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Research paper

A novel method for identification of damage location in frame structures using a modal parameters-based indicator

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Abstract: Diverse strategies for identifying and finding the damages in structures have been continuously engaging to originators within the field. Due to the direct connection between the firmness, characteristic frequency, and mode shapes within the structure, the modular parameters may well be utilized for recognizing and finding the damages in structures. In current consider, a modern damage marker named Damage Localization Index (DLI) is applied, utilizing the mode shapes and their derivative. A finite element model of a frame with twenty and thirty components has been utilized, separately. The numerical model is confirmed based on experimental information. The indicator has been explored for the damaged components of a frame with one bay. The results have been compared with those of the well-known index CDF. To demonstrate the capability and exactness of the proposed method, the damages with low seriousness at different areas of the structures are explored. The results are investigated in noisy condition, considering 3% and 5% noise on modal data. The outcomes show the high level of accuracy of the proposed method for identifying the location of the damaged elements in frames.

Keywords: damage detection, frame, modal parameters, mechanical failure, finite element model

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1. Introduction

Maintenance of structures to increase the structural performance and lifetime is of great importance to machine elements design industry. A great deal of research studies has been conducted to identify and detect damage location in structural systems [1–8]. The engineering structures endure some unforeseen external loads during their lifetime; they are likely to be exposed to damages and catastrophic failure. Structural health monitoring (SHM) has been an important field to study different methods for identification and localization of the structural damages. These methods can be classified into time domain and frequency domain approaches. The time domain approach has been proposed to detect the damages based on changes in displacement, accelerations, or strains. The changes in natural frequency [9], real-time frequency-domain decomposition [10], mode shapes, power spectral density [11], or mode shape curvatures [12–14] are used as parameters for identification of damages in frequency domain approaches. Most well-known methods are based on frequency and modal data, which are relatively easy to measure in real structures. Because of direct relationship between modal parameters (e.g., natural frequency and mode shape) and stiffness of the structures, any changes in the stiffness leads to changes in the modal frequencies and shapes. Fayyah et al. [15] proposed an index based on the combined effect of both the natural frequencies and mode shapes when a change in stiffness of the structural element occurs for detecting the damage severity in structural elements. Their proposed index compared the factor of reduction in stiffness according to reduction in natural frequencies and the factor of reduction in stiffness according to change in mode shape. Tomaszewska and Szafrański [16] focused on applicability of two modal identification techniques; peak picking based on correlation analysis, for ambient vibrations, and eigensystem realization algorithm, formulated for free-decay vibrations investigation. The techniques were evaluated on masonry tower and steel railway bridge. Hasni et al. [17] conducted an artificial intelligence approach for the detection of distortion-induced fatigue cracking of steel bridge girders based on the data provided by self-powered wireless sensors. In their study, the sensors had series of memory gates that cumulatively recorded the duration of the applied strain. They characterized the output from the sensors by Gaussian cumulative density function. They concluded that their models had acceptable detection performance, specifically for cracks larger than 10 mm. Donskoy and Liu [18] proposed and investigated a baseline-free Vibro-Acoustic Modulation damage detection approach that does not require the monitoring of relative Modulation Index change. Farrar et al. [19] adopted a statistical approach in their process of vibration-based damage detection and applied it to a large-scale laboratory structure. They showed that changes in frequency would not yield any information about the location of damage, though it detects the presence of damage. Fayyadh and Razak [20] proposed a new damage index based on a combination of mode shape vector and its derivatives. Efficiency of the index was examined by comparing it with COMAC for trivial damages. Taghipour et al. [21] proposed and investigated the accuracy of a novel damage indicator based on mode shapes and their derivatives. To demonstrate the competence and accuracy of the proposed indicator, damages with low severity at multiple locations over the structures including the elements near the supports were investigated. In that study, results under noisy conditions were also analyzed by including 3% and 5% noise on modal data. The results showed a high level of precision in identifying the location of the damaged elements in beams.

To further investigate the applicability of the proposed approach in the previously published work by the authors, in the present research study, a novel identification of damage location in frame structures based on mode shapes and their derivatives are studies in wider application conditions. One of advantages of this new approach is its applicability in frames to locate single and multiple structural damages. The numerical model was created based on finite element method which is programmed in MATLAB. To validate the model, its results are compared with those of experimental tests. The efficiency of the proposed method is examined under different boundary conditions using various numerical examples and comparing the results with those based on some other index. The paper is organized as follows: A summary of regulating equations are explained. Then, the proposed procedure is introduced. In the next step, accuracy of the numerical modeling is validated through an experimental model. After that, the application and efficiency of the index is evaluated using numerical examples. Also, to demonstrate the accuracy of the index in locating damaged elements, the results of the index are compared with the other index. Finally, a summary of the results is presented.

2. Theory of the problem

2.1. Regulating equations

Generally, the linear free vibration equation of an undamped system is expressed as:

$$[M]\,\{\ddot{x}\} + [K]\{xt\} = 0[M]\,\{\ddot{x}\} + [K]\{x\} = 0 \tag{2.1}$$

where, $[M]$ is the mass matrix, $[K]$ is stiffness matrix, $\{x\}$ is the displacement vector, and $\{\ddot{x}\}$ is second derivative of the displacement vector. The solution of the differential equation can be generally written as $x = Ae^{rt}$, with r being a complex number expressed as $r = \pm iw$. Substituting x and its derivatives into the above equation leads to $\left([k] - w^2[M]\right)\{x\} = 0$; In this equation, w represents the natural frequency. Eigenvalue and eigenvector matrix that are the natural frequencies, w, and mode shapes, $\{\varphi\}$, respectively, are built by performing the eigenvalue decomposition of this equation.

2.2. Frame element

The stiffness and mass matrices of the frame element in a finite element model for local coordinate system, considering the transverse and axial displacements and a rotation

(Fig. 1) in each node is expressed as [22]:

$$\hat{K}=\begin{bmatrix} C_1 & 0 & 0 & -C_1 & 0 & 0\\ 0 & 12C_2 & 6C_2L & 0 & -12C_2 & 6C_2L\\ 0 & 6C_2L & 4C_2L^2 & 0 & -6C_2L & 2C_2L^2\\ -C_1 & 0 & 0 & C_1 & 0 & 0\\ 0 & -12C_2 & -6C_2L & 0 & 12C_2 & -6C_2L\\ 0 & 6C_2L & 2C_2L^2 & 0 & -6C_2L & 4C_2L^2 \end{bmatrix} \tag{2.2}$$

$$\hat{M}=\rho AL\begin{bmatrix} 0.33 & 0 & 0 & 0.16 & 0 & 0\\ 0 & 0.37 & 0.05L & 0 & 0.12 & -0.03L\\ 0 & 0.05L & 0.009L^2 & 0 & 0.03L & -0.007L^2\\ 0.16 & 0 & 0 & 0.33 & 0 & 0\\ 0 & 0.12 & 0.03L & 0 & 0.37 & -0.05L\\ 0 & -0.03L & 0.007L^2 & 0 & -0.05L & 0.009L^2 \end{bmatrix} \tag{2.3}$$

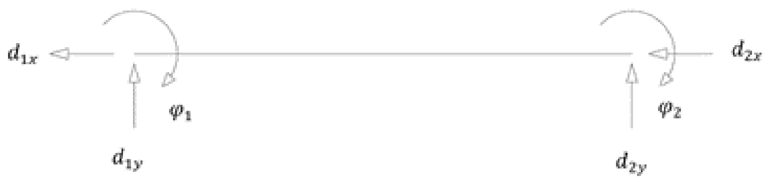

Fig. 1

3. Application of damage indicator

In this study, to detect the damages in the structure, a modern damage marker named Damage Localization Index is applied [21], DLI, based on mode shape and its derivatives has been proposed as follows:

$$\mathrm{DLI}_{(i)}=\frac{\sum\limits_{n=1}^{nm}\left\{\left|\left(\left|\left(\varphi_{h(i.n)}\times\left|\varphi''_{d(i.n)}\right|\right)\right|-\left|\left(\varphi_{d(i.n)}\times\left|\varphi''_{h(i.n)}\right|\right)\right|\right)\right|\right\}\times\varphi''_{dh(i.n)}}{nm} \tag{3.1}$$

$$\varphi''_{dh(i.n)}=\left\{\left|\left|\varphi''_{d(i.n)}\right|-\left|\varphi''_{h(i.n)}\right|\right|\right\} \tag{3.2}$$

where nm is the number of modes considered, n denotes the number of nodes, $\varphi_{h(i.n)}$ and $\varphi_{d(i.n)}$ are mode shapes of the undamaged and damaged beams at n-th mode in the i-th node or degree of freedom (*dof*), respectively, and $\varphi''_{h(i.n)}$ and $\varphi''_{d(i.n)}$ are the curvature mode shapes of the undamaged and damaged beams at n-th mode in i-th node or *dof*, respectively.

Curvature mode shape ($\varphi''_{i.n}$) would be obtained by using a central difference approximation as:

$$\varphi''_{i.n} = \frac{\varphi_{i-1.n} - 2\varphi_{i.n} + \varphi_{i+1.n}}{h^2} \tag{3.3}$$

where: $\varphi_{i.n}$ – mode shape at n-th mode in i-th *dof*, $\varphi''_{i.n}$ – curvature mode shape at n-th mode in i-th node or *dof*, h – length of element.

For a better presentation of the index values, the DLI is normalized in each node of structure, considering the mean and standard deviation. Also, negative values have been replaced with zero.

3.1. Validation of the numerical solution

In this study, the numerical model of the frame is validated using the frame tested by Esfandiary et al. [23]. The results obtained from the numerical model in the present study are compared with those of experimental results of the undamaged frame reported in [23]. Characteristics of the examined frame in [23] are as follows: length of the beam was 1000 mm, cross section area of the beam was $A = 184 \times 10^{-6}$ m^2, moment of inertia was $I = 2644 \times 10^{-12}$ m^4, density of the beam material was $\rho = 7800$ kg/m^3, modulus of elasticity of the beam material was $E = 2 \times 10^{11}$ N/m^2, and the Poisson's ratio of the beam was $\upsilon = 0.3$. The validity of the numerical model is demonstrated in Table 1 by comparing the first three natural frequencies of the numerical model and those of the experimental case.

Table 1. Comparison between the calculated natural frequencies of the undamaged frame from the FE model and the experimental measurements [16] for first three mode shapes

Methodology	First Natural Frequency	Second Natural Frequency	Third Natural Frequency
Numerical model	9.75	38.48	62.49
Experimental model [16]	8.98	35.55	58.2
Error	7.89%	7.61%	6.86%

According to Table 1, the calculated natural frequencies are in good agreement with the experimental data. In the following, performance of the proposed damage index is investigated. To demonstrate the applicability of the proposed damage index on the frames, it is used for a single span frame and the damaged elements are detected for different scenarios. In addition, the damage localization results in noisy condition are evaluated.

To investigate the efficiency of the index, the obtained results are compared with CDF [24] that is defined in Eq. (3.4), as follows:

$$\text{CDF} = \frac{1}{nm} \sum_{n=1}^{nm} \left(\varphi''_{hi} - \varphi''_{di}\right)_n \tag{3.4}$$

In the above equations, nm is the number of modes considered. φ''_{hi} and φ''_{di} are the mode shape curvature of undamaged and damaged structures, respectively.

4. Numerical analysis of a frame

In this section, to assess the applicability of the proposed index, different numerical examples are presented.

In this section, steel frame is used to indicate the performance of the proposed index. The frame has one floor, one span, and three members, and each member is divided into 10 equal elements. The frame meshing and specification for the finite element model are shown in Fig. 2. The element length, cross-section area, unit mass, and elastic modulus are 100 mm, 184 mm^2, 7800 kg/m^3, and 200×10^9 N/m^2, respectively. Two different damage cases are applied in various positions and members of the frame, as shown in Table 2. Damage detection results are compared to well-known index CDF.

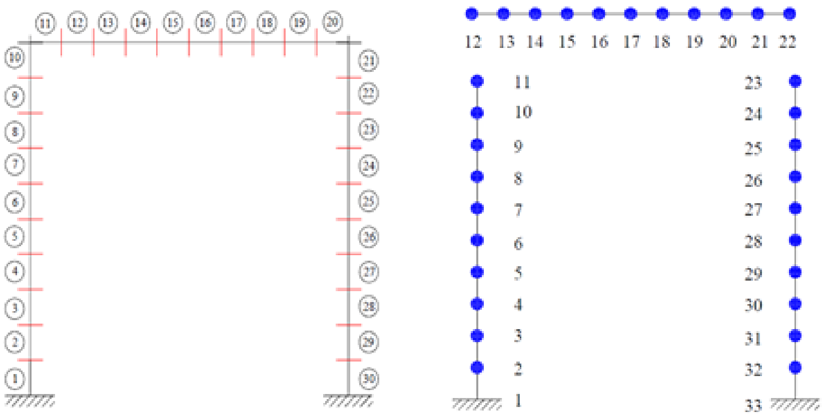

Fig. 2

Table 2. Damage scenarios of the Frame

Reduction in elasticity modulus of the element(s)	Element number	Damage scenarios
10%, 15%, 5%	5, 18, 27	Damage-1
15%, 10%	10, 15	Damage-2

For damage-1, three damaged elements are selected in three different frame members. For damage-2, one of the corner elements (connecting the beam to the column) is presented as the damaged element. As defined in Table 2, it is aimed to examine the efficiency of the index in different intensities and locations, particularly critical ones, by introducing the two damage scenarios.

Comparison of results from two indices DLI and CDF for damage-1 and damage-2 are shown in Fig. 3. It can be observed that in both scenarios the DLI identifies non-zero values in damaged elements only, while the CDF index shows non-zero values in some healthy elements, thus identifying them as damaged elements.

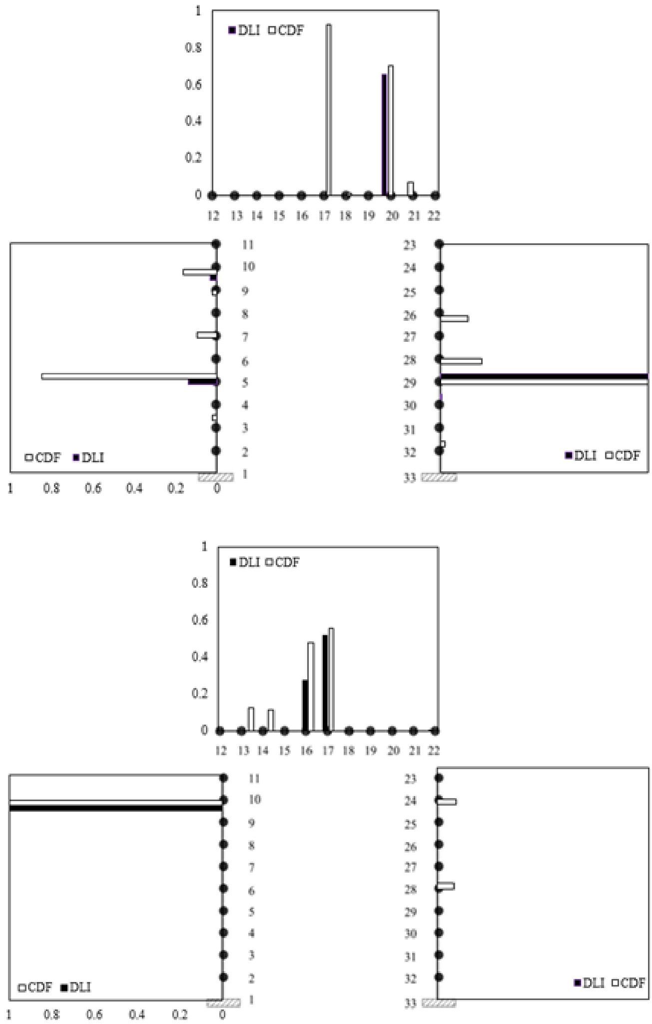

Fig. 3

As shown in Fig. 4, the DFI results are inspected to be more accurate than the CDF, in the presence of noise. To evaluate the effect of higher noise levels on the proposed index values, 5% noise is applied, and the results are compared, as demonstrated in Fig. 5.

From the comparison of results, as demonstrated in Fig. 5, it is deduced that the DFI is more reliable to identify damage correctly than the CDF in 5% noise condition, as well.

1. In symmetric cases, any damage to similar points (points with similar positions to the center line) results in similar changes in frequencies, whereas the methodology of this manuscript is based on the changes in modal shapes and their derivatives which are sensitive to the location of the damage even for symmetric frames. In other words,

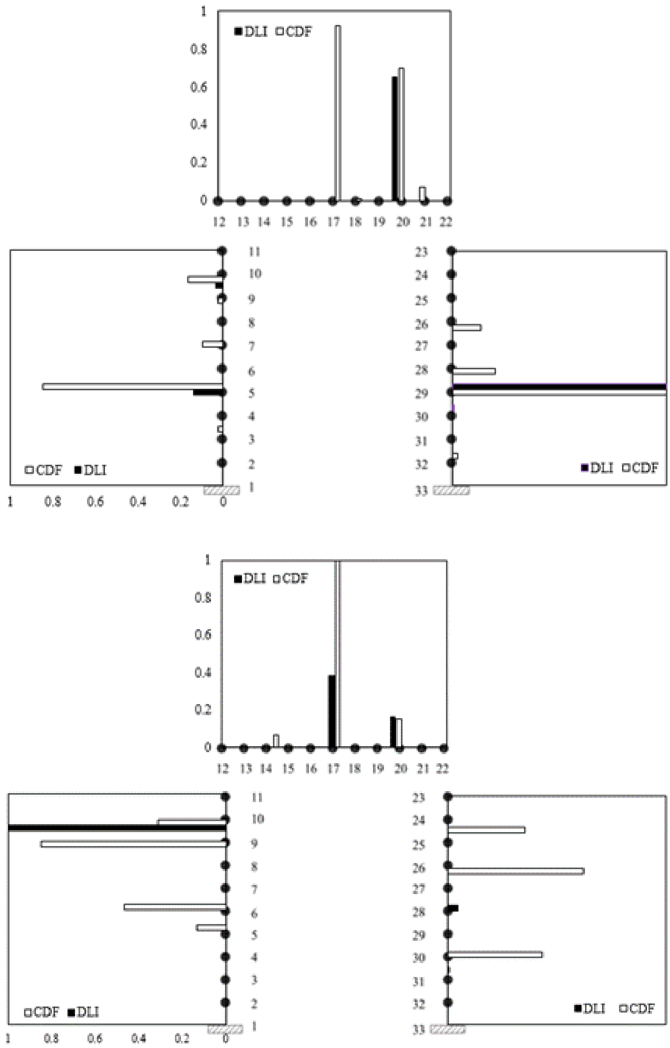

Fig. 4

the performance of the method doesn't change for a symmetric and non-symmetric structure.

2. In this research, the damage is not modeled directly by cracks or element thickness reduction, etc. In fact, the effects of the damages are considered in this study. Any damages in an element result in stiffness reduction in the element. So, the propagation of the damage to the adjacent elements could be easily modeled by reduction in element stiffness of those elements. Even, the reduction in element stiffness could be modeled by reduction in the Young's modulus.

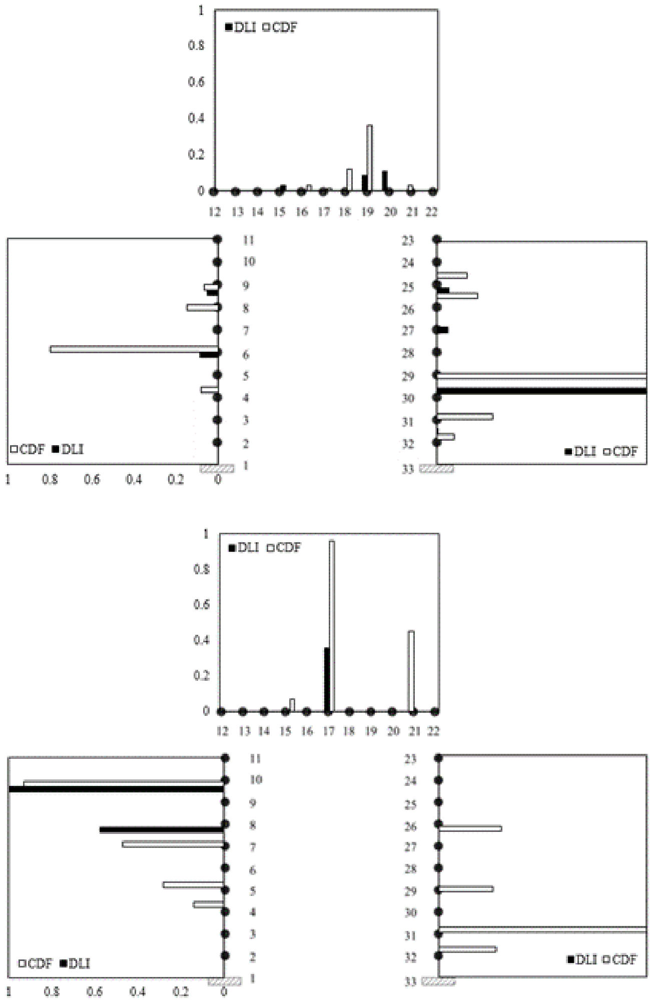

Fig. 5

For example, If the damage is the result of the element thickness reduction, the element thickness and consequently its stiffness is reduced. As the element stiffness is proportional to EI, or, in other words, to Et^3(E is the Young's modulus, I is the moment of inertia of the element cross section and t is the element thickness), any reduction in element thickness could be replaced by reduction in Young's modulus. Upon occurrence of any corrosion phenomenon or a local permanent crack in a part of the element, the equivalent moment of inertia and, consequently, the element stiffness is reduced which, once again, could be modeled by reduction in Young's modulus. In other words, in this study, regardless of the damage reason and its length, only the existence of the local damage in the elements are important; so the method is able to consider the damages larger than the length of the finite element. It is enough to reduce the stiffness (Young's modulus) of the adjacent elements. In this case, damage localization is even more comfortable in comparison to damage occurrence in a single element. Damage occurrence in adjacent elements causes more changes in modal shapes and their derivatives in the damage zone and damage detection is easier.

5. Conclusions

In the current study, the DLI was applied as an indicator for the identification of damage location in frames. To evaluate the accuracy of the numerical techniques, corresponding experimental measurements were used, and the first three frequencies obtained from the numerical study were validated against those experimental data. Various damage scenarios were studied. The results showed that in most cases, the proposed method can successfully estimate the location of the damage in the structure, using only one mode. Damage detection by the DLI has also been assessed in minor damaged areas and the efficiency of it was verified, as well. To further investigate the performance of the indicator, a comparison was made between the DLI and the well-known CDF index. The results show that the applied index performed better than the other indicator in locating the damage. Additionally, noise-sensitivity of the index is implemented. As a result, DLI found to be more effective than CDF. Overall, it can be concluded that the proposed procedure can identify the damage locations in real engineering structures, with reasonable accuracy.

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