model. The parameters considered in the model are reported in Table 1. The grid is supported at four-corner points of the bottom layer which are constrained in x, y, and z directions. An impulsive load pattern is applied vertically to the middle point of the bottom layer (node number 89) where the resulting acceleration response is measured by different sensor patterns. Several damage cases are considered to investigate the influence of location, severity, and number of damaged elements as well as sensor placements on the results. In this regard, three different damage scenarios and two different sensor placements are defined for with- and without-noise states. Tables 2-4 provide the specifications of these damage cases.



(a) Perspective view of flat double layer grid



(b)Top layer elements (c)Web elements (d) Bottom layer elements

nsor configuration a Sensor configuration b Sensor configuration a & b

Fig. 3 Perspective and plan views of flat double layer grid

Table 1 Specification of flat double layer grid

Parameter	Value
Length	28 m
Width	28 m
Height	1.45 m
Cross-sectional area	0.00541 m^2
Modulus of elasticity	200 GPa
Mass density	7860 kg/m^3

Table 2 Different damage scenarios

Damage scenario	Element number	Element position	Damage ratio (%)
A	45	TLE[a]	15
	157	BLE[b]	35
	312	WE[c]	20
B	35	TLE	10
	82	TLE	25
	168	BLE	15
	296	WE	20
	357	WE	35
C	23	TLE	25
	87	TLE	30
	103	TLE	15
	126	BLE	30
	164	BLE	25
	191	BLE	10
	215	WE	15
	257	WE	30
	309	WE	25
	368	WE	15

[a] Top layer element
[b] Bottom layer element
[c] Web element

Table 3 Different sensor configurations

Sensor configuration	Number of sensors	Node number
a	15	1, 8, 13, 18, 28, 33, 39, 43, 57, 61, 64, 66, 74, 79, 99
b	25	1, 5, 8, 12, 18, 25, 29, 32, 34, 39, 46, 55, 57, 60, 64, 68, 73, 82, 85, 90, 93, 96, 103, 108, 109

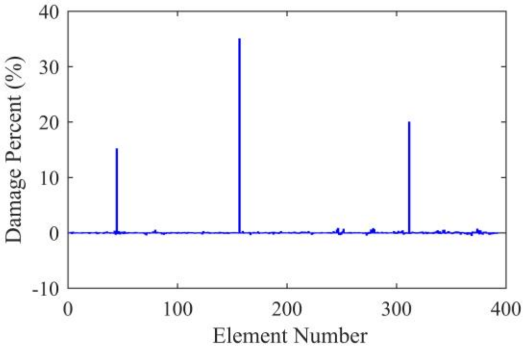
The results of damage identification process after the model updating procedure for each damage case are given in Fig. 4. In the first step of model updating analyses, with the results presented in Figs. 4(a)-4(f), it is assumed that acceleration measurements are noise-free, while in the second step of analyses with the results depicted in Figs. 4(g)-4(l), 5% noise is considered in the data measurements. Comparison between actual and predicted damage in two cases, case #1 and case #2, shows that both the location and severity of the damage have been successfully determined. Another important point which can be obtained is that elevation of the number of sensors in the updating process leads to more accurate results. Also, the same results can be seen for other cases in Figs. 4(c)-(f). Current procedure can find all damaged elements as well as their damage percentage accurately, despite the different damage scenarios and sensor configuration in the structure, suggesting the stability and robustness of this method in damage detection in large-sized flat double layer grids. It can be noticed from Figs. 4(g)-4(l) that, due to the influence of noise, intact elements have few deviations and appeared as negligible damaged elements. This undesirable effect of noisy measurements can be diminished by rearranging and increasing the number of data acquisition points.

4.2 Double layer diamatic dome

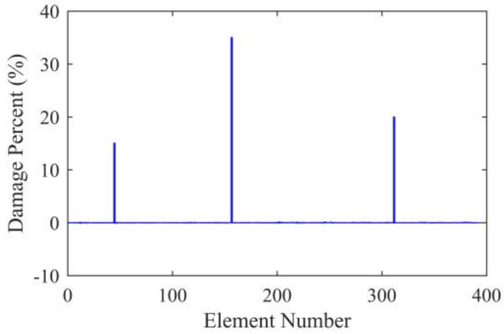
For further investigation, a double layer diamatic dome with 576 truss elements and 157 nodes is considered. The geometry of the truss model is shown in Fig. 5, and Table 5 lists the parameters used in the model. The material properties and cross-sectional area of members are the same as those considered for the previous example. The dome is supported at twelve points in the bottom layer which are constrained in x, y, and z directions. An impulsive load pattern is applied vertically to four nodes including node numbers 1, 50, 100, and 150 where the resulting acceleration response of the structure is measured by sensors in some predefined nodes. Several damage cases are considered to investigate the influence of location, severity, and number of damaged elements and sensor placements on the results. In this regard, three different damage scenarios and two different sensor placements are defined for with- and without-noise states. Tables 6-8 reports the specifications of these damage cases.

Table 4 Different damage cases

Damage case	Damage scenario	Sensor configuration	Noise level (%)
1	A	a	0.0
2	A	b	0.0
3	B	a	0.0
4	B	b	0.0
5	C	a	0.0
6	C	b	0.0
7	A	a	5.0
8	A	b	5.0
9	B	a	5.0
10	B	b	5.0
11	C	a	5.0
12	C	b	5.0



(a)



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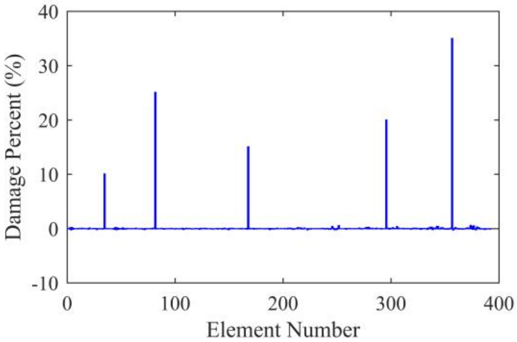

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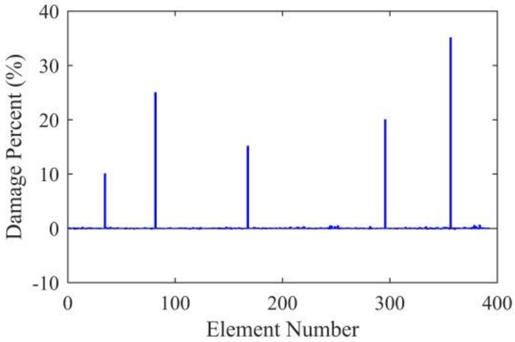

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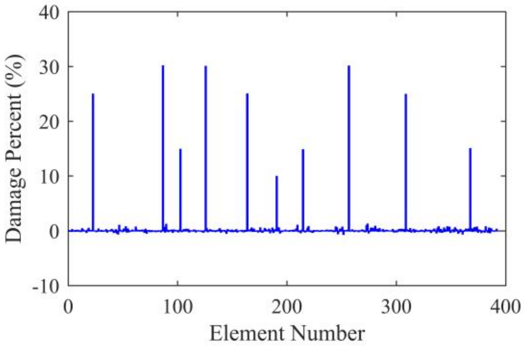
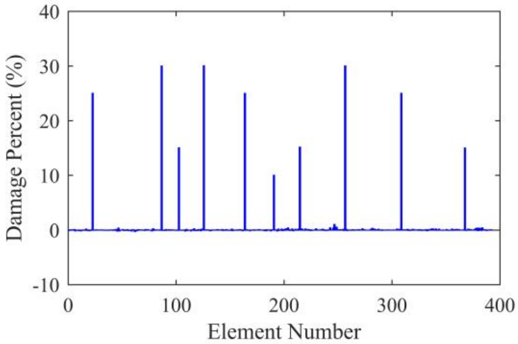


(e)



(f)

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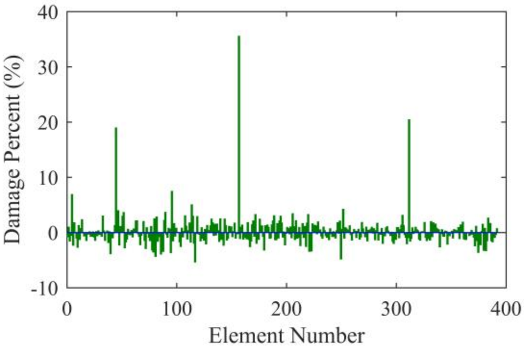
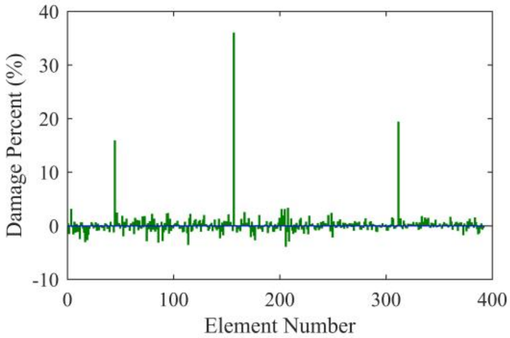


(g)



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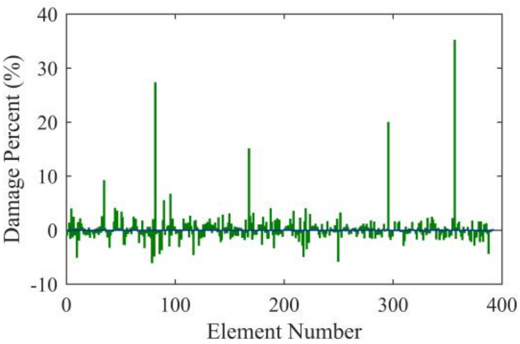
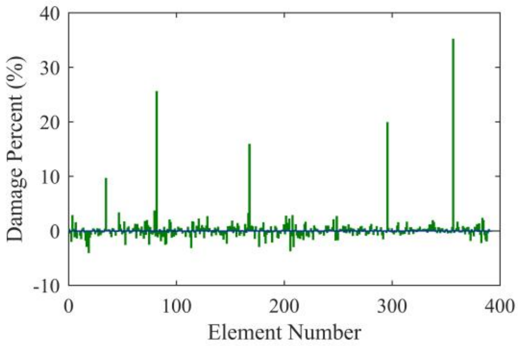
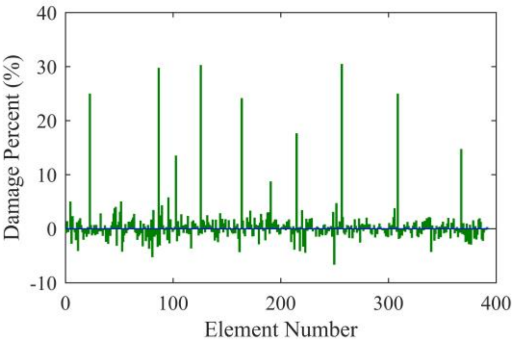


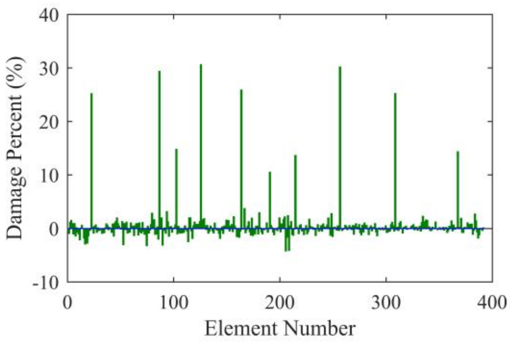
(i)



(j)

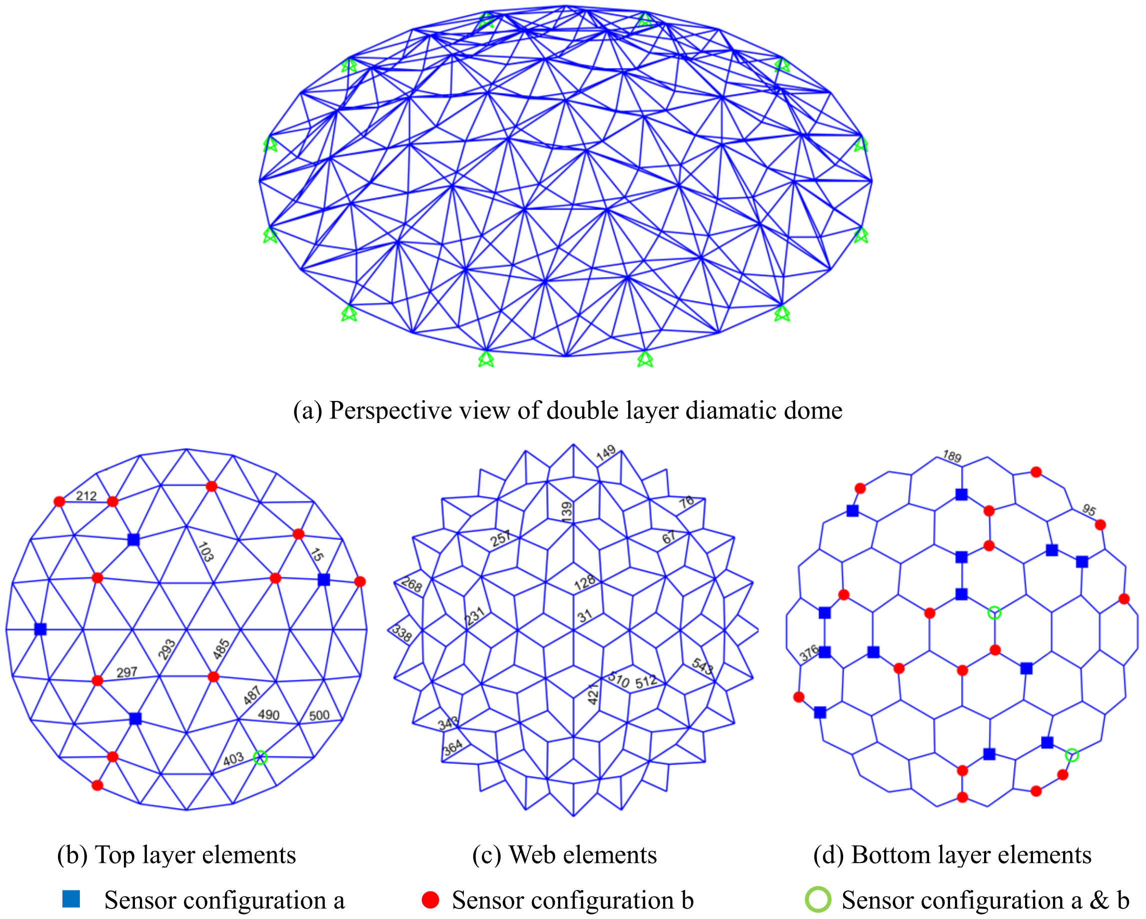


(k)



(l)

Fig. 4 Damage detection results: (a) Case #1, (b) Case #2, (c) Case #3, (d) Case #4, (e) Case #5, (f) Case #6, (g) Case #7, (h) Case #8, (i) Case #9, (j) Case #10, (k) Case #11, (l) Case #12



(a) Perspective view of double layer diamatic dome

(b) Top layer elements (c) Web elements (d) Bottom layer elements

Fig. 5 Perspective and plan views of double layer diamatic dome

Table 5 Specification of double layer diamatic dome

Parameter	Value
Span	42.321 m
Rise	6.875 m
Cross-sectional area	0.00541 m^2
Modulus of elasticity	200 GPa
Mass density	7860 kg/m^3

Damage identification results are summarized in Fig. 6 for each damage case just as provided in Table 8. Figs. 6(a)-6(f) display the results of models without noise in acceleration measurements while Figs. 6(g)-6(l) depict the results of models with 5% noise in the measured data.

Table 6 Different damage scenarios

Damage scenario	Element number	Element position	Damage ratio (%)
A	76	WE	10
	139	WE	15
	268	WE	20
	343	WE	25
	485	TLE	20
B	15	TLE	10
	95	BLE	15
	128	WE	20
	231	WE	25
	297	TLE	20
	364	WE	15
	403	TLE	10
	487	TLE	20
	500	TLE	25
	512	WE	15
C	31	WE	10
	67	WE	15
	95	BLE	20
	103	TLE	25
	149	WE	20
	189	BLE	15
	212	TLE	10
	257	WE	20
	293	TLE	25
	338	WE	15
	376	BLE	20
	421	WE	10
	490	TLE	20
	510	WE	25
	543	WE	15

As with example 1, both location and severity of the damage have been well established through comparing actual and predicted damage in case #1 and case #2. The other important point is the number of sensors; the more sensors in the updating process, the more accurate the results will be. According to Figs. 6(c)-6(f), similar results are valid for damage cases 3-6. Current procedure can find all damaged elements as well as their damage percentage accurately, despite the different damage scenarios and sensor configuration in the structure, demonstrating the stability and robustness of this method in damage detection in large-scaled double layer diamatic domes.

Table 7 Different sensor configurations

Sensor configuration	Number of sensors	Node number
a	20	8, 16, 20, 28, 38, 46, 50, 56, 67, 77, 85, 90, 99, 101, 112, 119, 136, 147, 152, 155
b	30	5, 9, 12, 16, 24, 29, 32, 39, 41, 47, 52, 57, 63, 68, 72, 78, 84, 89, 93, 97, 105, 108, 114, 119, 124, 128, 133, 138, 149, 155

Table 8 Different damage cases

Damage case	Damage scenario	Sensor configuration	Noise level (%)
1	A	a	0.0
2	A	b	0.0
3	B	a	0.0
4	B	b	0.0
5	C	a	0.0
6	C	b	0.0
7	A	a	5.0
8	A	b	5.0
9	B	a	5.0
10	B	b	5.0
11	C	a	5.0
12	C	b	5.0

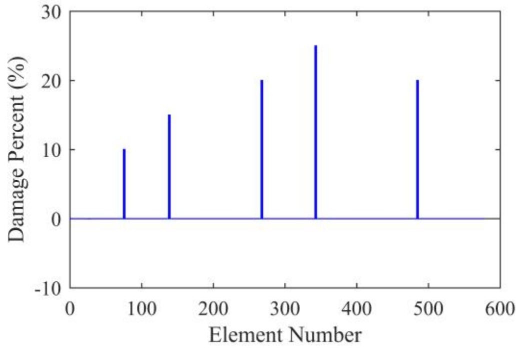
Based on Figs. 6(g)-6(l), due to the influence of noise, intact elements have some deviations and appeared as insignificant damaged elements. This undesirable effect of noisy measurements can be alleviated by rearranging and increasing the number of sensors.

Finally, two different error indices have been used to quantify the accuracy of the damage identification results and to evaluate the confidence plus robustness of the model updating method. The first criterion is Mean Absolute Error (MAE) which denotes the average difference between the actual and predicted results, and is expressed as follows

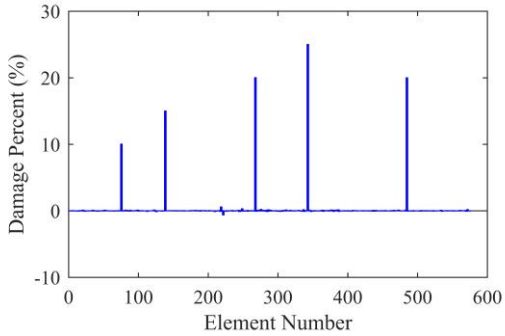
$$MAE = \frac{1}{n} \left\| \delta\theta - \delta\tilde{\theta} \right\| = \frac{1}{n} \sum_{i=1}^{n} \left| \delta\theta_i - \delta\tilde{\theta}_i \right| \tag{14}$$

Where, n is the number of updating parameters, $\delta\theta_i$ and $\delta\tilde{\theta}_i$ represent the ith component of the predicted and actual damage percent vector, respectively. Another criterion considered in this study is Mean Relative Error (MRE) which reveals the mean absolute error divided by the actual value, and is defined according to the following equation

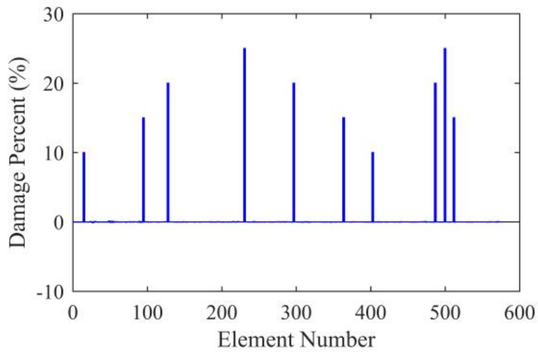
$$MRE = \frac{1}{n} \frac{\left\| \delta\theta - \delta\tilde{\theta} \right\|}{\left\| \delta\tilde{\theta} \right\|} = \frac{1}{n} \frac{\sum_{i=1}^{n} \left| \delta\theta_i - \delta\tilde{\theta}_i \right|}{\sum_{i=1}^{n} \left| \delta\tilde{\theta}_i \right|} \tag{15}$$



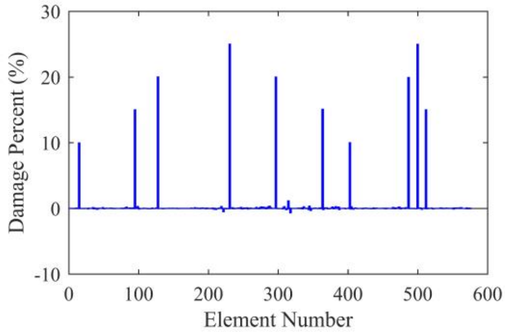
(a)



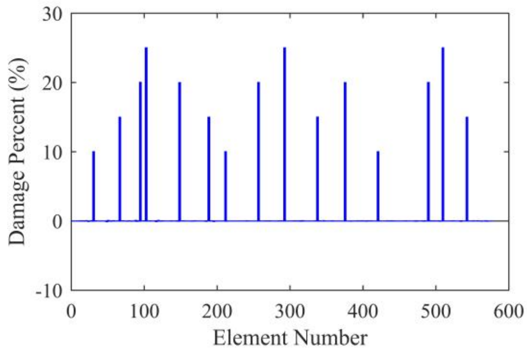
(b)



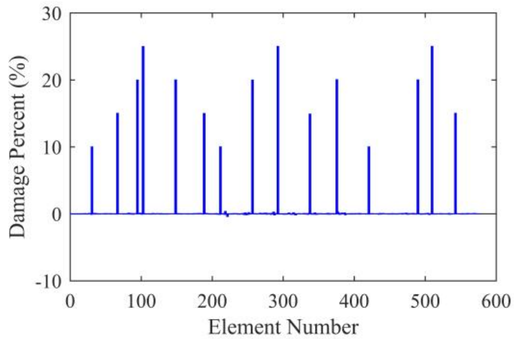
(c)



(d)

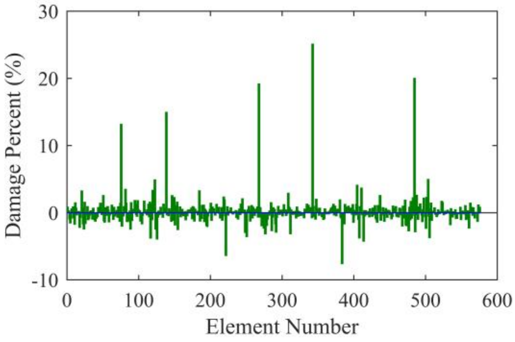


(e)

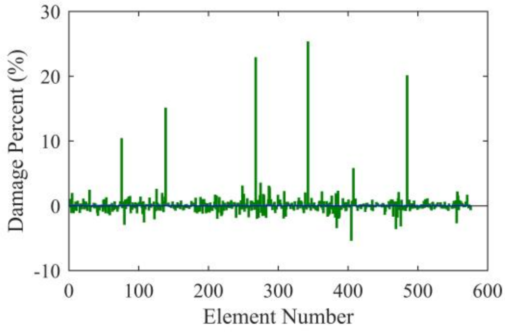


(f)

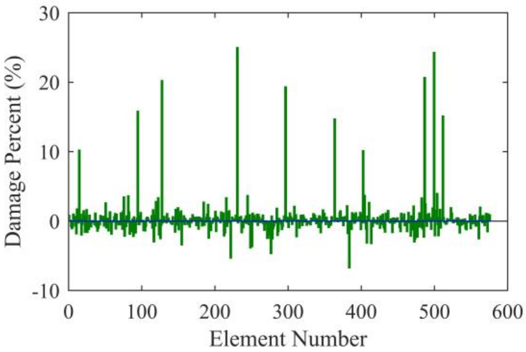
Continued-



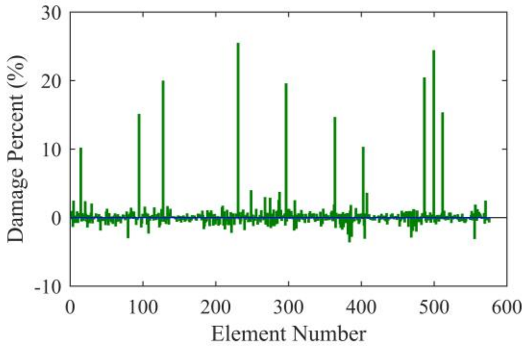
(g)



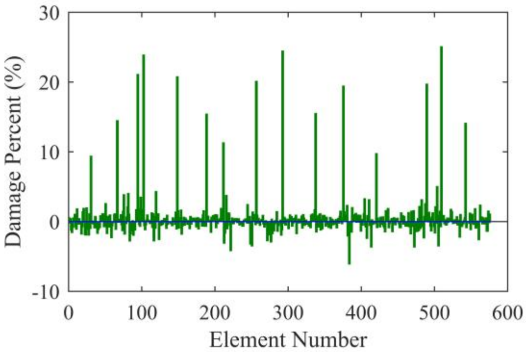
(h)



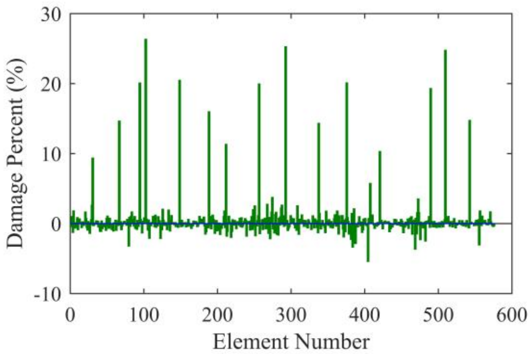
(i)



(j)



(k)

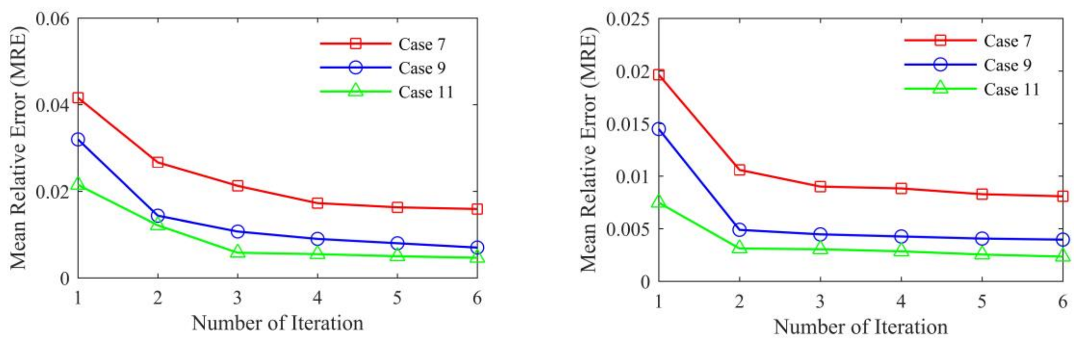


(i)

Fig. 6 Damage detection results: (a) Case #1, (b) Case #2, (c) Case #3, (d) Case #4, (e) Case #5, (f) Case #6, (g) Case #7, (h) Case #8, (i) Case #9, (j) Case #10, (k) Case #11, (l) Case #12

Table 9 Comparison of error indices

Damage case	Index			
	MAE		MRE	
	Ex. 1	Ex. 2	Ex. 1	Ex. 2
1	0.082	0.001	0.000	0.000
2	0.016	0.025	0.000	0.000
3	0.058	0.007	0.001	0.000
4	0.055	0.040	0.001	0.000
5	0.018	0.006	0.001	0.000
6	0.062	0.019	0.000	0.000
7	1.211	0.782	0.017	0.009
8	0.717	0.582	0.010	0.006
9	1.125	0.770	0.011	0.004
10	0.723	0.558	0.007	0.003
11	1.204	0.782	0.005	0.003
12	0.719	0.605	0.003	0.002



(a) (b)

Fig. 7 Convergence graphs of FE model updating process: (a) Flat double layer grid, (b) Double layer diamatic dome

Note that both indices are always non-negative where smaller values are regarded as better results. The above-mentioned error indices have been calculated for all damage cases as shown in Table 9. It can be observed that the computed values are very small for all cases, suggesting the stability and robustness of sensitivity-based FE model updating using time-domain data in damage detection of large-scaled space structures.

Another notable point is the rate of convergence which is one of the factors revealing the computational efficiency of an iterative numerical method. Thus, to study the efficiency of this method, convergence has been calculated and presented in Fig. 7, by evaluating the mean relative error in each iteration. In this regard, critical damage cases including case #7, case #9, and case #11 have been considered. These damage cases are noisy and have a smaller number of sensors. As shown in the graph below, requiring remarkably fewer iterations to converge, typically less than four, in both examples, demonstrates the computational efficiency of this method.

5. Conclusions

This study investigated the applicability of sensitivity-based FE model updating framework and vibration measurements for structural damage detection of large-sized space structures from a different point of view. No comprehensive study has been done in this context yet, especially in the time domain. In this process, acceleration response data in sensor placements, used at certain points, were measured with regards to impact loading. The modulus of elasticity of elements was considered as an updating parameter in FE model updating. This framework consisted of two phases, modeling and model updating. In the modeling phase, the initial model was modeled in Formian and transferred to AutoCAD and then to SAP2000. In the model updating phase, on the other hand, model updating process was performed by linking MATLAB and OpenSees software framework to each other.

Two case studies, a flat double layer grid and a double layer diamatic dome, with various damage scenarios, were carried out to assess the efficiency of the presented method. The results showed that this method is efficient in damage identification in large space structures. Furthermore, damage detection process was independent of size and feature of the structures. The greater the number of data acquisition device in the structure, the more accurate the results would be in the presence of noisy data.

Finally, to illustrate the accuracy of this method, two different error indices including Mean Absolute Error (MAE) and Mean Relative Error (MRE) were evaluated. According to the results, these index values were negligible suggesting the high accuracy of the method. Also, requiring to remarkably fewer iterations to converge, typically less than four, implied the high rate of convergency. Overall, it is deduced from the results that implementing this method in damage detection process has four important benefits: i) applicability for modeling space structures at any size and shape, ii) eliminating any error in the modeling and model updating process, iii) being straightforward, timesaving and computationally efficient and finally, iv) being capable of detecting, localizing, and quantifying damage in structures.

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References

Bakir, P.G., Reynders, E. and De Roeck, G. (2007), “Sensitivity-based finite element model updating using constrained optimization with a trust region algorithm”, *J. Sound Vib.*, **305**(1-2), 211-225.

Cattarius, J. and Inman, D. (1997), “Time domain analysis for damage detection in smart structures”, *Mech. Syst. Signal Pr.*, **11**(3), 409-423.

Cha, Y.J. and Buyukozturk, O. (2015), “Structural damage detection using modal strain energy and hybrid multiobjective optimization”, *Comput.-Aided Civil Infrastruct. Eng.*, **30**(5), 347-358.

Choi, S. and Stubbs, N. (2004), “Damage identification in structures using the time-domain response”, *J. Sound Vib.*, **275**(3-5), 577-590.

Chou, J.H. and Ghaboussi, J. (2001), “Genetic algorithm in structural damage detection”, *Comput. Struct.*, **79**(14), 1335-1353.

Friswell, M. and Mottershead, J.E. (2013), "*Finite element model updating in structural dynamics*", (Vol. **38**): Springer Science & Business Media.

Ghaffarzadeh, H. and Raeisi, F. (2016), "Damage identification in truss structures using finite element model updating and imperialist competitive algorithm", *Jordan J. Civil Eng.*, **159**(3317), 1-12.

Ghiasi, R., Fathnejat, H. and Torkzadeh, P. (2019), "A three-stage damage detection method for large-scale space structures using forward substructuring approach and enhanced bat optimization algorithm", *Eng. with Comput.*, **35**(3), 857-874.

Gholizad, A. and Safari, H. (2017), "Damage identification of structures using experimental modal analysis and continuous wavelet transform", *Numerical Methods in Civil Engineering*.

Gomes, H. and Silva, N. (2008), "Some comparisons for damage detection on structures using genetic algorithms and modal sensitivity method", *Appl. Math. Model*., **32**(11), 2216-2232.

Jaishi, B. and Ren, W.X. (2005), "Structural finite element model updating using ambient vibration test results", *J. Struct. Eng*., **131**(4), 617-628.

Kim, H. and Bartkowicz, T. (1993), "*Damage detection and health monitoring of large space structures*", Paper presented at the 34th Structures, Structural Dynamics and Materials Conference.

Lopez, F. and Zimmerman, D.C. (2002), "*Nonlinear damage detection using a time-domain minimum rank perturbation theory*", Paper presented at the Smart Nondestructive Evaluation for Health Monitoring of Structural and Biological Systems.

Majumder, L. and Manohar, C. (2003), "A time-domain approach for damage detection in beam structures using vibration data with a moving oscillator as an excitation source", *J. Sound Vib.*, **268**(4), 699-716.

Malekzehtab, H., Golafhani, A. and Mohajeri, S. (2011), "*Application of Genetic Algorithm Based Finite Element Model Updating in Damage Detection of Offshore Jacket Platforms*", Paper presented at the Second International Conference on Recent Trends in Transportation, Environmental and Civil Engineering, Bangalore, India.

Marwala, T. (2010a), "Finite-element-model Updating Applied in Damage Detection", *Finite-element-model updating using computional intelligence techniques: Applications to structural dynamics*, 203-223.

Marwala, T. (2010b), "*Finite element model updating using computational intelligence techniques: applications to structural dynamics*", Springer Science & Business Media.

Meruane Naranjo, V. and Heylen, W. (2008), "*Damage detection by a real-parameter hybrid genetic algorithm"*, Paper presented at the Proceedings of the European Workshop on Structural Health Monitoring.

Mottershead, J. E., Link, M., & Friswell, M. I. (2011), "The sensitivity method in finite element model updating: a tutorial", *Mech. Syst. Signal Pr*., **25**(7), 2275-2296.

Nguyen, C.U., Huynh, T.C. and Kim, J.T. (2018), "Vibration-based damage detection in wind turbine towers using artificial neural networks", *Struct. Monit. Maint*., **5**(4), 507-519.

Park, J.H., Lee, J.M., Kim, J.T. and Ryu, Y.S. (2006), "*Genetic Algorithm-based damage detection method using natural frequency and modal strain energy*", Paper presented at the Symposium on Optimization of Structural and Mechanical Systems, China.

Saberi, M. and Kaveh, A. (2015), "Damage detection of space structures using charged system search algorithm and residual force method", *Iranian J. Sci. Technol. T. Civil Eng.*, **39**(C2), 215-229.

Savadkoohi, A.T., Molinari, M., Bursi, O.S. and Friswell, M.I. (2011), "Finite element model updating of a semi-rigid moment resisting structure", *Struct. Control Health Monit*., **18**(2), 149-168.

Shahidi, S.G. and Pakzad, S.N. (2013), "Generalized response surface model updating using time domain data", *J. Struct. Eng*., **140**(8), A4014001.

Sun, H. and Büyüköztürk, O. (2016), "Probabilistic updating of building models using incomplete modal data", *Mech. Syst. Signal Pr*., ***75***, 27-40.

Sun, H., Luş, H. and Betti, R. (2013), "Identification of structural models using a modified Artificial Bee Colony algorithm", *Comput. Struct*., **116**, 59-74.

Trickey, S., Todd, M.D., Seaver, M.E. and Nichols, J.M. (2002), "*Geometric time-domain methods of vibration-based damage detection*", Paper presented at the Smart Nondestructive Evaluation for Health Monitoring of Structural and Biological Systems.

Wan, H.P. and Ni, Y.Q. (2018), “Bayesian modeling approach for forecast of structural stress response using structural health monitoring data”, *J. Struct. Eng*., **144**(9), 04018130.

Wan, H.P. and Ren, W.X. (2014), “Parameter selection in finite-element-model updating by global sensitivity analysis using Gaussian process metamodel”, *J. Struct. Eng*., **141**(6), 04014164.

Weber, B. and Paultre, P. (2009), “Damage identification in a truss tower by regularized model updating”, *J. Struct. Eng*., **136**(3), 307-316.

Xu, Z.D. and Wu, K.Y. (2012), “Damage detection for space truss structures based on strain mode under ambient excitation”, *J. Eng. Mech*., **138**(10), 1215-1223.

Yang, J. N., & Lin, S. (2005), “Identification of parametric variations of structures based on least squares estimation and adaptive tracking technique”, *J. Eng. Mech*., **131**(3), 290-298.

Zhang, X., Sim, S., & Spencer Jr, B. (2008), “*Finite element model updating of a truss model using incomplete modal data*”, Paper presented at the Proc. World Forum on Smart Materials and Smart Structures Technology.

Zimin, V. and Zimmerman, D. (2009), “Structural damage detection using time domain periodogram analysis”, *Struct. Health Monit*., **8**(2), 125-135.

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