Damage assessment in structures using combination of a modified Cornwell indicator and genetic algorithm

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Abstract. This paper presents a new methodology for damage identification and quantification in two- and three-dimensional structures. The application of the proposed methodology is investigated numerically using Finite Element Method (FEM) and Matlab program. We proposed a Modified Cornwell Indicator (MCI) that performs more efficient in damage detection than the standard Cornwell Indicator (CI). Furthermore, MCI is combined with Genetic Algorithm (GA) for further quantification of the detected damage. In GA, the modified damage indicator, MCI, is used as an objective function to compare between measured and calculated indicators. The results of the analysis show that the proposed technique is accurate and efficient, when compared with other techniques in the literature, to estimate the severity of structural damage.

Keywords: Two- and three-dimensional Structures, Genetic Algorithm, Damage identification, Modal analysis, Finite Element Method

1. Introduction

A Nondestructive Damage Identification (NDI) and Structural Health Monitoring (SHM) become important tools for damage assessment of structures in recent years [1-5]. It forms the basis of any decision to repair, rehabilitate, or replace a damaged structure. Shi et al. [6] developed an element wise damage sensitivity matrix based on Mean Square Error (MSE) changes in structure elements for quantifying the presence of damage. Yan et al. [7, 8] published two papers based on MSE and generalized flexibility technique using mode shapes and natural frequencies. The proposed technique has shown good accuracy for locating and quantifying the presence of damage.

Optimization techniques have been recently used for SHM. Khatir et al. [9] used different optimization techniques coupled with reduced model based on Proper Orthogonal Decomposition (POD) and Radial Basis Function (RBF) for crack location using experimental data. Khatir et al. [10] presented new application in plates using using eXtended IsoGeometric Analysis (XIGA) and Particle Swarm Optimization (PSO) for crack identification with different scenarios. Zenzen et al [11] presented inverse problem technique based on frequency response (FR) and PSO for beam and truss structure. Khatir et al. [12] presented new application for crack identification in beams and 2D structures based on inverse problem using PSO. The proposed application was validated experimentally. The change in generalized flexibility matrix was presented by Li et al.[13] to detect the location and extent of structural damage. Villalba and Laier [14] used a self-adaptive multi-chromosome GA for damage assessment in structures. The results showed that the proposed approach could detect the damage with higher accuracy through different damage scenarios. An algorithm to solve the inverse problem of detecting inclusion interfaces in a piezoelectric structure was proposed by Nanthakumar et al. [15]. The material interfaces were implicitly represented by level sets which were identified by applying regularization using total variation penalty terms. Ghasemi et al. [16] presented a design methodology based on a combination of IsoGeometric Analysis (IGA), level set and point wise density mapping techniques for topology optimization of piezoelectric/flexoelectric materials. A computational design methodology for topology optimization of multi-material-based flexoelectric composites was presented in reference [17].

The inverse problem using several optimization techniques with different objective functions coupled with FEM for damage detection with single and multiple damages was presented in references [18, 19]. Many researchers used the measured natural frequencies for damage detection and localization based on loss of rigidity [19, 20]. Pandey et al. [21] presented a technique for damage detection and localization based on the change in the structure flexibility matrix. Hwang and Kim [22] presented a new indicator based on frequency response for damage identification in beam-like structures. The evaluation to use of Frequency Response Function (FRF) with the help of optimization technique was presented by Mohan [23]. Many researchers have proposed several applications in literature for detecting and location the presence of damage in various types of structures. The use of the changes in the mode shape and mode-shape-slope parameters was investigated by Yen [24]. Yen [25] proposed a numerical method for structural damage identification using modal residual force criteria and matrix disassembly technique. Wu et al. [26] used Neural Network (NN) in damage identification employing back-propagation algorithm in their neural network architecture with one and two layers to identify the presence of damage in a three-story frame. The inverse problem for damage identification using multi-objective Particle Swarm Optimization (PSO) and GA has been evaluated by Perera et al. [27].

A review of damage detection and SHM of mechanical systems based on changes in the measured data of linear and non-linear vibrations was presented by Sinou [28]. Different detection techniques to diagnose damage detection in rotors with various modelling of the cracked elements was presented by Wauer [29]. A newly proposed approach for cracks detection in steel beams by sine-sweep vibration measurements was presented by Dougdag et al. [30]. Reduced model based on POD method was used for damage identification in beam structure coupled with optimization techniques to estimate the crack length and its position in a structure using boundary displacements as input data to build data matrix. GA and PSO, are then applied for the minimization of the objective function expressed as the difference between the boundary displacements of the actual crack and those of the estimated cracked plate are presented in the refs [31, 32].

Kaveh et al. [33] used Improved Charged System Search (CSS) for damage detection in truss structures using changes in natural frequencies and mode shapes. The CSS is a population based meta-heuristic algorithm proposed by Kaveh and Talatahari [34]. This algorithm is based on laws from electrostatics of physics and Newtonian mechanics. The proposed technique was used for damage detection and localization with different structures [35, 36]. A mixed particle swarm-ray optimization together with harmony search (HRPSO) was applied for structural damage identification as presented reference [37]. The application of recently developed optimization algorithms, so-called Colliding Bodies Optimization (CBO) and Enhanced Colliding Bodies Optimization (ECBO), in conjunction with structural modal information for damage detection of steel trusses were presented by Kaveh and Mahdavi [38]. Kaveh et al. [39] developed multi-agent meta-heuristic method, named Cyclical Parthenogenesis Algorithm (CPA), which was incorporated into a guided modal strain energy based structural damage detection technique. A structural damage identification approach was presented by Kaveh and Zolghadr [40] in order to localize and quantify multiple damage cases in different structures. The change of modal strain energy of a structural element due to damage was utilized to guide the structural identification process, which was formulated as an inverse optimization problem. The objective function of the optimization problem, which was defined using the generalized flexibility matrix (GFM) of the structure, was then optimized using the newly developed tug-of-war optimization (TWO) algorithm.

Maity and Saha [41] proposed neural network technique for detecting the damage through response measurement of structures. The idea was applied to a simple cantilever beam where strain and displacement were measured for damage identification by a back-propagation neural network. Maity and Tripathy [42] used GA for damage identification based on changes in natural frequencies. The inverse problem based on optimization terms and then to utilize a solution procedure to assess the damage location. Sahoo and Maity [43] presented a hybrid neuro-genetic algorithm in order to optimize the design of neural network for different type of structures. Majumdar et al. [44] presented a method for damage identification from changes in natural frequencies using Ant Colony Optimization (ACO) algorithm. Liu and Chen [45] presented an inverse approach for identifying stiffness distribution on structures using structural dynamics response based on the frequency domain. Tripathy and Maity [46] proposed an approach based on neural network algorithm for damage identification. The natural frequencies and mode shapes were used as input parameters to the neural network optimization for damage detection and localization by Mehrjoo et al. [47].

In this paper, a robust and efficient method for damage identification is presented. First, a modified version of Cornwell Indicator (CI) is proposed, i.e. Modified Cornwell Indicator (MCI). It is shown that MCI provides more accurate damage detection and localization than CI. Then, the damage indicators are used as input in an objective function, to be minimized in order to quantify damage and predict its severity using GA.

2. Methodology

2.1 Cornwell indicator

There are several methods for damage localization in structures using modal data directly by considering the modal deformation energy before and after damage. Among these methods, Cornwell et al. [48] proposed a damage indicator based on the variation of strain energy. The Cornwell Indicator (CI) is presented in the following paragraph.

For a beam having an elastic modulus *E*, second moment of inertia *I*, length *L* and deformation *u*, the potential energy is written as:

$$E_{pot} = \frac{1}{2}\int_0^L EI\left(\frac{\partial u}{\partial x}\right)^2 dx \tag{1}$$

For proper mode deformation $\phi_i(x)$, the beam is subdivided into *N* elements, and the energies associated with each element *j* due to the i^{th} mode is given by:

$$\left(E_{pot}\right)_i = \frac{1}{2}\int_0^L EI\left(\frac{\partial \phi_i(x)}{\partial x}\right)^2 dx \tag{2}$$

Considering the deformation, kinetic and dissipation energy of each *j* element and the total deformation energy of the beam for the i^{th} eigen mode, the energy fractions are then given by:

$$FU_{ij} = \frac{\left(E_{pot}\right)_{ij}}{\left(E_{pot}\right)_i} \tag{3}$$

The expressions of these energies analogous to equations (1) to (3) are written for a structure with defects as:

$$\left(E_{pot}\right)_i^* = \frac{1}{2}\int_0^L (EI)^*\left(\frac{\partial \phi_i^*(x)}{\partial x}\right)^2 dx \tag{4}$$

$$\left(E_{pot}\right)_{ij}^* = \frac{1}{2}\int_{a_j}^{a_{j+1}} (EI)_j^*\left(\frac{\partial \phi_i^*(x)}{\partial x}\right)^2 dx \tag{5}$$

$$FU_{ij}^* = \frac{\left(E_{pot}\right)_{ij}^*}{\left(E_{pot}\right)_i^*} \tag{6}$$

The symbol "*" in equations (4) to (6), refers to the damaged structure. Thus, CI is given by:

$$Ind_{Cor} = \frac{ZU_j - \overline{ZU}}{\sigma_{ZU}} \tag{7}$$

Where:

$$ZU_j = \frac{FU_{ij}^*}{FU_{ij}} \tag{8}$$

FU_{ij} : Fraction of deformation energy of undamaged state.

FU_{ij}^* : Fraction of deformation energy of damaged state.

$\overline{ZU}$: Average value of ZU .

σ_{ZU} : The standard deviation of ZU .

2.2 Modified Cornwell Indicator

We propose another way to write damage indicator, which we call Modified Cornwell Indicator (MCI) and has the symbol β_j for the j^{th} element. It is based on the calculation of the difference between the fractions of deformation energy, i.e. the largest value minus the smallest value of the healthy structure and damaged structure, respectively, which will be normalized with respect to their greater value. MCI is written in the following form:

$$\beta_j = \frac{FU_{ij} - FU_{ij}^*}{\left(FU_{ij} - FU_{ij}^*\right)_{\max}} \tag{9}$$

2.3. Genetic Algorithm

GA is a general optimization technique used to solve and optimize different problems in the engineering structure topic [18, 19, 49]. In GA, feasible solutions, also called individuals; are randomly generated in the studied research domain. They evolve towards the better solution in an iterative process inspired by the natural evolution. Each of the possible solutions has a set of properties or genes, which are parameters generally represented in binary encoding depending on the problem, which will be studied. Individuals are allowed to reproduce and cross among themselves in order to obtain solutions with better fitness values.

The highest probability of being chosen as parent of new individuals is given to the best feasible solutions for each iteration. The parent properties are combined by exchanging chromosome parts and producing new designs. Then, a possibility of mutation is imposed on the resulting individuals, which arbitrary changes digits inside a randomly selected chromosome. These basic operators are used as references to the next iteration containing the next generation of the same size and with better fitness compared with previous one. This process is continued until stopping criterion is satisfied, commonly until a maximum number of generations is reached or a satisfactory fitness value. The modal analysis based on the proposed indicator was considered as a reference. The minimization of the fitness function P is done iteratively. This fitness function is defined as the error between $Ind_j^{Measured}$ and $Ind_j^{Calculated}$, and is calculated from the following equation:

$$P = \sum_{j=1}^{Nbr} \left| Ind_j^{Measured} - Ind_j^{Calculated} \right| \tag{10}$$

Where

P : Fitness Function

$Ind_j^{Measured}$: Indicator vector measured

$Ind_j^{Calculated}$: Indicator vector calculated by GA.

j : Number of elements

These stages of the identification algorithm can be summarized as follows:

1- Creation of a starting population of N individuals, created in real encoding as a random generation. Each individual has 2 genes corresponding to the crack parameter P [Location and Level of damage]
2- Evaluation of each individual by introducing the proposed parameters.
3- Storing the population according to their fitness value and then ranked. A proportion for breeding a new generation is selected. The top ranked populations are more likely to be selected.
4- Crossover of individuals to produce the population of the next generation.
5- Mutation of a specified percentage of the resulting population.
6- Replacement of the old population by new one and coming back to step 2.

Through series of identification tests, the following genetic parameters were chosen based on the accuracy of results: population size = 200, crossover rate = 0.8 i.e. 100 individuals were selected for crossover, the mutation rate = 0.01. The mutation was used to avoid the convergence of the solution toward local optimums by creating diversity. This identification method was implemented in MATLAB, on a PC with Intel I3 Processor 3.0 GHz and 16 GB RAM.

3. Numerical examples

3.1 Damage detection based on MCI

3.1.1 2D truss structure

In this section, numerical results of a 2D truss structure are presented to demonstrate the viability of proposed MCI. A 10-bar planar truss shown in Fig. 1 is considered as a first numerical example. A non-structural mass of 454 kg is attached to the free nodes. This structure has been used as an example in the field of structural optimization by several researchers [33]. As it can be observed from Fig. 1, the structure has 8 degrees of freedom. Table 1 presents the mechanical properties used in this example. The first three mode shapes of the undamaged 10-bar planar truss are presented in Fig. 2. To evaluate the robustness of the proposed method, five damage cases are proposed, as presented in Fig. 3 and summarized in Table 2. All results for natural frequencies and damage indicators are presented in Table 3 and Fig. 4, respectively.

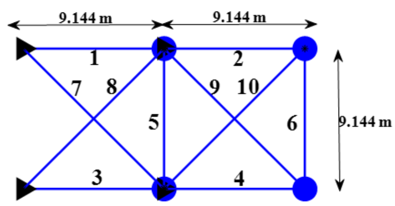


Fig. 1 A 10-bar planar truss.

Property [unit]	Value
E, modulus of elasticity [N/m^2]	6.98×10^{10}
S, cross-sectional area of the members [m^2]	0.0025
Added mass [kg]	454.0
ρ, material density [kg/m^3]	2770.0
L, main bar's dimension [m]	9.144

Table 1. Material properties for the 10-bar planar truss.

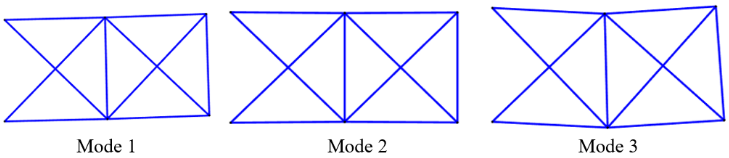


Fig. 2. The first three mode shapes of the 10-bar planar truss.

	Damaged elements	Reduction (D) in stiffness
Case 1	Element 9	$D_9 = 5\ \%$
Case 2	Elements 3	$D_3 = 10\ \%$
	Elements 7	$D_7 = 10\ \%$
Case 3	Elements 1	$D_1 = 5\ \%$
	Elements 5	$D_5 = 15\%$
	Elements 9	$D_9 = 5\ \%$
Case 4	Elements 7	$D_7 = 15\ \%$
	Elements 8	$D_8 = 20\ \%$
	Elements 9	$D_9 = 20\ \%$
	Elements 10	$D_{10} = 15\ \%$
Case 5	Elements 1	$D_1 = 5\ \%$
	Elements 2	$D_2 = 5\ \%$
	Elements 5	$D_5 = 15\ \%$
	Elements 6	$D_6 = 15\ \%$
	Elements 8	$D_8 = 10\ \%$
	Elements 9	$D_9 = 10\ \%$

Table 2. Reduction in stiffness in elements of the 10-bar planar truss for different damage cases.

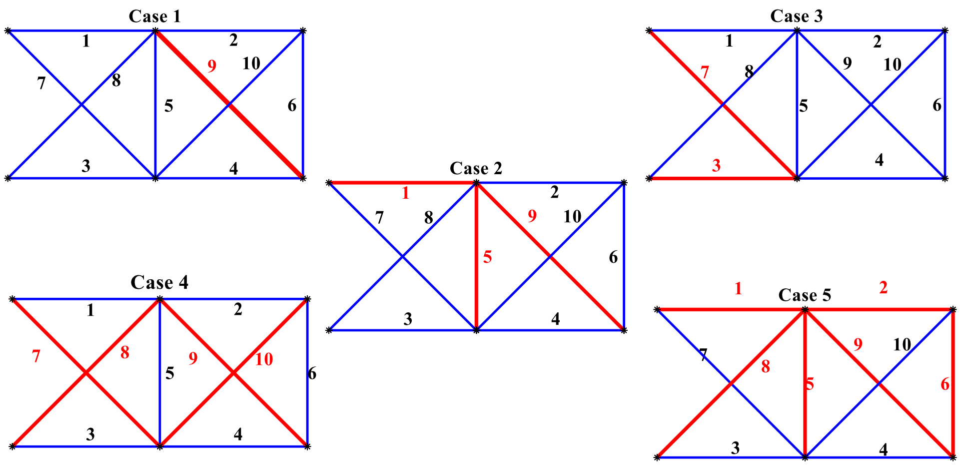
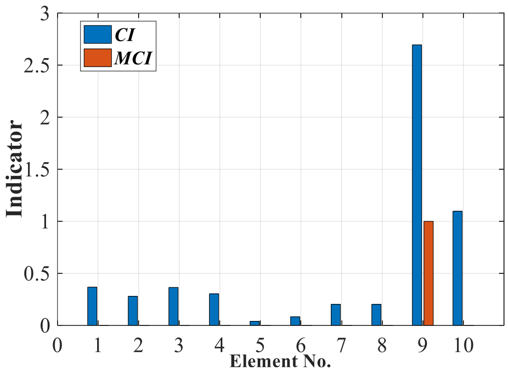


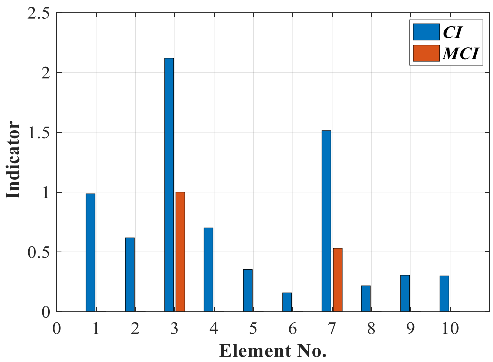
Fig. 3 Damage cases for the 10-bar planar truss.

Frequency [Hz]	Undamaged structure	Damaged structure									
		Case 1	Diff. %	Case 2	Diff. %	Case 3	Diff. %	Case 4	Diff. %	Case 5	Diff. %
f_1	6.642	6.633	0.1409	6.581	0.9266	6.582	0.9051	6.408	3.5299	6.528	1.7226
f_2	19.992	19.986	0.0263	19.907	0.4186	19.723	1.3447	19.718	1.3689	19.551	2.2032
f_3	21.419	21.408	0.0514	21.053	1.7089	21.391	0.1332	20.063	6.3314	21.004	1.9367

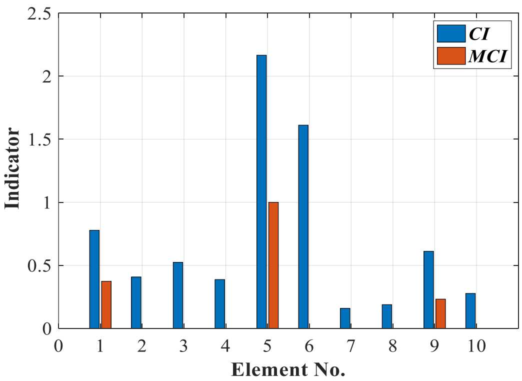
Table 3. Natural frequencies of undamaged and damaged 10-bar planar truss.



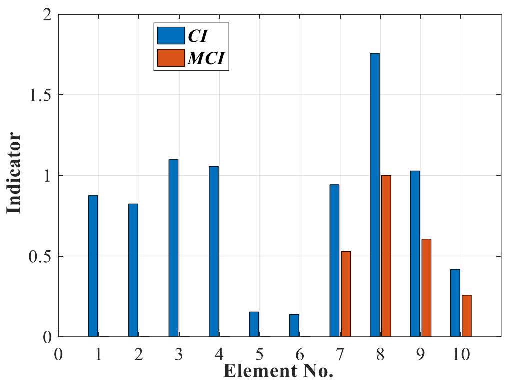
Case 1



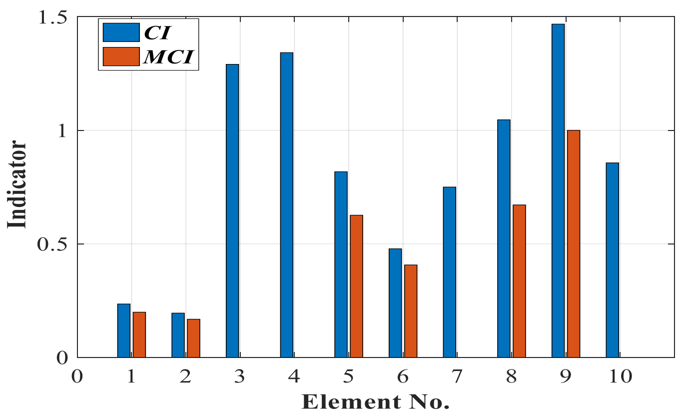
Case 2



Case 3



Case 4



Case 5

Fig. 4. Damage indicators for the five damage cases - 10-bar planar truss.

In all damage cases presented above, we can see better performance by MCI compared with CI. The results show good accuracy with small error in the case of single and multiple damage of 10-bar planar truss.

3.1.2. 3D frame structure

In the second example, a simulated 3D frame structure, shown in Figure 5, is used to verify the proposed technique in 3D configurations. The frame is divided into ten beam elements with 6 DOFs at each node. The properties of the beam element are listed in Table 4. The first three mode shapes of the undamaged 3D frame structure are presented in Fig. 6. To evaluate the robustness of the proposed method, three damage cases are proposed, as presented in Fig. 7 and summarized in Table 5. The natural frequencies of each damaged case are presented in Table 6.

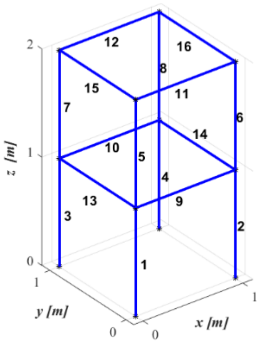


Fig. 5 The 3D frame structure.

Property [unit]	Value
E, Young's modulus [N/m^2]	2.1×10^{11}
S, Section [m^2]	0.5×10^{-3}
ρ, Density [Kg/m^3]	7800
I, Moment of inertia [m^4]	0.417×10^{-8}

Table 4. Material properties of the 3D frame structure.

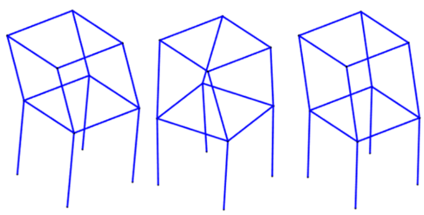


Fig. 6 The first three mode shapes of the 3D frame structure.

	Damaged elements	Reduction (D) in stiffness (E)
Case 1	Element 4	$D_4 = 5\ \%$
Case 2	Element 9	$D_9 = 20\ \%$
	Element 10	$D_{10} = 35\ \%$
Case 3	Element 9	$D_9 = 20\ \%$
	Element 10	$D_{10} = 20\ \%$
	Element 13	$D_{13} = 30\ \%$
	Element 14	$D_{14} = 30\ \%$

Table 5. Reduction in stiffness in elements of the 3D structure for different damage cases.

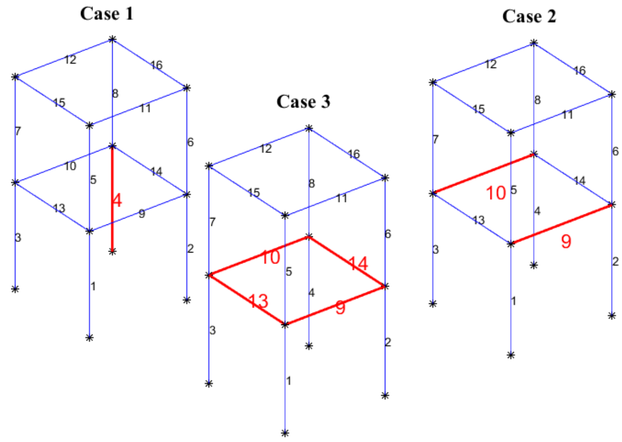
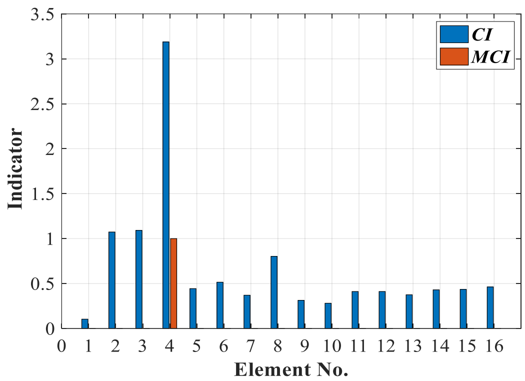


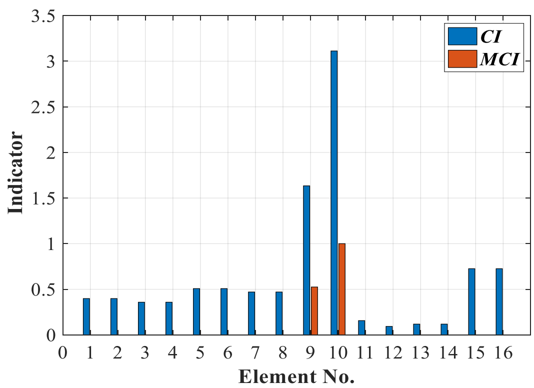
Fig. 7. Damage cases for the 3D structure

Frequency [Hz]	Undamaged structure	Damaged structure					
		Case 1	Diff. %	Case 2	Diff. %	Case 3	Diff. %
f_1	107.723	105.364	2.2	103.629	3.8	104.834	2.7
f_2	142.545	136.84	4	142.545	0	141.414	0.8
f_3	159.732	155.896	2.4	159.177	0.3	158.668	0.700

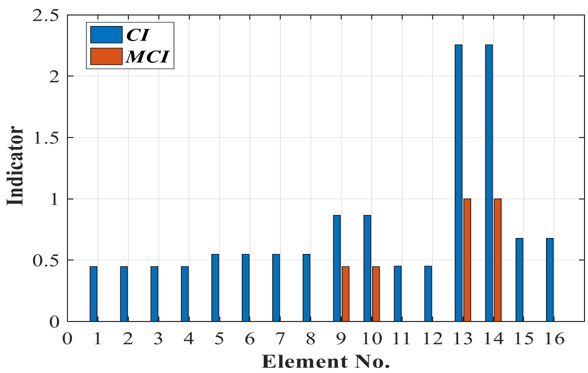
Table 6. Natural frequencies of undamaged and damaged 3D frame structure.



Case 1



Case 2



Case 3

Fig. 8 Damage indicators for the three damage cases - 3-D frame structure

In CI method, a threshold that separates healthy and damaged components must be fixed (see Fig. 9) because there are values at almost all elements. This is because we can notice the existence of indicator for several elements, which are not damaged. For example, apart from the damaged elements 1, 2, 5, 6, 8 and 9, we note the existence of CI value for other undamaged elements, which are 3, 4, 7 and 10. The use of CI to locate several damages in the studied structure is limited by the determination of a certain threshold separating the damaged state from the healthy state. This threshold is determined by numerical simulations and probabilistic statistical analysis. In contrast, the modified proposed indicator, MCI, facilitates the location of damage, since its concept is qualitative, i.e. when the indicator of damage is non-zero, it indicates the presence of damage.

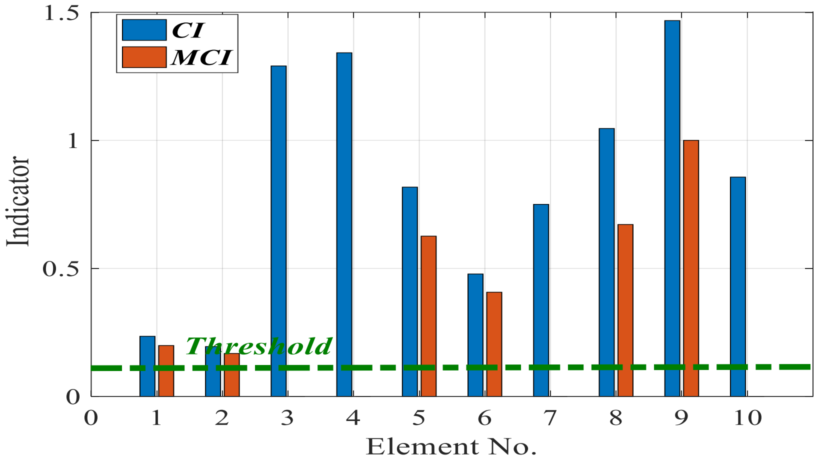


Fig. 9 Threshold representations that separates the healthy elements from the damaged ones (10-bar planar truss – Case 5).

3.2. Damage quantification using GA

In this section, damage quantification for the two structures presented earlier are studied using the proposed method. Through the results found by the two indicators in the studied cases, we notice that CI has difficulties to locate damage compared with MCI. We, therefore, investigate the performance of the combination of MCI with GA (MCI-GA), which can also be used to quantify the severity of damage. The algorithms are coded in Matlab.

3.2.1. 2D truss structure

In this case a 2D truss structure is considered to quantify the damage severity, we use GA and define MCI as objective function (GA-MCI approach) for damage identification. The maximum number of iterations considered is 500. For all examples, five damage scenarios are considered by reducing elastic modulus of some elements, as presented in section 3.1.1. The first damage scenario considers a single damage case, whereas others scenarios consider multiple damage cases. The results for all scenarios are presented in Fig 10. It can be seen that the proposed indicator MCI with GA can detect the damage after few iterations.

In Fig 10, the proposed indicator, MCI, with optimization technique (GA-MCI) is capable of finding all global optimal solutions (damage locations and severities). Every time that the algorithm finds a global optimal solution, the convergence curve touches exactly the correct level of damage for single and multiple damage. In the first damage case, damage element 1 has 0.05% loss of rigidity. In the second case, damage elements 2 and 4 have 1% and 0.05 %, respectively. Table 7 and Figs 11 and 12 compare the results obtained for both scenarios using GA-MCI with those obtained using CSS algorithm. According to Table 7 and Figs 11-12, the mean results for both cases obtained by the GA-MCI are converged just after few iterations and become closer to actual values when compared to the standard CSS algorithm.

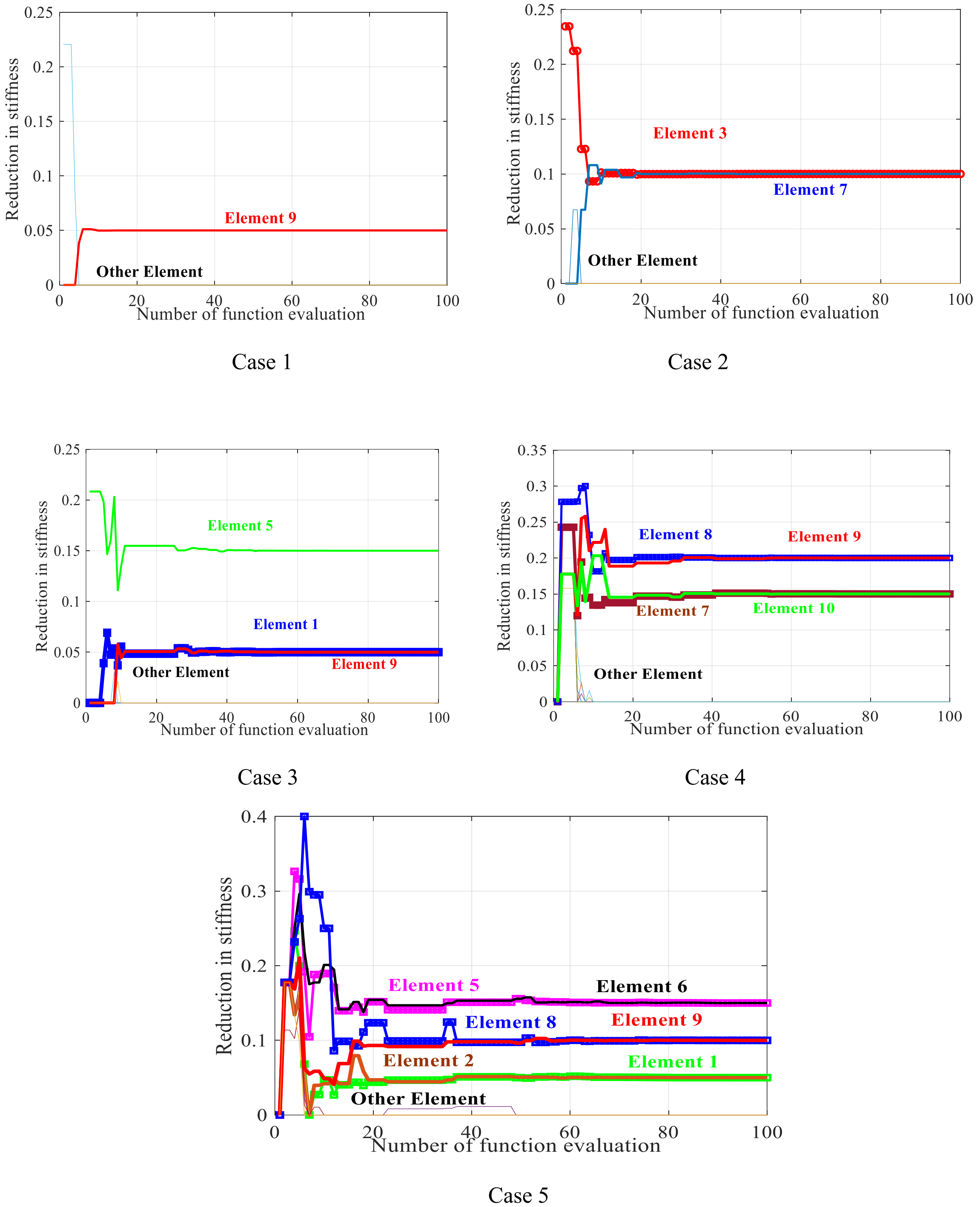


Fig. 10. Convergence of damaged elements for the five damage cases - 10-bar planar truss.

	Damage location	Exact damage severity	Convergence to best value	
			CSS [33]	MCI
Scenario 1	9	5%	25 Iteration	5 Iteration
Scenario 2	3	10%	28 iterations	10 iterations
	7	10%		

Table 7. Comparison between current results and reference solutions - 10-bar planar truss.

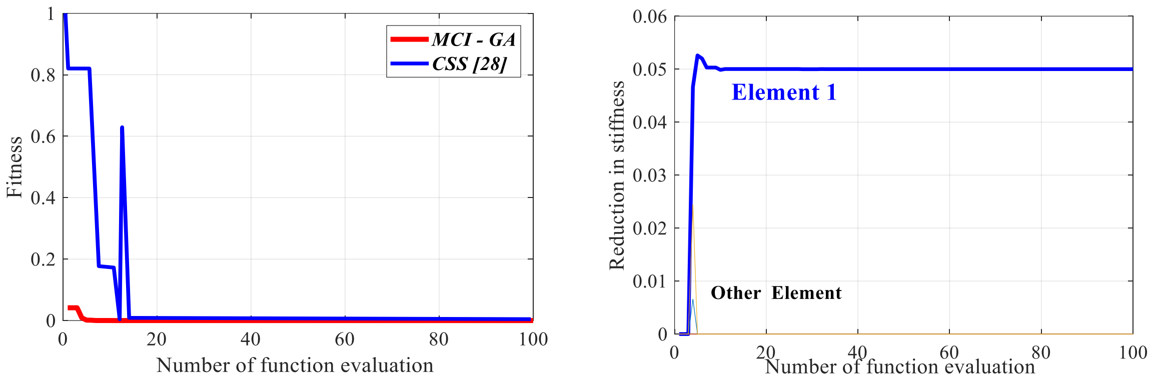


Fig. 11 CSS versus MCI-GA for damage case 1 - 10-bar planar truss.

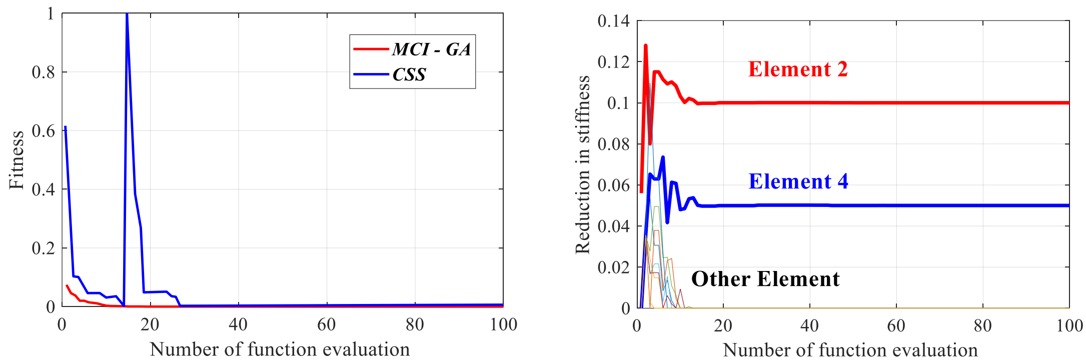


Fig. 12 CSS versus MCI-GA for damage case 2 - 10-bar planar truss.

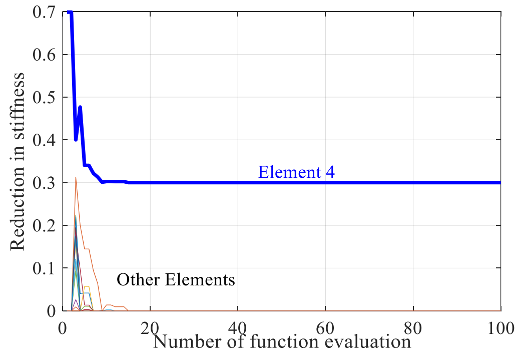
3.2.2 3-D frame structure

In this example, the three cases of damaged 3D frame structure presented in Table 5, in section 3.1.2, are used. We used also MCI as objective function for identification of damage location with severity. The results show that MCI-GA provides good results, as it can be seen in Figure 13.

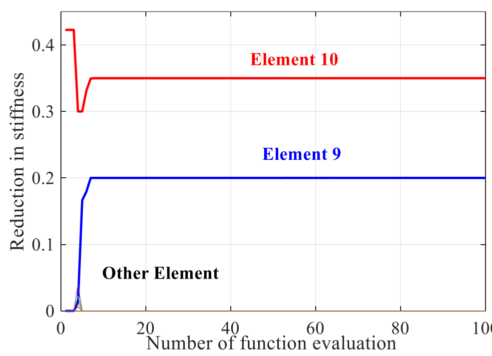
Generally speaking, when using MCI-GA, the algorithm is able to predict the damage location accurately, in the considered cases. The best convergence is achieved for the single damage case after 15 iterations and for multiple damage after 30 iterations. The accuracy of proposed indicator is compared to other techniques, such as using GA for damage identification based on frequencies as presented by Tiachacht et al. [50]. The accuracy of proposed indicators is shown from the results presented in Table 8.

	Damage location	**Exact damage severity**	**Convergence to best value**	
			Tiachacht et al. [50]	**MCI**
Scenario 1	4	5%	10 Iteration	8 Iteration
Scenario 2	9	20%	15 iterations	9 iterations
	10	35%		

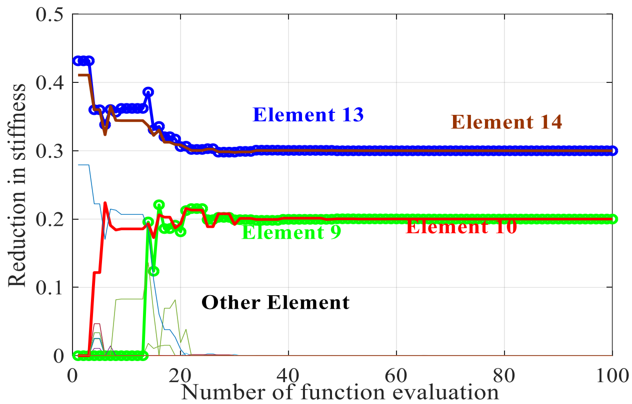
Table 8. Comparison between current results and reference solutions - 3D frame structure



Case 1



Case 2



Case 3

Fig. 13 Convergence of damage in elements for the different damage cases - 3D frame structure

	Damage location	Exact damage severity	Convergence to best value	
			Tiachacht et al. [50]	**MCI**
Scenario 1	4	5%	10 Iteration	8 Iteration
Scenario 2	9	20%	15 iterations	9 iterations
	10	35%		

Table 8. Comparison between current results and reference solutions - 3D frame structure

4. Conclusion

In the present study, two damage indicators are presented, namely the Cornwell indicator (CI) and newly proposed indicator, i.e. Modified Cornwell Indicator (MCI), are utilized for damage detection in 2D truss and 3D frame structures. Furthermore, an objective function based on MCI is defined for localizing and quantifying the damage severity of structural elements based on modal information of damaged structures. Then, the optimization algorithm, GA, is used to determine the damage in structures by optimizing a cost function. The capabilities of the proposed indicator is assessed for 2D truss and 3D frame structures using numerical examples. Different damage scenarios based on single and multiple damages are considered in each example. The results shown that the proposed indicator (MCI) is more robust for structural damage identification. The obtained results from the numerical studies indicated that GA-MCI is successful to predict the location and damage severity of damaged structures for different scenarios. In addition, the proposed approach provides improved results comparing with other similar techniques presented in the literature.

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