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Research Article

A Two-Stage Method for Structural Damage Prognosis in Shear Frames Based on Story Displacement Index and Modal Residual Force

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A two-stage method is proposed to properly identify the location and the extent of damage in shear frames. In the first stage, a story displacement index (SDI) is presented to precisely locate the damage in the shear frame which is calculated using the modal analysis information of the damaged structure. In the second stage, by defining a new objective function, the extent of the actual damage is determined via an imperialist competitive algorithm. The performance of the proposed method is demonstrated by implementing the technique to three examples containing five-, ten-, and twenty-five-story shear frames with noises and without them in modal data. Moreover, the performance of the proposed method has been verified through using a benchmark problem. Numerical results show the high efficiency of the proposed method for accurately identifying the location and the extent of structural damage in shear frames.

1. Introduction

Damage detection is one of the branches of structural health monitoring (SHM) which has recently attracted many scientific efforts. Health monitoring refers to a process of measuring and interpreting data from a system of sensors distributed about a structural system to objectively quantify the condition of the structure (Johnson et al. [1] and Zingoni [2]). Damage detection techniques have been successfully applied to several real-world problems. Based on the performance of structures, damage detection methods can be categorized into four levels [3]. The first level is devoted to detection of existing damage in a structure, and the second and third levels focus on the determination of the location and severity of damage in structures, respectively. The last level is a complete study that includes the estimation of the residual life of a structure, reaching a point that requires more information from fracture mechanics and structural reliability.

The fundamental idea for the vibration-based damage identification is that the damage-induced changes in the physical properties (e.g., mass, damping, and stiffness) will cause detectable changes in modal properties (e.g., natural frequencies, modal damping, and mode shapes). For instance, reductions in stiffness result from the onset of the cracks. Therefore, it is intuitive that damage can be identified by analyzing the changes in vibration features of the structure. In the rich literature of damage detection methods, the most important are the damage assessment methods based on observations of structural vibrations (Doebling et al. [4], Sohn et al. [5], and Salawu [6]). Most of these methods are based on detection of characteristic patterns of changes in the natural frequencies of the structure (Hassiotis and Jeong [7], Capecchi and Vestroni [8], and Xia and Hao [9]) or on observations of differences in the shapes of their natural modes (Maeck and De Roeck [10], Ndambi et al. [11], Xia et al. [12], and Maia et al. [13]) and static deflections (Rucka and Wilde [14] and Pai and Young [15]), as well as on accumulated strain energy (Cornwell et al. [16] and Zhang et al. [17]).

Koo et al. [18] and Sung et al. [19] presented algorithms for the localization and quantification of damage in shear buildings by the calculation of static displacements based on the flexibility matrix which was verified by numerical and experimental studies. Zhu et al. [20] estimated damage in a shear building by means of the sensitivity analysis of the first derivative of the first mode shape data. They defined the first mode shape slope as a sensitive parameter in occurring single damage scenarios and then developed this hypothesis for multiple damage occurrences. Recently, Ghodrati Amiri et al. [21] described a damage detection method in shear frames by means of modal residual force and static deflections obtained by modal flexibility based on the diagonalization method.

Optimization algorithms are successful tools for damage identification methods. Many successful applications of damage detection using the genetic algorithm (GA) (Mares and Surace [22], Chou and Ghaboussi [23], Ananda Rao et al. [24], Perera and Torres [25], Vakil-Baghmisheh et al. [26], Gomes and Silva [27], Nobahari and Seyedpoor [28], and Amiri et al. [29]), particle swarm optimization (PSO) algorithm (Seyedpoor [30]), pattern search optimization method (Kourehli et al. [31]), simulated annealing optimization method (Kourehli et al. [32]), Big Bang-Big Crunch (BB-BC) algorithm (Tabrizian et al. [33]), and charged system search optimization (Kaveh and Maniat [34]) have been reported in the literature. Amiri et al. [29] described a damage detection method based on defining the damage detection problem as an optimization problem by using genetic and pattern search algorithms in order to detect damage in plate-like structures. Bagheri et al. [35] studied an optimization strategy for solving an inverse problem to estimate damage in different types of structures by defining a cost function based on modal data and a free vibration scheme of structures.

Although, the use of an optimization algorithm enables us to identify the structural damage, they impose much computational effort to the process due to a great number of damage variables. The mentioned approaches have some advantages; they have some disadvantages as well, the most important being that they cannot be used in real large structures such as high-rise buildings, because the computational time is not suitable. In order to reduce the computational cost of the optimization process, some useful techniques can be employed. A useful technique is to reduce the dimension of optimization problem by excluding the healthy elements firstly and then applying the optimization method to the reduced problem for determining the extent of damaged elements (Guo and Li [36] and Fallahian and Seyedpoor [37]).

In this study, an efficient indicator based on the story displacement index containing a local characteristic of the shear frame is introduced to locate the damage quickly and accurately. The story displacement index (SDI) is calculated using the modal analysis information of damaged structure. In the second stage, by defining a new objective function, the extent of actual damage is determined by optimizing the objective function via an imperialist competitive algorithm (ICA) using the first-stage results. The performance of the proposed method has been verified through using a benchmark problem provided by the IASC-ASCE Task Group on structural health monitoring and a number of numerical examples.

2. Damage Detection Method

2.1. Story Displacement Based Index. It is assumed that a unique static load such as Fo is applied to a shear frame with N degrees of freedom. This load is defined as

$$\mathbf{Fo} = \{1.0 \quad 1.0 \quad 1.0 \quad \cdots \quad 1.0\}^T. \tag{1}$$

The static equilibrium equation of a shear frame in its healthy state can be expressed as follows:

$$\mathbf{Fo} = \mathbf{K}^h \boldsymbol{\Delta}^h, \tag{2}$$

where $\mathbf{K}^h$ and $\boldsymbol{\Delta}^h$ are the stiffness matrix and displacement vector in healthy state, respectively. From (2), the vector static displacement of healthy structure can be presented as

$$\boldsymbol{\Delta}^h = \left(\mathbf{K}^h\right)^{-1} \mathbf{Fo} = \mathbf{G}^h \mathbf{Fo} \tag{3}$$

in which $\mathbf{G}^h$ is the undamaged or healthy flexibility matrix. The flexibility matrix for a healthy structure can be written as

$$\mathbf{G}^h = \boldsymbol{\Phi} \boldsymbol{\Lambda}^{-1} \boldsymbol{\Phi}^T, \tag{4}$$

where $\boldsymbol{\Phi}$ is the mode shape matrix and $\boldsymbol{\Lambda}$ is a diagonal matrix whose members are the eigenvalues of the free vibration problem.

The static equilibrium equation of a shear frame in damaged state can be expressed as follows:

$$\mathbf{Fo} = \mathbf{K}^d \boldsymbol{\Delta}^d, \tag{5}$$

where $\mathbf{K}^d$ and $\boldsymbol{\Delta}^d$ are the stiffness matrix and displacement vector in damaged state, respectively. From (5), the damaged static displacement vector $\boldsymbol{\Delta}^d$ using the first m modes data can be presented as

$$\boldsymbol{\Delta}_m^d = \mathbf{G}_m^d \mathbf{Fo}, \tag{6}$$

where $\boldsymbol{\Delta}_m^d$ and $\mathbf{G}_m^d$ are the displacement vector and flexibility matrix in damaged structure which are calculated using the first m modes data, respectively. The flexibility matrix for a damaged structure can be written by considering modal data (natural frequencies and mode shapes) as

$$\mathbf{G}_m^d = \boldsymbol{\Phi}_m^d \left(\boldsymbol{\Lambda}_m^d\right)^{-1} \left(\boldsymbol{\Phi}_m^d\right)^T = \sum_{i=1}^{m} \frac{1}{\left(\omega_i^d\right)^2} \boldsymbol{\phi}_i^d \left(\boldsymbol{\phi}_i^d\right)^T, \tag{7}$$

where Φ_m^d is the damaged mode shape matrix that includes the first m damaged mode shape vectors and Λ_m^d is a diagonal matrix whose members are the eigenvalues of the damaged free vibration problem. For story s, the story displacement index is defined as

$$\mathrm{SDI}_s = \max\left[0, \frac{\Delta_m^d - \Delta^h}{\Delta^h}\right], \quad s = 1, \ldots, N. \tag{8}$$

According to (8), for a healthy story, the index will be equal to zero ($\mathrm{SDI}_s = 0$) and, for a damaged story, the index will be greater than zero ($\mathrm{SDI}_s \succ 0$).

2.2. Objective Function. It is generally known that the eigenvalue equation of an undamaged or healthy structure is as follows (Chopra [38]):

$$\left(\mathbf{K}^h - \left(\omega_k^h\right)^2 \mathbf{M}\right) \boldsymbol{\phi}_k^h = \mathbf{0} \quad k = 1, 2, \ldots, N, \tag{9}$$

where $\mathbf{M}$ is mass matrices in the undamaged or healthy structure and N is the total number of vibration mode shapes obtained. Equation (9) becomes as follows:

$$\left(\mathbf{K}^d - \left(\omega_k^d\right)^2 \mathbf{M}\right) \boldsymbol{\phi}_k^d = \mathbf{0} \quad k = 1, 2, \ldots, N, \tag{10}$$

where $\mathbf{K}^d$ and $\mathbf{M}$ are damaged global stiffness matrix and healthy mass matrix, respectively and ω_k^d is the natural frequency corresponding to the k vibration mode shape $\boldsymbol{\phi}_k^d$ in damaged structures. To determine damage-induced alteration stiffness, in this study, we apply degradation in story stiffness as follows:

$$\mathbf{K}_j^d = \left(1 - \alpha_j\right) \mathbf{K}_j^h, \tag{11}$$

where $\mathbf{K}_j^d$ and $\mathbf{K}_j^h$ are the damaged and healthy stiffness of the jth story, respectively, and α_j indicates the damage severity at the jth story whose values are between 0 for a story without damage and 1 for a ruptured story. The damaged stiffness matrix for an N-story shear building can be written as

$$\mathbf{K}^d = \begin{bmatrix} (1-\alpha_1) K_1^h + (1-\alpha_2) K_2^h & -(1-\alpha_2) K_2^h & \cdots & 0 \\ -(1-\alpha_2) K_2^h & (1-\alpha_2) K_2^h + (1-\alpha_2) K_2^h & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & & (1-\alpha_n) K_n^h \end{bmatrix}_{N*N}. \tag{12}$$

By solving (10), calculating vibration frequencies and mode shapes in the system, the orthogonal conditions apply to any two different modes, as indicated in (13); they do not apply to two modes having the same frequency (Chopra [38]). Consider

$$\left(\boldsymbol{\phi}_k^d\right)_p^T \mathbf{K}^d \left(\boldsymbol{\phi}_k^d\right)_q = 0 \quad p \neq q. \tag{13}$$

In the process of substituting the measured mode shapes of the damaged structure into (13) for two different modes, a dynamic residue vector can be defined for two different measured mode shapes as follows:

$$R_{p,q}(\boldsymbol{\alpha}) = \left(\boldsymbol{\phi}_k^d\right)_p^T \mathbf{K}^d \left(\boldsymbol{\phi}_k^d\right)_q, \tag{14}$$

where $(\boldsymbol{\phi}_k^d)_p^T$ and $(\boldsymbol{\phi}_k^d)_q$ are the pth and qth mode shapes from measurements, respectively. If structural damage is determined correctly, the residue would be next to 0 in (14). For all of modes in model N, we have $N_m = N(N-1)/2$ orthogonal relationships, and then the objective function can be formulated as follows:

$$F(\boldsymbol{\alpha}) = \|R(\boldsymbol{\alpha})\|_2 = \left(\sum_{t=1}^{N_m} \left|R_{p,q}(\boldsymbol{\gamma})\right|^2\right)^{1/2}; \quad p \neq q;\ 0 \leq \alpha_j \leq 1;\ j = 1, \ldots, m_e, \tag{15}$$

where $\|\ \|$ represents the Euclidean length of $R(\boldsymbol{\alpha})$ and me is the number of stories in which their SDI is greater than 0.02 in stage 1 ($\mathrm{SDI}_s \succ 0$).

During modal testing, it is customary to assume that the frequencies of vibration are accurately determined and those are in the determination of the amplitudes of the mode shapes in which the experimental errors occur. This assumption is usually valid since the frequency of shakers, even at resonance, can be quite accurately controlled. So the calculated data is simulated to the experimental one by adding noise to each mode shape using the following equation (Udwadia [39]):

$$\boldsymbol{\phi}_{j,x}^i = \boldsymbol{\phi}_j^i \left(1 + \eta \cdot \xi\right), \tag{16}$$

where $\boldsymbol{\phi}_{j,x}^i$ and $\boldsymbol{\phi}_j^i$ are the ith value of the jth mode shape vector with noise and without noise, η is the noise level (e.g., 0.05 relates to a 5% noise level), and ξ is a uniformly distributed number between −1 and +1 which is generated by MATLAB software.

2.3. Imperialist Competitive Algorithm. Imperialism is the policy of spreading the power of an imperial beyond its own boundaries. An imperialist dominate other countries by direct rule or by less obvious means such as control of market for goods or raw materials. Imperialist competitive algorithm (ICA) is a new sociopolitically motivated global search strategy that has recently been introduced for dealing with different optimization tasks. ICA simulates the social-political process of imperialism and imperialist competition. This algorithm contains a population of agents or countries. Similar to the other evolutionary algorithms that start with initial populations, ICA begins with initial empires. Any individual of an empire is called a country. Some of the best countries are selected to be the imperialist states and all the other countries form the colonies of these imperialists. The colonies are divided among the mentioned imperialists based on their power. After dividing all colonies among imperialists and creating the initial empires, these colonies start moving toward their relevant imperialist state. This movement is a simple model of assimilation policy that was pursued by some imperialist states (Atashpaz-Gargari and Lucas [40]).

The aim is to find a set of damage variables γ minimizing the $F(\boldsymbol{\alpha})$ as

$$\begin{aligned} \text{Find:}\quad & \boldsymbol{\alpha}^T = \{\alpha_1, \alpha_2, \alpha_3, \ldots, \alpha_{me}\} \\ \text{Minimize:}\quad & F(\boldsymbol{\alpha}) \\ \text{Subject to:}\quad & 0 \le \alpha_r \le 1, \quad r = 1, \ldots, me, \end{aligned} \tag{17}$$

where F is the objective function that should be minimized. In order to minimize (17), the optimization algorithm is started by producing the initial countries of size N_{Country}. The primary locations of the countries are determined by the set of values assigned to each decision variable randomly as

$$\alpha_{i,j}^0 = \alpha_{i,\min} + \text{rand} \cdot (\alpha_{i,\max} - \alpha_{i,\min}), \tag{18}$$

where $\alpha_{i,j}^0$ determines the initial value of the ith variable for the jth country, $\alpha_{i,\min}$ and $\alpha_{i,\max}$ are the minimum and the maximum allowable values for the ith variable, and rand is a random number in the interval $[0, 1]$. The most powerful countries N_{imp} are selected to form the empires. The remaining countries, N_{col}, individually belong to an empire as the colonies. Note that the initial number of colonies assigned to an empire should be directly proportional to its normalized power. In order to proportionally divide the colonies among the imperialists, a normalized cost for an imperialist is defined as

$$C_j = F_{\text{cost}}^{(\text{imp},j)} - \max_i \left(F_{\text{cost}}^{(\text{imp},i)}\right), \tag{19}$$

where $F_{\text{cost}}^{(\text{imp},j)}$ is the cost of the jth imperialist and C_j is its normalized cost. The colonies are divided among empires based on their power or normalized cost and, for the jth empire, it will be as follows:

$$\text{NC}_j = \text{Round}\left(\left|\frac{C_j}{\sum_{i=1}^{N_{\text{imp}}} C_i}\right| \cdot N_{\text{col}}\right), \tag{20}$$

where NC_j is the initial number of colonies associated to the jth empire which are selected randomly among the colonies. These colonies together with the jth imperialist form the empire number j. Then, after forming initial empires, the colonies in each of them start moving toward their relevant imperialist country. While moving toward the imperialist, a colony might reach a position with higher cost than that of imperialist. In this case, the imperialist and the colony change their positions. Then, the algorithm will continue by the imperialist in the new position and then colonies start moving toward this position.

After the exchanging step, calculate the total power of each empire, which depends on both the power of the imperialist country and the power of its colonies. Total power of an empire is mainly affected by the power of the imperialist country. But the power of the colonies of an empire has an effect, though negligible, on the total power of that empire. This fact is modeled by defining the total cost as

$$\text{TC}_j = F_{\text{cost}}^{(\text{imp},j)} + \xi \cdot \frac{\sum_{i=1}^{\text{Nc}_j} F_{\text{cost}}^{(\text{col},i)}}{\text{NC}_j}, \tag{21}$$

where TC_j is the total cost of the jth empire and ξ is a positive number which is considered to be less than 1. The value of 0.1 for ξ is found to be a suitable value in most of the implementations (Gargari et al. [41]). Similar to (19), the normalized total cost is defined as

$$\text{NTC}_j = \text{TC}_j - \max_i (\text{TC}_i), \tag{22}$$

where NTC_j is the normalized total cost of the jth empire. Having the normalized total cost, the possession probability of each empire is evaluated by

$$p_j = \left|\frac{\text{NTC}_j}{\sum_{i=1}^{N_{\text{imp}}} \text{NTC}_i}\right|, \tag{23}$$

when an empire loses all of its colonies, it is assumed to be collapsed. In this model implementation, where the powerless empires collapse in the imperialist competition, the corresponding colonies will be divided among the other empires. Moving colonies toward imperialists are continued and imperialist competition and implementations are performed during the search process. When the number of iterations reaches a predefined value or the amount of improvement in the best result reduces to a predefined value, the searching process is stopped.

3. Numerical Examples

In this section, the efficiency of the presented method is investigated by studying 5-story, 10-story, and 25-story shear frames. In all numerical examples, damage in the structure is simulated as a relative reduction in the stiffness story. Studies are carried out within the MATLAB [42] environment, which is used for the solution of problems and optimization.

3.1. Five-Story Shear Frame. The five-story shear frame is shown in Figure 1 selected from [21]. The mass and stiffness are presented in Table 1. In the five-story shear frame, three different damage scenarios given in Table 2 are induced in the structure and the proposed method is tested for each scenario. In this example, the first two vibration modes are

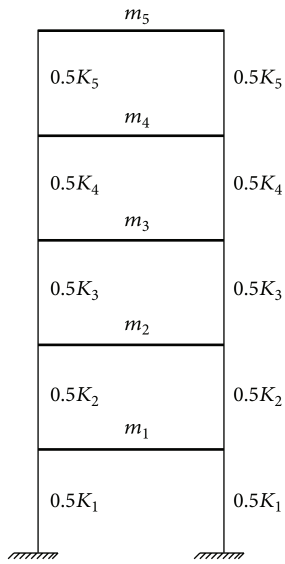


Figure 1: Five-story shear frame.

Table 1: The properties of the five-story shear frame.

Story number	Mass (kg)	Stiffness (N/m)
1	500	3500
2	400	3500
3	300	3000
4	250	2500
5	150	1500

Table 2: The considered damage scenarios in the five-story shear frame.

Damage scenario	Damage location	Stiffness reduction (%)
I	Story 2	10
II	Stories 1 and 4	20 and 15
III	Stories 3 and 5	20 and 15

utilized for damage detection. Figures 2(a)–2(c) show the SDI value with respect to story number for damage scenarios 1–3, respectively. As shown in the figures, the most potentially damaged stories are as follows: story 2 for damage scenario 1; stories 1 and 4 for damage scenario 2; and stories 3 and 5 for damage scenario 3. Here, those stories whose indexes exceed 0.02 are selected as suspected damaged stories. It is revealed that the damage variables for scenarios 1 to 3 can be reduced from 5 to 1, 2, and 2 variables, respectively.

The ICA is now employed to solve the reduced damage detection problem to determine the damage sizes. In this example, a population of 20 countries consisting of 2 empires and 18 colonies is used. The presented method starts with a random initial population of countries. The cost of each solution is evaluated by computing the objective function. Thereafter, the assimilation changes the positions of the colony and the imperialist and imperialist competition are applied to obtain the solution to the problem. The damage

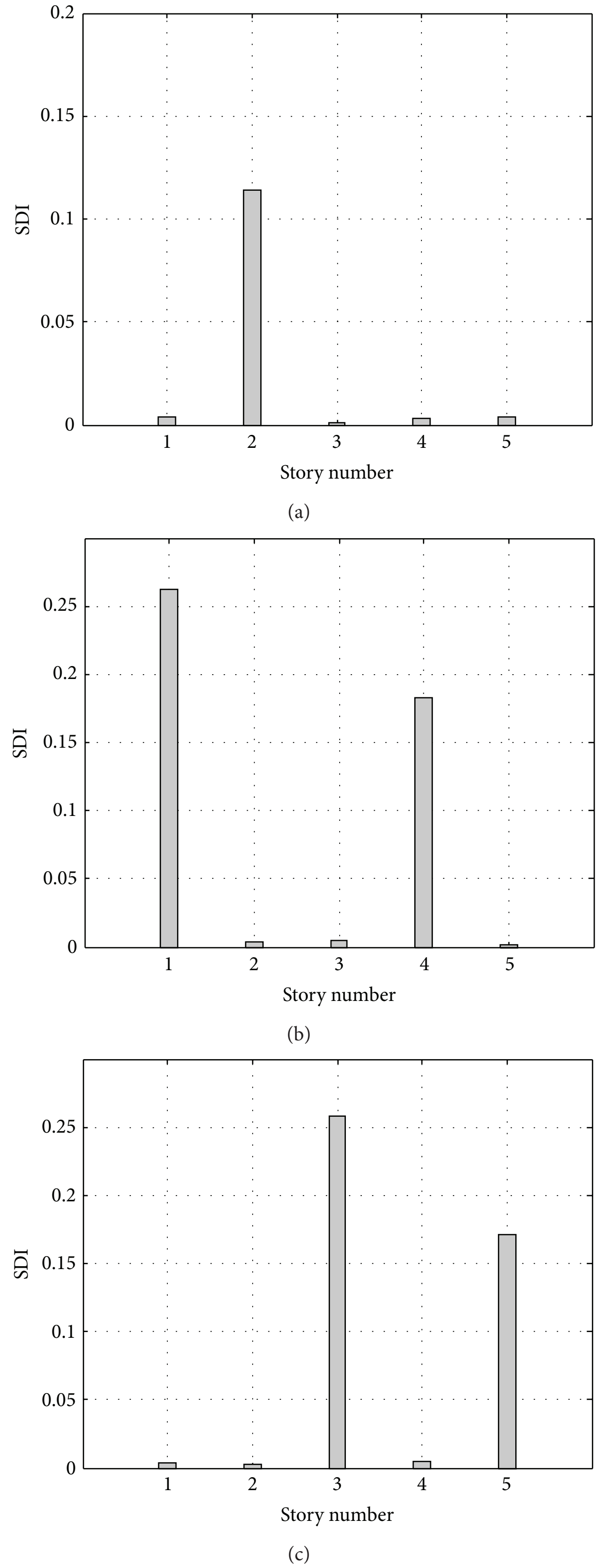


Figure 2: (a) Value of SDI in the five-story shear frame considering 2 modes for scenario I, (b) value of SDI in the five-story shear frame considering 2 modes for scenario II, and (c) value of SDI in the five-story shear frame considering 2 modes for scenario III.

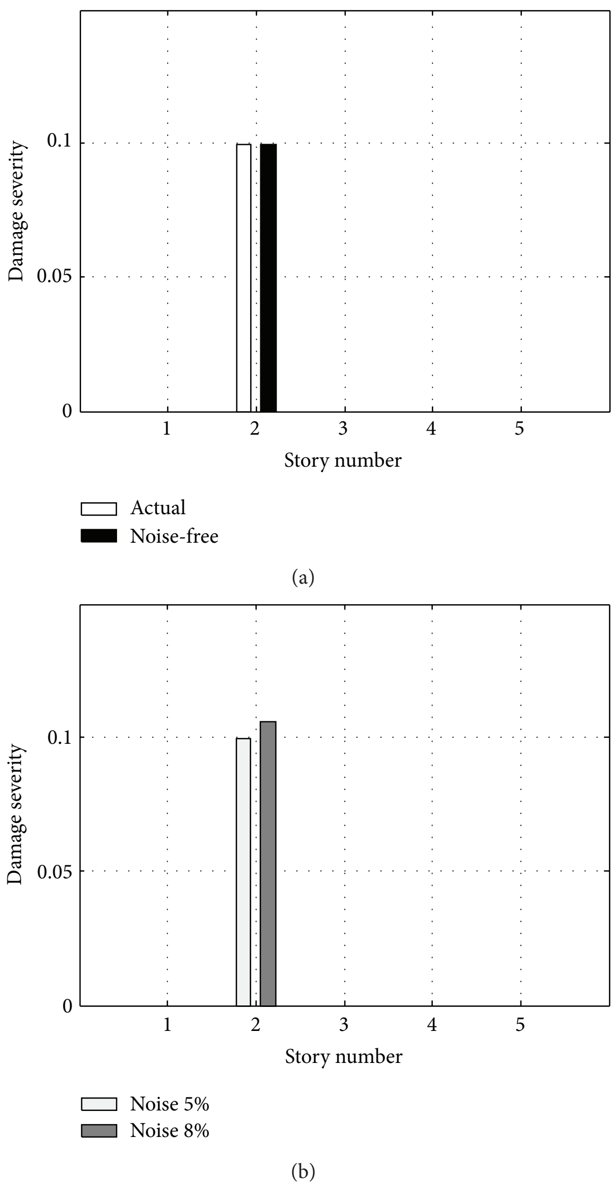


Figure 3: Damage detection results in the five-story shear frame for scenario I.

identification results, using the objective function with noise (5% and 8%) and without noise for scenarios 1–3, are shown in Figures 3 to 5, respectively. The results illustrate that the proposed method can detect the location and the extent of damage very quickly and accurately. The convergence history of the ICA for scenario 2 is shown in Figure 6.

3.2. Ten-Story Shear Frame. The ten-story shear frame is shown in Figure 7. The mass and stiffness are presented in Table 3. In the ten-story shear frame, three different damage scenarios given in Table 4 are induced in the structure and the proposed method is tested for each scenario. In this example, the first four vibrating modes are utilized for damage detection. Figures 8(a)–8(c) show the SDI value with respect to story number for damage scenario 1–3, respectively. As shown in the figures, the most potentially damaged stories

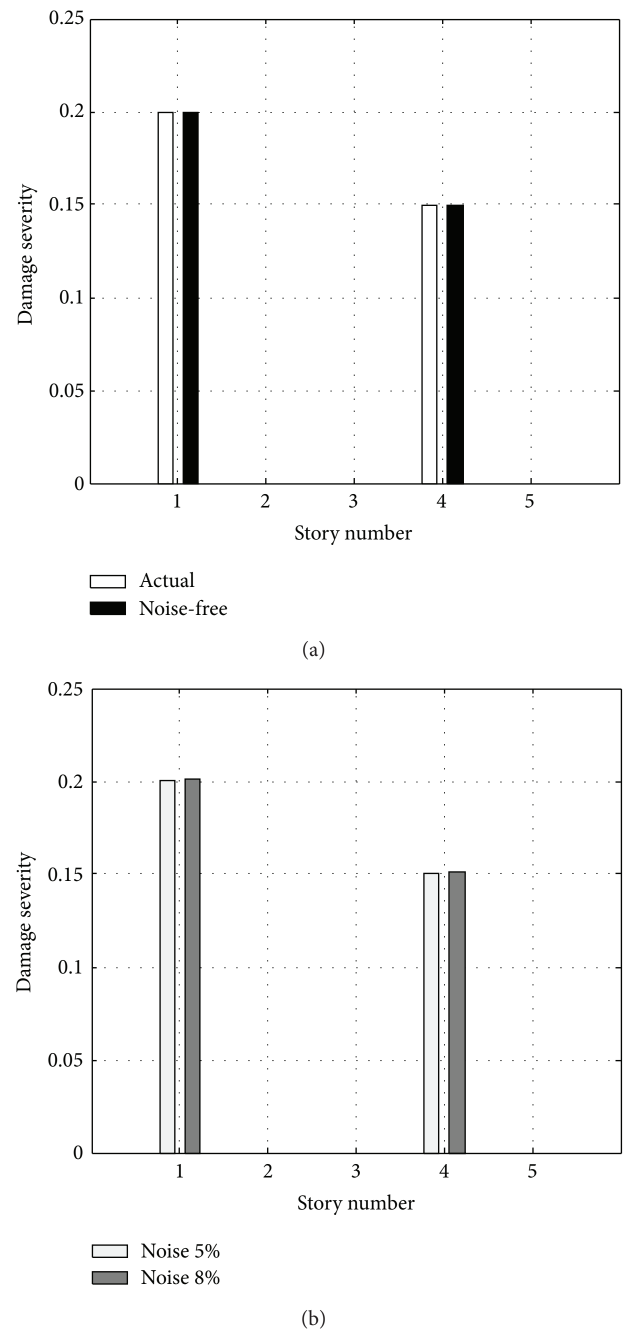
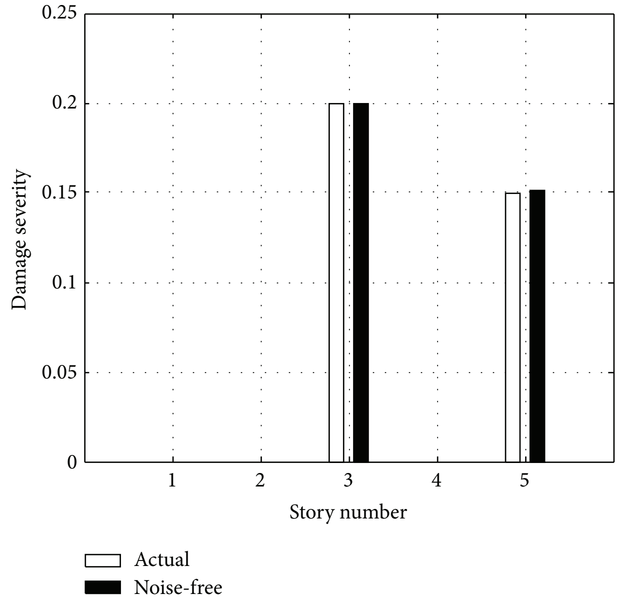


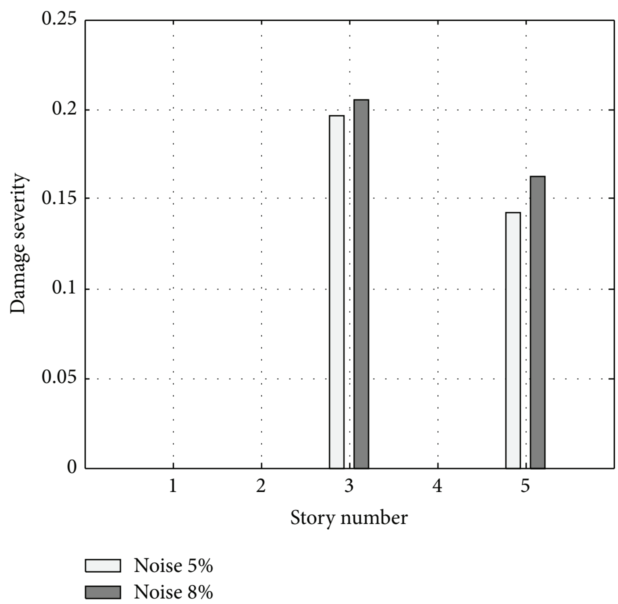
Figure 4: Damage detection results in the five-story shear frame for scenario II.

are as follows: story 5 for damage scenario 1; stories 2 and 8 for damage scenario 2; and stories 3, 5, and 10 for damage scenario 3. It is revealed that the damage variables for scenarios 1 to 3 can be reduced from 10 to 1, 2, and 3 variables, respectively.

The ICA is now employed to solve the reduced damage detection problem to determine the damage sizes. In this example, a population of 35 countries consisting of 5 empires and 30 colonies is used. The damage identification results, using the objective function with noise (5% and 8%) and without noise for scenarios 1–3, are shown in Figures 9 to 11,



(a)



(b)

Figure 5: Damage detection results in the five-story shear frame for scenario III.

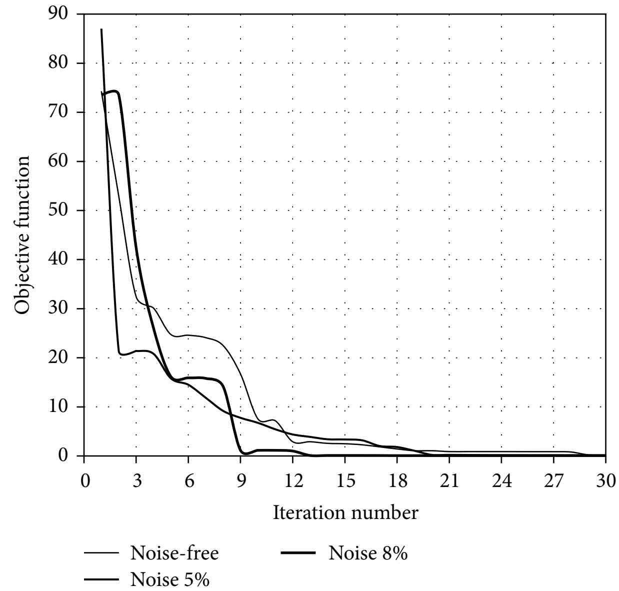


Figure 6: Convergence history of the ICA for the five-story shear frame for scenario II.

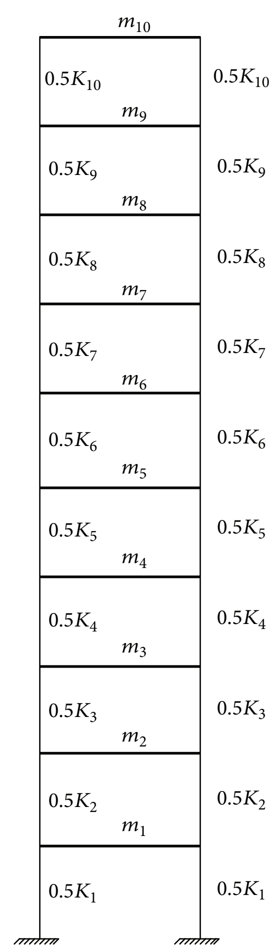


Figure 7: Ten-story shear frame.

Table 3: The properties of the ten-story shear frame.

Story number	Mass (kg)	Stiffness (N/m)
1-2	200	2500
3-4	200	2000
5-6	200	1500
7-8	200	1000
9-10	200	500

respectively. The convergence history of the ICA for scenario 3 is shown in Figure 12. The results illustrate that the proposed

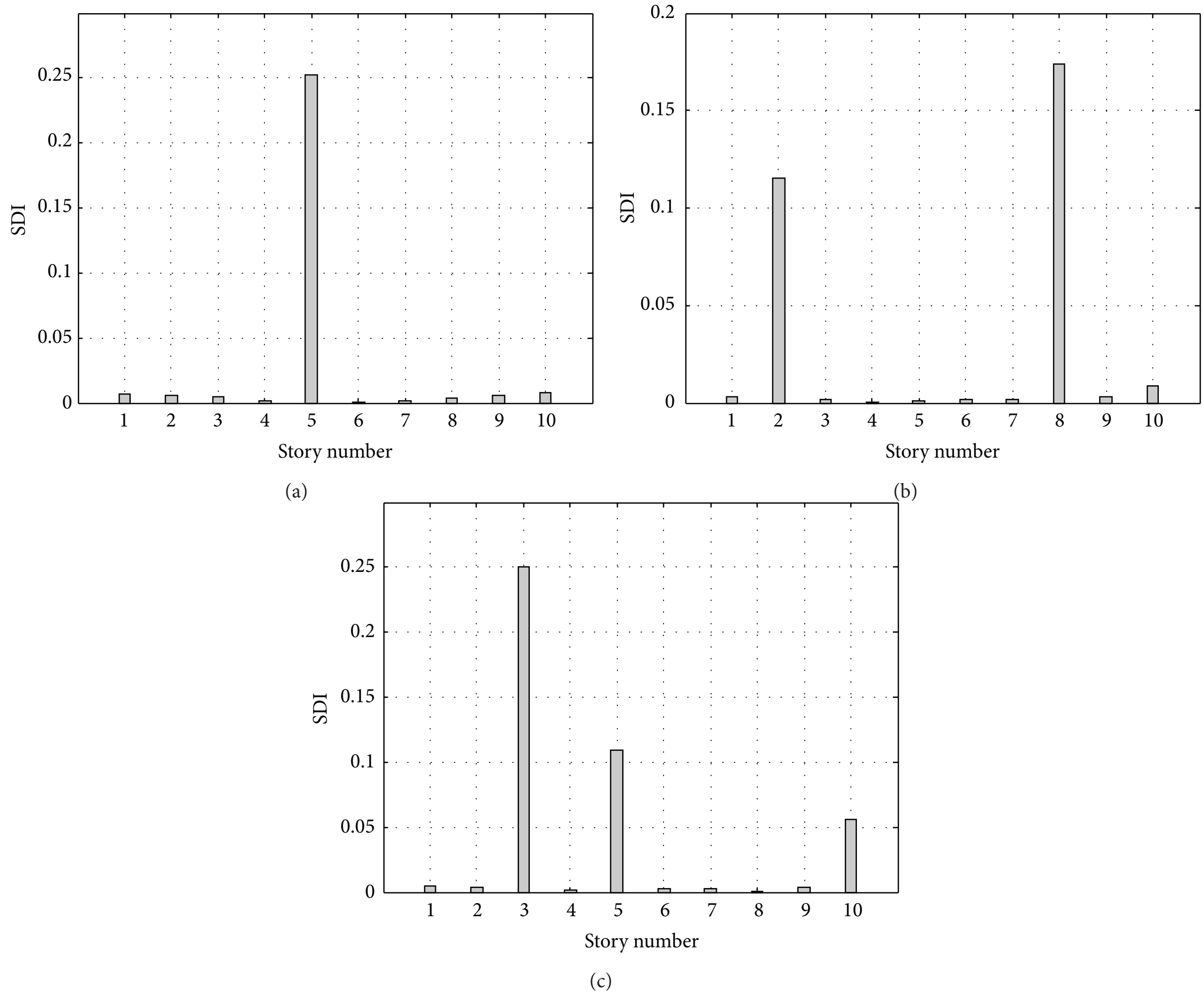


Figure 8: (a) Value of SDI in the ten-story shear frame considering 3 modes for scenario I, (b) value of SDI in the ten-story shear frame considering 3 modes for scenario II, and (c) value of SDI in the ten-story shear frame considering 3 modes for scenario III.

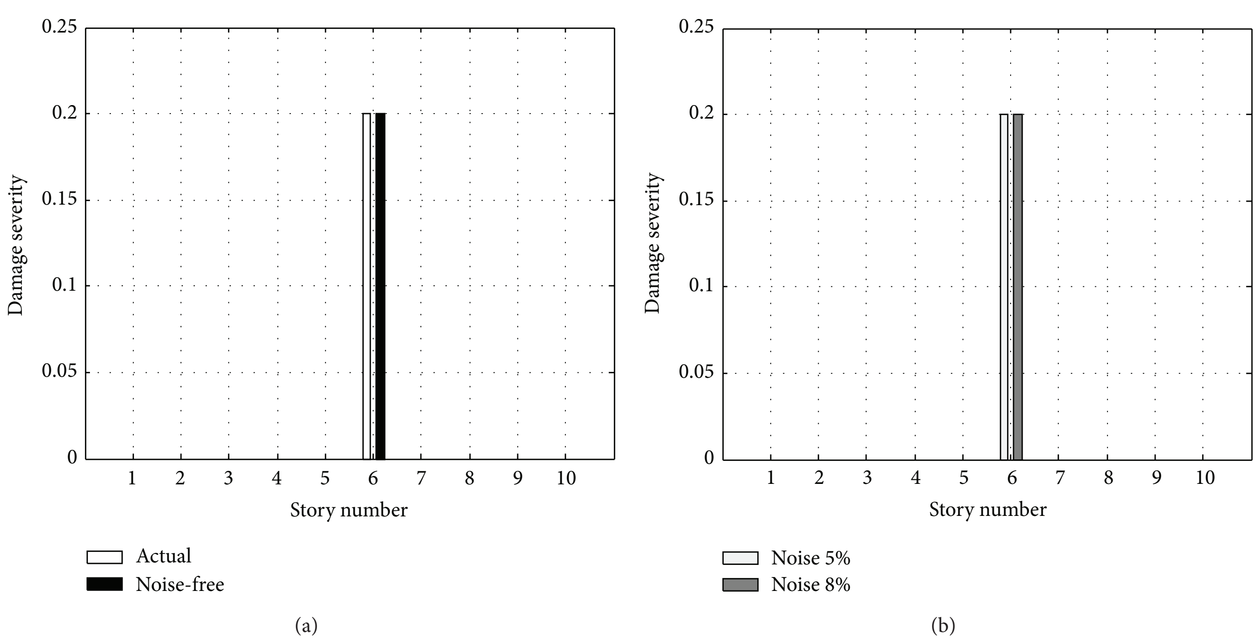
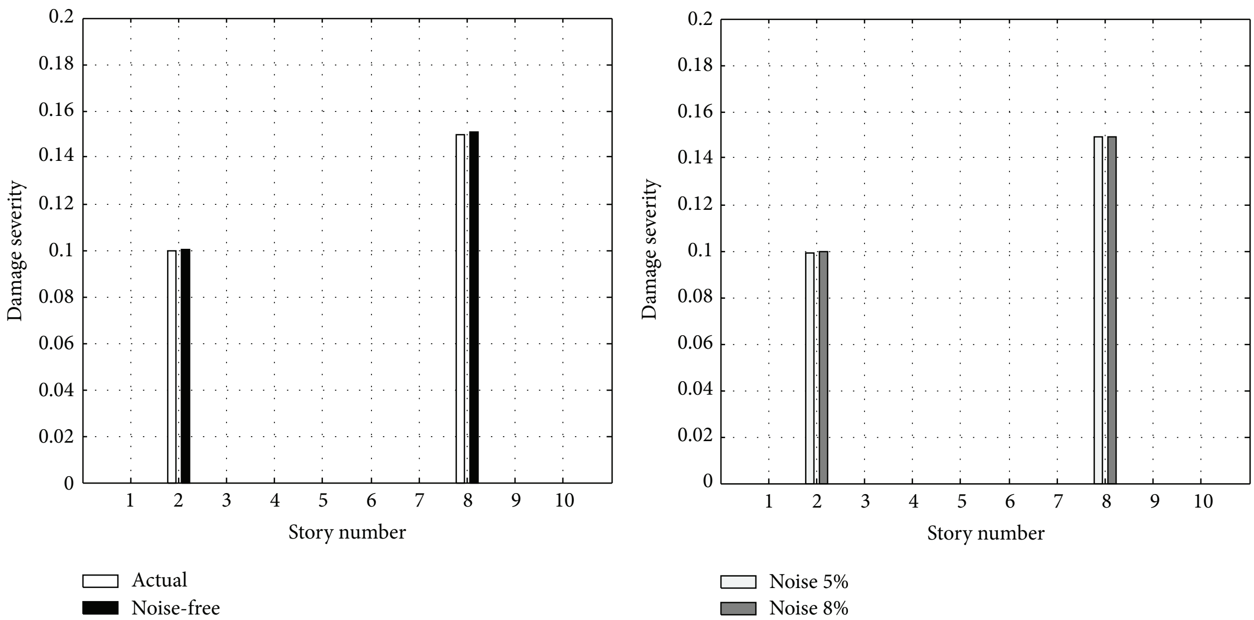
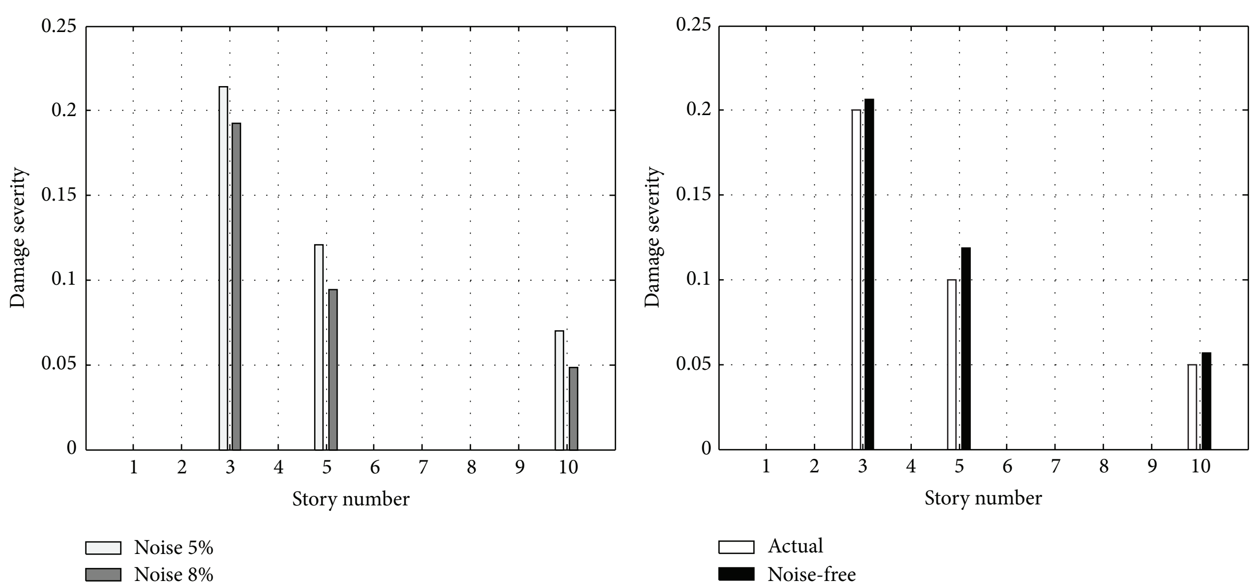


Figure 9: Damage detection results in the ten-story shear frame for scenario I.



(a) (b)

Figure 10: Damage detection results in the ten-story shear frame for scenario II.



(a) (b)

Figure 11: Damage detection results in the ten-story shear frame for scenario III.

method can detect the location and the extent of damage very quickly and accurately.

3.3. 25-Story Shear Frame. The 25-story shear frame is selected from [21]. The mass and stiffness are presented in Table 5. In the 25-story shear frame, three different damage scenarios given in Table 6 are induced in the structure and the proposed method is tested for each scenario. In this example, the first five vibrating modes are utilized for damage detection. Figures 13(a)–13(c) show the SDI value with respect to story number for damage scenarios 1–3, respectively. As shown in the figures, the most potentially damaged stories are as follows: story 10 for damage scenario 1; stories 5 and 20 for damage scenario 2; and stories 7, 12, 14, and 25 for damage scenario 3. It is revealed that the damage variables for scenarios 1 to 3 can be reduced from 25 to 1, 2, and 4 variables, respectively. In this example, a population of 40 countries consisting of 5 empires and 35 colonies is used. The damage

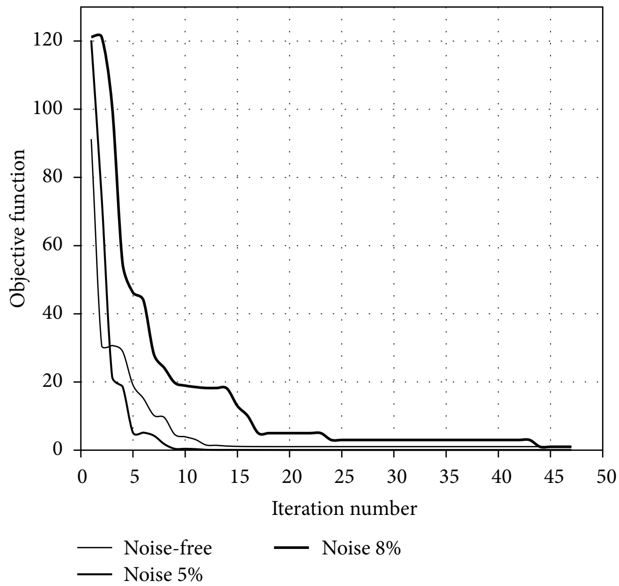


Figure 12: Convergence history of the ICA for the ten-story shear frame for scenario III.

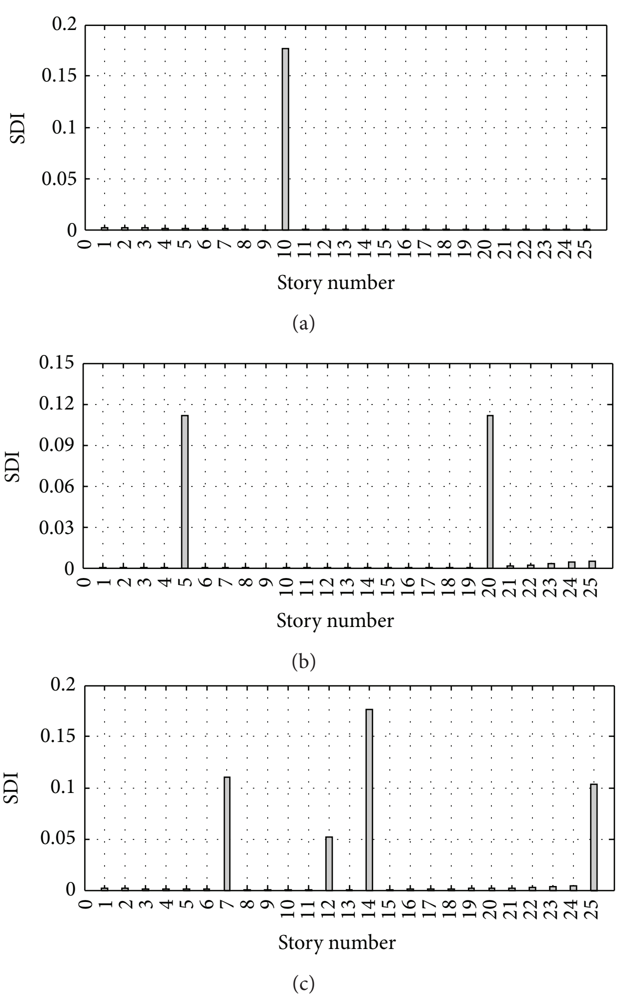


Figure 13: (a) Value of SDI in the 25-story shear frame considering 5 modes for scenario I, (b) value of SDI in the 25-story shear frame considering 5 modes for scenario II, and (c) value of SDI in the 25-story shear frame considering 5 modes for scenario III.

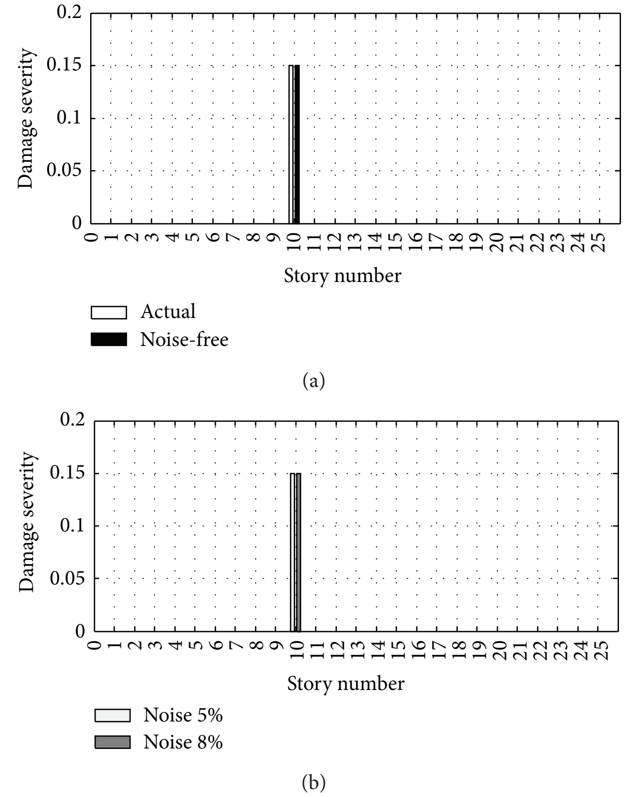


Figure 14: Damage detection results in the 25-story shear frame for scenario I.

Table 4: The considered damage scenarios in the ten-story shear frame.

Damage scenario	Damage location	Stiffness reduction (%)
I	Story 5	20
II	Stories 2 and 8	10 and 15
III	Stories 3, 5, and 10	20, 10 and 5

Table 5: The properties of the 25-story shear frame.

Story number	Mass (kg)	Stiffness (MN/m)
1–5	100	500
6–10	100	400
11–15	100	300
16–20	100	200
21–25	100	100

identification results for scenarios 1–3 are shown in Figures 14 to 16, respectively. The results illustrate that the proposed method can detect the location and the extent of damage very quickly and accurately. The convergence history of the ICA for scenario 3 is shown in Figure 17.

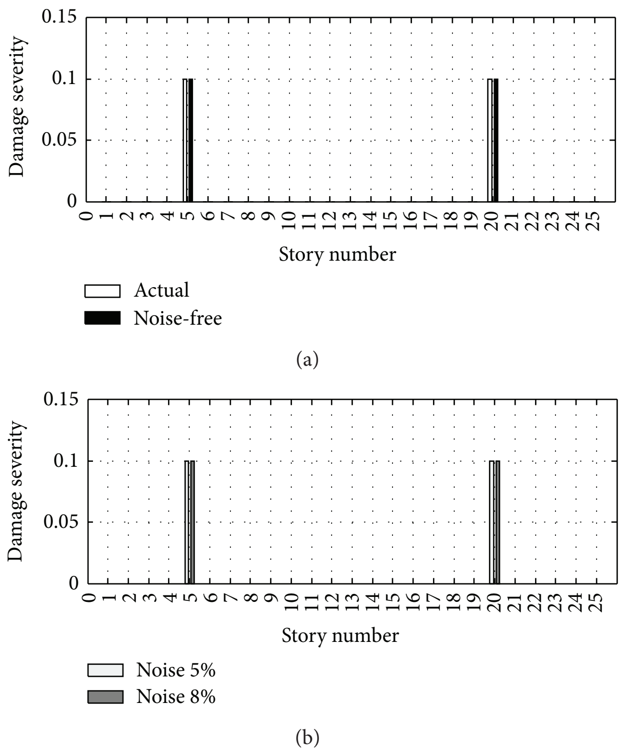


Figure 15: Damage detection results in the 25-story shear frame for scenario II.

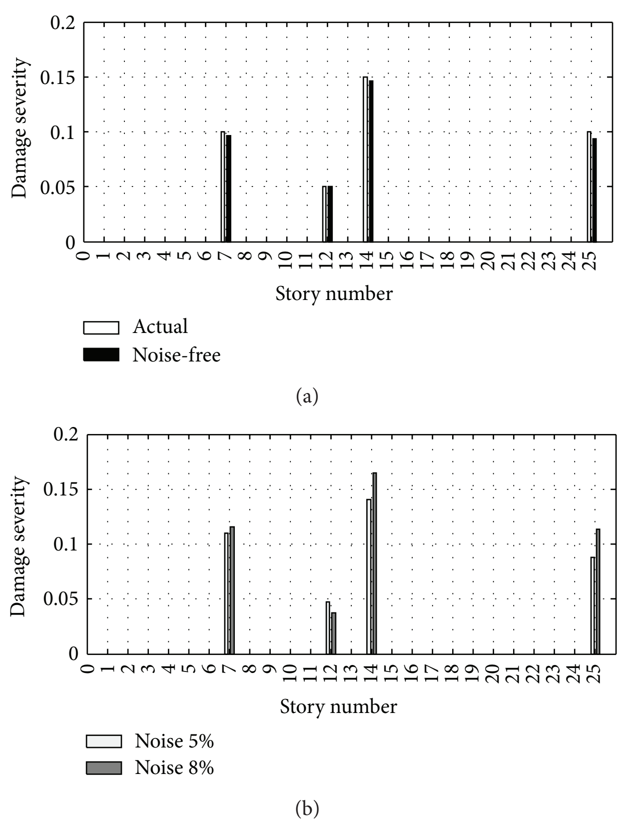


Figure 16: Damage detection results in the 25-story shear frame for scenario III.

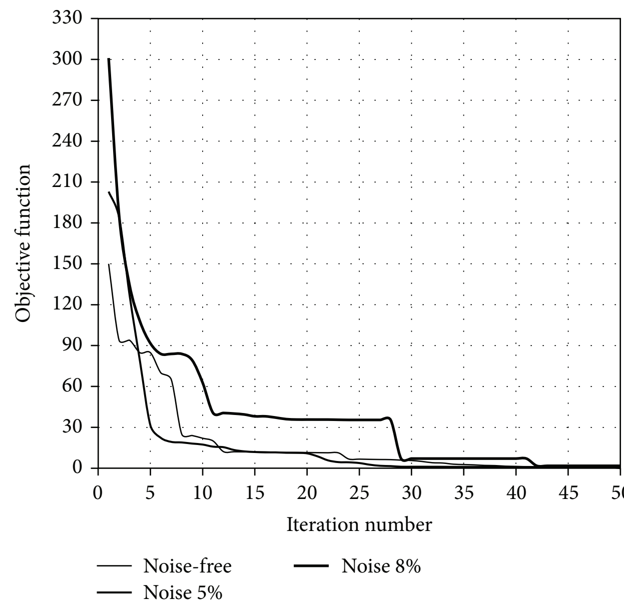


Figure 17: Convergence history of the ICA for the 25-story shear frame for scenario III.

Table 6: The considered damage scenarios in the 25-story shear frame.

Damage scenario	Damage location	Stiffness reduction (%)
I	Story 10	15
II	Stories 5 and 20	10 and 10
III	Stories 7, 12, 14, and 25	10, 5, 15, and 10

4. Experimental Verification Study

In the previous section, the proposed method was demonstrated through some numerical examples. However, it is useful to examine the experimental performance of the proposed method, using measured data from an experimental study. Therefore, in this section, the performance of the proposed damage detection method is verified through the benchmark structure. The benchmark structure is a four-story steel frame, two-bay by two-bay, and quarter-scale model structure constructed in the Earthquake Engineering Research Laboratory at the University of British Colombia. Geometry of the benchmark structure is shown in Figure 18. Details of the first phase of IASC-ASCE benchmark problem was presented by Johnson et al. 2004 [1] and also are available on IASC-ASCE Structural Health Monitoring Task Group's website.

The proposed method was applied to case 1 of this phase benchmark problem, and the finite element model of the 12-DOF shear building model is used. In this study, the three following damage scenarios have been considered:

(1) One brace of the first story is broken (scenario 1).

TABLE 7: Mass and horizontal story stiffness (MN/m) of undamaged and damaged 12-DOF model.

Story	DOF	Mass (Kg)	Undamaged Stiffness	Scenario 1 Stiffness	Scenario 2 Stiffness	Scenario 3 Stiffness
1	x	3452.40	106.60	106.60	106.60	106.60
1	y	3452.40	67.90	55.84	55.84	63.88
1	θ_z	3819.40	232.00	213.12	213.12	225.71
2	x	2652.40	106.60	106.60	106.60	106.60
2	y	2652.40	67.90	67.90	67.90	67.90
2	θ_z	2986.10	232.00	232.00	232.00	232.00
3	x	2652.40	106.60	106.60	94.54	106.60
3	y	2652.40	67.90	67.90	67.90	67.90
3	θ_z	2986.10	232.00	232.00	213.12	232.00
4	x	1809.90	106.60	106.60	106.60	106.60
4	y	1809.90	67.90	67.90	67.90	67.90
4	θ_z	2056.90	232.00	232.00	232.00	232.00

TABLE 8: The obtained results of damage detection for the benchmark structure.

Story	DOF	Scenario 1		Scenario 2		Scenario 3	
		Actual	Estimated	Actual	Estimated	Actual	Estimated
1	x	0	0	0	0	0	0
1	y	17.76	17.76	17.76	17.75	5.91	5.92
1	θ_z	8.14	8.15	8.14	8.14	2.71	2.71
2	x	0	0	0	0	0	0
2	y	0	0	0	0	0	0
2	θ_z	0	0	0	0	0	0
3	x	0	0	11.32	11.32	0	0
3	y	0	0	0	0	0	0
3	θ_z	0	0	8.14	8.15	0	0
4	x	0	0	0	0	0	0
4	y	0	0	0	0	0	0
4	θ_z	0	0	0	0	0	0

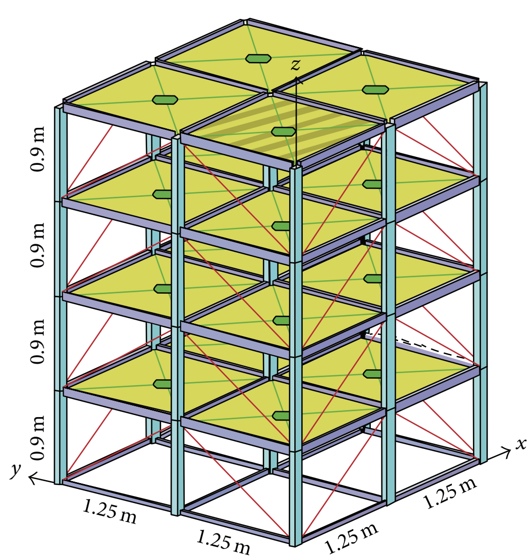


FIGURE 18: Geometry of the benchmark structure (Johnson et al. 2004 [1]).

(2) One brace at the first and third stories is broken (scenario 2).

(3) 1/3 of area of one brace at the first story is cut (scenario 3).

For each damage scenario, the mass and horizontal story stiffness are illustrated in Table 7.

Damage in the structures can be determined using the proposed method. In this example, the five three vibrating modes are utilized for damage detection. In this example, a population of 40 countries consisting of 5 empires and 35 colonies is used. Figures 19(a)–19(c) show the SDI value with respect to stiffness DOFs for damage scenarios 1–3, respectively. The results of the application of the proposed method to the benchmark structure are cited in Table 8. The convergence history of the ICA for scenarios 1–3 is shown in Figure 20. The results illustrate that the proposed method can detect the location and the extent of damage very quickly and accurately.

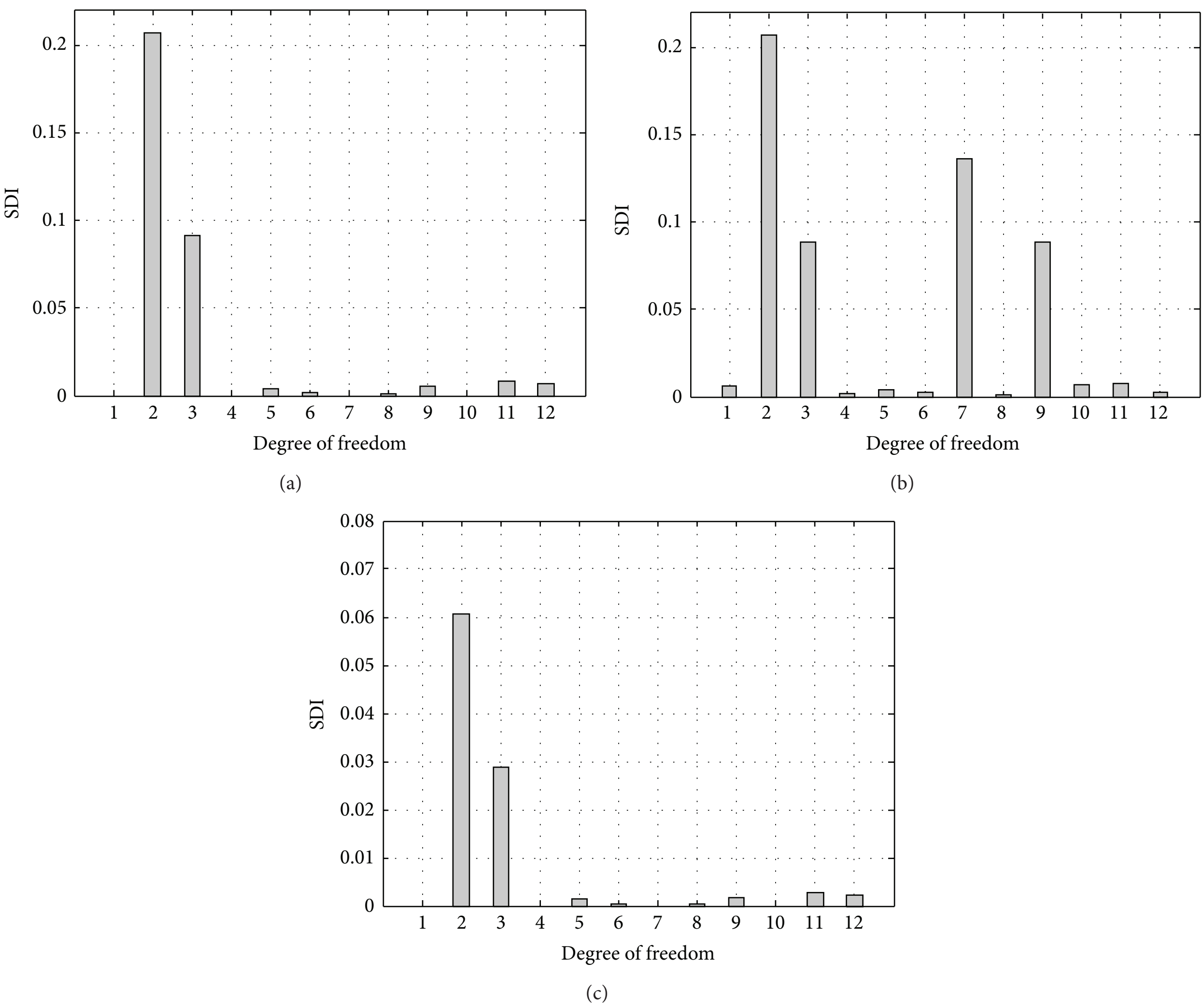


FIGURE 19: (a) value of SDI in the benchmark structure considering 5 modes for scenario 1, (b) value of SDI in the benchmark structure considering 5 modes for scenario 2, and (c) value of SDI in the benchmark structure considering 5 modes for scenario 3.

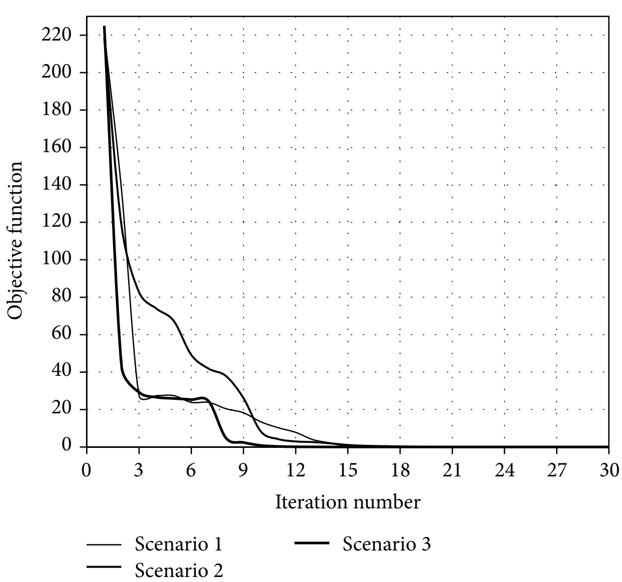


FIGURE 20: Convergence history for the three scenarios of the benchmark structure.

5. Conclusions

In this study, a new method is proposed to properly identify the location and the extent of damage in shear frames. The proposed method has two stages. In the first stage, a story displacement index (SDI) is presented to precisely locate the damage in the shear frame. The story displacement index is calculated using the modal analysis information of the damaged structure. In the second stage, by defining a new objective function using orthogonal conditions in mode shapes, the extent of the actual damage is determined via an imperialist competitive algorithm (ICA).

In order to assess the performance of the proposed method for structural damage detection, three examples, that is, 5-story shear frame, 10-story shear frame, and 25-story shear frame with noise (noise 5% and noise 8%) and without noise in modal data, are considered. To validate the efficiency and applicability of the proposed method, a study on the damage detection was conducted using the benchmark of the IASC-ASCE Task Group on Structural Health Monitoring. The obtained results indicated that the proposed method is a strong and viable method to the problem of detection and estimation of damage in the shear frames.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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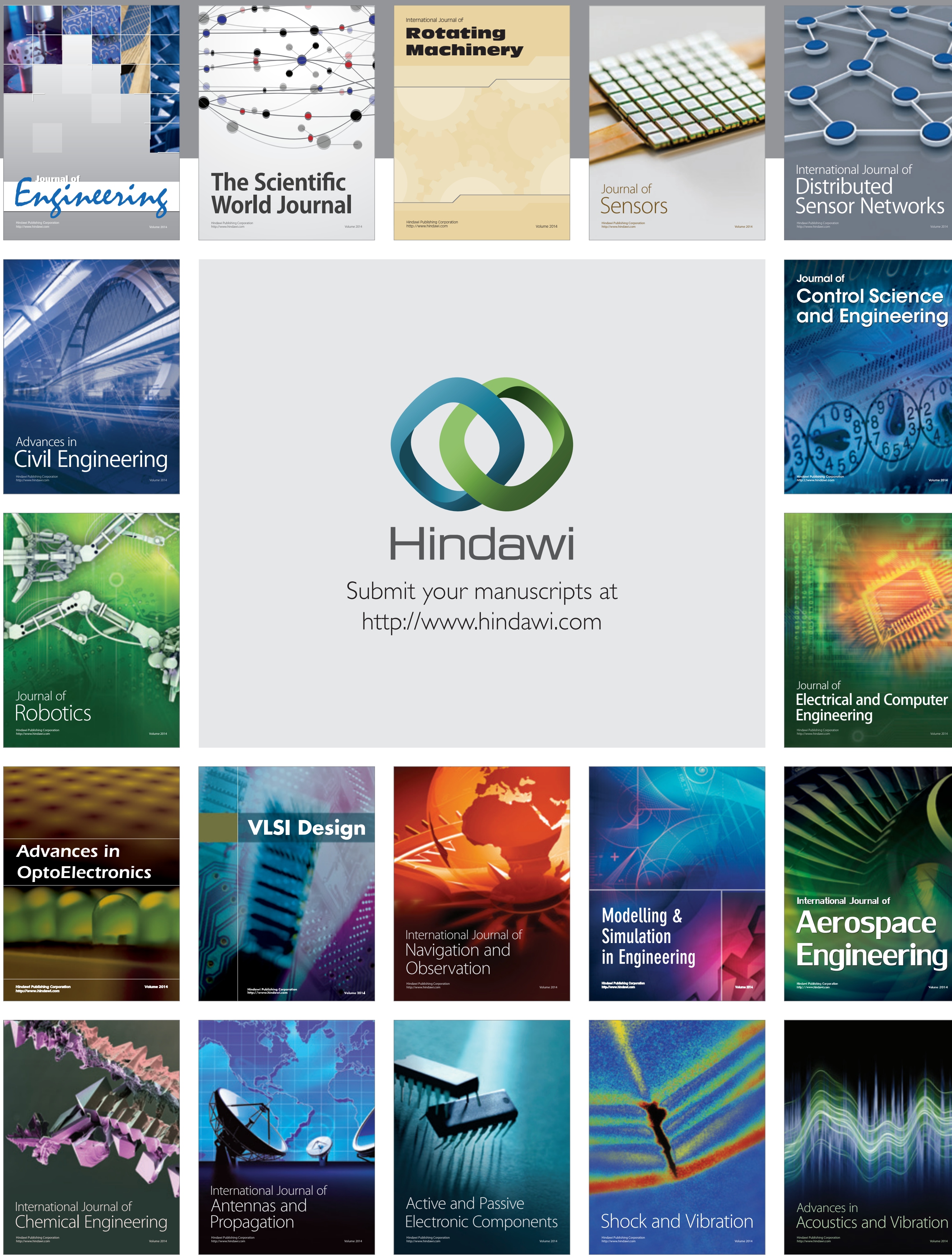

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