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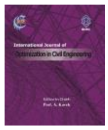

STRUCTURAL DAMAGE IDENTIFICATION USING THE FINITE ELEMENT MODEL UPDATING METHOD BASED ON STATIC RESPONSES OF THE STRUCTURE

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ABSTRACT

Detecting the location and severity of damage, particularly in the early stages, is a significant topic in structural engineering. This study proposes a new identification method that can achieve third-level damage detection of structures. The approach involves conducting a static load test to measure the structure's static responses, along with a finite element model updating method that utilizes an optimization strategy. Based on the structure's static responses, a new damage index is introduced. This index comprises two components: a location index, which represents the residual values between structural responses in intact and damaged states, and a severity index, which is defined based on the correlation coefficient between structural responses in actual damage scenarios and the outcomes from the model updating process. Jaya optimization algorithm is used in this regard. The effectiveness of the proposed method is assessed through four numerical examples involving beam and frame structures under various damage scenarios. In addition, the method's performance is evaluated for noisy data. The results demonstrate the proposed method's effectiveness and high precision in identifying structural damage. However, the results also indicate that the proposed approach is highly sensitive to noisy data.

Keywords: damage identification; structural static responses; finite element model updating method; optimization; Jaya algorithm.

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1. INTRODUCTION

Monitoring a system and detecting damage in early stages is a crucial concern in engineering fields, including civil, mechanical, and aerospace engineering. In civil engineering, for instance, damage to structural members can significantly impact the current and future performance of the entire structure, which is undesirable. However, depending on the level of damage, its effects on the system's performance may not be immediately noticeable. This delay can allow damage to worsen over time, potentially leading to severe failures or even collapse due to progressive damage. Therefore, early detection of any damage is essential.

Damage identification techniques can be categorized into visual (local) and global detection techniques. Because visual techniques have limitations—such as requiring detailed knowledge of the damage's surroundings and access to it—researchers have increasingly focused on developing global detection methods. One of the most widely used global approaches involves examining changes in the structure's vibration characteristics. Essentially, by comparing two states of the structure—the intact state and the damaged state—one can determine if any damage is present.

The fundamental concept of vibration-based damage identification is that a structure's dynamic properties are impacted by its physical characteristics, such as mass, stiffness, and energy dissipation mechanisms. Consequently, any changes in these physical characteristics will lead to detectable variations in the dynamic properties. In this context, the structural model updating technique has been widely used to identify damage in civil structures. Research studies such as Doebling et al. [1, 2] and Alkayem et al. [3] provide comprehensive reviews of the finite element (FE) model updating methods and their applications in damage identification. In this approach, the goal is to adjust the parameters of the structure's FE model to achieve perfect convergence between the numerical results and measured data from the monitored structure.

Several techniques have been developed for FE model updating strategies, as discussed in Mottershead and Friswell [4], Friswell and Mottershead [5], and Marvala [6]. These techniques are categorized into two main classes: direct methods and iterative/indirect methods [3]. Direct methods include techniques such as matrix-update, optimal matrix, error matrix, eigenstructure assignment, etc. In contrast, iterative and indirect methods comprise several subdivisions: sensitivity-based techniques (which include modal data-based and frequency response data-based strategies), computational intelligence techniques (using machine learning strategies and heuristic algorithms), response surface techniques, Bayesian-Monte Carlo techniques, etc. The application of these methods in damage identification has been explored in various research works and is not discussed in this study.

However, due to several advantages, such as the ability to solve complex optimization problems with high nonlinearity and multi-modal interactions, successful implementation in complex FE model updating, the elimination of the need to calculate the objective function gradient, and the capacity to overcome issues with local optima, model updating using heuristic algorithms has gained significant attention from researchers in the field of damage identification [3].

In damage identification using FE model updating, the primary concept is to establish residuals that represent the differences between the dynamic properties of the FE model of the intact structure and those of the damaged state. These residuals illustrate the deviations

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between the two conditions. Consequently, the objective function is typically formulated based on these residuals. Common dynamic properties used to calculate the residuals in damage identification through FE model updating include natural frequencies, mode shape vectors, frequency response functions, modal flexibility, modal strain energy, or a combination of these properties, each assigned different weights [3, 7, 8].

In this regard, several researchers, including Hou et al. [9], Ghasemi et al. [10], Nasery et al. [11], Ghannadi et al. [12], and Mahdavi and Kaveh [13], have addressed the topic of identifying structural damage through model updating using the structure's natural frequencies. Their work has led to the development of various frequency-based strategies. Additionally, the use of mode shape vectors in FE model updating for damage identification has received considerable attention from various researchers, such as Moreno-García et al. [14], Seyedpoor and Montazer [15], Safari and Gholizad [16], Li et al. [17], and Rahmanikhah et al. [18]. As a result, several methods based on these vectors have been established.

Several studies have explored the frequency response function and its application in model updating methods, including Lin and Zhu [19], Meo and Zumpano [20], Esfandiari et al. [21], Shadan et al. [22], Wang et al. [23], and Yin et al. [24]. In parallel, some researchers have focused on structural FE model updating strategies using modal flexibility, such as Yan and Golinval [25], Hosseinzadeh et al. [26], Dinh-Cong et al. [27], Wickramasinghe et al. [28], and Huang et al. [29]. Moreover, modal strain energy in structural damage identification has attracted researchers' attention, including Cha and Buyukozturk [30], Vo-Duy et al. [31], Kaveh and Zolghadr [32], Hosseini et al. [33], and Kiran and Bansal [34].

Previous research has shown that FE model updating methods based on residuals—defined using structural dynamic properties—can effectively identify structural damage. However, data that can be measured directly with devices such as sensors, along with a damage index formulated using these measurements, would be more practical and desirable.

This study proposes a third-level damage detection method—identifying the possible presence of damage, determining the exact location of damage, and accurately quantifying the degree of damage—for beam- and frame-like structures through the static responses. This method requires only the responses of the structure in two states: intact and damaged, when subjected to a static point load. Initially, a static load is applied at a specific point, and the structure’s responses are measured to gather experimental data. This process is repeated after damage occurs in some areas of the structure. Notably, the data for the intact state can be obtained immediately after the structure is first implemented. Tests conducted over specific time intervals can then gather data corresponding to the damaged state. In analytical simulations, both the intact and damaged states can be modeled using the FE method. This approach facilitates structural damage identification in early stages.

Next, a response-based damage index has been introduced, consisting of two components: the location index and the severity index. The location index identifies both the existence and location of damage by comparing the measured responses at monitored points. Following this, an FE model updating strategy is used. This involves defining an unconstrained optimization problem to determine the damage severity at the identified location. To solve this optimization problem, the Jaya optimization algorithm [35] is used; it is a parameter-less algorithm, which means it does not require specific parameters to be adjusted. However, most metaheuristic algorithms have control parameters that can

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significantly impact their efficiency. In these cases, parameter adjustments should be considered to achieve suitable performance [36, 37]. In the optimization procedure, the modulus of elasticity of the damaged element is considered a random variable to simulate a reduction in the element's stiffness. The objective function is also defined directly based on the linear correlation coefficient [38] between measured data from the structure in two states: intact and damaged. The efficiency of the proposed method is assessed through four numerical examples involving beam- and frame-like structures, considering various damage scenarios.

The proposed method has several advantages including: it achieves the third-level damage identification of structures; the static testing is straightforward, quick, cost-effective, and does not need sophisticated equipment; it can detect damage in various structural materials such as steel, concrete, aluminum, and wood; the data used in the detection process is measured directly from the structure using mounted sensors, and by conducting tests over certain time intervals, the condition of the structural members can be monitored, as a result, the decision about the remaining life of the structure or needing to rehabilitation, retrofitting, or repairing can be made by designer at early stages of damage.

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2. METHODOLOGY

This section outlines the procedure of the proposed method for structural damage identification. As mentioned earlier, this method is a third-level identification strategy that uses the static responses to detect damage in the structure's members. The following details the procedure step by step. To develop the theoretical procedure of the proposed method, we use the FE method, which models the structural system as a set of discretized components that can be assembled into a set of structural equations. For a beam element, the stiffness matrix, $\boldsymbol{k_e}$, and the nodal degrees of freedom (DOFs) vector, $\boldsymbol{d_e}$, in local coordinates are determined by Eqs. (1) and (2), respectively.

$$[\boldsymbol{k_e}] = \frac{EI}{L^3}\begin{bmatrix} 12 & 6L & -12 & 6L \\ 6L & 4L^2 & -6L & 2L^2 \\ -12 & -6L & 12 & -6L \\ 6L & 2L^2 & -6L & 4L^2 \end{bmatrix} \tag{1}$$

$$\{\boldsymbol{d_e}\} = \{v_1 \quad \theta_1 \quad v_2 \quad \theta_2\} \tag{2}$$

where E is the material's modulus of elasticity, I is the section's moment of inertia, L is the element's length, and v and θ are the nodal transitional DOF in the plane perpendicular to the element's axis and the rotation about the axis perpendicular to that plane, respectively.

However, for a frame element, the stiffness matrix, the nodal DOFs vector, and the transformation matrix are determined by Eqs. (3) to (5), respectively, where u is the nodal transitional DOF in the plane along the element's axis. In the transformation matrix, $s = \sin\gamma$ and $c = \cos\gamma$. Therefore, the element's global stiffness matrix can be computed using Eq. (6).

$$[\boldsymbol{k_e}] = \begin{bmatrix} EA/L & 0 & 0 & -EA/L & 0 & 0 \\ 0 & 12EI/L^3 & 6EI/L^2 & 0 & -12EI/L^3 & 6EI/L^2 \\ 0 & 6EI/L^2 & 4EI/L & 0 & -6EI/L^2 & 2EI/L \\ -EI/L & 0 & 0 & EI/L & 0 & 0 \\ 0 & -12EI/L^3 & -6EI/L^2 & 0 & 12EI/L^3 & -6EI/L^2 \\ 0 & 6EI/L^2 & 2EI/L & 0 & -6EI/L^2 & 4EI/L \end{bmatrix} \tag{3}$$

$$\{\boldsymbol{d_e}\} = \{u_1 \quad v_1 \quad \theta_1 \quad u_2 \quad v_2 \quad \theta_2\} \tag{4}$$

$$[\boldsymbol{T}] = \begin{bmatrix} c & s & 0 & 0 & 0 & 0 \\ -s & c & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & c & s & 0 \\ 0 & 0 & 0 & -s & c & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

$$[\overline{\boldsymbol{k}}_{\boldsymbol{e}}] = [\boldsymbol{T}]^T[\boldsymbol{k_e}][\boldsymbol{T}] \tag{6}$$

After assembling the elements into a set and applying the boundary conditions, the equilibrium equation of a structure with linear behavior under a series of static loads can be written as Eq. (7).

$$[\boldsymbol{K}]\{\boldsymbol{D}\} = \{\boldsymbol{F}\} \tag{7}$$

where $\boldsymbol{K}$ is the global stiffness matrix, $\boldsymbol{D}$ is the structural response vector, and $\boldsymbol{F}$ refers to the vector of external loads applied to the structure's nodes. Therefore, the structural responses are determined as follows.

$$\{\boldsymbol{D}\} = [\boldsymbol{K}]^{-1}\{\boldsymbol{F}\} \tag{8}$$

In this study, to simulate damage in structural members, the element's stiffness is decreased by reducing its modulus of elasticity.

$$E_{e.i.dam} = E_{e.i.int}(1-\psi) \tag{9}$$

where $E_{e.i}$ is the modulus of elasticity of the ith element of the structure, with subscripts *int* and *dam* pointing to the intact and damaged states, respectively, and ψ denotes the reduction coefficient. Therefore, the structural response vectors in the intact and damaged states are written as Eqs. (10) and (11), respectively.

$$\{\boldsymbol{D_{int}}\} = [\boldsymbol{K_{int}}]^{-1}\{\boldsymbol{F}\} \tag{10}$$

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$$\{\boldsymbol{D_{dam}}\} = [\boldsymbol{K_{dam}}]^{-1}\{\boldsymbol{F}\} \tag{11}$$

The residual between structural responses in two intact and damaged states is calculated by subtracting Eq. (11) from Eq. (10).

$$\{\boldsymbol{R}\} = \{\boldsymbol{D_{int}}\} - \{\boldsymbol{D_{dam}}\} = ([\boldsymbol{K_{int}}]^{-1} - [\boldsymbol{K_{dam}}]^{-1})\{\boldsymbol{F}\} \tag{12}$$

where $\boldsymbol{R}$ is a vector of response-based residuals introduced as a location index indicating the existence and location of damage in the structure's elements.

Next, the severity of damage in the affected elements is determined. For this purpose, a model updating strategy is used that benefits from computational intelligence techniques based on optimization algorithms. To effectively implement this strategy, three key parameters are critical:

- First, selecting the appropriate updating parameters significantly influences the quality of the updating method. These parameters are chosen based on the structure type and the overall parameters used in the modeling process. Selected parameters must correlate with the damage locations and affect the objective function. A smaller set of parameters is preferable, as it eliminates unnecessary variables and reduces computational costs.
- Second, the objective function not only impacts the interpretation of the correlation between results but also affects the efficiency of the optimization algorithm. In addition, the optimization process requires solving the FE problem at least once in each iteration to evaluate the objective function value. If this process is inefficient, interactive model updating becomes practically challenging.
- Lastly, it is essential to apply all system constraints correctly, if any exist.

In this study, the modulus of elasticity of the damaged element is considered as the updating parameter. In the optimization problem, the objective function is defined as the severity index. This index is based on the linear correlation coefficient [38] between the measured data from the damaged state and those from the model updating procedure.

For two quantitative vectors, $\{\boldsymbol{X}\} = \{x_1.x_2.x_3 \dots .x_n\}$ and $\{\boldsymbol{Y}\} = \{y_1.y_2.y_3 \dots .y_n\}$, with an unknown joint distribution, the correlation index (correlation similarity coefficient) and correlation distance are determined using Eqs. (13) and (14), respectively.

$$CI(\{\boldsymbol{X}\}.\{\boldsymbol{Y}\}) = \frac{cov(\{\boldsymbol{X}\}.\{\boldsymbol{Y}\})}{\sigma(\{\boldsymbol{X}\})\sigma(\{\boldsymbol{Y}\})} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{13}$$

$$CD(\{\boldsymbol{X}\}.\{\boldsymbol{Y}\}) = 1 - CI(\{\boldsymbol{X}\}.\{\boldsymbol{Y}\}) \tag{14}$$

where

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$$\bar{x}_i = \frac{1}{n}\sum_{i=1}^{n} x_i \quad . \quad \bar{y}_i = \frac{1}{n}\sum_{i=1}^{n} y_i \tag{15}$$

where cov and σ stand for covariance and standard deviation, respectively, and CD returns distances between observations in the 1-by-n data vector $\{\boldsymbol{X}\}$ and the 1-by-n data vector $\{\boldsymbol{Y}\}$. The Correlation coefficient can vary within the interval [-1, 1]. A value of 1 indicates a perfect linear relationship between two variables, meaning they change in the same direction. Conversely, a correlation coefficient of -1 signifies a perfect linear relationship in the opposite direction. If the variables are independent, the correlation coefficient equals zero; however, the reverse is not necessarily true.

According to the above definitions, an unconstrained optimization problem in the model updating technique is defined as follows:

$$\begin{aligned} &Find: \quad \{\boldsymbol{\Pi}\} = \{E_{e1.dam}.E_{e2.dam}.E_{e3.dam}\dots.E_{em.dam}\} \\ &to\ minimize: \quad \Lambda = |CD(\{\boldsymbol{D}_{dam}\}.\{\overline{\boldsymbol{D}}_{dam}\})| \end{aligned} \tag{16}$$

where $\boldsymbol{\Pi}$ is the updating parameters' vector, which consists of the modulus of the elasticity for the damaged elements, m is the number of elements that have sustained damage, and Λ stands for the objective function in the optimization problem—is a function of the desired response vectors of the damaged structure in its actual state, denoted as $\boldsymbol{D_{dam}}$, and the updated state, denoted as $\overline{\boldsymbol{D}}_{\boldsymbol{dam}}$.

Many evolutionary and swarm intelligence-based algorithms are probabilistic and rely on common control parameters, such as population size, number of generations, and elite size. In addition to these common parameters, each algorithm has its own specific parameters that need to be tuned. Properly tuning these specific parameters is critical, as it significantly affects the algorithm's performance. Improper tuning can lead to either much computational effort or a local optimum solution. In this paper, the Jaya algorithm [35] is used to solve the optimization problem. This algorithm requires no specific parameters and consists of one phase, described below.

Let $g(\boldsymbol{Z})$ be an objective function that needs to be minimized or maximized. At iteration i, let $j = 1.2.3 \dots. q$ be the number of design variables, and $s = 1.2.3 \dots. k$ be the population size. Candidates are initialized as follows:

$$Z_{j.s} = l_{j.s} + (u_{j.s} - l_{j.s})_{j.s} \cdot \beta_{j.s} \tag{17}$$

where β is a random number with a uniform distribution, and l and u are the lower and upper limits of the variables, respectively. The best and worst candidates are obtained using the best and worst values of $g(\boldsymbol{Z})$ in the candidate solutions and are introduced by $g(\boldsymbol{Z})_{best}$ and $g(\boldsymbol{Z})_{worst}$. If $Z_{j.s.i}$ denotes the value of the jth variable for the sth candidate during the ith iteration, this value can be updated as follows:

$$\bar{Z}_{j.s.i} = Z_{j.s.i} + \alpha_{1.j.i}\left(Z_{j.bast.i} - |Z_{j.s.i}|\right) - \alpha_{2.j.i}\left(Z_{j.worst.i} - |Z_{j.s.i}|\right) \tag{18}$$

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where $Z_{j.best.i}$ and $Z_{j.worst.i}$ are the values of variable j in the ith iteration for the best and worst candidates, respectively; $\bar{Z}_{j.s.i}$ is the updated value of $Z_{j.s.i}$, and $\alpha_{1.j.i}$ and $\alpha_{2.j.i}$ are two random numbers for the jth variable during the ith iteration in the range [0, 1]. In Eq. (18), the second term indicates the solution's tendency to move toward the best solution, while the third term indicates the tendency to avoid the worst solution. If the updated value results in a better function value, as described in Eq. (19), it is accepted.

$$\boldsymbol{Z}_{s.i} = \begin{cases} \bar{\boldsymbol{Z}}_{s.i}\,. & if\colon\ g(\bar{\boldsymbol{Z}}_{s.i}) \leq f(\boldsymbol{Z}_{s.i}) \\ \boldsymbol{Z}_{s.i}\,. & otherwise \end{cases} \tag{19}$$

At the end of each iteration, all accepted function values are considered as input to the next iteration. Fig. 1 shows the pseudocode of an unconstrained Jaya algorithm.

```
*Input*
    Initialize the population size (N), the number of design variables (s), the upper limits of
    variables (u), the lower limits of variables (l), the current number of function evaluations
    (iter_current=0), the maximum number of function evaluations (iter_max), or any termination
    criteria

*Initialization*
    Initialize candidate by Eq. (17)
    Calculate the fitness value of every candidate and compute the best and worst solutions in the
    population
    Update the current number of function evaluations, iter_current= iter_current+N

*Main loop*
    While iter_current< iter_max or any termination criteria satisfied
        For i=1:N
            Modify the solutions by Eq. (18)
            Select the better solution by Eq. (19)
        End for
        Update the current number of function evaluations, iter_current= iter_current+N
    End while

*Output*
    Report the optimal solution
```

Figure 1: Pseudocode of an unconstrained Jaya optimization algorithm

3. NUMERICAL EXAMPLES

This section evaluates the efficiency of the proposed method for structural damage identification through four numerical examples involving beam and frame structures. First, a location index based on the structure's static responses is used to detect the potential presence and location of damage. In real life, these data can be collected using measurement devices such as sensors mounted on the structure. Increasing the number of measurement points enhances the accuracy of damage identification. Next, an FE model updating method based on an optimization algorithm is applied as a severity index to quantify the extent of damage in affected elements across various damage scenarios. Finally, the impact of noise on the measured data and its effects on the proposed method are examined.

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3.1. Simply supported beam

A simply supported steel beam is used for the first example. The beam has a total length of 5 m, a cross-sectional width of 0.25 m, and a height of 0.20 m. The material's density is 7800 kg/m3, and the modulus of elasticity is 206 GPa. In the FE model, as shown in Fig. 2, the beam is divided into 20 equal elements, while each node has two DOFs. A static load of 200 kN is applied at the beam's midpoint. To evaluate the performance of the proposed approach under different structural conditions, multiple damage scenarios are considered in the monitored structures, as detailed in Table 1.

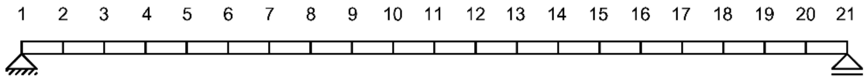

Figure 2: FE model of the simply supported beam

According to Eq. (12), the difference between structural responses in two intact and damaged states is determined. Fig. 3 shows the difference in rotations, scaled to their maximum value and denoted as the rotation difference ratio (RDR), for multiple damage scenarios presented in Table 1.

Table 1: Damage scenarios in the monitored structures

		Damage scenarios		
		Scenario 1	**Scenario 2**	**Scenario 3**
Simply supported beam	Damage element	3	1, 5	4, 8, 13, 19
	Damage severity	20 (%)	65, 30 (%)	45, 60, 50, 70 (%)
Cantilevered beam	Damage element	7	4, 11	1, 4, 9, 12
	Damage severity	60 (%)	40, 75 (%)	25, 20, 45, 50 (%)
One-bay frame	Damage element	19	6, 13	5, 9, 12, 18
	Damage severity	70 (%)	25, 50 (%)	30, 40, 50, 55 (%)
Two-bay frame	Damage element	16	11, 34	5, 12, 23, 32
	Damage severity	25 (%)	30, 70 (%)	60, 45, 50, 80 (%)

As shown in Fig. 3, the RDR values at certain points deviate from the slope of the line connecting data from previous nodes. This pattern holds across all three damage scenarios. Specifically, in a damaged element, values jump noticeably, indicating both the presence and precise location of the damage. In Fig. 3, small arrows indicate the locations of these jumps in the damaged elements.

To achieve third-level damage identification, it is necessary to quantify the extent of damage within the affected element. Accordingly, the optimization problem formulated in Eq. 16 is solved using the Jaya algorithm [35]. Fig. 4 illustrates the results for scenario 3. Figs. 4(a) and (b) illustrate the damage severity across all four variables for both the initial and final populations. As shown in Fig. 4(b), the Jaya algorithm successfully identifies the exact damage severity values; for each variable, all individuals in the final population converge to the same value.

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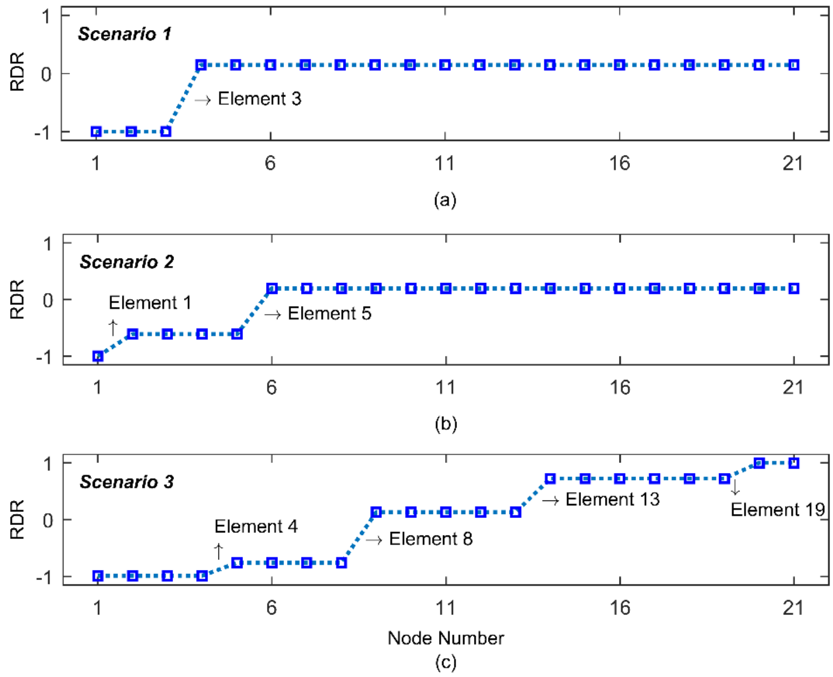

Figure 3: RDR values in the simply supported beam: (a) scenario 1; (b) scenario 2; and (c) scenario 3

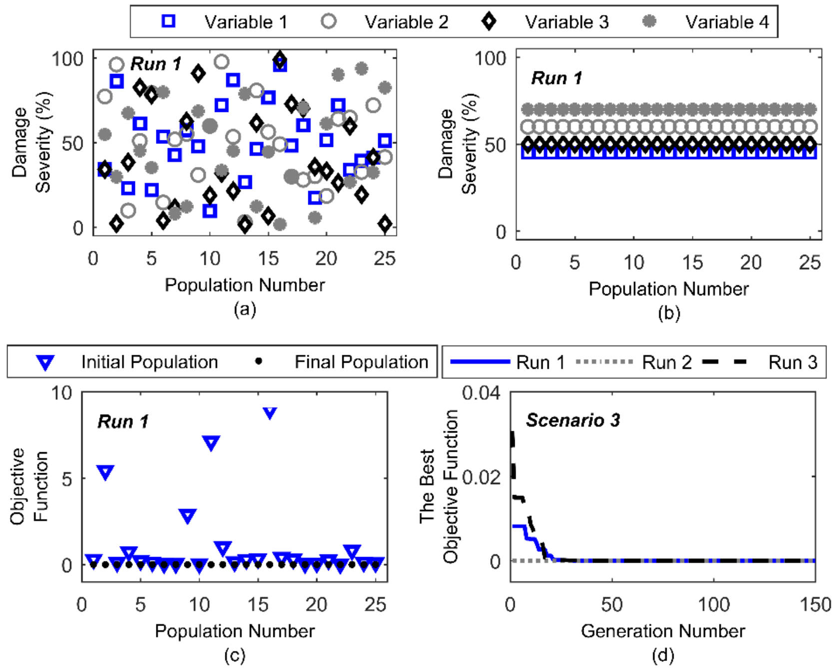

Figure 4: Results of the Jaya algorithm in the simply supported beam for scenario 3: (a) damage severity values in the initial population; (b) damage severity values in the final population; (c) objective function in the initial and final populations; and (d) convergence history of the best objective function in the sequential generations

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Fig. 4(c) shows the objective function values in the initial and final generations. Moreover, Fig. 4(d) illustrates the convergence history of the best objective function across three different runs. The objective function, designated as the severity index, is formulated based on the correlation distance between the measured data and the results obtained from model updating. As shown in Fig. 4(d), the results of all three runs ultimately converge to zero, indicating a perfect direct relationship between the responses. Fig. 5 shows the results of applying the proposed method for damage identification, along with the actual damage for all three damage scenarios presented in Table 1. These results indicate that the proposed method can achieve third-level damage identification, providing accurate results.

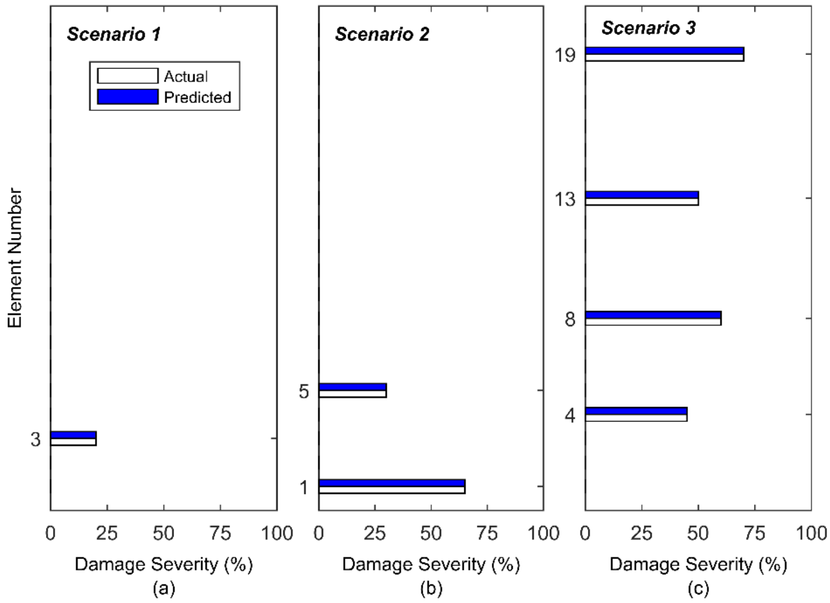

Figure 5: Results of damage identification in the simply supported beam: (a) scenario 1; (b) scenario 2; and (c) scenario 3

3.2. Cantilevered beam

A cantilevered steel beam is the second example. In the FE model, the beam is divided into 15 equal elements, as shown in Fig. 6. The beam has an overall length of 2.74 m with a rectangular cross-section with a width of 0.076 m and a height of 0.00635 m. The material's density is 7860 kg/m3 and the modulus of elasticity is 210 GPa. A static point load of 1 N is applied at node 16. Fig. 7 shows the RDR values for the cantilevered beam for all damage scenarios listed in Table 1. As shown in Fig. 7, the presence and precise location of the damage can be identified through the observed jumps in the RDR values.

After identifying the damage location in the monitored structure, the next step is to quantify the severity of the damage in those elements using the severity index. This involves defining an optimization problem within the model updating procedure, as presented in Eq. 16, and solving it to determine the degree of damage, as explained in the previous example. Fig. 8 shows the outcomes of applying the proposed damage identification method for three different damage scenarios. The results of Figs. 5 and 8 indicate the effectiveness and capability of the proposed method in identifying damage in beam-like structures.

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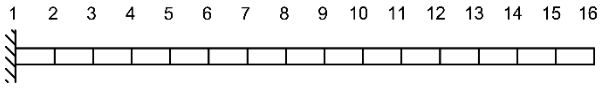

Figure 6: FE model of the cantilevered beam

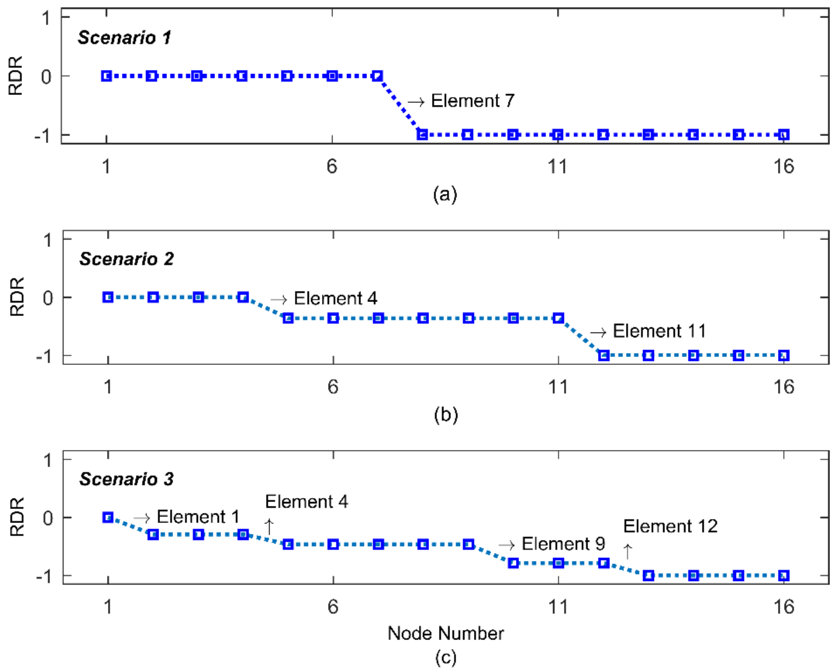

Figure 7: RDR values in the cantilevered beam: (a) scenario 1, (b) scenario 2, (c) scenario 3

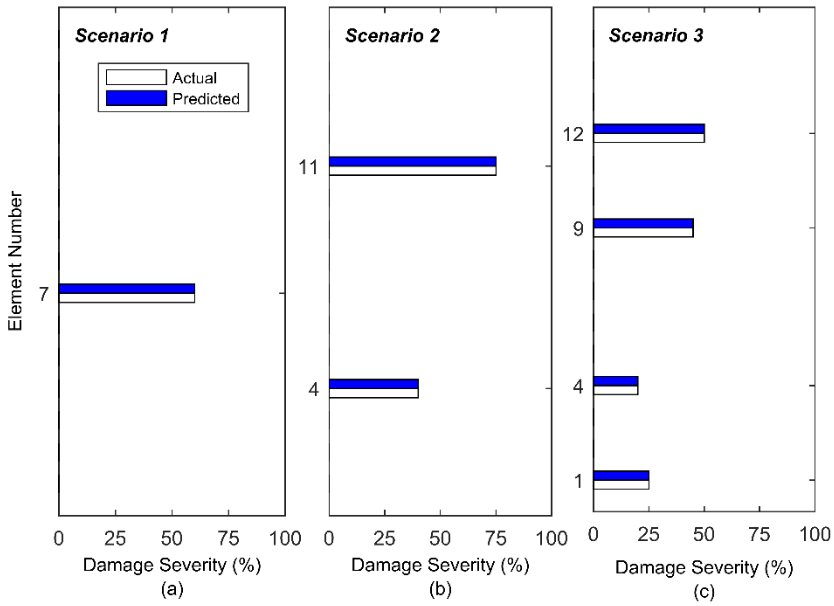

Figure 8: Results of damage identification in the cantilevered beam: (a) scenario 1; (b) scenario 2; and (c) scenario 3

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3.3. One-bay frame

A one-bay frame is considered the third example. Members have a rectangular cross-section with width 0.15 m and height 0.2 m. The frame bay length is 1.2 m, and its height is 1.6 m. The modulus of elasticity is 25 GPa, and the material's density is 2500 kg/m3. The frame is divided into 22 equal elements, and each node has three DOFs. A static point load of 200 kN is applied horizontally at the top of the frame on the left side. Fig. 9 illustrates the FE model of the frame.

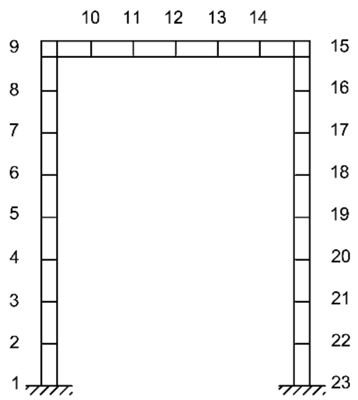

Figure 9: FE model of the one-bay frame

The structural responses under the static point load can be calculated using Eqs. (10) and (11). Consequently, the differences in the nodal axial displacements for two intact and damaged states of the frame are determined by Eq. (12). Fig. 10 illustrates these differences, scaled to their maximum values, and denoted as the displacement difference ratio (DDR). Notably, the responses of the nodes situated on the vertical members are divided by their maximum values, and the same procedure is applied to the nodes on the horizontal members. As shown in Fig. 10, for all scenarios, the line connecting adjacent nodes breaks at the damaged locations. These noticeable jumps in the DDR values clearly indicate the presence and location of damage.

Once the damage is found and its location is known, the extent of the damage in the affected parts is assessed. To achieve this, the objective function in Eq. (16) is formulated using the correlation distance between the measured data and the data obtained from the model updating process, which is defined as the severity index. As shown in Fig. 11, the proposed method successfully identifies all the damage scenarios listed in Table 1 with precision.

3.4. Two-bay frame

A frame with two identical bays with characteristics similar to the third example is considered the fourth example. Fig. 12 shows the frame's FE model, which consists of 36 equal elements. A static point load of 200 kN is applied horizontally at the top of the frame on the left side.

Fig. 13 shows the DDR values for different damaged scenarios listed in Table 1. As shown in this figure, the existence and location of the damage can be clearly detected.

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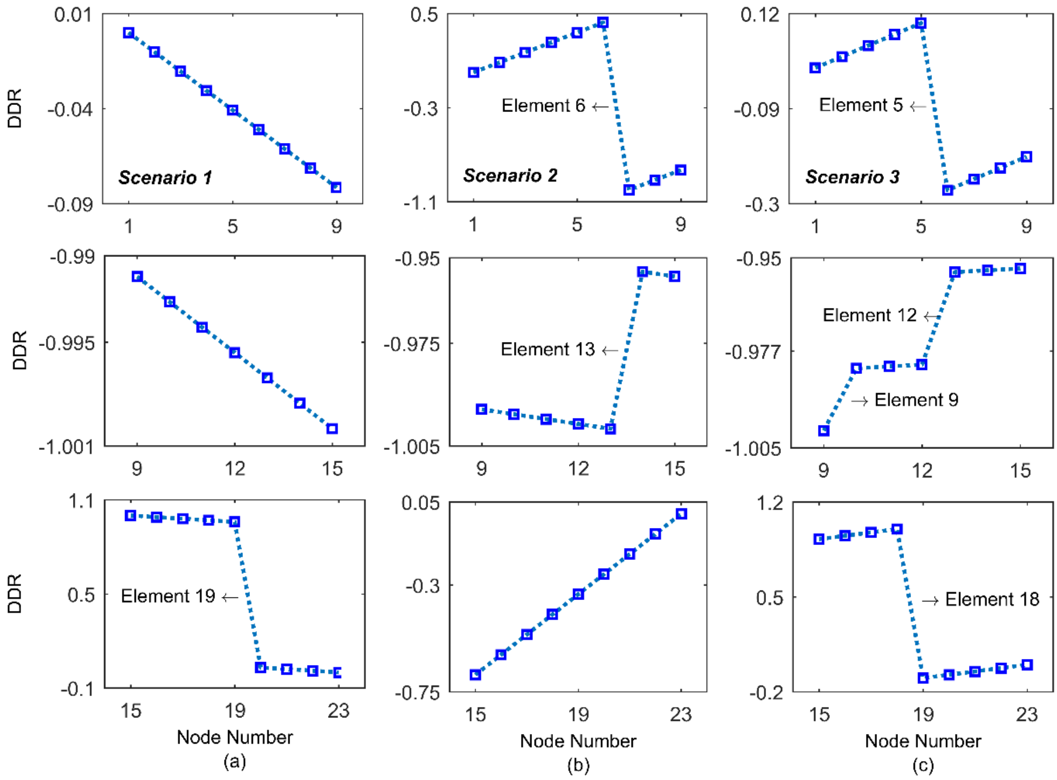

Figure 10: DDR values in the one-bay frame: (a) scenario 1; (b) scenario 2; and (c) scenario 3

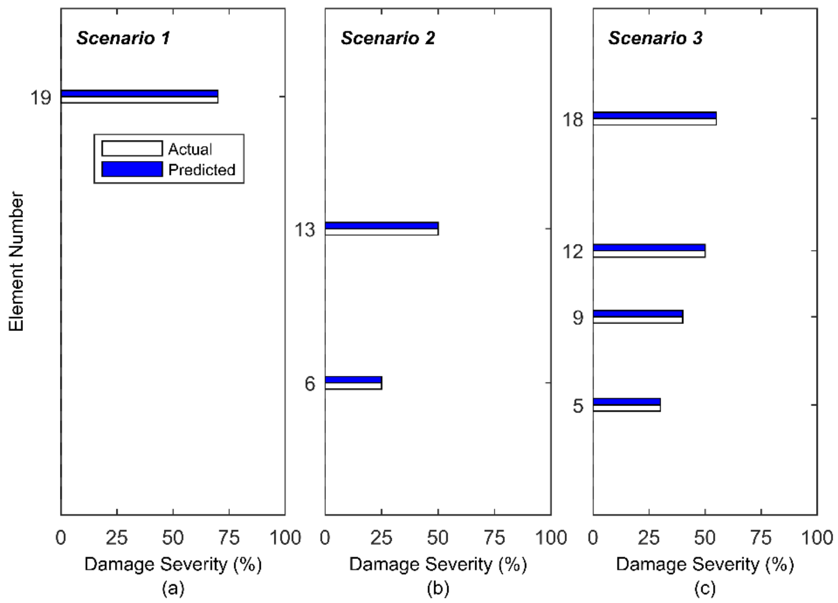

Figure 11: Results of damage identification in the one-bay frame: (a) scenario 1; (b) scenario 2; and (c) scenario 3

Fig. 14 presents the results of the proposed damage identification method across three

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distinct damage scenarios. These findings indicate that the method effectively and accurately identifies damage in the frame-like structures, corroborating the conclusions previously established for beam-like structures.

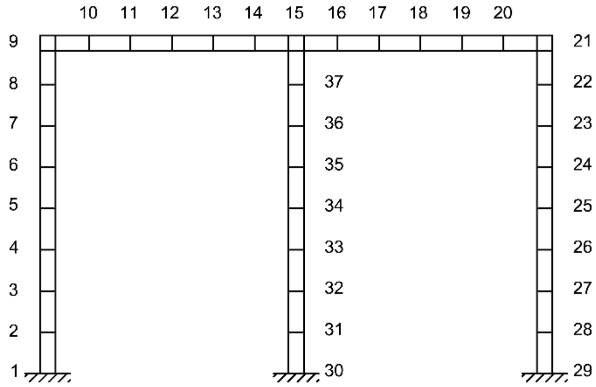

Figure 12: FE model of the two-bay frame

3.5. Data polluted by noise

Here, the efficiency of the proposed method for detecting damage in structural members is investigated, particularly when the measured responses are polluted with noise. To this end, a series of pseudo-random numbers is added to the measured responses, creating noisy data as follows:

$$\{\boldsymbol{D}_{int}^{*}\} = (\{\boldsymbol{\Gamma}\} + \eta\{\boldsymbol{\Theta}_1\})^T\{\boldsymbol{D}_{int}\} \tag{20}$$

$$\{\boldsymbol{D}_{dam}^{*}\} = (\{\boldsymbol{\Gamma}\} + \eta\{\boldsymbol{\Theta}_2\})^T\{\boldsymbol{D}_{dam}\} \tag{21}$$

where $\boldsymbol{D}_{int}^{*}$ and $\boldsymbol{D}_{dam}^{*}$ are the structural static responses under noisy conditions for the intact and damaged states respectively, $\boldsymbol{\Gamma}$ is a column vector of ones, η is the noise level, and $\boldsymbol{\Theta}$ is a vector of components uniformly distributed over [-1, 1].

The results obtained from the proposed method, for instance, in scenario 2 for the simply supported beam and one-bay frame, are shown in Figs. 15 and 16, respectively. These results include analyses conducted at three distinct noise levels: 0.1%, 0.5%, and 1%.

As shown in Figs. 15 and 16, the efficiency of the proposed method for identifying damage locations is highly dependent on the precision of the measured data, because the location index is derived directly from the structural responses. In other words, the proposed approach is sensitive to noisy data when identifying locations; this sensitivity is more pronounced for frame structures than beams. However, if the damage location can be determined in any way, Fig. 17 shows the damage severity in the affected members for the simply supported beam and the one-bay frame using the proposed method. Consistent with the observations regarding the location index, during the updating process, the performance of the severity index in damage severity estimation is also affected by the noise added to the responses.

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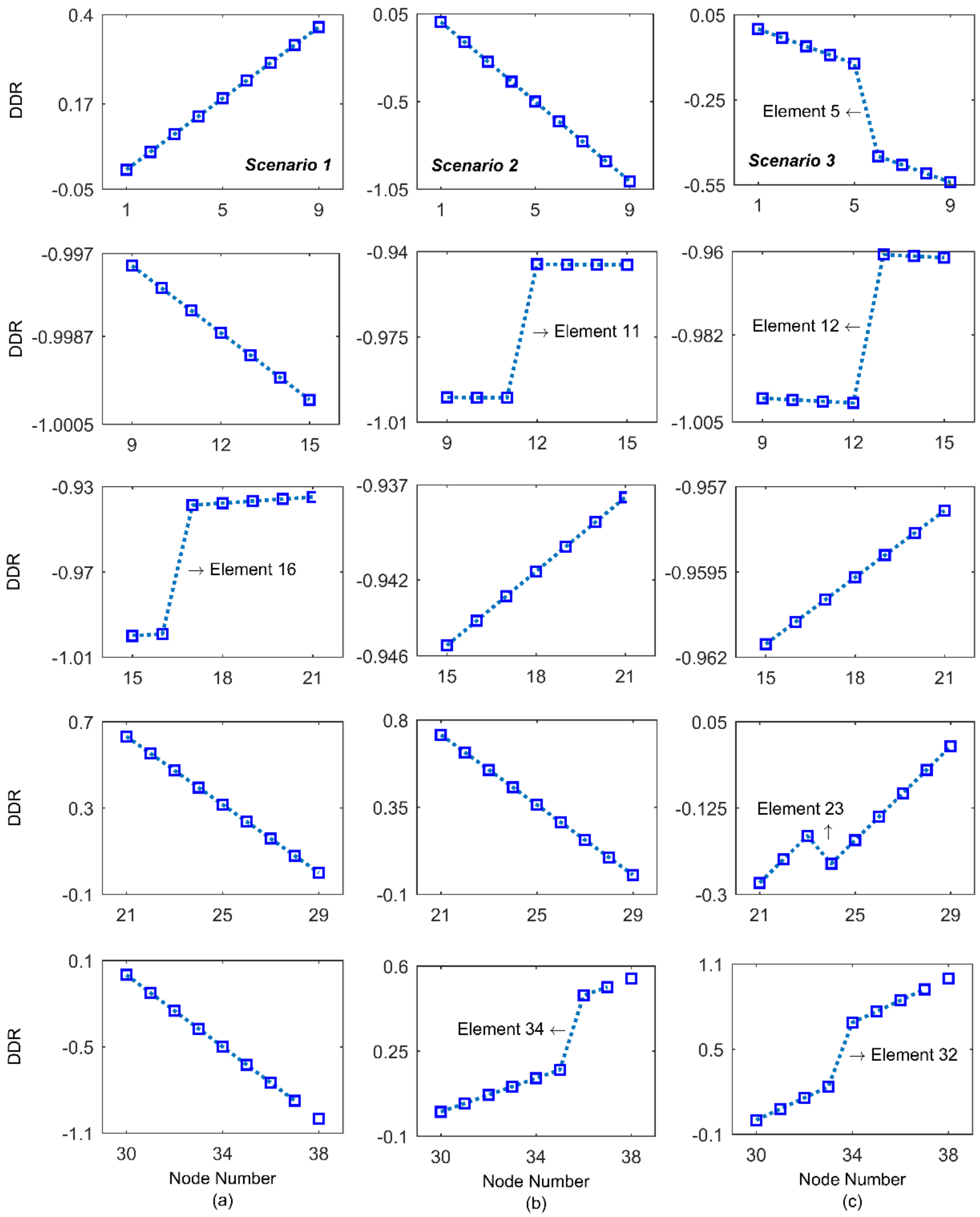

Figure 13: DDR values in the two-bay frame: (a) scenario 1, (b) scenario 2, (c) scenario 3

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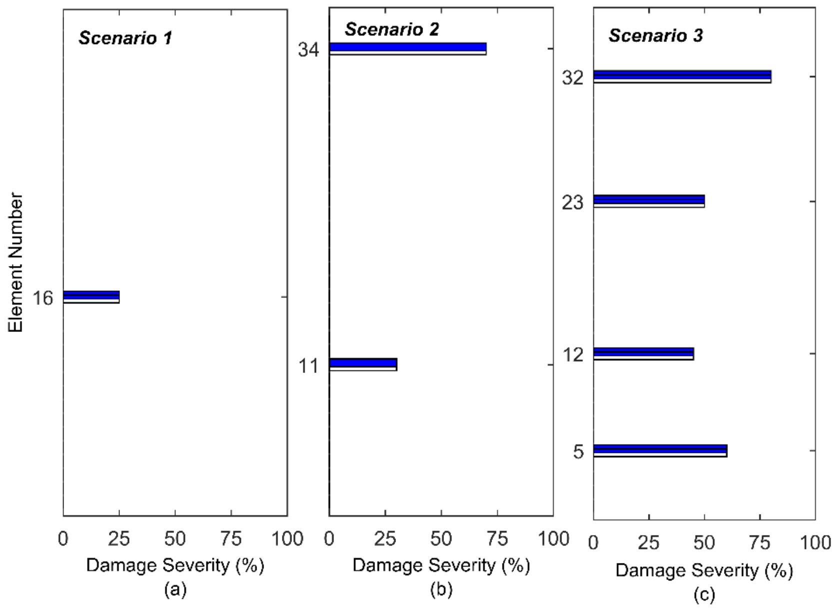

Figure 14: Results of damage identification in the two-bay frame: (a) scenario 1, (b) scenario 2, (c) scenario 3

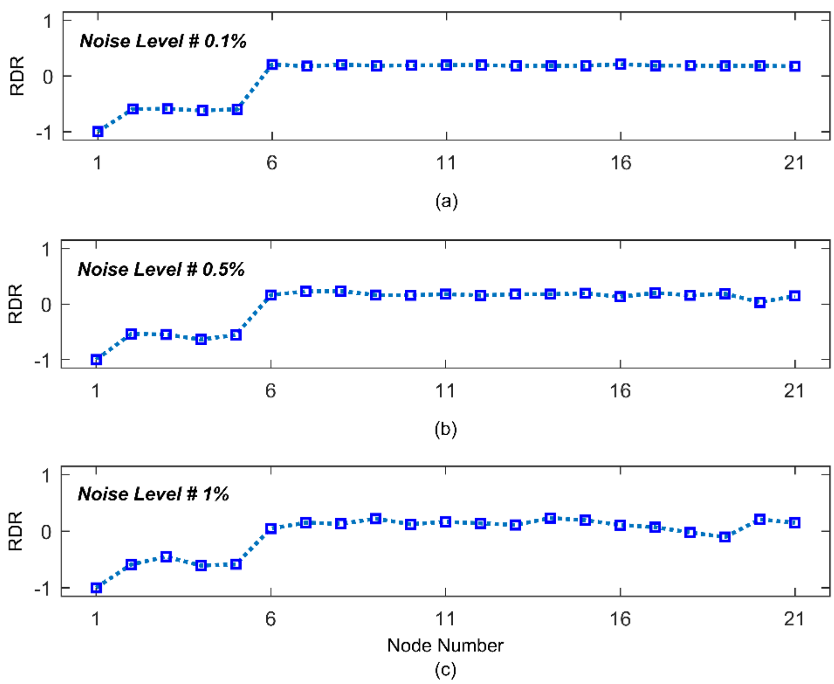

Figure 15: RDR values in the simply supported beam for scenario 2 with noisy level of: (a) 0.1%; (b) 0.5%; and (c) 1%

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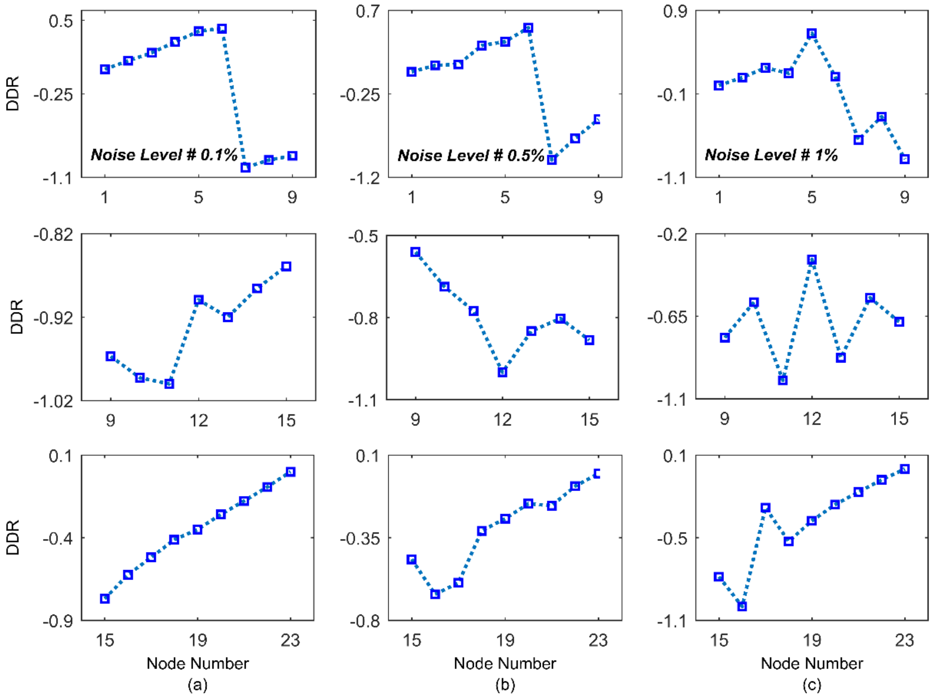

Figure 16: DDR values in the one-bay frame for scenario 2 with noisy level of: (a) 0.1%; (b) 0.5%; and (c) 1%

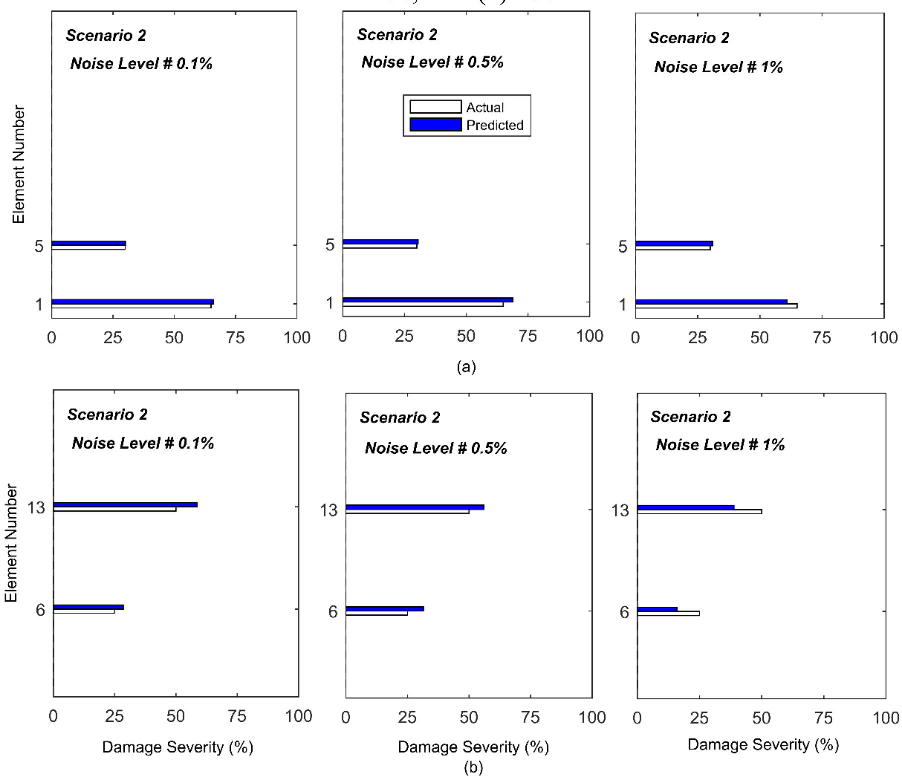

Figure 17: Damage severity in scenario 2 for noisy data: (a) the simply supported beam; and (b) the one-bay frame

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4. CONCLUSIONS

This study presents a new method for identifying structural damage. The strategy involves applying a static point load to a structure and measuring its responses in both intact and damaged conditions. By calculating a residual value from these responses as a location index, the method determines both the presence and exact location of any damage. Then, a finite element model updating procedure, integrated with the Jaya optimization algorithm, is used to quantify the severity of the identified damage. This is achieved through a severity index, formulated as an objective function based on the correlation coefficient between the measured structural responses and those obtained via model updating. The efficiency of the proposed method is evaluated in four numerical examples, which include beam and frame structures under various damage scenarios within the identification process. Results demonstrate that structural damage alters residual values, thereby disrupting the continuity of the profile connecting these values at adjacent nodes and revealing the precise location of the damage. In addition, the severity index provides an accurate extent of damage in affected elements. However, the evaluation shows significant sensitivity to noisy data, which is an important consideration for practical applications.

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