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Damage identification of a 2D frame structure using two-stage approach †

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Abstract

In this article, a two-stage damage identification approach is employed to detect the site and extent of multiple damage cases in a 2D frame structure. In the first stage, Damage locating vector (DLV) method based on a new indicator called EDS (Exponential decreased stress) is applied to localize the damaged elements. Next, the damage extents of suspected elements are quantified using two metaheuristic algorithms, Water evaporation optimization (WEO) and accelerated WEO. Numerical example consists of a 2D frame structure with two types of meshing elements, 35 and 105 frame elements. For every state, two multiple damage cases are tested in noisy condition. To compare performance of the two-stage method with one-stage optimization method, the studied cases are also run using these two metaheuristic algorithms. The results indicate that the two-stage approach is more effective than one-stage because the number of intact element detected as damaged one and computational errors for actual damaged elements in one-stage method are more while the two-stage approach spends a much shorter time.

Keywords: Damage detection; Water evaporation optimization (WEO); Damage locating vector (DLV); 2D frame structure; Two-stage approach; Exponential decreased stress (EDS)

1. Introduction

Many terrible accidents caused by unexpected damages in structures. SHM (Structural health monitoring) is extensively utilized to identify damage of structures and protect they better [1]. Many different methods of damage identification have been reviewed by researchers [2, 3].

Some typical methods work based on flexibility change [4, 5]. The Damage locating vector (DLV) is a kind of flexibility change method that firstly proposed by Bernal [6]. Many researchers developed the DLV method [7-9]. Quek et al. [8] proposed a new indicator called normalized cumulative energy (nce) and extended the DLV method. Vo-Duy et al. [9] employed the DLV and nce index to localize multiple damage sites in laminated composite beams. Dinh-Cong et al. [10] proposed a two-stage assessment method using DLV and Differential evaluation (DE) algorithm for damage detection of cross-ply laminated composite beams. Nguyen-Thoi et al. [11] utilized a combination of DLV and DE algorithm for structural damage assessment. Also, many researchers have tested optimization method and other methods to identify damage in engineering structures [12-17].

The DLV method can be used to localize damage sites and if the method is combined with an optimization method, the resulting method will be a two-stage damage identification approach and can be utilized to localize and quantify damages. Some researchers utilized this type and other two-stage methods [18-22]. According to mentioned references, one-stage detecting damage methods have been commonly used among different methods in which researchers have allocated a long time for solving inverse optimization problem to assess damage of damaged elements along with disruptive healthy elements. It decreases the accuracy of identifying damage extent while two-stage approaches have converted the process to two separate stages, locating damage elements and quantifying damage extent, by discriminating between damaged and healthy element and eliminating healthy elements.

In the current study, the application of DLV approach and two optimization algorithms, Water evaporation optimization (WEO) and accelerated WEO, to identify damages of a 2D frame structures has been studied. In the first stage, damaged elements of the structure are localized by employing DLV and using a new index called Exponential decreased stress (EDS). The EDS index is formulated based on axial stress of frame elements. This index increases the stress of intact elements and decreases the stress of damaged elements through exponent of the stresses. In the second stage, a metaheuristic algorithm quantifies damage extent of elements introduced as suspected in the first stage. To show robustness and reliability of this approach and proposed EDS, a 2D-frame with two type of meshing elements has been examined with noise; also the

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considered scenarios have been run using nce index and the results have been shown. Then damage extent of suspected elements is quantified by WEO and accelerated WEO algorithms.

The sections of this study are as follows: In Sec. 2, theoretical description is presented. The Water evaporation optimization and accelerated WEO algorithms are presented in Sec. 3. Numerical examples are studied in Sec. 4. Finally, the conclusion is given in Sec. 5.

2. Theoretical description

As before mentioned, this approach has two main stages: localizing damaged elements using DLV method and quantifying damage extent of suspected elements by an optimization algorithm.

It should be noted that the damage is identified using reduction in elasticity modulus of frame elements in this study.

2.1 Damage locating vector method and EDS index

Bernal (2002) proposed DLV (Damage locating vector) in which load vectors are obtained through created changes of flexibility matrix and loading up the vectors into freedom degrees leads zero stress over damaged elements. Changes of flexibility matrix in the pre and post damaged states are utilized to design static force vectors. Structural flexibility matrix, F, using dynamic parameters of structure can be written:

$$\mathbf{F} = \sum_{i=1}^{ndf} \frac{1}{\omega_i^2} \boldsymbol{\varphi}_i \boldsymbol{\varphi}_i^{\mathrm{T}} \tag{1}$$

where *ndf* is the number of structural freedom degrees; ω_j and $\boldsymbol{\varphi}_i$ are the *j*th natural frequency and mass-normalized mode shape, respectively. According to this equation, the flexibility matrix can be calculated by a few low modes fairly accurate, *nm* [23]:

$$\tilde{\mathbf{F}} \approx \sum_{i=1}^{nm} \frac{1}{\omega_i^2} \boldsymbol{\varphi}_i \boldsymbol{\varphi}_i^{\mathrm{T}} \tag{2}$$

For obtaining DLV vector, consider a number of load distribution whose application to freedom degrees of the healthy and damaged structures causes identical deformation. If we define the loads within an L matrix, we have:

$$(\tilde{\mathbf{F}}_h - \tilde{\mathbf{F}}_d) \times \mathbf{L} = 0 \ \text{ or } \ \Delta\tilde{\mathbf{F}} \times \mathbf{L} = 0 \tag{3}$$

in which, *h* and *d* refer to intact and damaged states, respectively. There are two condition for above equation: First condition $\Delta\tilde{\mathbf{F}} = 0$, in this case, there is no damage in structure so $\Delta\tilde{\mathbf{F}} \neq 0$, second $\Delta\tilde{\mathbf{F}}$ is not full rank and L includes a number of vectors that makes the null space. To determine the vectors corresponding to null space of $\Delta\tilde{\mathbf{F}}$, Singular value decomposition (SVD) is used as follows (Bernal 2002):

$$\Delta\tilde{\mathbf{F}} \overset{SVD}{=} \mathbf{U}\sum\mathbf{V}^{\mathrm{T}} = [\mathbf{U}]\begin{bmatrix} \mathbf{S}_{r_1} & \mathbf{0} \\ \mathbf{0} & \mathbf{S}_{r_n} \approx \mathbf{0} \end{bmatrix}\begin{bmatrix} \tilde{\mathbf{V}}^T \\ \mathbf{L}^T \end{bmatrix} \tag{4}$$

where it is clear that $\mathbf{S}_{r_1} > \mathbf{S}_{r_2} > \ldots > \mathbf{S}_{r_n}$. According to the equation, L is the right null space of $\Delta\tilde{\mathbf{F}}$ and DLVs. Loading every column of them onto freedom degrees makes zero stress in damaged elements. But many excessive intact elements are probably localized due to use DLV. To solve this problem, some researchers have used nce (Normalized cumulative energy) and ncs (Normalized cumulative stress) indices.

Axial stresses of healthy and damaged frame elements usually are more and less than 1, respectively. The EDS index uses the point and increases the stress of healthy elements and decreases the stress of damaged ones through exponent of stresses. Thus, those elements which have least EDS are reported as suspected damaged elements. If *i*th column of L is applied to the structure, stress of elements is given by:

$$\sigma_i^e = \mathrm{E}^e \varepsilon^e \tag{5}$$

where

$$\sigma_i^e = [\sigma_i^1, \sigma_i^2, \ldots, \sigma_i^{ne}] \ ; \ e = [1, 2, \ldots, ne] \tag{6}$$

where *ne* is the number of structural elements; *E* and *ε* are elasticity modulus and strain, respectively. The EDS of every element is equal to:

$$\overline{eds^e} = \frac{eds^e}{\max_k\{eds^k\}} \tag{7}$$

where

$$eds^e = \prod_{i=1}^{nDLV} \sigma_i^{e^2} \tag{8}$$

where *ndlv* is the number of DLVs. It is clear that the high number of DLVs makes more desirable results.

It should be noted that the mode shapes of all Degrees of freedom (DOFs) are required to be measured. While measuring the full set of mode shapes is not needed. It is better to measure the mode shapes of the damaged structure in partial DOFs firstly. Then the incomplete mode shapes are expanded with all DOFs of the structure by some methods proposed in Refs. [24-26].

2.2 Optimization method

To estimate damage extent of suspected damaged elements, an inverse optimization problem should be solved. It should be noted that any metaheuristic algorithm such as Grey wolf optimizer algorithm [27], Teaching–learning-based optimization algorithm [28] and Flower pollination algorithm [29] etc.

can be used and it is possible that the results of these algorithms be better than results of WEO and accelerated WEO. But these two algorithms have been chosen because they have been introduced newly and not used in damage detection literature yet.

An objective function based on changes of structural modal flexibility is defined. Structural flexibility is more sensitive to damage than modal data including natural frequencies and mode shapes. According to these point, Perera et al. [30] proposed following objective function:

$$\mathrm{F} = 1 - MACFLEX = 1 - \prod_{j=1}^{nm} MACFLEX_j \tag{9}$$

where

$$MACFLEX_j = \frac{|\{\mathrm{F}_j^{num}\}^T\{\mathrm{F}_j^{\exp}\}|^2}{(\{\mathrm{F}_j^{num}\}^T\{\mathrm{F}_j^{num}\})(\{\mathrm{F}_j^{\exp}\}^T\{\mathrm{F}_j^{\exp}\})} \tag{10}$$

in which, $\{\mathrm{F}_j^{num}\}$ and $\{\mathrm{F}_j^{\exp}\}$ are computed and measured (Experimental) flexibility vectors corresponding to jth mode respectively, which collect the diagonal terms of the flexibility matrix, MAC is a modal assurance criterion which measures correlation between two vector $\{\mathrm{F}_j^{\exp}\}$ and $\{\mathrm{F}_j^{num}\}$. Objective function values are normalized between 0 and 1 that low and high values of them indicate low and high correlation, respectively.

The details of used metaheuristic algorithms are expressed in Sec. 3.

3. Optimization algorithms

Water evaporation optimization (WEO) [31] and accelerated WEO [32] are a physical-based metaheuristic algorithm and a version of WEO developed to solve engineering and multidisciplinary optimization problems, respectively.

3.1 Water evaporation optimization (WEO)

WEO has presented based on inspiration of evaporation of water molecules on the surface of solid materials and steps of the algorithm implementation are as follows:

3.1.1 Initializing algorithm parameters

Firstly, algorithm parameters including number of iteration ($t_{\max}$), number of water molecules or individuals (nWM), maximum and minimum values of Monolayer evaporation probability and Droplet evaporation probability (MEP_{min} = 0.03, MEP_{max} = 0.6, DEP_{min} = 0.6 and DEP_{max} = 1) are determined. Then the positions of individuals are randomly initialized in a n-dimensional search space:

$$WM_{i,j}^{(0)} = Round(x_{j,\min} + rand_{i,j}\ .\ (x_{j,\max} - x_{j,\min})) \tag{11}$$

where $WM_{i,j}^{(0)}$ is the initial values of jth variable corresponding to ith water molecule; $rand_{i,j}$ is a random number uniformly distributed in the range (1,0); $x_{j,max}$ and $x_{j,min}$ are the maximum and minimum permissible values for the jth variable.

3.1.2 Generating water evaporation matrix

WEO consists of two independent sequential phases: Monolayer and droplet evaporation where water molecules are updated globally and locally respectively in these phases. Variations of charge value are q < 0.4e and q > 0.4e in the droplet and monolayer evaporation phases, respectively.

For monolayer evaporation phase ($t \le t_{\max}/2$), the objective function value of molecules (Fit_i^t) is scaled to the range [−3.5, −0.5]. Then the corresponding substrate energy vector ($E_{sub}(i)$) is defined as follows:

$$E_{sub}(i)^t = \frac{(E_{\max} - E_{\min}) \times (Fit_i^t - Min(Fit))}{(Max(Fit) - Min(Fit))} + E_{\min} \tag{12}$$

where $E_{\min}$ and $E_{\max}$ equal −3.5 and −0.5, respectively; Min and Max are minimum and maximum functions, respectively. Then MEP is constructed as follows:

$$MEP_{ij}^t = \begin{cases} 1 & if\ \ rand_{ij} < \exp(E_{sub}(i)^t) \\ 0 & if\ \ rand_{ij} \ge \exp(E_{sub}(i)^t) \end{cases} \tag{13}$$

where MEP_{ij}^t is the updating probability for jth variable of ith water molecule in the tth iteration.

For the droplet evaporation phase ($t > t_{\max}/2$), the objective function value of molecules (Fit_i^t) is scaled to the range [−50°, −20°] by using contact angle vector ($\theta(i)^t$):

$$\theta(i)^t = \frac{(\theta_{\max} - \theta_{\min}) \times (Fit_i^t - Min(Fit))}{(Max(Fit) - Min(Fit))} + \theta_{\min}\,. \tag{14}$$

Then DEP is constructed as follows:

$$\begin{gathered} DEP_{ij}^t = \begin{cases} 1 & if\ \ rand_{ij} < J(\theta_i^{(t)}) \\ 0 & if\ \ rand_{ij} \ge J(\theta_i^{(t)}) \end{cases} \\ J(\theta) = J_0 P_0 (\frac{2}{3} + \frac{\cos^3\theta}{3} - \cos\theta)^{-2/3}(1-\cos\theta) \\ J_0 P_0 = \frac{1}{24} \end{gathered} \tag{15}$$

where MEP_{ij}^t is the updating probability for jth variable of ith water molecule in the tth iteration; J_0 and P_0 are constant values; J is evaporation flux where maximum and minimum value of it are 1 and 0.6, respectively.

3.1.3 Generating random permutation based step size matrix

A random permutation based step size matrix is defined as follows:

$$S = rand.\ (WM^{(t)}[p1(i)(j)] - WM^{(t)}[p2(i)(j)]) \qquad (16)$$

where $p1$ and $p2$ are different rows permutation functions; i and j are the number of water molecules and design variables of the problem, respectively; WM is the evaporated set of water molecules.

3.1.4 Generating evaporated water molecules and updating the matrix of them

The evaporated set of water molecules ($WM^{(t+1)}$) is generated according to the product of step size matrix and evaporation probability matrix:

$$WM^{(t+1)} = Round\left(WM^{(t)} + S \times \begin{cases} MEP^{(t)} & t \le t_{max}/2 \\ DEP^{(t)} & t > t_{max}/2 \end{cases}\right). \qquad (17)$$

The rounding function rounds the design variables' values to the nearest discrete available value. The best individual is returned after evaluating the molecules based on the objective function.

3.1.5 Terminating condition check

Steps 2 to 4 are continued to repeat until termination condition, number of iterations (t), is met.

3.2 Accelerated WEO

In accelerated WEO, updating molecules is worked by using monolayer and droplet evaporation phases simultaneously. Steps of the accelerated WEO implementation are as follows:

3.2.1 Initializing algorithm parameters

In this step, the worst water molecule (Worst-WM) in objective function value terms is monitored in addition to detail of the one described in the WEO.

3.2.2 Generating water evaporation matrix

Firstly, the distance vector between all individuals and the worst current one (*dist*) is calculated:

$$dist_i = |worstWM - WM_i|, i = 1,\ 2, ...,\ nWM. \qquad (18)$$

The individuals are sorted based on their distance values in ascending order. Then the DEP and MEP matrices are calculated for updating the first and second half of the molecules, respectively, by using Eqs. (13) and (15). It should be noted that the evaporation and droplet probability matrices and their corresponding details, contact angle vectors and substrate energy include *nWM*/2 rows. Then mixed evaporation matrix (MDEP) is assembled using the pseudo code shown in Fig. 1.

```
for i=1:nWM
      dist(i)=norm(WM(i,:)-worst-WM);
end
[a,b]=sort(dist);
for i=1:nWM/2
      droplet-WM(i,:)=WM(b(i),:);
end
Generate the corresponding θ vector and DEP matrix using Eqs. (14)
 and (15), respectively.
for i=1: nWM/2
      monolayer-WM(i,:)=WM(b(size(nWM/2+i),:);
end
Generate the corresponding E_sub vector and MEP matrix using Eqs.
(12) and (13), respectively.
for i=1:size(WM,1)
      if i<= nWM/2
            MDEP(b(i),:)=DEP(i,:);
      else
            MDEP (b(i),:)=MEP(i-size(WM,1)/2,:);
      end
end
```

Fig. 1. Pseudo code for constructing the MDEP matrix.

3.2.3 Generating random permutation based step size matrix

In this step, a random permutation based step size matrix is calculated same as the one described in the WEO.

3.2.4 Generating evaporated water molecules and updating the matrix of them

The evaporated set of individuals ($WM^{(t+1)}$) is generated according to the product of step size matrix and *MDEP*:

$$WM^{(t+1)} = Round(WM^{(t)} + S \times MDEP^{(t)})\ . \qquad (19)$$

Then the best molecule is returned after evaluating the molecules corresponding to their objective function values.

3.2.5 Terminating condition check

Steps 2 to 4 are continued to repeat until termination condition, number of iteration of the algorithm (t), is met.

4. Numerical example

In this section, to demonstrate the ability of EDS and the algorithm, a 2D frame structure with two different meshing using some multiple cases are studied. For each state, two multiple cases with two and four damaged elements are considered. For each case, the EDS of all elements with various numbers of modes (6, 8 and 10 first modes) are shown in noisy condition. To precisely localize damaged elements, the DLV and the algorithms have been run 30 times for every case. Then mean EDS values of elements are shown. Also the mean and the best (with least value of objective function) solutions of the algorithms, damage severity of suspected elements, have been reported. To compare of the two-stage method with optimization method, the studied cases are also run using optimization method (within one step and solving an

Table 1. Physical properties of the frame.

Property (Unit)	Value
E, elasticity modulus (GPa)	210
ρ, mass density (kg/m^3)	7850
A, cross section area (m^2)	1.74×10^{-2}
I, moment of intertia (m^4)	3.281×10^{-4}

inverse optimization problem) in noisy condition and the results are reported. Although existence of many number of modes helps the algorithms easily converge the right state of damage in the second stage, it increases the rate of program running and results in more time to the algorithms. Therefore, the number of considered modes in the objective function should be selected in a way that induces appropriate balance for the algorithms. For running algorithms in this approach, the six first modes have been utilized for all cases which is equal to lowest number of considered modes for the first stage. The number of iterations and population sizes are considered as 100 and 50, respectively. The physical properties of the frame's elements are given in Table 1. Also the length of every element in the first and second meshing states is 1 and 1/3 m, respectively. Error values considered to generate noisy data of natural frequencies and mode shapes are 1 % and 3 %, respectively, as follows [13]:

$$\omega_i^{noisy} = \omega_i^d \times (1+\alpha\times 0.01) \quad (20)$$

$$\varphi_{ij}^{noisy} = \varphi_{ij}^d \times (1+\alpha\times 0.03) \quad (21)$$

in which *noisy* implies a noisy value; α is a uniformly distributed randomly number between -1 and +1.

4.1 Frame with 35 elements

This structure was investigated in the field of damage detection by Mousavi and Gandomi [26]. The frame includes 35 elements and 24 joints as shown in Fig. 2. In the figure, the damaged elements of cases are bolded. The details of two damage cases with multiple damage extent is given in Table 2.

For the two cases, EDS of all elements in noisy condition have been shown in the Figs. 3 and 4. Also, the NCE values of all elements in noisy condition have been shown in the Figs. 5 and 6.

The Figs. 3 and 4 show that the EDS of damaged elements is less than others and they are identified as suspected damaged elements. Also, the figures show that the more number of modes is used, the higher precision in measurement of EDS becomes obtained and damaged elements are identified better. According to the Figs. 5 and 6, the NCE index has not been able to detect all of the damaged elements in second scenario.

Tables 3 and 4 show damage extents of suspected damaged elements estimated by WEO and accelerated WEO algorithms within 30 runs.

Table 2. Damage cases of the frame with 35 elements.

Case	Damaged elements	Extent of damage
1	4, 20	0.25, 0.20
2	2, 6, 10, 21	0.25, 0.29, 0.35, 0.30

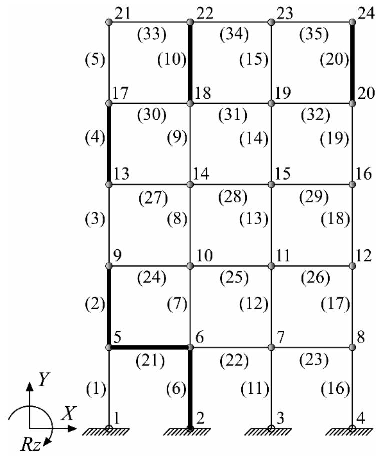

Fig. 2. Frame with 35 elements.

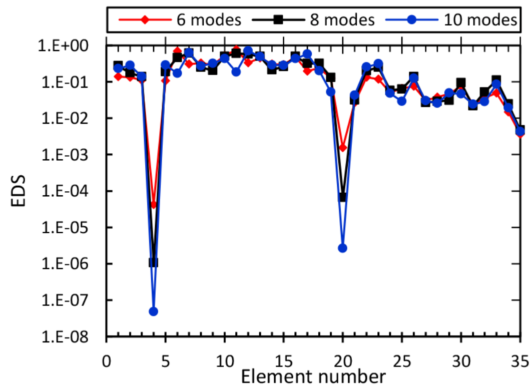

Fig. 3. The EDS values of the frame with 35 elements for first case in noisy condition.

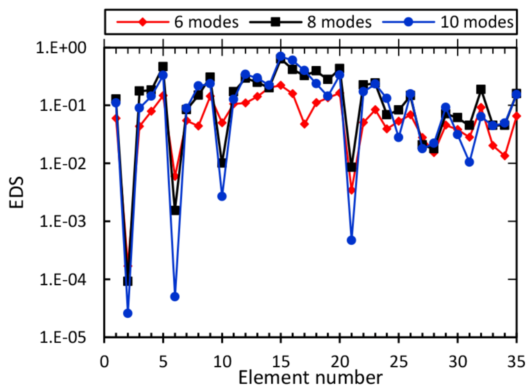

Fig. 4. The EDS values of the frame with 35 elements for second case in noisy condition.

Table 3. Damage extents of suspected damaged elements for first scenario of frame with 35 elements.

Algorithms		Elements and damage extents	
		4	20
WEO	Best	0.25	0.20
	Mean	0.25	0.20
Accelerated WEO	Best	0.25	0.20
	Mean	0.25	0.20

Table 4. Damage extents of suspected damaged elements for second scenario of frame with 35 elements.

Algorithms		Elements and damage extents			
		2	6	10	21
WEO	Best	0.25	0.29	0.35	0.30
	Mean	0.248	0.292	0.349	0.299
Accelerated WEO	Best	0.25	0.29	0.35	0.30
	Mean	0.249	0.289	0.349	0.299

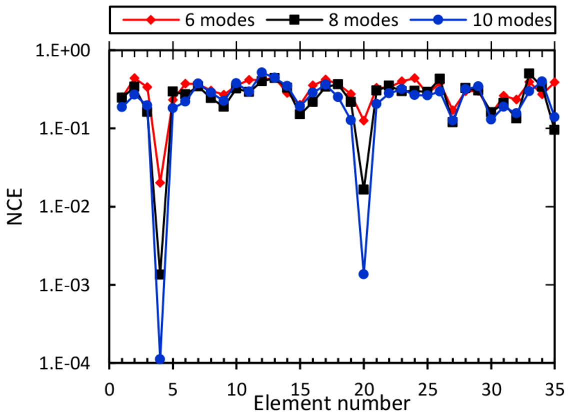

Fig. 5. The NCE values of the frame with 35 elements for first case in noisy condition.

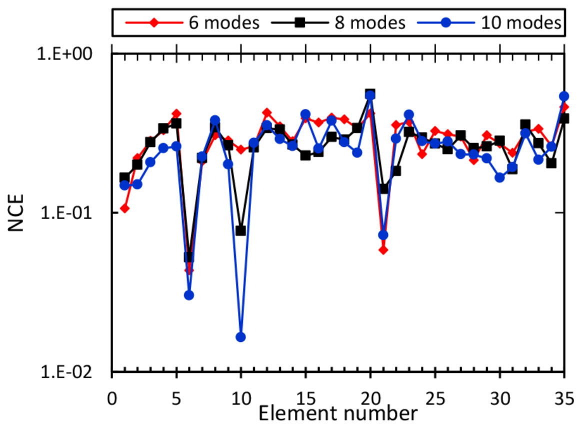

Fig. 6. The NCE values of the frame with 35 elements for second case in noisy condition.

Table 5. Damage cases of the frame with 105 elements.

Case	Damaged elements	Extent of damage
1	21, 45	0.25, 0.19
2	22, 35, 51, 70	0.15, 0.25, 0.35, 0.28

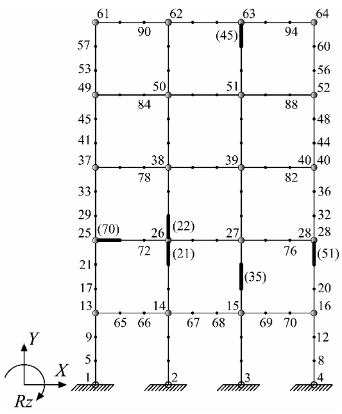

Fig. 7. Frame with 105 elements.

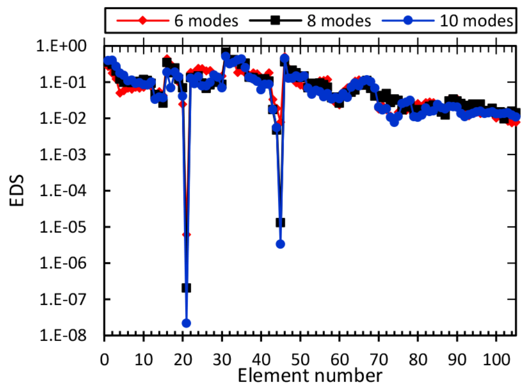

Fig. 8. The EDS values of the frame with 105 elements for first case in noisy condition.

4.2 Frame with 105 elements

The frame includes 105 elements and 94 joints as shown in Fig. 7. In the figure, the damaged elements of cases are bolded. The details of two damage cases with multiple damage extent is given in Table 5.

For the two cases, EDS of all elements in noisy condition have been shown in the Figs. 8 and 9. Also, the NCE values of all elements in noisy condition have been shown in the Figs. 10 and 11.

According to the Figs. 10 and 11, the NCE index has not been able to detect all of the damaged elements in second scenario. So efficiency of the NCE index is low in finding the damaged elements corresponding to scenario with more damaged elements.

According to the results, the EDS values of damaged elements in all scenarios for eight first modes are low enough to identify them. So the efficient number of modes required to

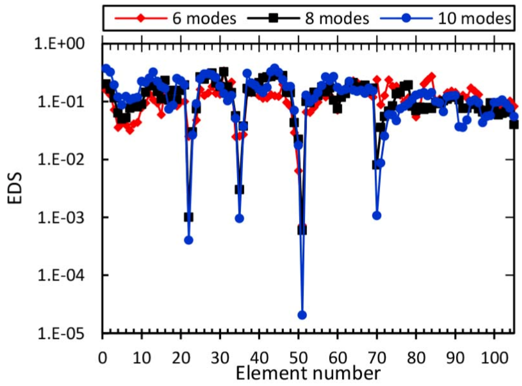

Fig. 9. The EDS values of the frame with 105 elements for second case in noisy condition.

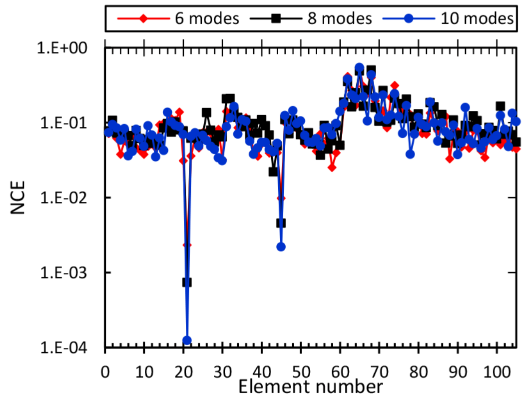

Fig. 10. The NCE values of the frame with 105 elements for first case in noisy condition.

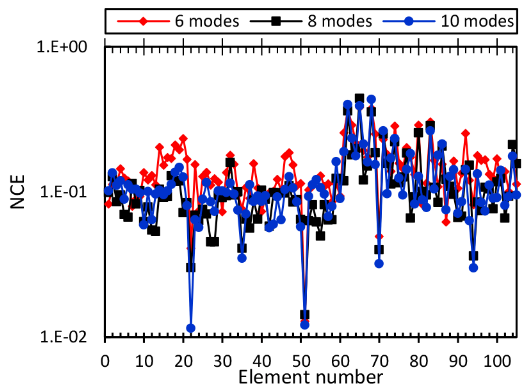

Fig. 11. The NCE values of the frame with 105 elements for second case in noisy condition.

determine damage locations is eight.

Tables 6 and 7 show damage extents of suspected damaged elements estimated by WEO and accelerated WEO algorithms within 30 runs.

According to Tables 3, 4, 6 and 7, both algorithms are able to quality the damage extents with good accuracy.

Table 6. Damage extents of suspected damaged elements for first scenario of frame with 105 elements.

Algorithms		Elements and damage extents	
		21	45
WEO	Best	0.25	0.19
	Mean	0.25	0.19
Accelerated WEO	Best	0.25	0.19
	Mean	0.25	0.19

Table 7. Damage extents of suspected damaged elements for second scenario of frame with 105 elements.

Algorithms		Elements and damage extents			
		22	35	51	70
WEO	Best	0.15	0.25	0.35	0.28
	Mean	0.15	0.25	0.349	0.278
Accelerated WEO	Best	0.15	0.25	0.35	0.28
	Mean	0.15	0.252	0.35	0.281

4.3 Comparing the approaches' performance

To show ability of the two-step and optimization approaches to find damage site and quality damage extent, the all of the cases are also run using the algorithms within one step. For running algorithms in this approach, the six first modes have been utilized for all cases; the number of iterations and population sizes are considered as 1000 and 500, respectively. The best results (with least value of objective function) are shown in Tables 8 and 9 for the frame with 35 and 105 elements, respectively. The misidentified elements found by the algorithms are underlined for a better understanding of the results in the Tables 8 and 9.

For the frame with 35 elements, the values less than 0.01 have been considered equal to zero. About the frame with 105 elements, the values less than 0.03 and 0.05 have not been reported for WEO and accelerated WEO algorithms, respectively, because they were many. According to Tables 8 and 9, most of the misidentified values relates to element 62 (0.18) corresponding to Case 2 and accelerated WEO algorithm. As it is clear, the number of misidentified elements is high especially in cases with four actual damaged elements. These values demonstrate that the optimization method is not efficient when the elements of structure or damaged elements are more while spends too time for solving inverse optimization problem. Also, it is concluded that because of less number of algorithm's variables in two-stage approach, type and efficiency of an algorithm is less important than in one-stage optimization method.

On comparing the performance of these two algorithms in one-step method, the sum errors of misidentified elements obtained from accelerated WEO is more than WEO. Also, computational errors for actual damaged elements corresponding to WEO is less than accelerated WEO. Thus the performance of WEO is better than accelerated WEO in running one-

Table 8. Results of optimization method for the frame with 35 elements.

Case	Algorithms	Damaged element(s)	Damage extent
1	WEO	4, 25	0.25, 0.20
	Accelerated WEO	4, 25	0.25, 0.20
2	WEO	2, 6, 10, 11, 17, 21, 27, 31, 34	0.26, 0.29, 0.34, 0.01, 0.01, 0.31, 0.02, 0.02, 0.04
	Accelerated WEO	2, 6, 8, 10, 13, 21, 33, 35	0.26, 0.29, 0.01, 0.34, 0.01, 0.29, 0.02, 0.02

Table 9. Results of optimization method for the frame with 105 elements.

Case	Algorithms	Damaged element(s)	Damage severity
1	WEO	21, 45, 65, 66, 83, 89, 92, 95	0.24, 0.19, 0.05, 0.03, 0.06, 0.05, 0.05, 0.04
	Accelerated WEO	3, 21, 38, 45, 64, 65, 68, 74, 77, 80, 92, 98, 101, 108	0.06, 0.27, 0.05, 0.21, 0.07, 0.06, 0.09, 0.08, 0.13, 0.07, 0.14, 0.05, 0.08, 0.07
2	WEO	20, 22, 35, 44, 51, 53, 59, 62, 68, 70, 71, 78, 86, 100	0.06, 0.15, 0.23, 0.08, 0.34, 0.04, 0.07, 0.07, 0.12, 0.28, 0.12, 0.03, 0.05, 0.03
	Accelerated WEO	22, 26, 35, 38, 44, 50, 51, 55, 59, 62, 70, 72, 74, 77, 92, 95, 104	0.22, 0.05, 0.22, 0.05, 0.07, 0.07, 0.36, 0.08, 0.07, 0.18, 0.28, 0.08, 0.09, 0.08, 0.14, 0.08, 0.07

step method.

5. Conclusions

In this paper, a two-stage approach based on DLV (Damage locating vector) and two metaheuristic algorithms, Water evaporation optimization (WEO) and accelerated WEO, is employed to identify damage of a 2D frame structure. In the DLV method, suspected damaged elements are found by a new proposed index called EDS (Exponential decreased stress) according to axial stress of elements. Numerical example including two types of meshing elements is examined by different multiple cases. Also the cases are tested by one-stage optimization method and using these two algorithms. Results conclude that the two-stage method are efficient especially in the frame with more elements and damaged elements. The error in computation of damage extent for suspected damaged elements and misidentified elements corresponding to one and two-stage approach are 0.180 and 0.002, respectively.

References

[1] M. Naderi and M. Khonsari, Real-time fatigue life monitoring based on thermodynamic entropy, *Structural Health Monitoring,* 10 (2) (2011) 189-197.

[2] B. Gunes and O. Gunes, Structural health monitoring and damage assessment Part I: A critical review of approaches and methods, *International Journal of Physical Sciences*, 8 (34) (2013) 1694-1702.

[3] M. Markou and S. Singh, Novelty detection: A review—part 2: Neural network based approaches, *Signal Processing*, 83 (12) (2003) 2499-2521.

[4] X. Chen and L. Yu, Flexibility-based objective functions for constrained optimization problems on structural damage detection, *Proc. of International Conference on Computer-aided Material and Engineering,* Hangzhou, China (2011).

[5] M. Nobahari and S. M. Seyedpoor, An efficient method for structural damage localization based on the concepts of flexibility matrix and strain energy of a structure, *Structural Engineering and Mechanics*, 46 (2) (2013) 231-244.

[6] D. Bernal, Load vectors for damage localization, *Journal of Engineering Mechanics*, 128 (1) (2002) 7-14.

[7] Y. Gao, B. F. Spencer Jr. and D. Bernal, Experimental verification of the flexibility-based damage locating vector method, *Journal of Engineering Mechanics,* 133 (10) (2007) 1043-1049.

[8] S. Quek, V. Tran, X. Hou and W. Duan, Structural damage detection using enhanced damage locating vector method with limited wireless sensors, *Journal of Sound and Vibration,* 328 (4) (2009) 411-427.

[9] T. Vo-Duy, N. Nguyen-Minh, H. Dang-Trung, A. Tran-Viet and T. Nguyen-Thoi, Damage assessment of laminated composite beam structures using Damage locating vector (DLV) method, *Frontiers of Structural and Civil Engineering,* 9 (4) (2015) 457-465.

[10] D. Dinh-Cong, T. Vo-Duy, N. Nguyen-Minh, V. Ho-Huu and T. Nguyen-Thoi, A two-stage assessment method using damage locating vector method and differential evolution algorithm for damage identification of cross-ply laminated composite beams, *Advances in Structural Engineering*, 20 (12) (2017)1807-1827.

[11] T. Nguyen-Thoi, A. Tran-Viet, N. Nguyen-Minh, T. Vo-Duy and V. Ho-Huu, A combination of Damage locating vector method (DLV) and Differential evolution algorithm (DE) for structural damage assessment, *Frontiers of Structural and Civil Engineering* (2016) 1-17.

[12] S. R. Hoseini Vaez and T. Arefzade, Vibration-based damage detection of concrete gravity dam monolith via wavelet

transform, *Journal of Vibroengineering,* 19 (1) (2017).

[13] S. R. Hoseini Vaez and N. Fallah, Damage detection of thin plates using GA-PSO algorithm based on modal data, *Arabian Journal for Science and Engineering*, 42 (3) (2017) 1251-1263.

[14] A. Kaveh, S. R. Hoseini Vaez, P. Hosseini and N. Fallah, Detection of damage in truss structures using Simplified Dolphin Echolocation algorithm based on modal data, *Smart Structures and Systems,* 18 (5) (2016) 983-1004.

[15] J. Xiang, U. Nackenhorst, Y. Wang, Y. Jiang, H. Gao and Y. He, A new method to detect cracks in plate-like structures with though-thickness cracks, *Smart Structures and Systems,* 14 (3) (2014) 397-418.

[16] S. J. Kim, Damage detection in composite under in-plane load using tap test, *Journal of Mechanical Science and Technology,* 29 (1) (2015) 199-207.

[17] A. Maghsoodi, A. Ohadi, M. Sadighi and H. Amindavar, Damage detection in multilayered fiber–metal laminates using guided-wave phased array, *Journal of Mechanical Science and Technology,* 30 (5) (2016) 2113-2120.

[18] N. I. Kim, H. Kim and J. Lee, Damage detection of truss structures using two-stage optimization based on micro genetic algorithm, *Journal of Mechanical Science and Technology,* 28 (9) (2014) 3687-3695.

[19] J. Xiang and M. Liang, A two-step approach to multi-damage detection for plate structures, *Engineering Fracture Mechanics*, 91 (2012) 73-86.

[20] Z. B. Yang, X. F. Chen, Y. Xie, H. H. Miao, J. J. Gao and K. Z. Qi, Hybrid two - step method of damage detection for plate - like structures, *Structural Control and Health Monitoring*, 23 (2) (2016) 267-285.

[21] J. Xiang and M. Liang, Wavelet - based detection of beam cracks using modal shape and frequency measurements, *Computer - Aided Civil and Infrastructure Engineering*, 27 (6) (2012) 439-454.

[22] J. Xiang, T. Matsumoto, J. Long, Y. Wang and Z. Jiang, A simple method to detect cracks in beam-like structures, *Smart Structures and Systems*, 9 (4) (2012) 335-353.

[23] A. Pandey and M. Biswas, Damage detection in structures using changes in flexibility, *Journal of Sound and Vibration*, 169 (1) (1994) 3-17.

[24] F. Au, Y. Cheng, L. Tham and Z. Bai, Structural damage detection based on a micro-genetic algorithm using incomplete and noisy modal test data, *Journal of Sound and Vibration*, 259 (5) (2003) 1081-1094.

[25] J. Carvalho, B. N. Datta, A. Gupta and M. Lagadapati, A direct method for model updating with incomplete measured data and without spurious modes, *Mechanical Systems and Signal Processing*, 21 (7) (2007) 2715-2731.

[26] M. Mousavi and A. H. Gandomi, A hybrid damage detection method using dynamic-reduction transformation matrix and modal force error, *Engineering Structures*, 111 (2016) 425-434.

[27] S. Mirjalili, S. M. Mirjalili and A. Lewis, Grey wolf optimizer, *Advances in Engineering Software*, 69 (2014) 46-61.

[28] R. V. Rao, V. J. Savsani and D. P. Vakharia, Teaching–learning-based optimization: a novel method for constrained mechanical design optimization problems, *Computer-Aided Design*, 43 (3) (2011) 303-315.

[29] X. S. Yang, M. Karamanoglu and X. He, Flower pollination algorithm: a novel approach for multiobjective optimization, *Engineering Optimization*, 46 (9) (2014) 1222-1237.

[30] R. Perera, A. Ruiz and C. Manzano, Performance assessment of multicriteria damage identification genetic algorithms, *Computers & Structures*, 87 (1) (2009) 120-127.

[31] A. Kaveh and T. Bakhshpoori, Water evaporation optimization: a novel physically inspired optimization algorithm, *Computers & Structures*, 167 (2016) 69-85.

[32] A. Kaveh and T. Bakhshpoori, An accelerated water evaporation optimization formulation for discrete optimization of skeletal structures, *Computers & Structures*, 177 (2016) 218-228.

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