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Structural Damage Detection Based on Improved Multi-Particle Swarm Co-Evolution Optimization Algorithm

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Abstract

This chapter presents an improved multi-particle swarm co-evolution optimization algorithm (IMPSCO) to detect structural damage. Firstly, IMPSCO is integrated with Newmark's algorithm for damage detection and system identification, which just need few sensors. In addition, for reducing the searching parameters, a two-stage damage detection method based on modal strain energy and IMPSCO is presented. In order to validate the proposed method, a seven-story steel frame experiment in laboratory conditions is performed and a comparison is made between the proposed approach and genetic algorithm (GA). The results show that: (1) the proposed methods can not only effectively locate damage location but also accurately quantify the damage severity. Besides, it has excellent noise-tolerance and adaptability; (2) for integrating IMPSCO and Newmark's algorithm, it implements only by using any kinds of structural time-series responses and the excitation force; (3) compared with genetic algorithm, IMPSCO is more efficient and robust for damage detection with a better noise-tolerance.

Keywords: structural damage detection, improved multi-particle swarm co-evolution optimization (IMPSCO) algorithm, time-domain, frequency-domain, modal strain energy, Newmark's algorithm

1. Introduction

Structural health monitoring (SHM) and damage detection are taking an increasingly important role in civil engineering structures. As the main part of SHM programmes, damage localization and quantification strategies can provide basic information about the health of structural systems. Numerous methods have been developed and employed for damage detection based on vibration data. It can be divided in two major groups [1]. The First group are approaches in which a direct methodology is introduced for damage detection. Such an aim was achieved by performing signal processing-based procedures [2] and mathematical

analysis [3]. The Second group are defining damage detection problem as an inverse problem and solving it by employing optimization procedures [4, 5].

During the last two decades, standard particle swarm optimization (PSO) and its corresponding approaches [6–9] have been applied to damage detection problems due to the virtues in global optimization. For example, Begambre and Laier [10] proposed PSOS model-based damage detection algorithm using frequency domain data to locate the damage location and quantify the damage extent. Therein, the minimization function is based on the frequency response functions of the system. Furthermore, Mohan et al. [11] also evaluated the use of frequency response function with the help of PSO for structural damage identification, which verified by beam plane frame structures. Nanda et al. [5] proposed unified particle swarm optimization (UPSO) technique for solving crack assessment problems in frame-like structures. In recent years, the multi-particle swarm co-evolution optimization (MPSCO) by integrating the collaborative theory in ecology with the principle of automatic adjustment has become a popular hotspot [12–14]. Nevertheless, such efforts cannot completely solve the problem of local optimum. Therefore, many scholars proposed many multi-stage damage detection methods, namely, firstly using other relevant method to initially locate damage location and utilizing optimization algorithm to accuracy identify damage. For instance, Seyedpoor [15] presented a two-stage damage detection method based on modal strain energy and PSO to identify damage. Vo-Duy et al. [16] presented a two-step approach based on modal strain energy method and an improved differential evolution algorithm for damage detection in laminated composite structures.

However, during practical applications, there exist some drawbacks. For example, standard PSO algorithm and improved PSO are computationally intensive because they must deal with a great number of damage variables. Therefore, an improved MPSCO algorithm called IMPSCO is proposed and applied to structural damage detection. In IMPSCO, the evolutionary theory is integrated with MPSCO as to reduce the possibility of falling into the local optimum. Furthermore, IMPSCO integrates with Newmark's algorithm in time-domain for damage detection. Because it just uses any kinds of structural time-series responses and only requires very few sensors in practical applications. In addition, this chapter also presents a two-stage method based on modal strain energy change ratio and IMPSCO algorithm for the purpose of reducing the complexity to localize and quantify the structural damage.

The organization of the chapter is as follows: Section 2 provides the basic theory of IMPSCO. Section 3 describes the damage detection strategy based on IMPSCO in time domain. Section 4 describes the two-stage damage methods based on modal strain energy and IMPSCO. Experimental study is presented in Section 5. Section 6 gives the concluding remarks.

2. Improved multi-particle swarm co-evolution optimization algorithm

With basic MPSCO, multi-subpopulations are divided into two layers. All particles from the upper-layer follow the optimum of the entire population so as to obtain a faster convergence speed, while all particles from the lower layer follow the optimum of the subpopulation to which it belongs, so as to ensure the population diversity. Although the performance of basic MPSCO is better than standard PSO in some aspects, the subpopulations in lower-layer still perform the process of standard PSO, which makes its falling into the local optimum possible.

To solve this problem, the IMPSCO algorithm is proposed and applied to locate and quantify damage of a structure in this study.

In nature, some species disappear because of environmental variation, while some new species will emerge at the same time so that the species diversity is balanced. Accordingly, the searching procedure of PSO can be regarded as a nature evolution procedure. More specifically, if a particle is recorded as the worst particle many times, it indicates that this particle is unable to meet the current requirement and needs to be eliminated. Consequently, the improved multi-particle swarm co-evolution optimization algorithm is presented, in which the particles to be deleted are replaced with the gravity position of the selected excellent particles in current entire population. After the replacement, the particles can quickly get out of the local optimum. All in all, the proposed IMPSCO algorithm is shown in **Figure 1**.

Step 1: (population initialization). Generate m subpopulations randomly, and then divide them into the upper layer with only one subpopulation and the lower layer with $m - 1$ subpopulations. For each subpopulation, it contains n particles. Meanwhile, set the iteration index k to zero.

Step 2: (fitness calculation). Calculate the fitness values of each particle and save the personal best values and its corresponding particle's location as $gbestj$ and $gbestvalj$ ($j = 1, 2 \ldots m$), respectively. Meanwhile, record the best individual in the entire population and its corresponding fitness as $gbestval$ and $gbest$.

Step 3: (particles updating). Update the particles in the upper layer and the lower layer according to Eqs. (1) and (2), respectively, and the worst particle in the entire population is recorded:

$$v_i^{k+1} = \omega v_i^k + c_1 r_1 (p_i - z_i^k) + c_2 r_2 (p_g - z_i^k)$$
$$z_i^{k+1} = z_i^k + v_i^{k+1} \tag{1}$$

$$v_i^{k+1} = \omega v_i^k + c_1 r_1 (p_i - z_i^k) + c_2 r_2 (p_{lg} - z_i^k)$$
$$z_i^{k+1} = z_i^k + v_i^{k+1} \tag{2}$$

where i is the particle's index in the swarm; z_i and v_i represent the position and velocity of the particle, respectively; p_i represents the optimal position of the particle; p_g and p_{1g} represent the optimal position of the entire population and the subpopulation to which the particle belongs, respectively; r_1 and r_2 are the random numbers between zero and one; c_1 and c_2 are the learning factors; ω is the inertia weight.

Additionally, the maximum velocity of each particle cannot exceed V_{max} which is set to be 20% of the length of the search space.

Step 4: (optimum updating). Calculate the fitness of each updated particle and compare it with the values above. If it is preferable, then update $pbest$, $pbestval$, $gbest$, $gbestval$, $gbestj$ and $gbestvalj$, correspondingly. Let $k = k+1$.

Step 5: (worst particle replacement). Repeat Steps 3 and 4. When the particle is recorded as the worst for the predetermined times, I_w replaces it with G_g as shown in Eq. (3), and its worst record returns to zero:

$$G_g = \frac{\sum_{j=1}^{s} z_j}{s} \tag{3}$$

where s and z_j represent the number of the selected excellent particles and their position, respectively.
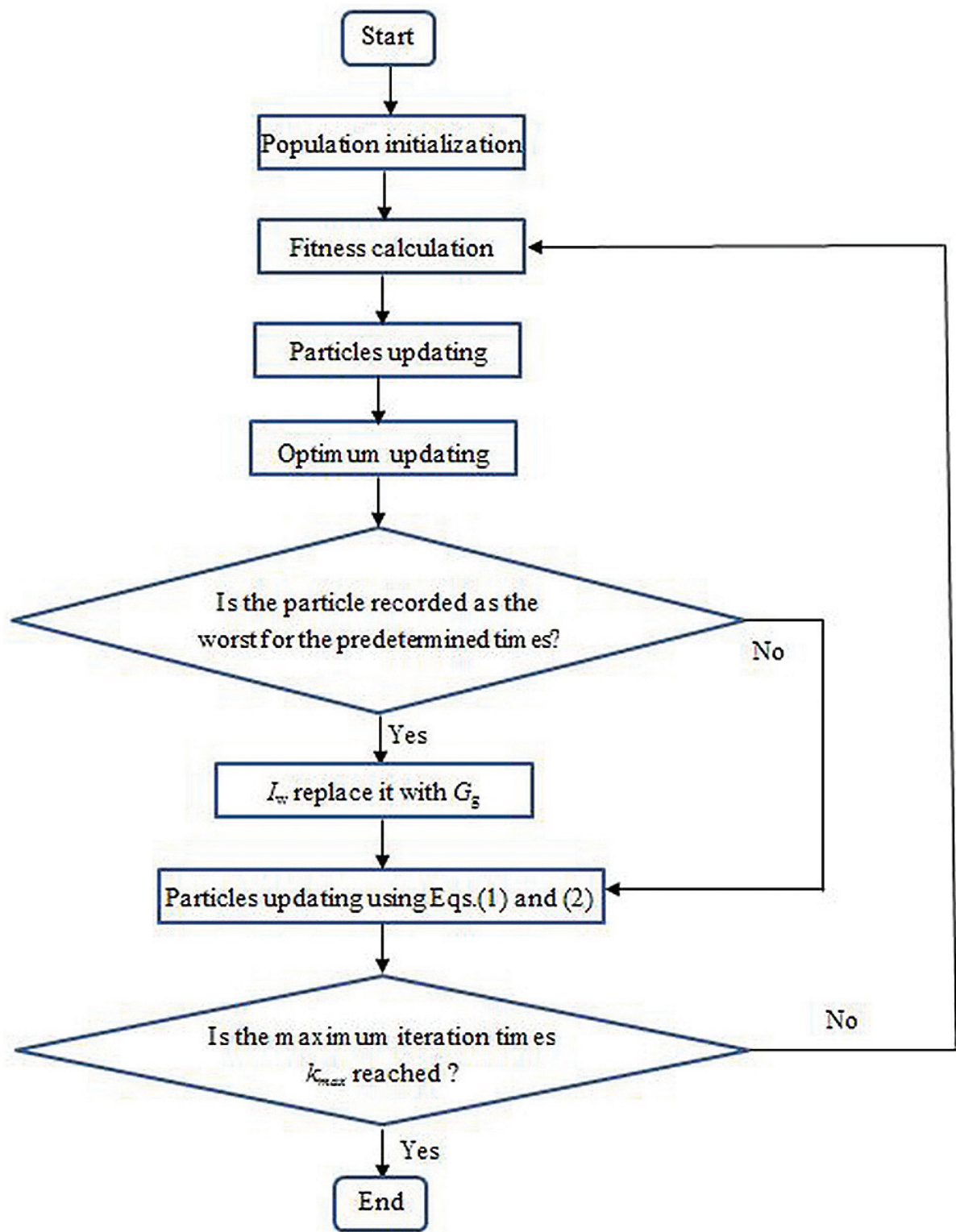
Figure 1. The flow chart of the IMPSCO algorithm.

Step 6: Go to Step 3, and repeat until the maximum iteration times $k_{\max}$ is reached.

Compared with MPSCO, IMPSCO added the process of worst particle replacement, which is able to avoid the problem of local optimum. Moreover, it can increase computing efficiency.

3. Damage detection strategy based on time-domain

On the basis of the abovementioned, this section proposes a time-domain damage detection strategy by integrating the IMPSCO and Newmark's algorithm. It contained two steps, namely, determination of damage threshold and parameter identification with IMPSCO and Newmark's algorithm [17]. For parameter identification, it involves parameters encoding, establishment of fitness function and parameters setting. The schematic diagram of the damage detection strategy based on time-domain is depicted in **Figure 2**.

3.1. Determination of damage threshold

It is difficult and significant task to determine the damage threshold because the threshold is usually used to judge damage. If the identification results are higher than the threshold, it indicates that the damage occurs; otherwise the damage is excluded because of the inevitable measurement noise. Eventually, the damage detection is performed. In this study, the damage threshold is set to 2% validated by the statistical hypothesis testing. The details can be seen in Ref. [18].

3.2. Parameters encoding

The first task is to encode parameters involving the IMPSCO. For a frame, generally, the floor stiffness is encoded directly as the parameter to be optimized in the intact state. However, the actual stiffness values cannot be obtained accurately, so we turn to focus on detecting the stiffness reduction for damage scenarios. Therefore, the floor stiffness ratio of the damaged structure to the undamaged structure, which is defined as the rigidity coefficient, is introduced and encoded to make the detection results simple and clear. In addition, with the Rayleigh
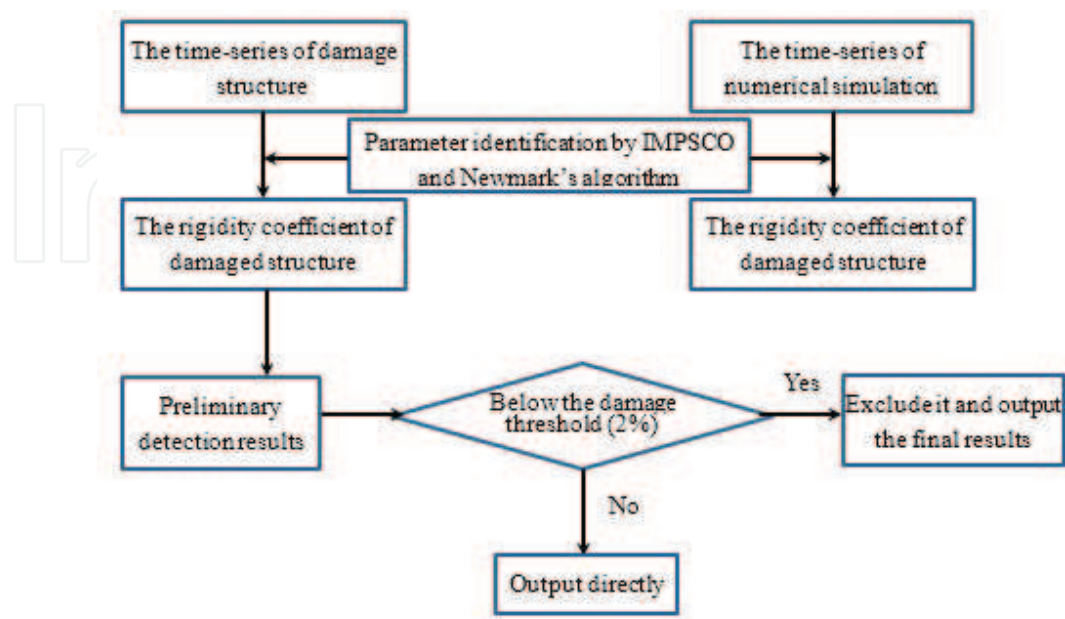
Figure 2. The schematic diagram of the damage detection strategy based on time-domain.

damping taken into consideration, the mass and stiffness damping coefficients α and β should also be encoded.

3.3. Parameters setting in IMPSCO

In this study, the parameters are set as follows: the total number of subpopulation $m = 3$; each population size $n = 10$; learning factors $c_1 = c_2 = 2$; limited times for the worst record $I_w = 10$; maximum iteration times $k_{max} = 60$; the number of the selected excellent particles s = 6; the inertia weight w is linearly decreased from 0.9 to 0.4 before the 45th iteration and afterwards it maintains at 0.4 to enhance the local search capability.

3.4. Establishment of fitness function

The most important task is to determine the fitness function for the IMPSCO. Firstly, the structural mass matrix M, stiffness matrix K and damping matrix C are constructed with the generation of particles. And then the simulated time-series responses can be obtained by using Newmark's constant-average acceleration method. Only if the analytical responses are close to the measured ones can it be determined that the structural properties represented with the particles agree well with actual damage situations. Consequently, the fitness function can be represented with

$$F(\theta) = \frac{1}{\sum_i^N \sum_l^L (X_{i,l}^{mea} - X_{i,l}^{sim})^2} \tag{4}$$

where θ is the parameters vector; N is the number of measuring points; L is the length of response data and $X_{i,l}^{mea}$ and $X_{i,l}^{sim}$ are the measured and simulated time-series responses, respectively.

When $F(\theta)$ reaches the maximum, the values of θ are the optimal solution.

4. Two-stage damage detection strategy based on modal strain energy and IMPSCO

Just as it is mentioned above, IMPSCO integrated with Newmark's algorithm can locate damage location and quantify damage severity. However, for structural damage detection, the damage variables are always in great number. Therefore, just used IMPSCO to detection damage can lead to time consuming. For the sake of reducing the number of optimization variables in structural damage detection using IMPSCO, this chapter also presents a novel two-stage structural damage detection method by the means of combination of modal strain energy (MSE) and IMPSCO. More specifically, in the first stage, the modal strain energy is used to exclude the possible healthy variables. In the second stage, IMPSCO, regarded structural frequency as fitness function, is applied to precisely locate and quantify damage. The schematic diagram of the two-stage damage detection based on modal strain energy and IMPSCO is depicted in **Figure 3**.
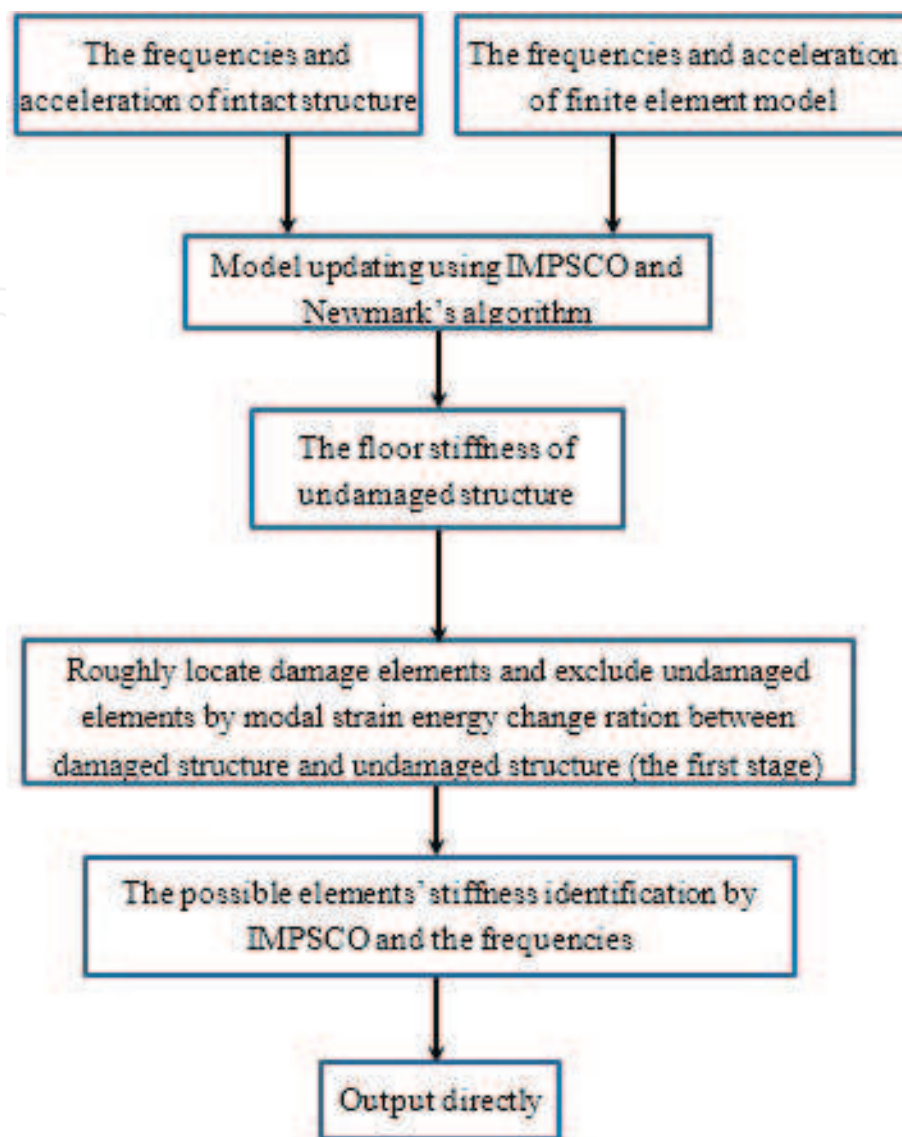
Figure 3. The schematic diagram of the two-stage damage detection based on modal strain energy and IMPSCO.

4.1. The first stage: modal strain energy

The purpose of modal analysis here is to obtain the modal parameters of the structure, such as natural frequencies and mode shapes. So, it has the mathematical form of [19]

$$(\boldsymbol{K} - \omega_i^2 \boldsymbol{M})\phi_i = 0 \qquad (\ i = 1, \ldots\ldots, n) \qquad (5)$$

where $\boldsymbol{K}$ and $\boldsymbol{M}$ are the stiffness and mass matrices of the structure, respectively; ω_i and ϕ_i are the i-th circular frequency and mode shape vector of the structure, respectively. Also, n is the total degrees of freedom of the structure. Mode shapes are usually normalized with respect to the mass matrix and the relations are thus established.

The modal strain energy of the i-th element in mode j can be expressed as:

$$MSE_{ij}^u = \{\phi_j^u\}^T[\boldsymbol{K}_i^u]\{\phi_j^u\} \tag{6}$$

$$MSE_{ij}^d = \{\phi_j^d\}^T[\boldsymbol{K}_i^d]\{\phi_j^d\} \tag{7}$$

where $\boldsymbol{K}_i$ is the stiffness matrix of the i-th element of the structure and ϕ_j is the vector of corresponding nodal displacements of element i in mode j; u and d are undamaged and damaged structures, respectively.

The modal strain energy change ratio between initial structure and damage structure is used to exclude the possible undamaged elements, which can be seen as follows:

$$MSEC_{ij} = MSE_{ij}^u - MSE_{ij}^d = \{\phi_j^d\}^T[\boldsymbol{K}_i^u]\{\phi_j^d\} - \{\phi_j^u\}^T[\boldsymbol{K}_i^u]\{\phi_j^u\} \tag{8}$$

$$MSECR_{ij} = \frac{|MSEC_{ij}|}{MSE_{ij}^u} \tag{9}$$

$$MSECR_i = \max\left[\frac{1}{m}\sum_{j=1}^{m}\frac{MSECR_{ij}}{MSECR_{j,\max}}, 0\right] \tag{10}$$

where $MSEC_{ij}$ is the modal strain energy change of the i-th element in mode j; $MSECR_{ij}$ is the modal strain energy change ratio of the i-th element in mode j; $MSECR_i$ is the modal strain energy change ratio of the i-th element; $MSECR_{j,\max}$ is the maximum of the absolute value of the $MSECR_{ij}$ in mode j.

It should be noted that the damaged elements are still unknown for a damaged structure in this stage; therefore, the element stiffness matrix of the intact structure is used for estimating the parameter $MSECR_{ij}$ in this chapter. So a damage threshold calculation method as shown in Ref. [19] is utilized to determine the modal strain energy change ratio threshold. In other words, the $MSECR_i$ will be less than the threshold for an undamaged variable, but greater than the threshold for the possible damaged variable.

4.2. The second stage: identifying the damage accurately

In this stage, IMSPCO presented in Section 2 is used to identify the damaged elements accurately as well as to determine the extent of damage. In addition, the procedure and parameters of IMSPCO are the same as Section 3. But the minimization objective function is using the error of frequencies between measured and analysed. The details can be seen as follows:

$$F = \frac{1}{\sum_{j=1}^{r}(\omega_j^* - \omega_j)^2} \tag{11}$$

where ω_j^* denotes the measured circular frequency of the j-th mode, which is calculated from vibration testing; ω_j is the analytical circular frequency of the j-th mode, which can be calculated as follows:

$$\omega_j^2 = \frac{\{\phi_j\}^T [\boldsymbol{K}^u - \Delta \boldsymbol{K}]\{\phi_j\}}{\{\phi_j\}^T [\boldsymbol{M}]\{\phi_j\}} \tag{12}$$

Where ϕ_j is the experimental mode shape vector of the j-th mode; K^u and M are the stiffness and mass matrices of the intact structure, respectively; ΔK is the stiffness matrix changes due to structural damage, which can be represented with:

$$\Delta \boldsymbol{K}_i = b_i \times \boldsymbol{K}_i^u \tag{13}$$

in which, b_i is the damage extent of i-th element of the structure, which can be represented with:

$$b_i = \frac{K_i^u - K_i^d}{K_i^u} \times 100\% \tag{14}$$

5. Experimental study

5.1. Steel frame

A seven-floor steel frame of 1.4125 m in height is constructed and tested in the laboratory [20]. The model is designed with flexible columns and relatively rigid beams to simulate a shear building, as shown in **Figure 4**. The cross-section properties of the structural members are listed in **Table 1**. The mass of the structure is concentrated at the floors, and the structural model is regarded as a lumped mass model. Therefore, the steel frame can be simplified as a 7 degree of freedom spring-mass system with the masses $M_1\ldots\ldots M_6$ = 3.78 kg and M_7 = 3.3 kg.
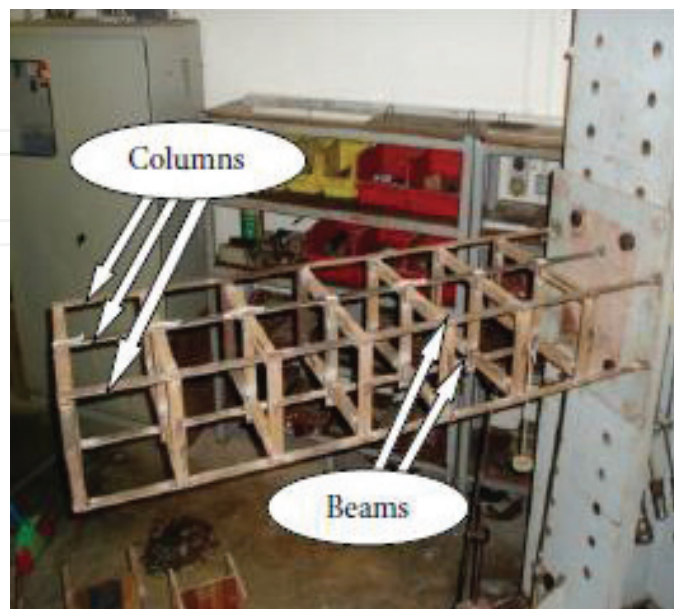

Figure 4. Seven-floor steel frame model.

Parameter	Beams	Columns
Sectional dimension	$25 \times 25 \times 3\ mm$ (SHS)	$25 \times 4.6\ mm$
Cross-sectional area A (m^2)	264×10^{-6}	115×10^{-6}
Cross-sectional moment of inertia I (m^4)	2.17×10^{-8}	2.03×10^{-10}
Elasticity modulus E (Pa)	206×10^9	206×10^9
Density ρ (kg/m^3)	7850	7850

Table 1. Structural properties.

5.2. Dynamic test

1. Damage scenarios: As the structure is constructed with six columns per floor, damage is simulated by cutting the centre column partially or completely to keep the symmetry of the model. Small damage is produced by four partial cuts near the top and bottom of the column, whereas large damage is simulated by a complete cut at the mid-height of the column, as indicated in **Figure 5**. The expected reduction of floor stiffness due to the small damage is estimated by the software of ABAQUS. The finite element models of both the undamaged and damaged columns are established, and the displacements under the same nodal loads are calculated and compared to determine the change in column stiffness. As there are six columns in each floor, the small damage results in a reduction in the floor stiffness with 4.1%. As for the case of large damage, the column damage is 100% resulting in a reduction in floor stiffness of 1/6 ≈ 16.7%. More details can be seen in the literature [20]. The two damage scenarios are shown in **Table 2**.

2. Experimental data acquisition: **Figure 6** illustrates the dynamic testing and data acquisition system. For ease of setup, the model is mounted horizontally and excited by vibration exciter vertically at the seventh floor. The force generated is measured by an Integrated Circuit Piezoelectric (ICP) force sensor (model PCB-208C02). Meanwhile, the structural responses are measured using the ICP accelerometers mounted at each floor. The data are recorded at a sampling frequency of 5,000 Hz.

5.3. Damage detection using IMPSCO combined with Newmark's algorithm

5.3.1. Identification of undamaged structure (Case 1)

Firstly, 500 data points of the acceleration responses at each floor and the corresponding force are extracted by the installed sensors when the structure is intact. Then follow the steps presented in **Figure 1**. Consequently, the floor stiffness is identified for the intact structure.
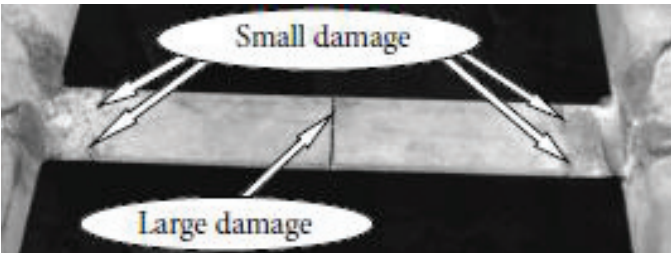

Figure 5. Damage applied to the column.

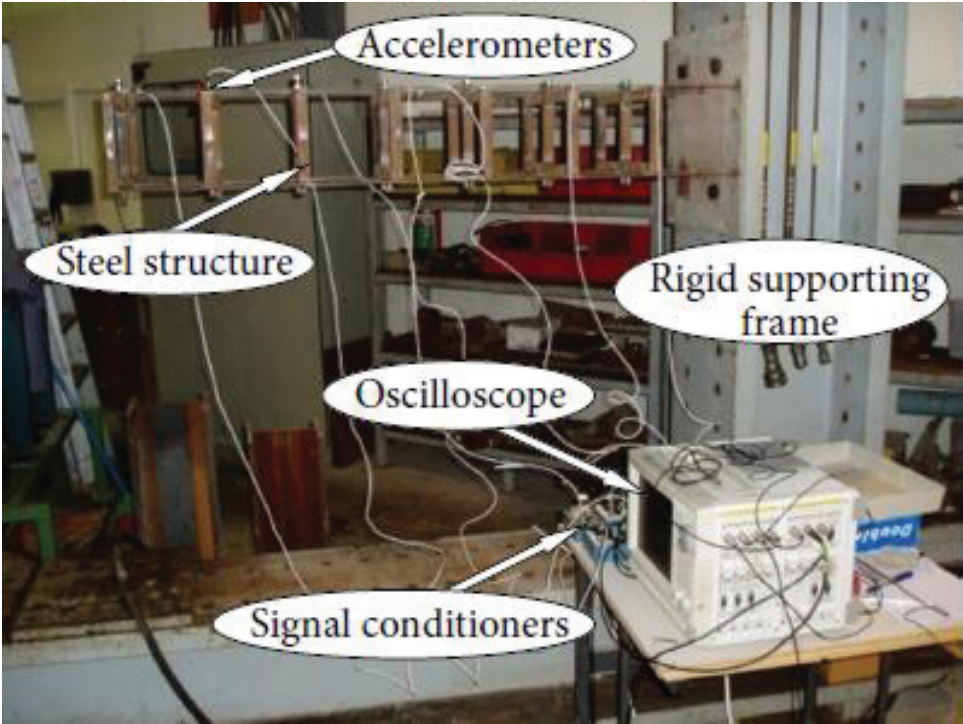| Case no.	Small damage	Large damage
Case 0	–	–
Case 2	–	Story 4
Case 3	Story 6	Story 4

Table 2. Damage scenarios.

Figure 6. Test setup.

Identification of undamaged structure: For the intact structural model, each floor stiffness and damping coefficient are encoded as $\theta = [K1, K2,…K7, \alpha, \beta]$. The search range of Ki ($i = 1, 2,…, 7$) is within the interval of [0–800 kN/m], and the search range of α and β is within the intervals of [0–4] s-1 and [0–0.001]s, respectively. By following the steps presented in Section 3, the floor stiffness of the intact structure can be identified.

Because the IMPSCO algorithm is a probabilistic optimization algorithm, the evolutionary process is always accompanied with randomness. Consequently, it is difficult to judge whether the detection result is correct from a single test.

The detection process is repeated for 15 times using the same method in order to improve the identification precision. The average values for the 15 times are regarded as the final results, as shown in **Table 3**.

It can be seen from **Table 3** that the identification result of k_1 is significantly lower, and this is due to the less rigid connection at the base of the structure or the modelling errors of the initial numerical model. In addition, the identification results of α and β are 0.75102223 and 0.00000286, respectively.

Floor stiffness	K1	K2	K3	K4	K5	K6	K7
Identification (kN/m)	300	626	553	566	547	574	519

Table 3. Identification results of floor stiffness in intact state.
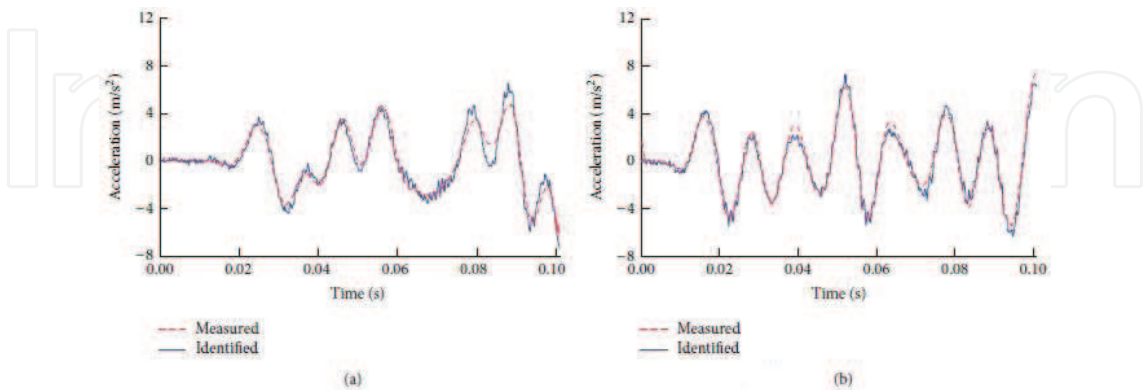

Figure 7. The comparison results of acceleration response. (a) The second floor; (b) the fifth floor.

Then the acceleration responses can be calculated by the identified results according to Newmark's algorithm, which is plotted along with the measured values in **Figure 7**. For the simplicity, only the comparison results of the second and fifth floors are given as shown in **Figure 7**. It indicates that the identified and measured acceleration responses are in good agreement, which validates the reasonability of applying the identified floor stiffness of the undamaged structure to the detection of the rigidity coefficients under the different damage scenarios.

5.3.2. Identification of damaged structure

The identification procedure is similar to that of intact structure in Section 5.3.1, except that the parameters encoded are replaced with $\theta = [R_1, R_2, …, R_7]$, in which $R_i = 1 - b_i$ $(i = 1, 2, …, 7)$ represents the rigidity coefficient and belongs to [0, 1].The final identification results are listed in **Table 4**.

It is seen from **Table 4** that the maximum relative error of identification results is 1.4%, which occurs in the second floor for the Case 2. As the rigidity coefficient introduced in the parameter encoding reflects the structural stiffness reduction, the effect on the damage identification results owing to the modelling error of the initial numerical model can be reduced to a great extent. This implies that the proposed structural damage detection strategy is effective and reliable.

5.3.3. Comparison and discussion

A comparison is made among the theoretical damage extent, identification results by genetic algorithm (GA) and IMPSCO, and the results are shown in **Figure 8**.

On the basis of damage threshold determined in Ref. [16], the floor whose damage extent is lower than 2% is intact. It is found from **Figure 8** that damage locations can be correctly localized

Damage scenarios	R1	R2	R3	R4	R5	R6	R7
Case 2							
Identification	0.993	0.986	0.993	0.839	0.999	0.993	0.998
Theoretical values	1.000	1.000	1.000	0.833	1.000	1.000	1.000
Relative error (%)	0.7	1.4	0.7	0.7	0.1	0.7	0.2
Case 3							
Identification	0.994	0.994	0.995	0.843	0.992	0.966	1.000
Theoretical values	1.000	1.000	1.000	0.833	1.000	0.959	1.000
Relative error (%)	0.6	0.6	0.5	1.2	0.8	0.7	0.0

Table 4. Identification results of all damage scenarios.
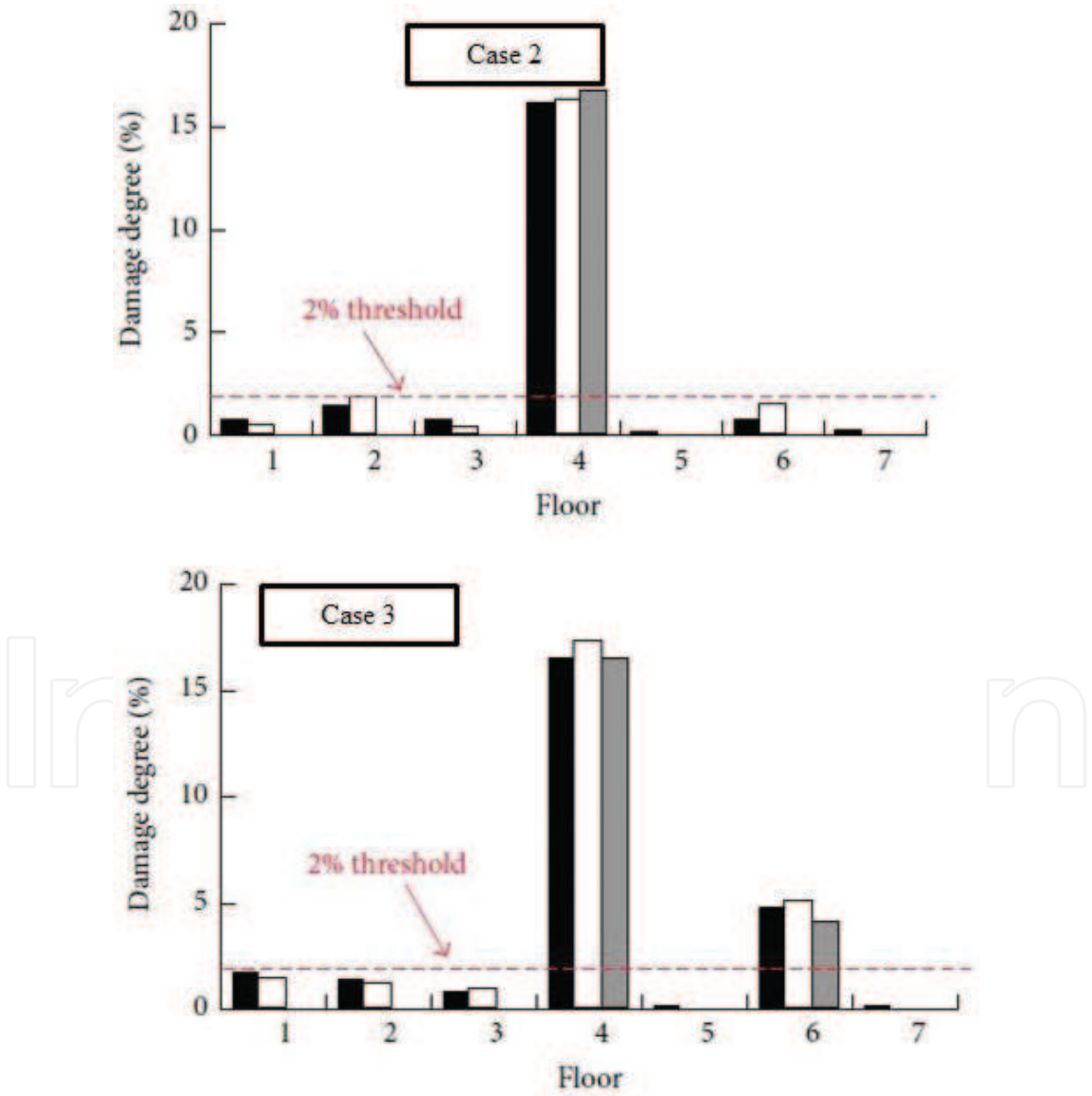

Figure 8. Identification results of all damage scenarios.

using IMPSCO and GA for all damage scenarios. In addition, the detection of damage extent is also accurate and reliable using the two optimization methods. Furthermore, IMPSCO is more efficient and accurate than GA in general. Although GA is capable of detecting damage, it costs more running time than IMPSCO.

All in all, the proposed damage detection strategy can not only localize the damage correctly but also quantify damage precisely.

5.4. Damage detection using model strain energy and IMPSCO

5.4.1. Identification of undamaged structure

Because the advantage of the two-stage damage detection method based on model strain energy and IMPSCO is that it can filter the undamaged elements. For modal updating, all elements are the possible variables. Therefore, in this section, we just used the result in Section 5.3.1 as intact structure.

5.4.2. Identification of damaged structure

5.4.2.1. Case 2

In the first stage, the modal strain energy change ratio of 7 elements is analysed, and then the index *MSECR* is evaluated. Specifically, the circular frequencies and mode shapes in intact and damaged cases are obtained by Fast Fourier Transform (FFT), and then the *MSECR* of the first four modes are calculated by Eq. (10) and depicted as in **Figure 9(a)**. Therein, the first four modes are used to calculate modal strain energy. The line of the *MSECR* threshold also plotted in **Figure 9(a)**. The value is set to 0.14 [21]. We can see from **Figure 9(a)** that the possible damaged elements are both elements 4 and 5 for Case 2.

In the second stage, IMPSCO is then employed to solve the reduced damage elements optimization detection problem to precisely locate damage location and quantify damage severity. Therein, the searching elements in IMPSCO algorithm are the possible damaged elements located in the first stage, namely elements 4 and 5. **Figure 9(b)** shows the final damage identification result. It is observed from **Figure 9(b)** that the identified damage is 0.171 for element 4 and the induced damage is 0.167 for element 4. The relative error between identified and induced damage is 2.4%. This indicates that the proposed IMPSCO algorithm can detect damage correctly.

5.4.2.2. Case 3

Case 3 is a multi-damage pattern that involves large damage scenarios in element 4 and small damage scenarios in element 6. As detection of the process for Case 2, the first four modes of the *MSECR* values are presented in **Figure 10(a)**, from which it can be seen that the values of *MSECR* for elements 4, 5 and 6 exceed the *MSECR* threshold. Therefore, it can be concluded that the possible damaged elements are elements 4, 5 and 6.

After roughly determining damage locations, IMPSCO is then utilized to accurately identify damage. The identification results for Case 3 are depicted in **Figure 10(b)**. The identified
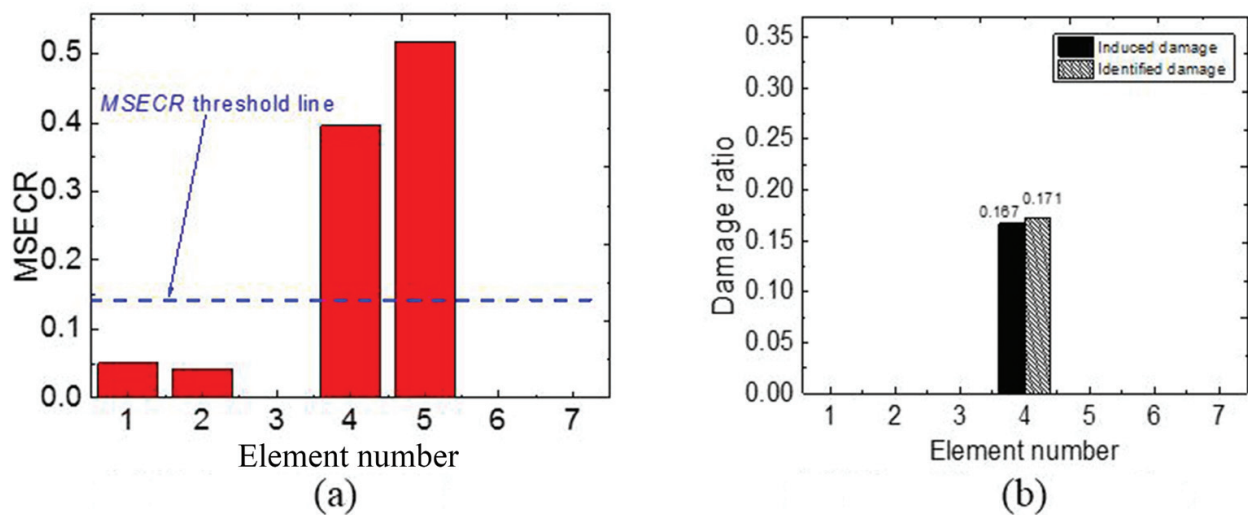
Figure 9. Identification results for Case 2. (a) Value of *MSECR*; (b) ientification results.
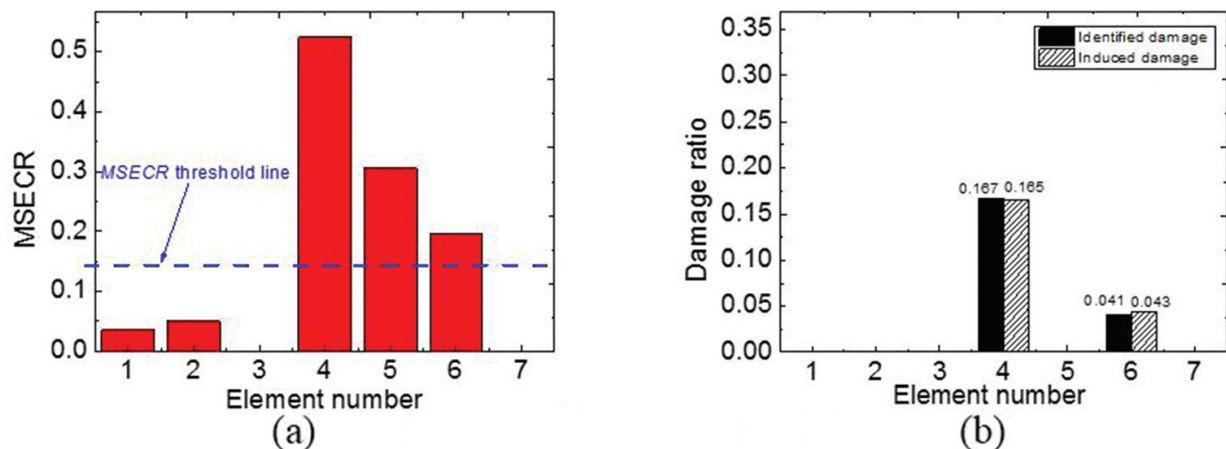

Figure 10. Identification results for Case 3. (a) Value of *MSECR*; (b) ientification results.

damaged severity is close to that of the induced damage, and the relative errors are 1.2 and 4.2% for element 4 and 6, respectively. This indicates that the proposed method is effective in precisely locating and quantifying damage.

5.4.3. Discussion

It can be seen from **Figures 9** and **10** that element 5 (Story 5) experienced an incorrect location in the first stage. There are two possible reasons for the misdetection. The first one is that the element 5 is adjacent to damaged elements (element 4 for Case 2 as well as elements 4 and 6 for Case 3) and thus its values of modal strain energy may be higher than that of other undamaged elements. In addition, the modal strain energy threshold is ensured by sampling survey, which is performed by numerical simulation. The precision of the threshold is also related to the sample size. The second reason is that subtle differences exist in the modal parameters between the finite

model and experimental one for the intact structure. All in all, the efficiency of the proposed two-stage damage detection method depends on the precision of the finite element model and sample size in ensuring modal strain energy threshold.

From **Figures 9(b)** and **10(b)**, the damage severity is 0 for element 5. Specifically, this is the damage detection results by use of IMPSCO in the second stage. As a consequence, it can be concluded that IMPSCO can accurately locate and quantify damage. In summary, the proposed two-stage damage detection method is applicable to identify damage location and its severity.

6. Concluding remarks

This chapter proposes an improved multi-particle swarm co-evolution optimization (IMPSCO), and combined it with Newmark's algorithm. In addition, this chapter also presents a novel two-stage damage detection method based on modal strain energy and IMPSCO to locate damage location and quantify damage extent. The following conclusions can be made:

1. The performance comparison has proved that IMPSCO algorithm is more precise and faster than standard MPSCO in damage detection. Moreover, it has better noise-tolerance and robustness than standard MPSCO.

2. The proposed IMPSCO algorithm integrated with Newmark's algorithm is applicable and effective for detecting and quantifying damages using the noise polluted measured data. It is noted that the proposed strategy is implemented only by using any kinds of structural time-series responses and the excitation force.

3. The combination of modal strain energy and IMPSCO algorithm can provide an efficient and fast tool for properly detecting damage in simulation test and experimental example.

4. Compared with genetic algorithm, IMPSCO is more efficient and robust for damage detection with a better noise-tolerance.

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