T.C.
ERCIYES UNIVERSITY
INSTITUTE OF SCIENCE AND TECHNOLOGY
DEPARTMENT OF CIVIL ENGINEERING

INVESTIGATION OF DAMAGE DETECTION BASED ON VIBRATION AND FLEXIBILITY APPROACHES FOR STRUCTURAL HEALTH MONITORING.

Prepared by
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Supervisor
Asst. Prof. Dr. Müslüm KILINÇ

M.Sc. Thesis

December 2017
KAYSERİ

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CONFORMITY TO SCIENTIFIC ETHICS

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Hussein Ali RUDAİNİ

SUITABILITY TO THE REGULATIONS AND TO THE THESIS PROPOSAL

This Master of Science Degree thesis entitled: **"Investigation of Damage Detection Based On Vibration And Flexibility Approaches For Structural Health Monitoring."** has been prepared in accordance with the Thesis Proposal and with the Guidelines for Writing Thesis of Erciyes University

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APPROVAL:

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BAHÇECİK BARAJI İÇİN RADYAL-KAPAKLI VE SERBEST-AKIMLI OGEE SAVAKLARIN KARŞILAŞTIRILMASI

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ÖZET

Hasar algılama problemini çözmek için metaheuristik optimizasyon teknikleri (Cuckoo (CS), parçacık yığını (SPO), diferansiyel evrim (DE) ve Saten bowerbird optimizasyon algoritması (BSO) olarak adlandırılan yeni bir algoritma) kullanılır. Aralarında yapılan karşılaştırma, nüfusa dayalı yöntemlerin aynı grubuna ait oldukları için yapılabilir. Yapısal sağlık izleme literatüründe, optimizasyon probleminin uygunluğu olarak birçok objektif fonksiyonlar kullanılmaktadır. Hasar oluşumuna bağlı olarak sistemin esneklik değişikliğine dayalı hasar yerini ve hasar ciddiyetini bulmak için kullanılırlar. Çözümle bütünleşmek için optimizasyon algoritmalarının davranışını etkilemek.

Bu tez, daha önceki tüm sözleme tekniklerinin performansını ve aralarındaki karşılaştırmayı içeren bir çalışmayı sunmaktadır. Karşılaştırma çerçevesi olarak seçilen optimizasyon problemi, dinamik analiz alanındaki ders kitaplarından örneklerdir. Sonuçlar Saten bowerbird optimizasyon algoritmasının (BSO) genel olarak hasar tespit probleminin bir göstergesi olarak iyi performans gösterdiğini göstermektedir. en iyi yakınsama hedef fonksiyonu

Anahtar Kelimeler: Hasar tespiti; modal veri; esneklik matrisi; statik yer değiştirme; gugukum optimizasyon algoritması, Diferansiyel evrim algoritması, Parçacık Swarm Optimizasyonu, Satine bowerbird optimizasyon algoritması.

COMPARISON OF FREE-FLOW AND RADIAL-GATED OGEE SPILLWAYS FOR BAHCELIK DAM

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M.Sc. Thesis, December 2017
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ABSTRACT

The metaheuristic optimization techniques (Cuckoo (CS), Particle Swarm (SPO), Differential Evolution (DE) and a new algorithm called Satin Bowerbird Optimization Algorithm (SBO)) are used to solve damage detection problem. In the field of structural health monitoring literature, they are many objective functions are used as the fitness of optimization problem. They are utilized to find the damage location and damage severity based on the system flexibility change due to damage occurrence.

This thesis presents a study the performance of all previous mention techniques and comparison among them. The comparison between them can do because they belong to the same group of population-based methods. Also, comparison of objective functions is done based on their influence on optimization algorithms behavior to converge to the solution. The optimization problem chosen as the comparison framework is the examples from the textbooks in the field of dynamic analysis. The results show the Satin Bowerbird Optimization Algorithm (BSO) generally has good performance as an indicator of damage detection problem.The best convergence objective function is the first objective function (the maximum element in the difference of the flexibility matrices) has a good convergence with high sensitivity to noise while the second and the third objective function (the maximum element in the difference of the flexibility matrices, the flexibility matrix error residual criterion) have quite good convergence and less sensitive to noise than first one.

Key Words: Damage detection; modal data; flexibility matrix; static displacement; cuckoo optimization algorithm, Differential evolution algorithm, Particle Swarm Optimization, Satin bowerbird optimization algorithm.

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LIST OF SYMBOLS AND ABBREVIATIONS

symbol	**Description**
M or m	the global mass or element mass matrix
c	the viscous damping coefficient
K or k	the global stiffness or element stiffness matrix
p(t)	an external dynamic force
$\ddot{u}(t)$	an acceleration vector
$\dot{u}$ (t)	a velocity vector
u(t)	a displacement vector
T_n	the natural period of vibration
ω_n	the natural circular frequency of vibration
[Φ]	the mode shape matrix
φ_i	the mass-normalized ith mode shape of the structure
N	the number of measured modes.
E	the modulus of elasticity
A	the section area
I	the moment of inertia of the section
L	the length of the element
α	the step size
⊕	entry wise multiplication
λ	a Lévy flight parameter
(FL)	fitness based on an objective function
(Fi).	nest's fitness
(xn)	the new nests
xb	the nests
Fb	the fitness of the nests
xp	the best nest of the generation
Fp	the best nest fitness of the generation
Xi	Current position
Yi	Best previous position
Vi	Velocity
c1, c2	learning factors

symbol	**Description**
pbest	local best
gbest	global best
F	differential weight.
Vj	donor vector
ri	a uniformly distributed random number within the interval [0,1],
Cr	crossover probability controls the crossover
R	a randomly chosen index
DOFs	Degree of freedoms
uj	the trial vector
fit_i	the fitness of i th solution
N	the number of population
$f(x_i)$	the value of the objective function in ith position or ith bower.
X_{ik}	kth member of ith bower or solution vector.
X_{jk}	a target solution among all solutions in the current iteration
j	is calculated based on probabilities derived from positions by the roulette wheel procedure, which means that the solution having a larger probability to be selected as xj.
$X_{elite.}$	is the position of a bower which has the highest fitness in the current iteration and is saved in each cycle of the algorithm
pj	the obtained probability values which they lied between 0 and 1 based on the goal bower.
σ	a proportion of space width
$[F]_E$.	the experimental flexibility matrix
(a) is	the stiffness reduction factor
$[F(a)]_D$	the numerical flexibility matrix with (a) reduction in the stiffness matrix
DF	the difference matric $[F]_E - [F(a)]_D$ or $Fd - Fh$

symbol	**Description**
F1	the objective function 1
(δ_{ij})	In each DOF the maximum absolute value of the elements in the difference matric |(DF)
F2	the objective function 1
u_d	the damaged static displacement vector
${K_i}^{a_i}$	a reduction in the stiffness element
Ki	the healthy stiffness matrix of the element i
${G_d}^a$	a reduction in the flexibility matrix
u_a	the healthy static displacement vector
DE	error vector=$u_a - u_d$
F3	the objective function 3

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INTRODUCTION

Structural health monitoring (SHM) system is the carrying out the process for damage detection which is a statistical pattern recognition that goals to classify data. This data consist of groups of measurements or observations come from information extracted from the experiment and from the earlier information. They are covers all stages from problem formulation up to the interpretation of the results.

Analysis of existing structures is essential for the damage detection, which determines their structural integrity and prevents unexpected failures. Then decide whether a structure can do its intended function even after its design life. This is possible when the frequency of use or loading on the structure is less than originally estimated, or when an excessive level of safety has been built into the design. Therefore, the authorities can avoid the unnecessary process of replacing the structure which would result in high cost.

The great benefit of structural health monitoring can be shortly described as cost-saving and safety improvement in different types of structures. One of the most important tasks of these systems is to identify damage at an early stage of its development. A variety of methods may be used to identify, locate, or quantify the extent of damage or fault in a structural or mechanical component, estimation of the extent or severity of the damage and predict the remaining useful life of the structural component. However, the preferable method is the one which maximizes the probability of detecting the damage, while also considering the feasibility of in-situ testing, ease of use, economic factors, Be independent of changes in the operational and environmental conditions and Be independent of human judgment and ability.[1]

Damage is defined as the changes in the material properties and geometry of structure which affect the performance of structure negatively in current time or in future. There are many factors may its cause these changes such as aging, environmental conditions, loads, subjected to an unusual event in its lifetime. In order to avoid unexpected failures in the structure during design-life which may happen in a large structure can lead to a loss of life and have considerable cost. [2]

Model-based damage detection which is defined as extracted the physical model of structure or identified its parameter with the response at a different state of structure to learn structural damage. to make these state of structural vibration properties closely it is required the finite element model of the structure. One major difficulty is that an accurate initial finite element model is required for the updating. The advantage is not only the location of the damage but also the severity of it can be identified. The features of these methods are dependent on the geometry of damage and not sensitive to its severity. [3]

Dynamic response based methods are damage detection methods based on the dynamic of structure properties which they change if damage occurs. That's relying on the fact that it is a function of the physical properties such as (stiffness, damp, mass), so it directly affected by the change in these properties. The structural damage alters the structural properties, which in turn changes the structural dynamic properties extracted from the measured data. Damage-sensitive feature selection is extremely important to perform an effective and economic SHM.

Dynamic response based methods have the ability to deal with complicated, large and inaccessible structures to identify, locate damage in the structure. The performance of self-diagnosis and early warning for the structural healthy state using the sensor networks, actuators, and computational capabilities has extended from control engineering to civil engineering in the field of SHM.

The optimization is finding the solutions to a specific problem in a best possible way. That's solutions come from minimizing or maximize an objective function with or without some constraints by choosing values for the objective function variables within an acceptable range which satisfy the constraints.

İn civil engineering field the optimization goals are to design a structure in the best possible way with taking into consideration the safety requirements and the cost which are the high priority factors in the designing structures and utilized in order to reach the optimum result in the problem of damage detection.

Using Change in stiffness or flexibility matrix are generally relying on the variation between the original numerical model of the structure and the corresponding dynamic response measured.

Based on the idea that the stiffness is changing with time, in contrast, mass and damping do not change with time. And the reduction in stiffness matrix can be computed as

$$K_d = (1 - a \quad)K$$

Where

K_d is the stiffness of damaged element, K is the stiffness of undamaged element and a is the damage in the element

Finally, can be detected the damaged element by assembled them to global stiffness based on their contribution. the drawback of this algorithm is the difficulty of constructing the stiffness matrix from dynamic measurement and for overcome this difficulty [5,6,7,8].they have proposed method with high accuracy result by constructing the flexibility matrix using a few lower models

$$F = \sum \frac{1}{{\omega_i}^2} \psi_i {\psi_i}^T$$

the detection of current flexibility matrix is viewed as a local optimization problem. The damage localization is achieved as a comparison of the currently estimated flexibility matrix using evolutionary algorithms with the stiffness matrix of the undamaged structure.

CHAPTER 1

GENERAL INFORMATION ABOUT THE TOPIC OF THE THESIS

1.1. Statement of the Problem

Optimization based the finite element model is applied to predict damage location and severity in frames. The changes in flexibility matrix are used as dynamic indicators to describe damaged elements . Objective functions including dynamic properties provide minimization of dynamic properties differences between the numerical model and simulated damaged model. The presence of damages in structural elements is identified by stiffness reduction as a reduction in modulus of elasticity.

1.2. Literature Review

there are many methods are used in damage detection problem based on the dynamic properties and several approaches were investigated for damage detection [11,12]. Among these, flexibility-based damage detection algorithms have been shown to be sensitive to damage and robust to high frequency noise. [10]

Using the changes in the flexibility matrix based on an inverse relationship between the flexibility and stiffness matrix .therfore, the stiffness decrease due to the damage will increase the flexibility which is employed to locate damage. [9,6]. In last decade, there are many researches based on the flexibility using physical and optimization technique for damage detection problem as shown below:

- For multiple damages, there are difficulties to use the flexibility matrix change directly because of that improvement was introduced to describe the relationship between the flexibility matrix change as a function of the elemental stiffness matrix change.then using a pseudo inverse technique to obtained the change in the elemental stiffness.[7]

- Monitors the structures remotely without human involvement. DELORES (DEtection and LOcalization of RESponse anomalies) which utilizes vibration recordings from the healthy and current states of a structure to declare its current health. It extended versions of the dynamic damage locating vector (DDLV) and the stochastic dynamic damage locating vector (SDDLV) methods, which include an outlier analysis scheme for a more unambiguous localization of potential damages.[13]

- An estimation method of the flexibility matrix of beam-type structures considering translational and rotational DOFs that can be measured by accelerometers and gyroscopes, respectively. The efficacy of the proposed method is numerically validated using a simply supported beam model. [14]

- A practical application of a flexibility-based damage detection algorithm, the stochastic damage locating vector (SDLV) method, is developed and implemented for full-scale health monitoring of an in-service highway bridge. [15]

- Study the truss structure was subjected to three damage cases by reducing the cross sectional area of a single element. Modal Analysis was performed and the frequency and mode shapes were extracted for both the healthy and unhealthy states of the truss structure. Using these parameters, the other parameters namely Frequency change, Damage Location Assurance Criterion (DLAC), Mode shape Curvature and Curvature Damage Factor (CDF) were studied. These parameter changes are useful to predict damage information, such as the presence and location of damage in a structure. [16]

- Uses the modal flexibility method incorporating two damage indices (DIs) based on lateral and vertical modes to localize damage in cables such as those used in suspension bridges. The competency of those DIs in damage detection is tested by the numerically obtained vibration characteristics of a suspended cable in both intact and damaged states. [17]

- Comparison between Modal parameters and modal flexibility methods numerically and experimentally is done. [18]

- An application of the damage locating vector (DLV) approach to the experimental (Phase II) data obtained from the experimental benchmark structure of the IASC-ASCE task group on SHM, which is a laboratory (scaled) size steel frame. The successes and limitations of the DLV method of detecting and locating the simulated damages were discussed. [19]

- Using structural-dynamics based methods to address the existing challenges in the field of Structural Health Monitoring (SHM). [20]

- a new model updating approach is to detect damage location and severity in the SHM field using the Modal Assurance Criterion (MAC) by employing the main diagonal and anti-diagonal of the Generalized Flexibility Matrix (GFM) for the damaged structure and the analytical model .using DPSO which is a modified version of standard PSO algorithm to minimize the objective function.[21]

- Local Flexibility (LF) method is proposed for vibration-based damage localization and quantification using quasi-static flexibility which is composed directly of modal parameters.[22]

- A residual flexibility estimating at non-excited structural degrees of freedom is proposed to obtain more accurate flexibility matrices by including the effects of residual dynamics in the flexibility matrix. The data is toke from the vibration parameters of the experimental structure.[23]

- A method is proposed to computing complete structural flexibility matrix from a dynamically measured flexibility matrix. The method is derived and applied to both numerical and experimental measured flexibility matrices.[24]

Damage detection optimization based finite element model is applied to detect, locate and severity level of damage in structures. it has been studied by many researches as shown below:

- A genetic algorithm (GA) is proposed to detect damage location and severity in space frames. the study shows that GA optimization is a convenient method for damage identification. [25]

- A finite element method and heuristic optimization techniques (genetic algorithm) are proposed to detect n and identify of structural damage by minimizing dynamic parameters objective function of a square plate of composite material. The study shows that GA is solved the problem efficiently.[26]

- Three methods are proposed to detect damage location and severity using modal data with and without noise and static displacement of a damaged structure. these methods use the simulated annealing algorithm optimization to solve the objective functions The studying results indicated that these methods are viable for damage identification.[27]
- A Finite Element Model and a heuristic algorithm (Imperialist Competitive Algorithm (ICA))is proposed to detect damage location and severity in truss structures by minimizing an objective function of dynamic parameters of the damaged and undamaged state of a structure. The studying results indicated that the method viable for damage identification.[28]
- A self-organizing map (SOM) is proposed to detect damage location and severity. The studying results indicated that the method has successful results to extract damage from the random vibration.[29]
- A Differential Evolution optimization (DE) is proposed to detect damage location and severity by minimizing an objective based on the difference between the experiment and analytic flexibility matrices of the structure. a comparison is proposed between Differential Evolution optimization with Particle Swarm Optimization and Simulated Annealing that shows the Differential Evolution method outperformed the others and a satisfactory damage identification.[30]
- Stain bowerbird algorithm optimization (SBO) a novel optimization algorithm proposed to solve various non-linear optimization problems.[31]
- A Differential Evolution optimization (DE) is proposed a new heuristic approach which is a population-based algorithm .it is utilized to finding the true global minimum careless of the initial parameter values .the algorithm is used few parameters and fast convergence.[32]
- A global artificial fish swarm algorithm (GAFSA) is proposed to detect damage location and severity in the SHM field. The studying results indicated that the method has successful results to extract the damage location and the severity of damage with a good noise immunity.[33]

1.3. Objectives of the Study

The overall goal of the research is to evaluate the structural condition using flexibility-based methods and implement efficient and accurate algorithms to detect damages for civil structures. More specifically, the population-based optimization algorithm Cuckoo algorithm (CS), Differential Evolution algorithm (DE), Particle swarm optimization (PSO), Satin bowerbird optimization algorithm (BSO)are utilized in order to achieve the optimum results in the damage detection problem. estimate structural parameter such as modal flexibilities, natural frequencies and mode shapes from structural dynamic analysis of health structure and scenario for damage structure. And examine and compare the objective functions which are based on the flexibility matrix.

Different damage scenarios are examined to find out the effectiveness of the algorithms and find out the accuracy of objective functions to detect the damaged part of the structure and the severity of this damage.

CHAPTER 2

MATERIALS AND METHOD

2.1 Equations of motion

2.1.1 Single degree of freedom system (SDF)

SDF is one of the simplest systems consist of a mass located at the roof level With a stiffness from the massless spring and dissipates vibration energy which refers as a damper as shown in Figure (1, a).The system can be represented as in Figure (1, b).Below is the equation of motion for damped SDOF system.

$$m.\ddot{u}(t) + c\,.\,\dot{u}\,(t) + k\,.\,u(t) = p(t) \qquad (2.1)$$

m is the mass,

c is the viscous damping coefficient,

k is the stiffness,

p(t) is an external dynamic force, and

$\ddot{u}(t)$ is an acceleration

$\dot{u}\,(t)$ is a velocity and $u(t)$ is a displacement.

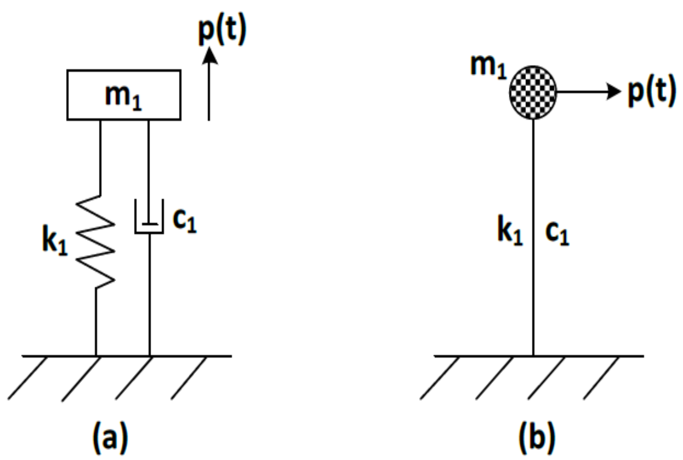

Figure 2.1. ((a).a single DOF system, (b) representation of a single DOF system). [34].

2.1.2. Systems with multiple degrees of freedom (MDF)

MDF consists of masses centered at the roof level with the massless spring providing stiffness and the dissipation of vibration energy done by the viscous dampers which are represented as follows:

$$[m].\{\ddot{u}(t)\} + [c].\{\dot{u}(t)\} + [k].\{u(t)\} = \{p(t)\} \quad (2.2)$$

[m] is the mass,

[c] is the viscous damping coefficient,

[k] is the stiffness,

$\{p(t)\}$ is the external dynamic force

$\{\ddot{u}(t)\}$ is the acceleration

$\{\dot{u}(t)\}$ is the velocity

$\{u(t)\}$ is the displacement

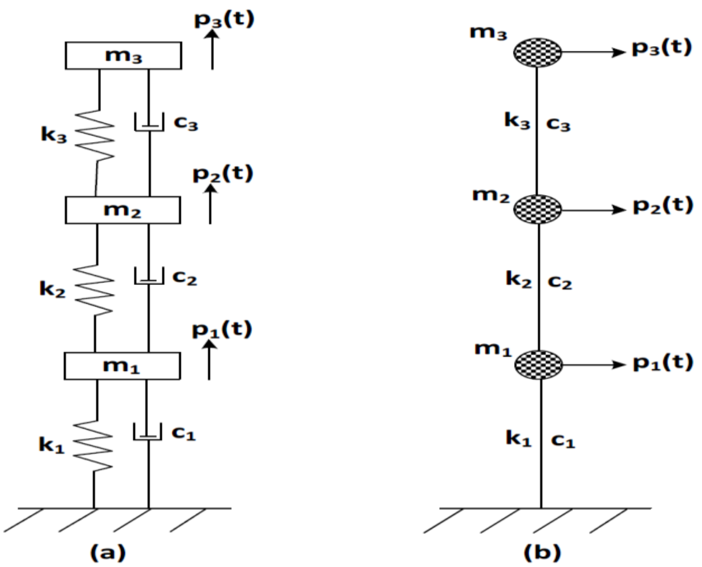

Figure 2.2. (a) a multiple DOF systems (b) representation of multiple DOF systems. [34].

The system properties could be calculated as follows:

$$[\mathrm{m}] = \begin{bmatrix} \mathrm{m1} & 0 & 0 \\ 0 & \mathrm{m2} & 0 \\ 0 & 0 & \mathrm{m3} \end{bmatrix}$$

$$[\mathrm{k}] = \begin{bmatrix} k1 + k2 & -\mathrm{k2} & 0 \\ -\mathrm{k2} & \mathrm{k2 + k3} & -\mathrm{k3} \\ 0 & -\mathrm{k3} & \mathrm{k3} \end{bmatrix}$$

$$[\mathrm{c}] = \begin{bmatrix} c1 + c2 & -\mathrm{c2} & 0 \\ -\mathrm{c2} & \mathrm{c2 + c3} & -\mathrm{c3} \\ 0 & -\mathrm{c3} & \mathrm{c3} \end{bmatrix}$$

$$\{\mathrm{p(t)}\} = \begin{Bmatrix} \mathrm{p1(t)} \\ \mathrm{p2(t)} \\ \mathrm{p3(t)} \end{Bmatrix}$$

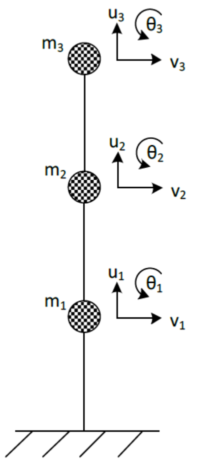

Figure 2.3. A three-story structure. [34].

2.2. Free vibration

The vibration of a structure without applied external forces but by initial displacement or velocity is referred to as free vibration. [34].The system equation of motion without damping can be shown as:

$$[m].\{\ddot{u}(t)\} + [\mathrm{k}].\{u(t)\} = \{0\} \qquad (2.3)$$

The equation is homogeneous differential equations and it coupled the mass and stiffness. The system consists of a natural period (T_n).The natural period refers to the time required for one cycle for the n-th natural mode of the harmonic motion.

The following equation shows the relation between the natural period and the natural circular frequency of vibration (ω_n) is as follows:

$$T_n = \frac{2\pi}{\omega_n} \quad (2.4)$$

The natural circular frequency of free vibration is the vibration of the system when applied initial displacement or velocity at the initial time which left the system to vibrate.

2.3. Dynamic Characteristics of the Structure

2.3.1. Natural frequencies and mode shapes

The structural properties (stiffness and mass) have given the natural frequencies and modes of a system by using the eigenvalue problem which could represent as follows:

$$\{u(t)\} = q_n(t).\{\varphi_n\} \quad (2.5)$$

where:

{u(t)} is the system displacements vector,

{φn} is the deflected mode shape vector which does not vary with time and

qn(t) is the time variation of the displacements, which can be described by the following harmonic function:

$$q_n(t) = A_n \cos(\omega_n\ t) + B_n \sin(\omega_n\ t) \quad (2.6)$$

Combining Eqs (2.5) and (2.6) we take

$$\{u(t)\} = \{\varphi_n\}.(A_n \cos(\omega_n\ t) + B_n \sin(\omega_n\ t)) \quad (2.7)$$

The second derivative of the displacement vector can be calculated as follows:

$$\{\ddot{u}(t)\} = \{\varphi_n\}.(-\omega_n^2.A_n\cos(\omega_n t) - \omega_n^2.B_n\sin(\omega_n t)) \quad (2.8)$$

Eq. (2.8) can also be written as follows:

$$\{\ddot{u}(t)\} = -\omega_n^2.q_n(t).\{\varphi_n\} \quad (2.9)$$

Calculation of the equation of motion for a free vibrated as follows:

$$(-\omega_n^2.[m].\{\varphi_n\} + [k].\{\varphi_n\}).q_n(t) = \{0\} \quad (2.10)$$

Where there are two choices to solve the equation $q_n(t) = 0$ that solution will be ignored because of that implies no motion of the structure and

$$(-\omega_n^2.[m].\{\varphi_n\} + [k].\{\varphi_n\}) = 0$$

Which its results an important condition as shown below:

$$[k].\{\varphi_n\}) = \omega_n^2.[m].\{\varphi_n\} \quad (2.11)$$

This can also be written as:

$$([k].-\omega_n^2.[m]).\{\varphi_n\} = \{0\} \quad (2.12)$$

The real eigenvalue problem in this equation is used with the system without damping to distinguished it from the complex eigenvalue for a system with damping, the solution of this equation is produced the mode shapes and natural frequencies which called characteristic equation.

$$det([k].-\omega_n^2.[m]) = 0 \quad (2.13)$$

There are N real and positive roots for ω_n in this equation with the stiffness matrix [K] and mass [M] which they are positive definite and symmetric.

İn all civil engineering structure the definite property of stiffness matrix is assured and rigid-body motion is prevented .the positive definite property of the mass matrix is also assured due to the fact that there are non-zero of the lump masses for all DOFs.

Retained in the dynamic analysis .there will be a thorough analysis of this fact in paragraph 2.3.1 where the DOFs with zero lump masses are eliminated using the static condensation procedure .the natural frequencies ω_n (n = 1, 2, ..., n) of vibration are determined by the n roots of equation (2.13). The characteristic equation of these roots is referred as an eigenvalue.

Equation (2.12) can be solved for the corresponding vectors ({φn}) to within a multiplicative constant provided the natural frequencies (ω_n) are known. These vectors can also be referred as eigenvectors and the natural mode shapes of vibration of the structure is represented by its mode shape calculation of structure is very useful because it represents the shape of the building vibrating in free motion .therefore in a vibrating system with (n) DOFs, there exist (n) natural vibration frequencies (ωn) correspond to natural period (T_n) and (n) natural mode shapes vectors ($\{\varphi_n\}$) with (n = 1, 2, ..., N). Because the vibration properties are natural properties of the structure of free vibration and dependent on its mass and stiffness properties, the term natural is used in emphasizing this fact.

2.3.2. Calculation of dynamic characteristic of a structure

Calculation of dynamic characteristic can be done by solving the eigenvalue problem using (mass and stiffness matrix) which provide the structural mode shapes and natural frequencies.

The following steps show the procedure for obtaining the dynamic characteristic of the structure with N degree of freedom. [35, 36]

1. Normalize stiffness matrix calculation.

$$[k] = m^{-1/2}.[k].m^{-1/2} \tag{2.14}$$

2. Calculation of the symmetric eigenvalue problem for stiffness matrix.

$$[k].[R] = [R].[\Lambda] \tag{2.15}$$

The eigenvector of stiffness matrix $[k]$ are in the columns of matrix $[R]$ while matrix $[\Lambda]$ is diagonal with its elements being squares of the natural frequencies.

$$[R] = [r_1\ r_2\ r_3 \ldots .\ r_n] \text{ and } [\Lambda] = [\omega_1{}^2\ \omega_2{}^2\ \omega_3{}^2 \ldots .\ \omega_n{}^2] \tag{2.16}$$

3. The mode shape is calculated as follow

$$[\Phi\ ] = [m]^{-1/2}.[R] \tag{2.17}$$

4. Natural frequencies arrangement in sequence from smallest to largest

$$(\omega_1 < \omega_2 < \omega_3 < \cdots < \omega_n)$$

Application of this classification should be done on the corresponding natural mode shapes and natural period .with this classification natural frequencies and mode shapes of the structure with the biggest contribution are brought in the first place.

2.3.3. Normalization of modes

The reference to the procedure stated in the previous paragraph, an NXN matrix dimensions are used to calculate the mode shapes. The structures first mode shape is represented by the first column and the second mode is represented by the second column and so on.

$$[\Phi] = \begin{bmatrix} \varphi_{11} & \varphi_{12} & \cdots & \varphi_{1N} \\ \varphi_{21} & \varphi_{21} & \cdots & \varphi_{2N} \\ \varphi_{31} & \varphi_{32} & \cdots & \varphi_{3N} \\ \vdots & \vdots & \vdots & \vdots \\ \varphi_{N1} & \varphi_{N2} & \cdots & \varphi_{NN} \end{bmatrix} \tag{2.18}$$

a specific natural frequency of a system has a unique mode shape multiplying by a constantly called scale which is arbitrary. for practical purpose mode shapes is scaled (i.e., normalized) by a chosen convention. The most common mode shape normalization illustrated below:

A. Mass normalization

Mass normalization is a method to normalize the mode shape of the system which should be satisfied the following equation. [37]

$$\{\varphi_n\}^T\ [M].\{\varphi_n\} = 1 \tag{2.19}$$

Using Equation (1.19) for the (first, second…etc.) mode shape of the structure and assuming the same mass m for all DOFs the constants (A1, A2…etc.) can be calculated:

$A_1{}^2.\{\varphi_1\}^T.\begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & m \end{bmatrix}.\{\varphi_1\} = 1$ In the same way

$$A_2{}^2.\{\varphi_1\}^T.\begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & m \end{bmatrix}.\{\varphi_2\} = 1 \quad (2.20)$$

$A_1 = \sqrt{\frac{1}{\{\varphi_1\}^T.\begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & m \end{bmatrix}.\{\varphi_1\}}}$ In the same way

$$A_2 = \sqrt{\frac{1}{\{\varphi_2\}^T.\begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & m \end{bmatrix}.\{\varphi_2\}}} \quad (2.21)$$

So the mass normalized mode shape becomes:

$[\varphi_1] = A_1.\{\varphi_1\}$,

$$[\varphi_2] = A_2.\{\varphi_2\}\text{…….etc.} \quad (2.22)$$

Numerically the result of this method in a modal mass matrix is an identity matrix.

The advantage of this method is simplified both computational and data storage requirements when the calculation of modal dynamic response. Especially with a model of a heavy, massive structure, the magnitude of the eigenvectors is very small.

B. Unity to largest element normalization

Unity to largest element normalization is a method to normalize the mode shapes of the system in each mode shape divided all elements by the value of the largest element.

C. Unity to top story normalization

Unity to top story normalization is a method to normalize the mode shapes of the system in each mode shape divided all elements by the value of the top story.

2.3.4. Effective stiffness matrix

The dynamic analysis of structure need to calculate its mass and stiffness and these properties come in the top priority of computation. these properties should not contain DOF's with zero mass or have zero displacements .it can overcome this by using the below procedures to omitted these DOFs.

- Static condensation of the rotational DOFs of the structure.

- Rearrangement of the matrix of stiffness by omitted the DOFs based on the boundary condition of the structure.

2.3.5. Static condensation

In order to eliminate the rotational DOFs of the structure which has zero mass .this method rely on the idea that can be omitted the rotational inertia term in the rotational DOF.

For the sake of convenience, a simple beam element in the two-dimensional space with 3 DOFs for each node (2 translational and 1 rotational) is considered and its stiffness matrix is calculated as follows [38]

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

Where:

E is the modulus of elasticity,

A is the section area

I am the moment of inertia of the section and

L is the length of the element.

In a dynamic analysis of the beam element, the axial DOFs (u_{xj} and u_{xk}) can be easily subtracted from the stiffness matrix of the structure, as they are uncoupled from the other DOFs of the element. From the remaining DOFs, it should be kept in mind that the masses are ideally assigned to the y-translational ones. This assumption, however, is not valid in frame elements, where the masses are assigned to both x- and y-translational DOFs.

As a result, the rotational degrees of freedom are eliminated from the final stiffness matrix of the structure with the procedure of static condensation. It should be noted that the DOFs that are condensed, are still part of the rest calculations in the analysis of the structure. Also, this procedure should be applied to the calculation of the stiffness matrix of the whole structure and not at the stiffness matrix of each element, as it would lead to mechanisms.

The mathematical equation that calculates the condensed stiffness matrix [K_c] is the following:

$$[K_c]=[K_{aa}]-[K_{ab}]\,[K_{bb}]^{\wedge}(-1)\,[K_{ba}] \quad (2.23)$$

Where

K_{aa} - includes the rows and columns of the non- condensed DOFs.

K_{ab} - includes the rows of the non- condensed and the columns of the condensed DOFs.

K_{ba} - includes the rows of the condensed and the columns of the non- condensed DOFs.

K_{bb}- includes the rows and columns of the condensed DOFs.

2.4. Optimization

A damage identification optimization problem is finding the actual statues of the structure in terms of minimizing the errors between the dynamic properties of damaged structure and dynamic properties of the healthy structure. Many different methods have been developed for damage identification optimization.

The heuristic optimization is one of these methods which is not a new concept and has many algorithms as techniques, most of them inspired by natural phenomena. They are usually employed for nonlinear problems with large and complex design spaces, or with discontinuous objective functions, problems that are very difficult to solve with classic methods. Because the selection of suitable algorithm is concerned, the formulation of a wide variety of optimization algorithm that can solve the even large-scale structural problem. Each algorithm has powerful and weaknesses in its operation.

The candidate algorithms are population-based techniques, working with a group of candidate solutions to the given problem, leading them towards an optimum.

The framework was developed for the implementation and study these algorithms allowed the adaptation and implementation of all under the same paradigm. In the present thesis the optimization problems are solved using the following algorithms:

1. Cuckoo algorithm (CS)
2. Differential Evolution algorithm (DE)
3. Particle swarm optimization(PSO).
4. Satin bowerbird optimization algorithm (SBO).

2.4.1. Cuckoo algorithm

CS algorithm has become a very popular because of its simplicity, efficiency and fast convergence characteristics.

The CS algorithm is simulated birds life called Cuckoo where they put their eggs in the nests of other host birds of different types. There is probability to discover that eggs do not host birds own, that’s lead to destroy the eggs or leave the nest.

The following simplifying assumptions were used:

1. Set of the solution is produced in selected nest randomly based on the idea that each cuckoo puts one egg at a time.

2. The best solution will be generated the new generation.

3. a constant host nest is available and the probability to discover the eggs by host birds is probability=[0 to 1], when the host bird discover the egg, in this case, it will be left the nest by building a new nest in new location (new random solutions at new locations) or destroyed the egg .for simplicity, a part of the nests being left by building new nests (with new random solutions at new locations).

Lèvy Flights

In nature, the search of animals for food is in a random way because their walking from the current location to the next location and the direction of their walking is based on the transition probability. And can be modeled mathematically as a Lévy flight which is a mathematical interpretation of a random walk in which the length of the step is distributed according to a heavy-tailed probability distribution. After a large number of steps, the distance from the origin of the random walk tends to a stable distribution. [39, 40]

The following steps are used to implement the algorithm:

Step1: generate an initial population of n host nests randomly $x_i(i=1,2,...,n)$ and evaluate its fitness based on objective function F_i.

Step2: apply Lévy flight s to produce new nests as follow:

$$x_L = x_i + \alpha \oplus L\acute{}evy(\lambda) \qquad (2.24)$$

Where

α = the step size,

$\oplus$ = entry wise multiplication and

λ = a Lévy flight parameter ($1<\lambda\leq 3$).

Step3: evaluate the new nest's fitness based on objective function (F_L) and compare them to the previous nest's fitness (Fi).

Step4: in case a minimization problem, if $F_L<F_i$, then xi is replaced by x_L.

Step5: A fraction pa of the worst nests obtained after Step4 are replaced by new nests (x_n) using a random flight.

Step6: evaluate the new nests (x_n) fitness.

Step7: update the best nest xp of the generation.

Step8: in case a minimization problem, The best nest obtained until the current iteration, x_b, is replaced by x_p, if the fitness of the nests x_p,F_p is less than the fitness of the nests x_b ,F_b .

Step9: return to Steps2 until stopping criteria is achieved and return x_b

2.4.2. Particle swarm optimization

PSO is an optimization algorithm (proposed in 1995) by [Dr. Eberhart and Dr. Kennedy], it simulates large group social behavior as flying flocks of birds or fish which communicate during flight. It has potential solutions called particles (the birds flock) which have individual intelligence, some social behavior and regulates their movement towards a destination. Suppose a group of birds is searching food in an area randomly which has only one piece of food. The birds don't have any knowledge about the piece of food place. But they know the distance between them and the food in each iteration.so they follow the bird which has the nearest distance to the food.

The particle has three vectors (current position, previous best position, velocity).The particle position has a dimensional space(N) equals the number of variables of the problem which needs to determine. [41, 42]

Current position, $X_i = (x_{i1}, x_{i2}, . . ., x_{iN})$

Best previous position, $Y_i = (y_{i1}, y_{i2}, . . ., y_{iN})$

Velocity, Vi = (vi1, vi2,. . .,viN).

The basic steps of PSO algorithm can be summarized as

1. Initialization a group of random particles (solutions) and finds the optimal solution to updating generations.

2. In every iteration, updated the best solution fitness (pbest) called local best which the particle has reached so far.

3. Updated the best solution fitness (gbest) called global best which any particle has reached so far and gives out the information to others.

4. Update velocity and new positions as follows

$$V_i = V_{(i-1)} + c_1 * rand() * (pbest_{(i-1)} – Y_i) + c_2 * rand() * (gbest - Y_i) \quad (2.25)$$

$$X_i = X_{i-1} + V_i \quad (2.26)$$

Where

V_i is the particle velocity which should be limited to Vmin and Vmax which they specified by the user.

X_i is the current particle (solution).

pbest and gbest are defined above.

rand () is a random number between (0,1).

c_1, c_2 are learning factors.

2.4.3. Differential Evolution algorithm (DE)

DE is an optimization algorithm (proposed in 1997) by [Rainer Storn and Kenneth Price] and it is one of evolutionary programming which is more robust on achieving optimal solution than many other heuristic algorithms with its uncomplicated structure. it uses similar principles with Genetic Algorithms.it considered as a best genetic type algorithm to solve the problems which have real value design variables.The advantages of Differential Evolution algorithm can be described briefly as simple build, easy, fast, and powerful. so it has been used in the application for various science and engineering problems to find out suitable solutions without any skillful knowledge or complicated design algorithms. It uses mutation as the primary search mechanisms and selection to move the search mechanisms toward the prospective space in the solution space in comparison with Genetic Algorithm which relies on a crossover, as a technique of probability and useful transfer of information among search space.[43]

The basic steps of DE algorithm can be summarized as:

1. Initialize random vectors within the corresponding range which has N parameter equal to problem variables.

$X_i = (x_{i1}, x_{i2}, \ldots, x_{iN})$ where i=1,…….,N

2. In the mutation, the operation is generated a mutant vector called donor vector which adding a behavioral parameter called weight difference vector which affects the convergence speed of the population.

For each generation

$$V_j = x_{r1} + F\,(x_{r2} - x_{r3}) \tag{2.27}$$

Where

F = differential weight.

x_{r1}, x_{r2} and x_{r3} = randomly chosen from the current population,

V_j= donor vector.

3. In the crossover, the operation is generated a trial vector to enhancing the diversity of the population by combining the components of the donor vector with the target vector. The components of the trial vector uj are obtained as

For each generation

$$u_{ij} = \begin{cases} V_{ij} & \text{for } r_i \leq C_r \text{ or } i = R \\ x_{ij} & \text{otherwise} \end{cases} \tag{2.28}$$

Where

ri = a uniformly distributed random number within the interval [0,1],

Cr= crossover probability controls the crossover by determining the average proportion f parameters the trial vector inherits from the donor vector,

R is a randomly chosen index, R= [1; 2;…; N] , which ensures that at least one element of the trail Vector differs from that of the target vector.

4. It is used the objective functions to evaluate the generation by comparing the new fitness value with previous fitness value and comparing these values .in case the new value lower than old value then replace the old generation with new one.

$$u_{ij} = \begin{cases} u_j & \text{if fittness}(u_j) \leq \text{fittness}(x_j) \\ x_j & \textit{otherwise} \end{cases} \tag{2.29}$$

Therefore, if the trial vector yields a fitness value lower or equal to that obtained with the target vector, it replaces the target vector in then next generation, otherwise, the target vector is retained in the population. The algorithm proceeds for a fixed number of generations or until some stopping criterion is reached.

2.4.4. Satin bowerbird optimization algorithm

In SBO algorithm, when the mating season began adult birds start to build bower using a different material such as flowers, fruits, branches, sparkling objects as well as dramatic gestures to attract females. The male birds build its own bower based on natural instinct and imitation of other males. The female will choose the most beautiful bower and dramatic gestures of males.

SBO algorithm is organized in the several stages as follows. [31]

1. Generating a set of random bower:

Initialization random vectors within the corresponding range which has N parameter equal to problem variables with considering they are uniform distribution between the lower and upper limit

$X_i = (x_{i1}, x_{i2}, . . ., x_{iN})$ where i=1,…….,N

2. Calculating the probability of each population member

Attractiveness and selection the bower from the female based on the probability. The selection the bower from male to build is also based on the probability assigned to it and computed as below

$$prob_i = \frac{fit_i}{\sum_{n=1}^{N} fit_n} \tag{2.30}$$

$$fit_i = \begin{cases} \frac{1}{1+f(x_i)} & f(x_i) \leq 0 \\ 1 + |f(x_i)| & f(x_i) < 0 \end{cases} \tag{2.31}$$

Where

fit_i is the fitness of i th solution is achieved by Eq. (1.31).

N is the number of bowers. In this equation,

$f(x_i)$ is the value of objective function in ith position or ith bower.

The objective function is a function that should be optimized. Eq. (1.31) has two parts.

The first part calculates the final fitness where values are greater than or equal to zero, while the second part calculates the fitness for values less than zero. This equation has two main characteristics:

a. For f (x_i) =0 both parts of this equation have fitness value of one.

b. Fitness is always a positive value.

3. Elitism

Based on the stain bird life, the experience of male bird is the most factors that influence on the build his bower and decorate it beside his natural instinct .so the older one will able to build a better bower.

Elitism is one of the important faces of evolutionary algorithms. Elitism keeps the best solution (solutions) to exist at every stage of the optimization process. The elite of iteration can be proposed as the best position which is the position of the best bower built by birds, has the highest fitness and can be able to influence the other position.

4. Determining new changes in any position

In each cycle of the algorithm, new changes at any bower are calculated according to Eq. (3).

$$X_{ik}^{new} = X_{ik}^{old} + \lambda_k \left[\left[\frac{X_{jk} + X_{elite.k}}{2}\right] - X_{ik}^{old}\right] \quad (2.32)$$

Where

X_{ik} is kth member of ith bower or solution vector.

X_{jk} is a target solution among all solutions in the current iteration

value j is calculated based on probabilities derived from positions by the roulette wheel procedure, which means that the solution having a larger probability to be selected as xj.

$X_{elite.}$ is the position of a bower which has highest fitness in the current iteration and is saved in each cycle of the algorithm

Parameter λk is the attraction power in the goal bower which is calculated the amount of step for each variable as below:

$$\lambda_k = \frac{a}{1+p_j} \quad (2.33)$$

Where

α is the greatest step size and

pj is the obtained probability values which they lied between 0 and 1 based on the goal bower.

5. Mutation

What happens in this environment is the possibility of the male being attacked by other animals or destroying his bower by another male to reuse these materials. In order to simulate it in each cycle of the algorithm by Appling random changes with a certain probability which is employed a normal distribution (N) with an average of X_{ik}^{old} and variance of σ2 as below.

$$X_{ik}^{new} \sim N(X_{ik}^{old}, \sigma^2) \tag{2.34}$$

$$N(X_{ik}^{old}, \sigma^2) = X_{ik}^{old} + (\sigma *, N(0,1)) \tag{2.35}$$

σ is a proportion of space width as below.

$$\sigma = z * (Var_{max} - Var_{min}) \tag{2.36}$$

var_{max} and var_{min} are upper bound and lower bound assigned to variables, respectively.

Z parameter is the percent of the difference between the upper and lower limit which is variable.

6. Combining old population and the population obtained from Changes After evaluation of the old population and the population obtained is combined these population and sorted then create a new population according to the previously defined number while the others are deleted.

7. The algorithm is repeated the step 2-6 for a fixed number of generations or until some stopping criterion is reached.

2.5. Objective Function

2.5.1. Objective function based on flexibility matrix

The fact that the **flexibility** increase with the existence of damage in a structure and it is easily extracted from a measurement of dynamic response .therefore, the change in flexibility matrix can be employed as an indicator to damage existence in the structure. The flexibility matrix is written as below [5-8]:

$$F = [\Phi][\Lambda]^{-1}[\Phi]^{T} = \sum_{i=1}^{N} \frac{1}{\omega_i^{2}} \varphi_i \quad \varphi_i^{T} \tag{2.37}$$

where

$[\Phi]$ = the mode shape matrix

$[F]$ = diag $[\Lambda]$ is a diagonal matrix

ω_i is the i.th circular frequency

φ_i is the mass-normalized ith mode shape of the structure

N is the number of measured modes.

2.5.1.1. The maximum element in the difference of the flexibility matrices

The difference of the experimental flexibility matrix with the numerical flexibility matrix corresponding to the damaged and healthy conditions of the structure [ ] can be written as :

$$DF = Fd - Fh \tag{2.38}$$

For each degree of freedom, using the maximum absolute value of the elements (δ_{ij}) in the difference matric |(DF) can be employed as the objective function as below:

$$\overline{\delta_j} = \max|\delta_{ij}| \tag{2.39}$$

$$F2 = \sum_{j=1}^{N} \overline{\delta_j} \tag{2.40}$$

Where

F1= the objective function

2.5.1.2. Static displacements computed by flexibility matrix

A common framework to imply static based procedure is Created a mathematical model which could simulate the behavior of considering structure. Then, measurements of the response of healthy structure such as (displacements, strains, etc.) are recorded as a result of applying the loads to it. After damage occurs, measurement of the response of damaged structure is recorded as a result of applying the loads on it t. Then, the change in response measurements between the healthy and damaged are matched and found the correlation between them.[43]

A unit static forces as static force is applied to the structure with N DOFs as

$$\text{Force} \quad = \{1.0 \quad 1.0 \quad \cdots \quad 1.0\}^T \tag{2.41}$$

Use this vector in the damaged structure to find the static displacement vector using only the first several modes as below.

$$u_d = G_d . \text{Force} \tag{2.42}$$

The simulation of structure is used a reduction in the stiffness element as

$$K_i{}^{a_i} = (1 - a_i)K_i \tag{2.43}$$

Where

Ki is the healthy stiffness matrix of the element in, and

αi is the damage severity, which can be a number between 0 and 1 for healthy and fully damaged cases, respectively.

The global stiffness matrix of the structure is described as below:

$$K(a_1, a_2, \dots, a_N) = \cup_{i=1}^{N} K_i{}^{a_i} \tag{2.44}$$

Where

N is the element number of the structure.

Using optimization problem as damage detection problem to finding the damage severity. The objectives function for damage detection based on data-fitting methodology. That's mean the algorithm searches for the best solution reaching ud under unit static force vector as below.

$u_d = G_d{}^a . \text{ Force}$ ………………………………………………………………… (1.45)

G_d is the damage flexibility matrix with unknown damage severities that is formed using the first modes data. a data-fitting strategy is used to find error vector between the calculated displacements of the measured model data and the displacements of unknown damage as below.

$$DE = u_a - u_d \tag{2.46}$$

The minimization objective function can be written as below:

$$F_3(a_1, a_2, \dots, a_N) = DE^T . DE \tag{2.47}$$

2.5.1.3. Flexibility matrix error residual

Using the modal flexibility error residual can achieve a good describe the damage in the structure, by comparison, the experimental model with the numerical model can be employed as the objective function as below:

$$DF(a) = [F]_E - [F(a)]_D \tag{2.48}$$

$$F1 = norm[DF(a)]\ {}_{Fro}^{\ 2} \tag{2.49}$$

Where

$|\cdot|_{fro}^2$ = the Frobenius norm of the residual matrix.

$[F]_E$= the experimental flexibility matrix.

$[F(a)]_D$ Is the numerical flexibility matrix with (a) is the stiffness reduction factor.

F1= the objective function (fro the Frobenius norm of (DF) matrix)..[ ]

CHAPTER 3

RESULTS

3.1. Results of Damage Identification Optimization Problems

In this thesis, different examples of various damage scenarios are modeled in Matlab code to be the experimental data. The noise effect is taken in simulated damaged structure. A program in MATLAB software is used to find the numerical model on all algorithms procedures. The examples are selected to be able to compare the result with the textbook result and to be sure the finite element and vibration properties are correct, in general, the procedure to find the damaged element can briefly demonstrate as:

The finite element Matlab code has information such as node coordinate ,element connectivity ,properties of truss element (modulus of elasticity, cross-sectional area ,the boundary condition)in case the structure is truss and added properties like (moment of inertia, polar moment of inertia, position ratio, etc.) in case the structure is beam or frame.

Then, The global consistent mass matrix and global stiffness matrix for each (healthy state and damage state of the structure) are obtained.

The constraint DOFs is removed from the matrices and applied the design equation to find the eigenvalues (square natural frequency) and eigenvectors (natural mode shapes).Then the flexibility matrices are obtained.to simulate the experimental data in real life, noise applies to the frequencies of the structure to examine the algorithms behavior and the objective function efficiency to converge to the solution using the noise ratio 0%, 5% and 10% as real-life simulation. The noisy frequencies will be randomly choosing and its value is same for all algorithms to examine its affected on objective functions. The algorithms have parameters can influence the algorithm behavior and make the algorithm performance best. The parameters for each algorithm are illustrated in table 3.1 below:

Table 3.1. The parameters of algorithms

Algorithm	The parameters
CS	Number of initial population =20 The probability to discover the eggs by host birds =0. 25 Lower bound =0 Upper bound =1 Maximum iteration =90
DE	Number of initial population =20 Crossover Probability=0.2 Lower bound =0 Upper bound =1 Maximum iteration =90
SPO	C1=2, C2=2, W=0.8. Initial population =20. Lower bound =0 Upper bound =1 Maximum iteration =90
SBO	Parameter values of á = 2. Parameter values of z= 0.2. The mutation probability is 0.5. A number of initial population =20. Lower bound =0 Upper bound =1 Maximum iteration =90

The damage cases in the examples are tested using the four candidate algorithms and three objective functions based on flexibility matrix.To compare the efficiency of all algorithms and objective functions is used equally Maximum iteration for all algorithms as in table (3.1) and used three lower mode shapes as follows:

Example 1:

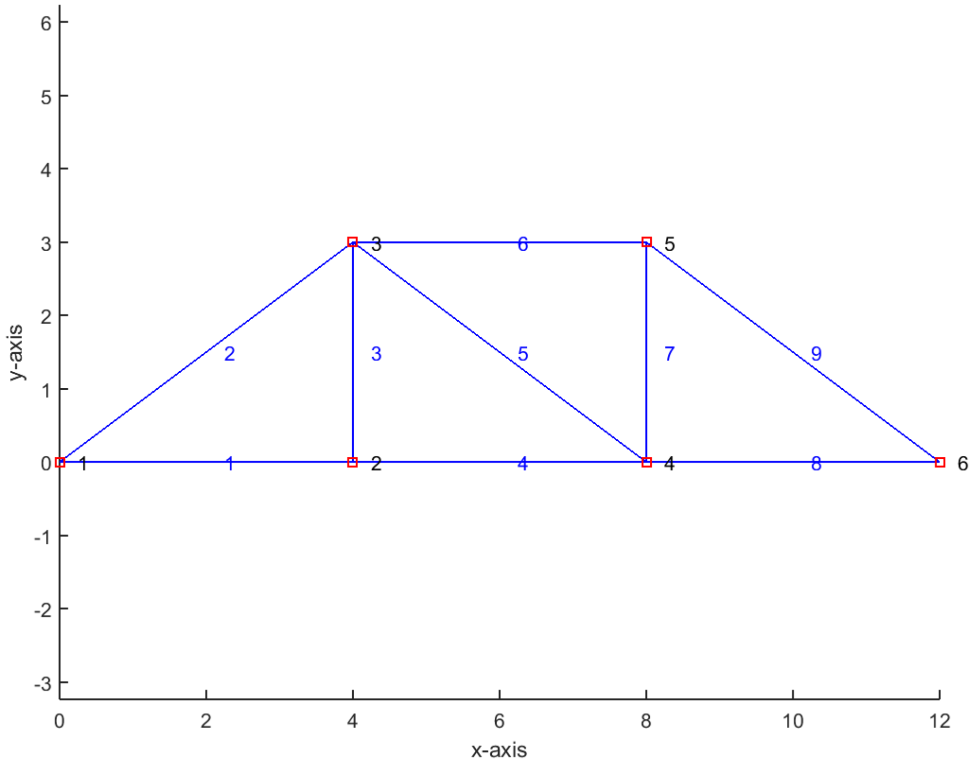

Figure 3.1. Structure for example 1

Table 3.2. Structural properties of example 1

Structure property	property value
Structure type	2D truss
Node number	6
Element number	9
Mass type	consistent
Modulus of elasticity	$200\text{x}10^9$ pa
Mass density	7860 kg/m3
Cross-section area	0.0025 m2
Boundary condition (Constraint)	Joint 1 → pin Joint 6 → roller

Table 3.3. Damage scenarios

Damage Scenario	elements	Damage %
1	element 6	0.1
2	element 6 , 4	0.2 ,0.6 respectively

A. Damage scenario 1

Table 3.4 shows the frequencies values of healthy structure, the frequencies are given by the textbook and the frequencies for damage scenario 1 of the structure, respectively. The corresponding mode shapes are shown in figure 3.2.and figure 3.3.

Table 3.4. The first 3 frequencies for example 1- Damage scenario 1

order	Healthy structure frequencies values by FE	Healthy structure frequencies values by [44]	Damage structure frequencies values by FE
1	240.87 rad/s	240.9 rad/s	239.93 rad/s
2	467.94 rad/s	467.9 rad/s	463.66 rad/s
3	739.85 rad/s	739.8 rad/s	739.45 rad/s

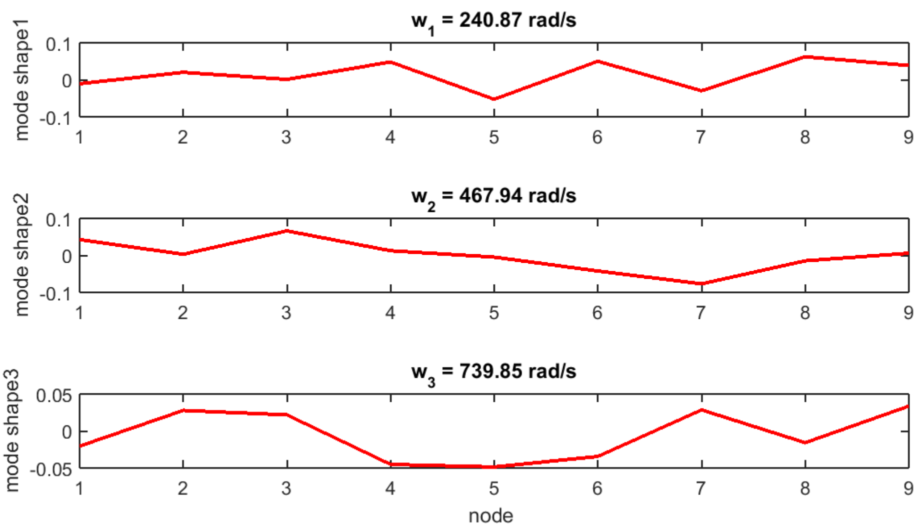

Figure 3.2. Mode shape of healthy structure of example 1

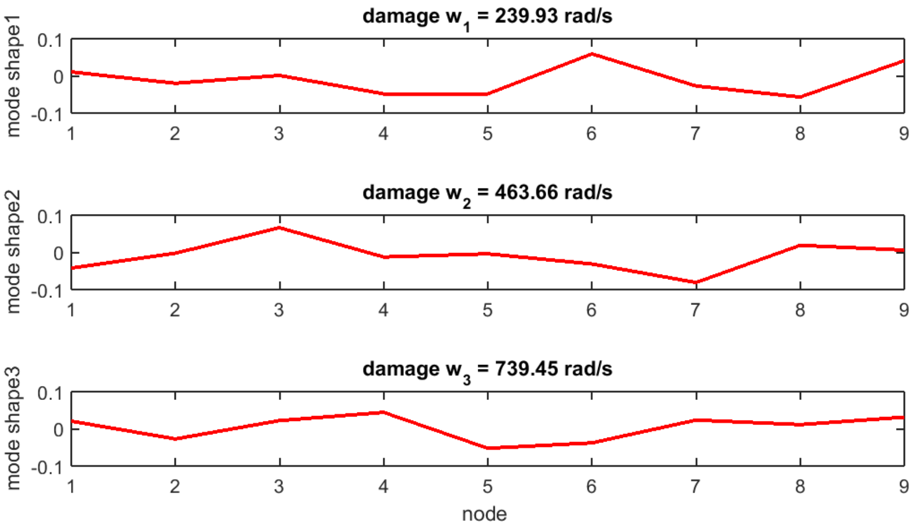

Figure 3.3. Mode shape of damage structure of example 1-scenario 1

A.1 objective function (F1)

A.1.1 with noise ratio =0

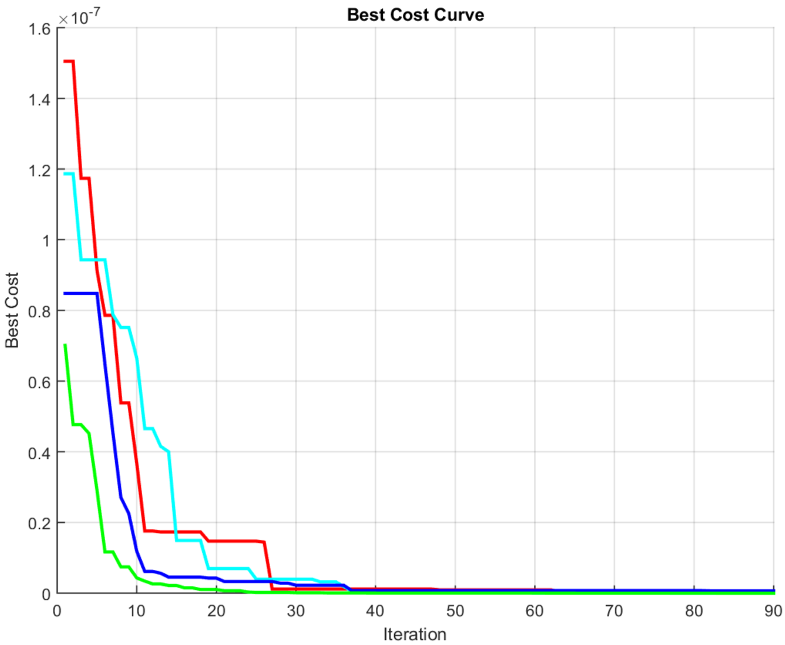

Figure 3.4. Best cost of algorithms of example1- damage scenario 1 using objective function 1 noise=0

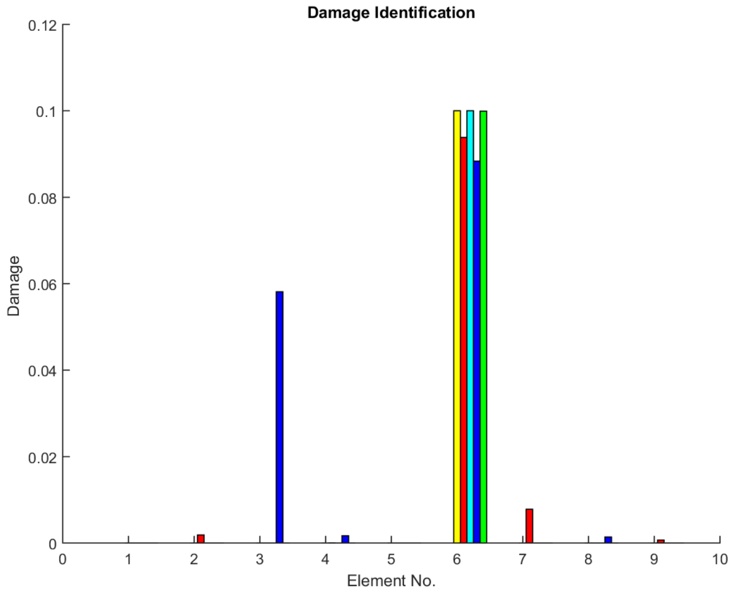

Figure 3.5. Damage detection of example 1 - scenario 1 using objective function 1 noise=0

CS DE PSO SBO

A.1.2 with noise ratio =0.05

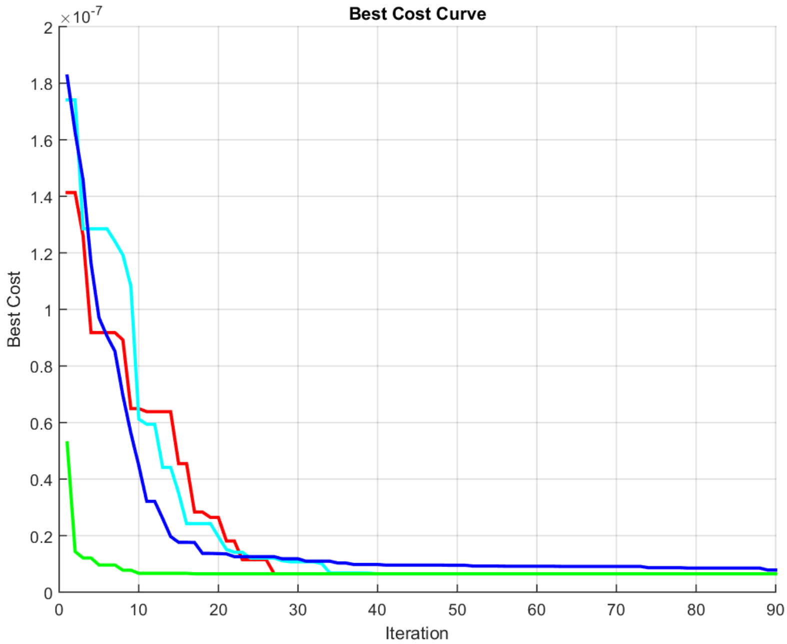

Figure 3.6. Best cost of algorithms of example1- scenario 1 using objective function 1 noise=0.05

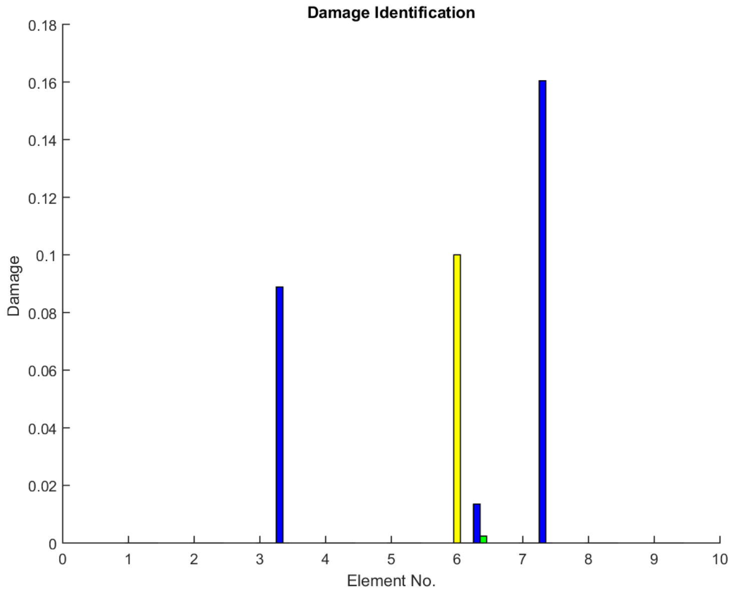

Figure 3.7. Damage detection of example 1 - scenario 1 using objective function 1 noise=0.05

CS DE PSO SBO

A.1.3 with noise ratio =0.1

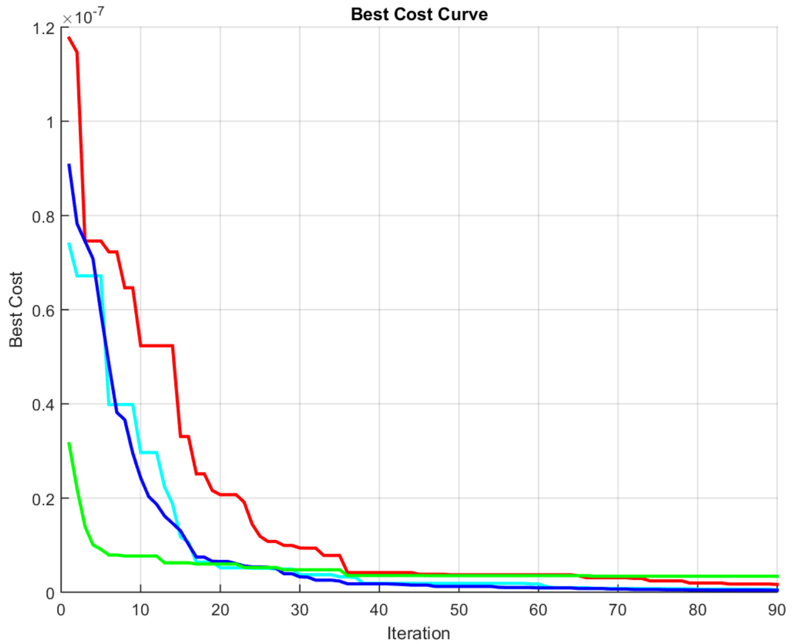

Figure 3.8. Best cost of algorithms of example1- scenario 1 using objective function 1 noise=0.1

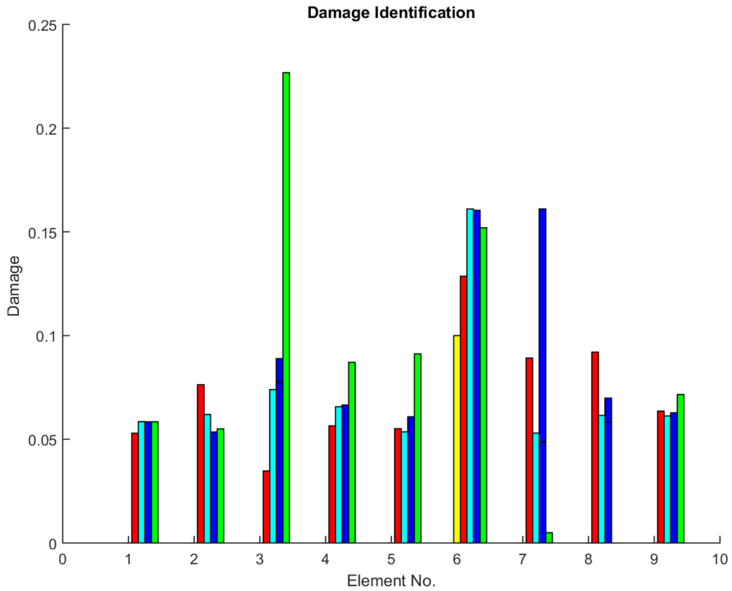

Figure 3.9. Damage detection of example 1 - scenario 1 using objective function 1 noise=0.1

CS DE PSO SBO

Observation1: using SBO, DE, CS algorithm to solve the objective function F1 in example 1 damage scenario 1 gives a clear indication of the position of the damaged element in the truss as shown in figure 3.5. when applying noise it showed the bad performance of the objective function to guide the algorithms to define the position and has an error in determine the severity of damage as shown in figure 3.7 and figure 3.9.

A.2. objective function (F2)

A.2.1 with noise ratio =0.0

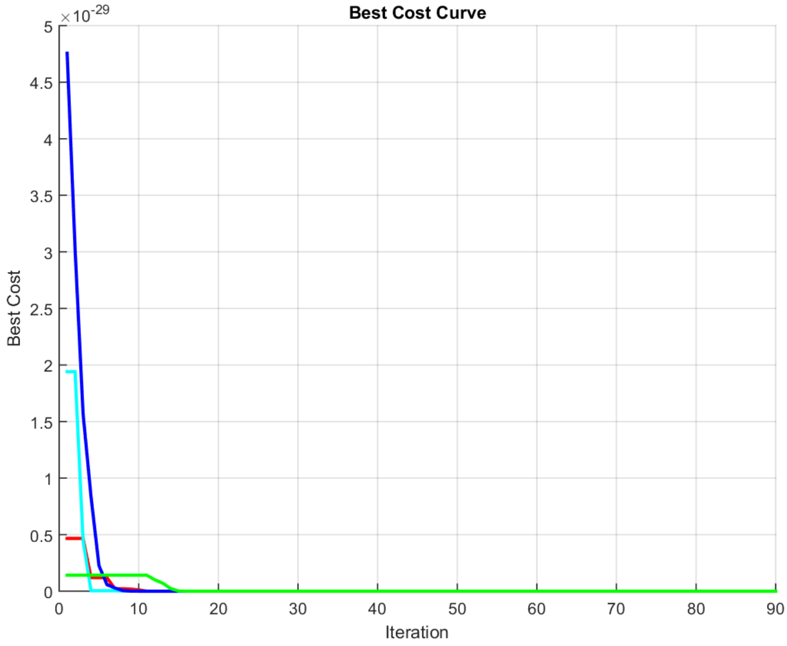

Figure 3.10. Best cost of algorithms of example1- scenario 1 using objective function 2 noise=0

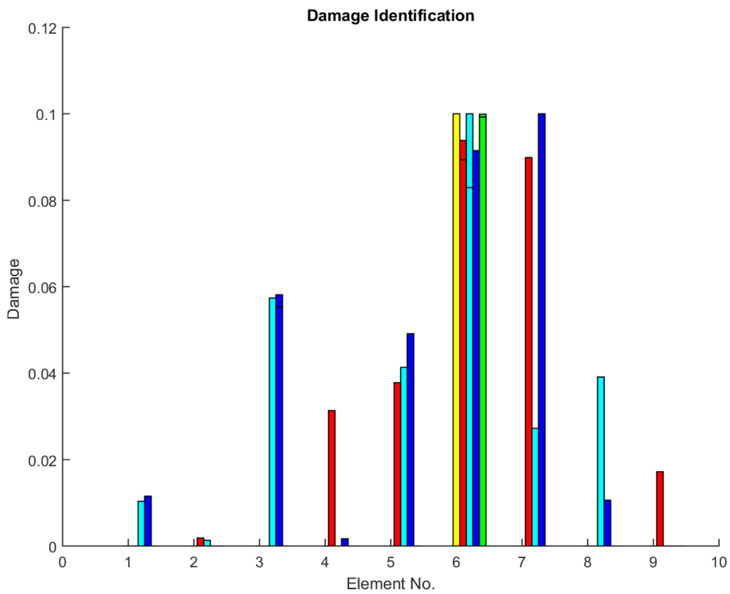

Figure 3.11. Damage detection of example 1 - scenario 1 using objective function 2 noise=0)

CS DE PSO SBO

A.2.2 with noise ratio =0.05

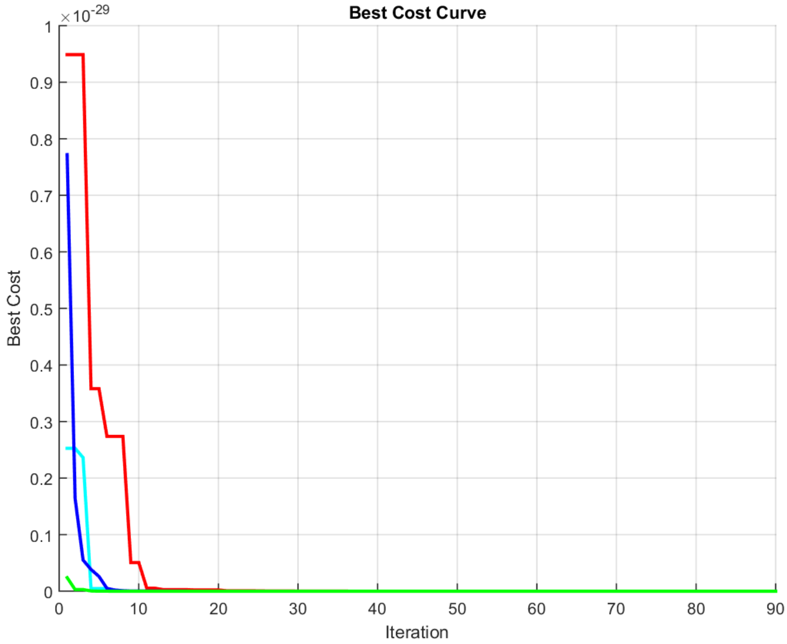

Figure 3.12. Best cost of algorithms of example1- scenario 1 using objective function 2 noise=0.05

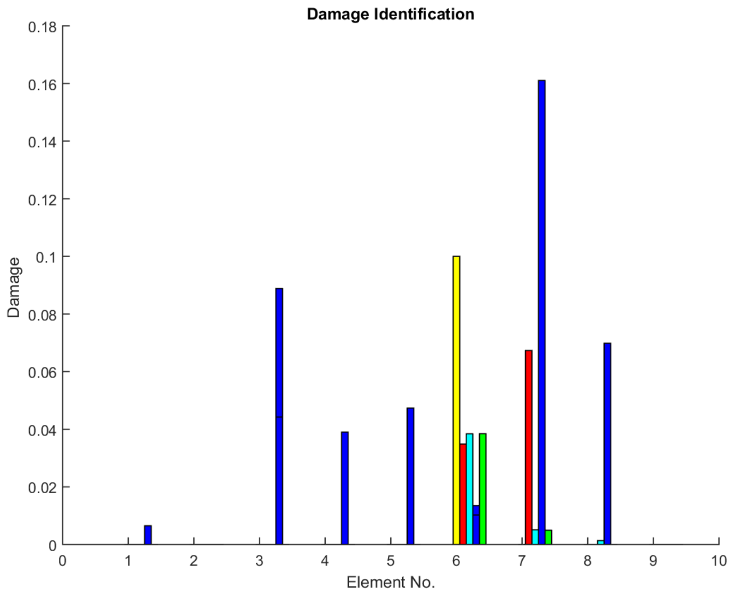

Figure 3.13. Damage detection of example 1 - scenario 1 using objective function 2 noise=0.05)

CS DE PSO SBO

A.2.2 with noise ratio =0.1

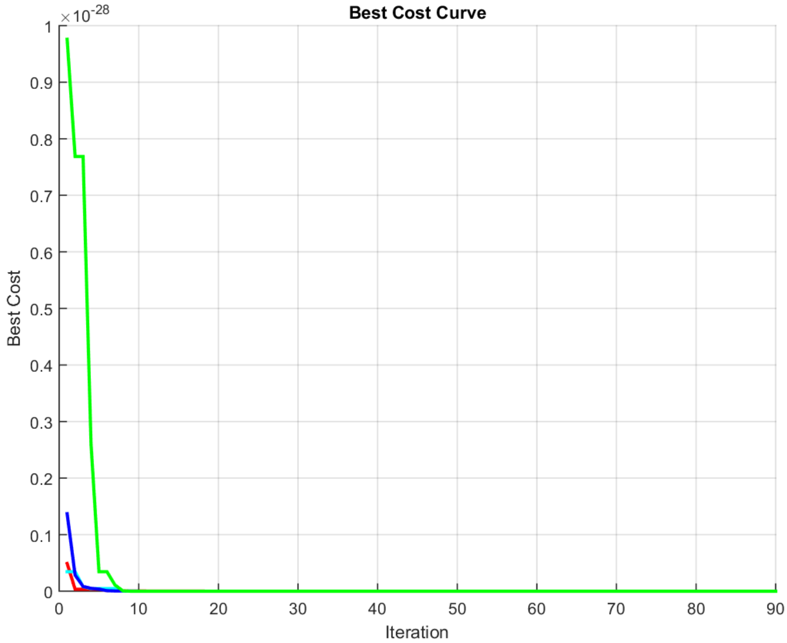

Figure 3.14. Best cost of algorithms of example1- scenario 1 using objective function 2 noise=0.1

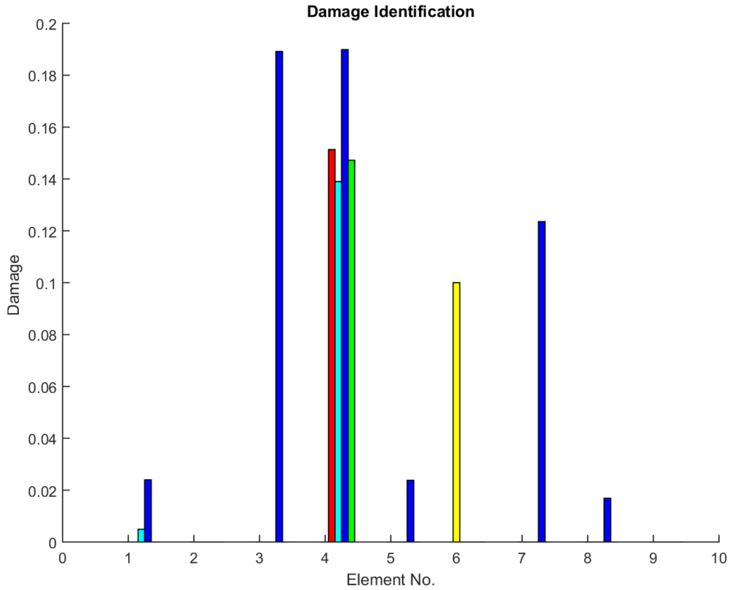

Figure 3.15. Damage detection of example 1 - scenario 1 using objective function 2 noise=0.1

CS DE PSO SBO

Observation2: using SBO algorithm to solve the objective function F2 in example 1 damage scenario 1 gives a clear indication of the position of the damaged element in the truss and guide the algorithm to define the position and determine the severity of damage but the other algorithms need more iteration as shown in figure 3.11. but when applying the noise, it gives an acceptable performance with 0.05 noise and misleading the position and severity of damage with noise 0.1 as shown in figure 3.13 and as shown in figure 3.15.

A.3. objective function (F3)

A.3.1 with noise ratio =0.0

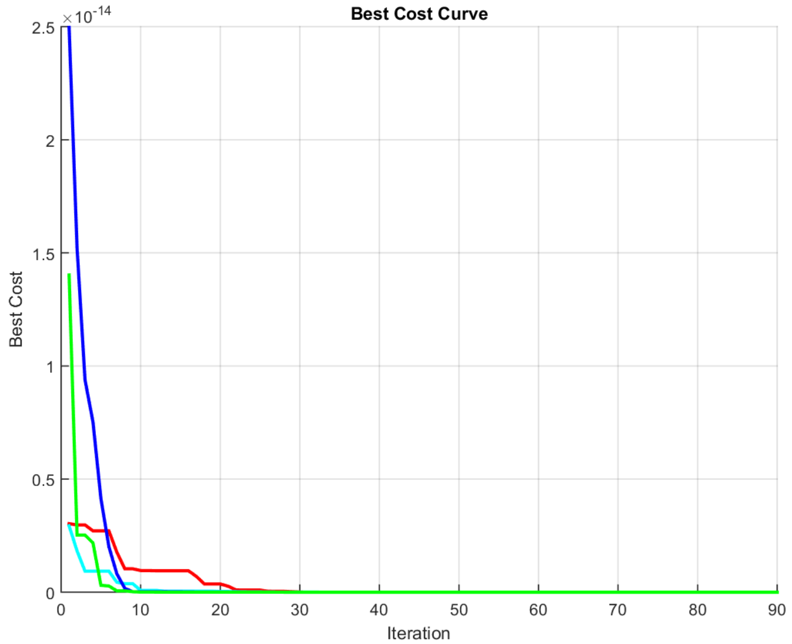

Figure 3.16. Best cost of algorithms of example1- scenario 1 using objective function 3 noise=0

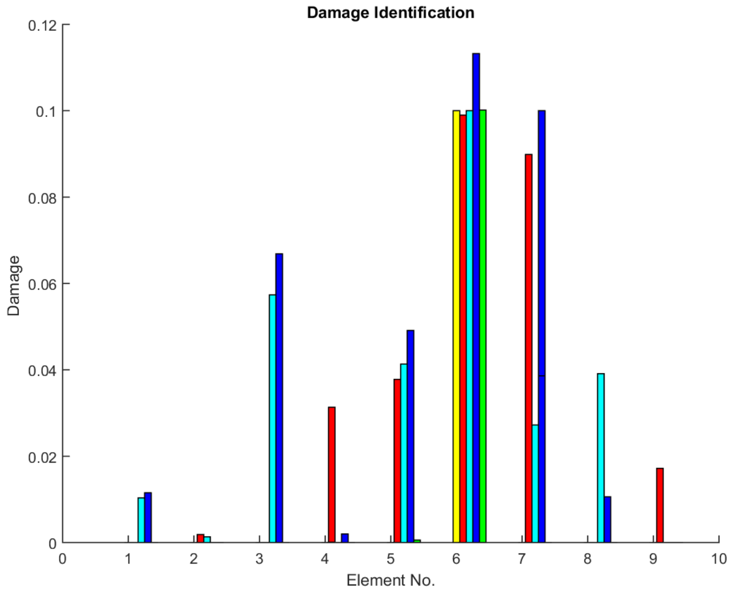

Figure 3.17. Damage detection of example 1 - scenario 1 using objective function 3 noise=0

CS DE PSO SBO

A.3.2 with noise ratio =0.05

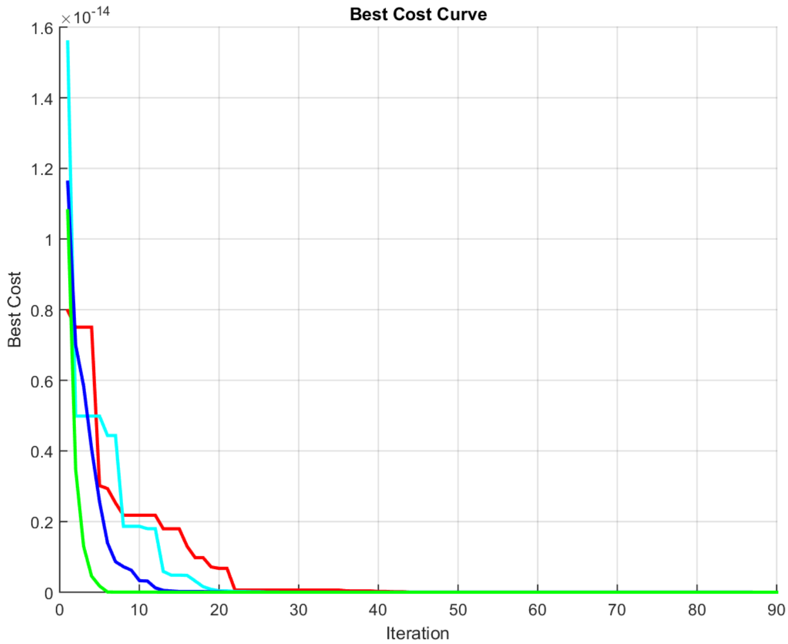

Figure 3.18. Best cost of algorithms of example1- scenario 1 using objective function 3 noise=0.05

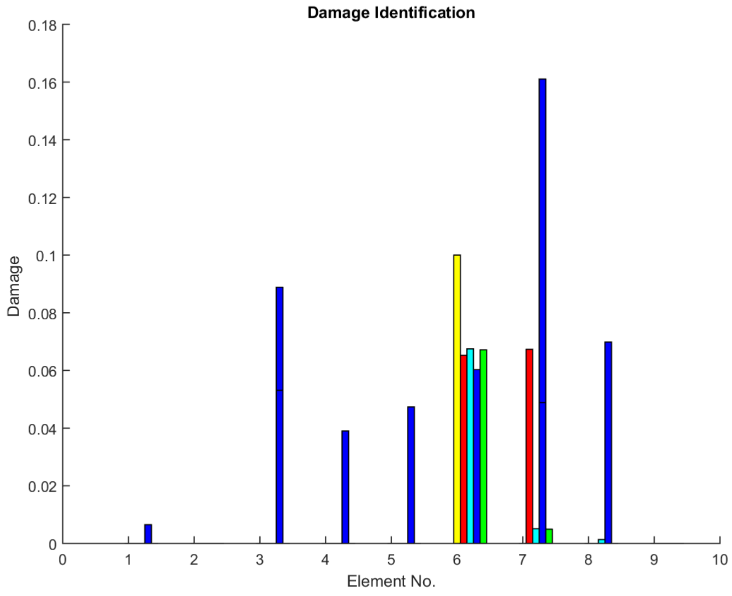

Figure 3.19. Damage detection of example 1 - scenario 1 using objective function 3 noise=0.05

CS DE PSO SBO

A.3.4 with noise ratio =0.1

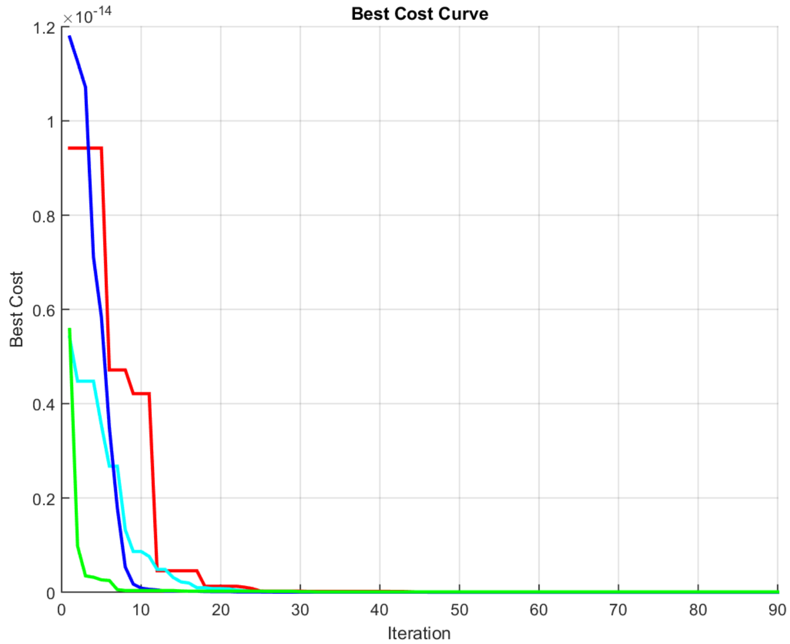

Figure 3.20. Best cost of algorithms of example1- scenario 1 using objective function 3 noise=0.1

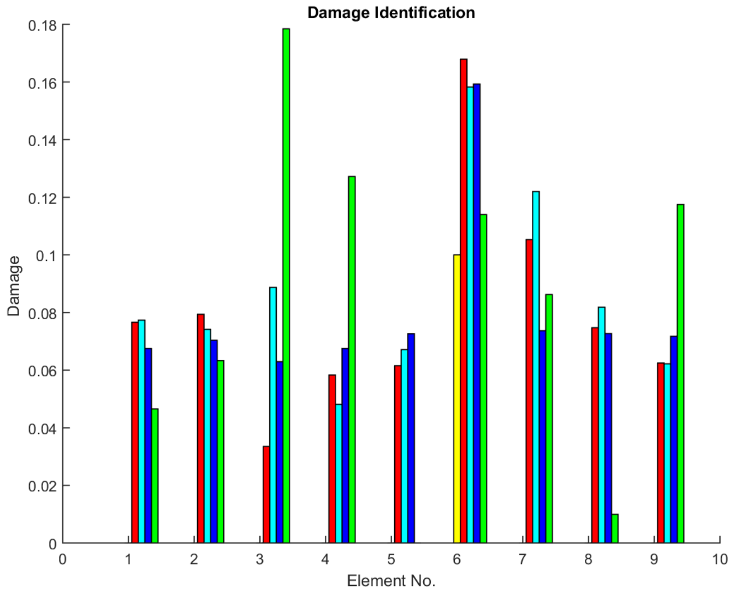

Figure 3.21. Damage detection of example 1 - scenario 1 using objective function 3 noise=0.1

CS DE PSO SBO

Observation3:: using SBO algorithm to solve the objective function F3 in example 1 damage scenario 1 gives a clear indication of the position of the damaged element in the truss and guide the algorithm to define the position and determine the severity of damage but the other algorithms need more iteration as shown in figure 3.17 but when applying the noise, it gives an acceptable performance with 0.05 noise and misleading the position and severity of damage with noise 0.1 as shown in figure 3.19 and figure 3.21.

B. Damage scenario 2

Table 3.5 shows the frequencies values of damage scenario of the structure and the corresponding mode shapes are shown in figure 3.1.2 .1.

Table 3.5. the first 3 frequencies for Damage scenario 1

Order	Healthy structure frequencies values by FE	Healthy structure frequencies values by [38]	Damage structure frequencies values by FE
1	240.87 rad/s	240.9 rad/s	205.99 rad/s
2	467.94 rad/s	467.9 rad/s	424.96 rad/s
3	739.85 rad/s	739.8 rad/s	738.98 rad/s

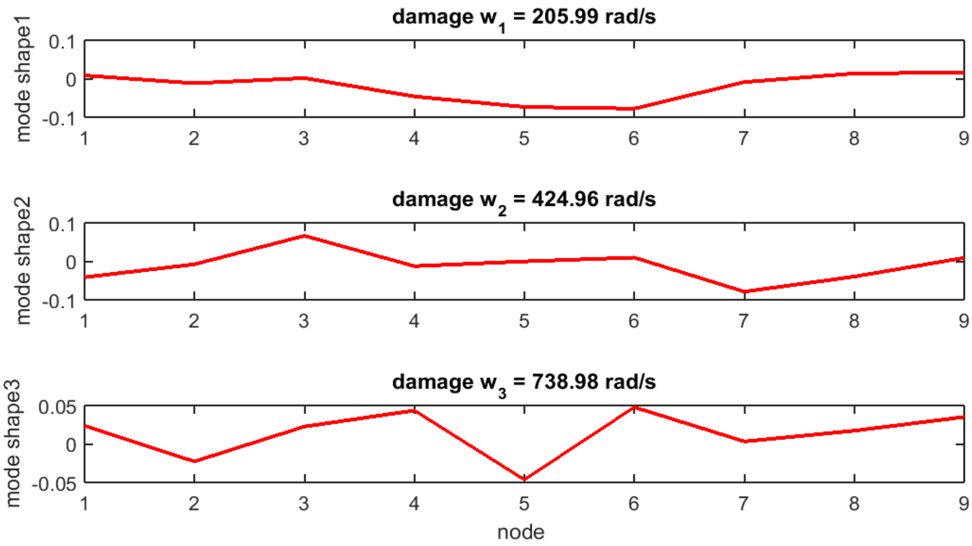

Figure 3.22. Mode shape of damage structure of example 1 damage scenario 2

B.1 objective function (F1)

B.1.1 with noise ratio =0.0

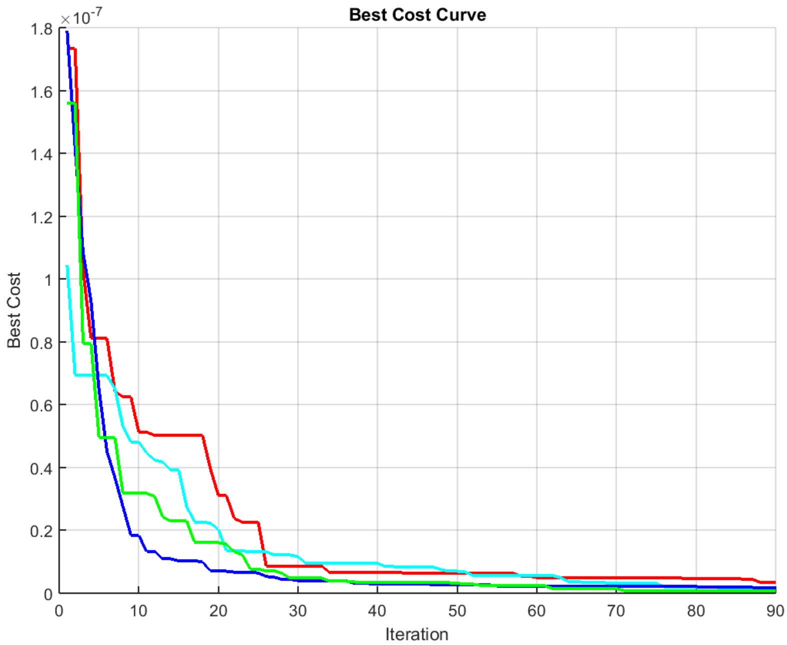

Figure 3.23. Best cost of algorithms of example1- scenario 2 using objective function 1 noise=0

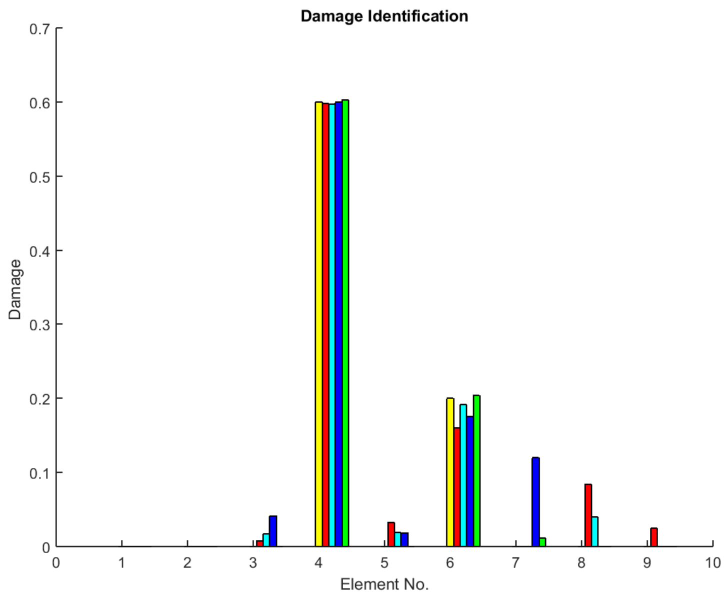

Figure 3.24. Damage detection of example 1 - scenario 2 using objective function 1 noise=0

B.1.1 with noise ratio =0.05

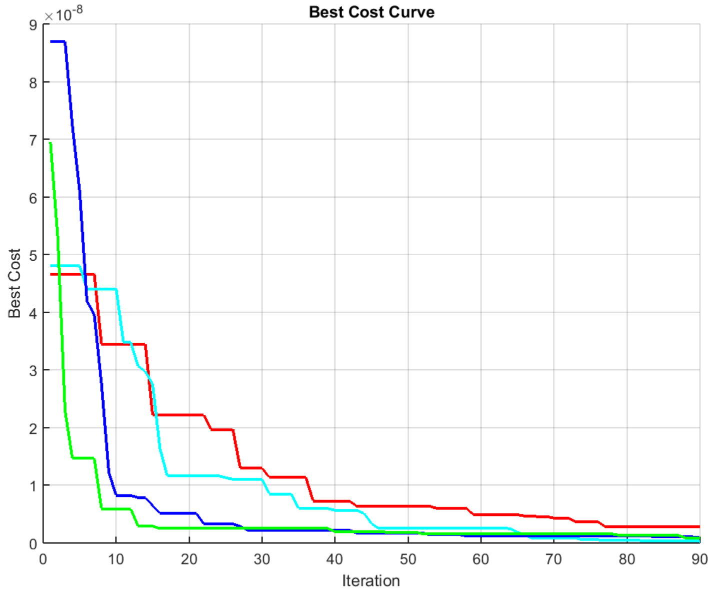

Figure 3.25. Best cost of algorithms of example1- scenario 2 using objective function 1 noise=0.05

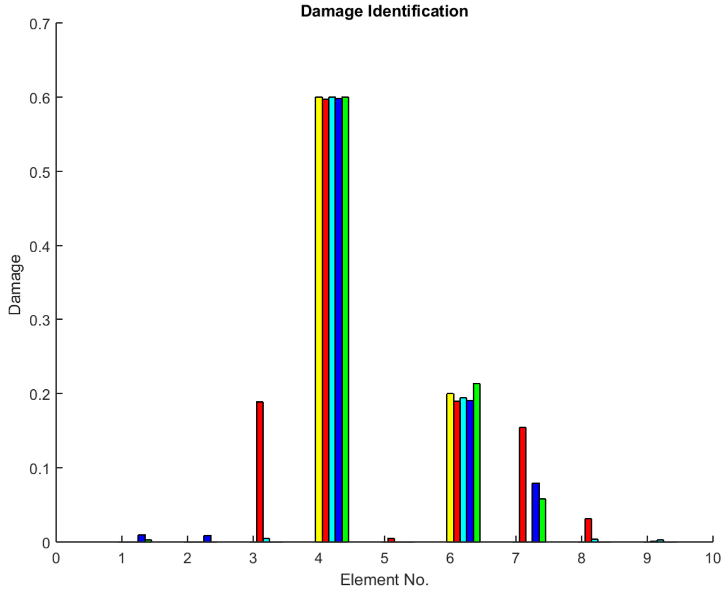

Figure 3.26. Damage detection of example 1 - scenario 2 using objective function 1 noise=0.05

CS DE PSO SBO

B.1.1 with noise ratio =0.1

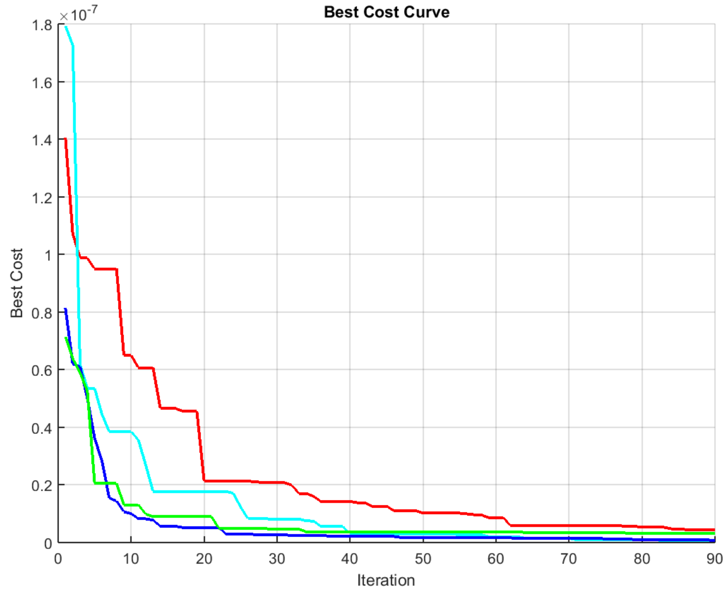

Figure 3.27. Best cost of algorithms of example1- scenario 2 using objective function 1 noise=0.1

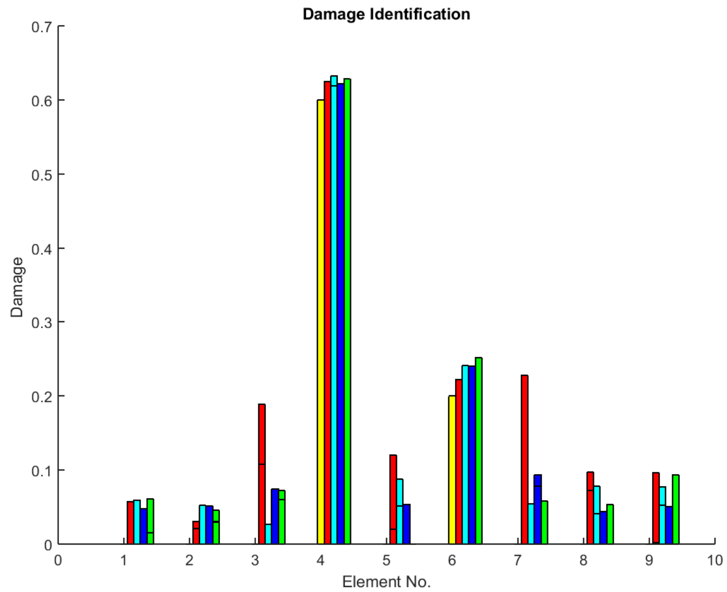

Figure 3.28. Damage detection of example 1 - scenario 2 using objective function 1 noise=0.1

CS DE PSO SBO

Observation4: using SBO, DE algorithm to solve the objective function F1 in example 1 damage scenario 2 gives a clear indication of the position of the damaged element in the truss as shown in figure 3.24. when applying noise it shows it has a good performance of the objective function to guide the algorithms to define the position and has some error in determining the severity of damage as shown in figure 3.26 and figure 3.28.

B.2. objective function (F2)

B.2.1. with noise ratio =0

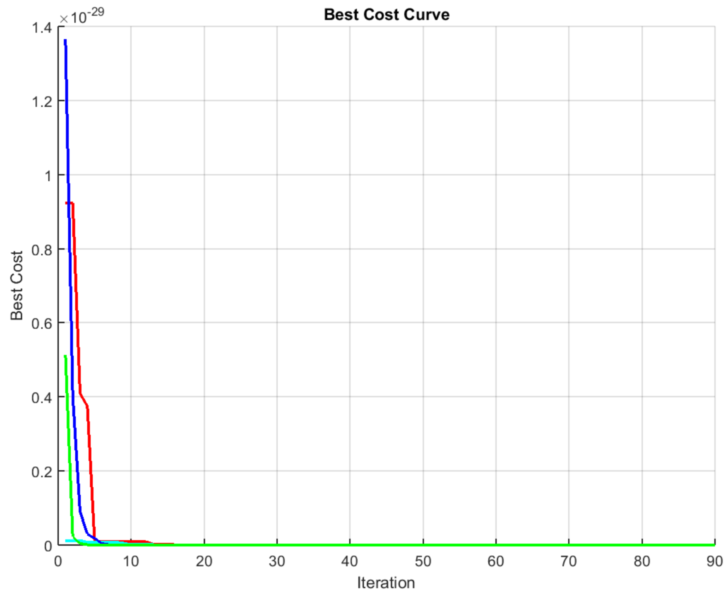

Figure 3.29. Best cost of algorithms of example1- scenario 2 using objective function 2 noise=0

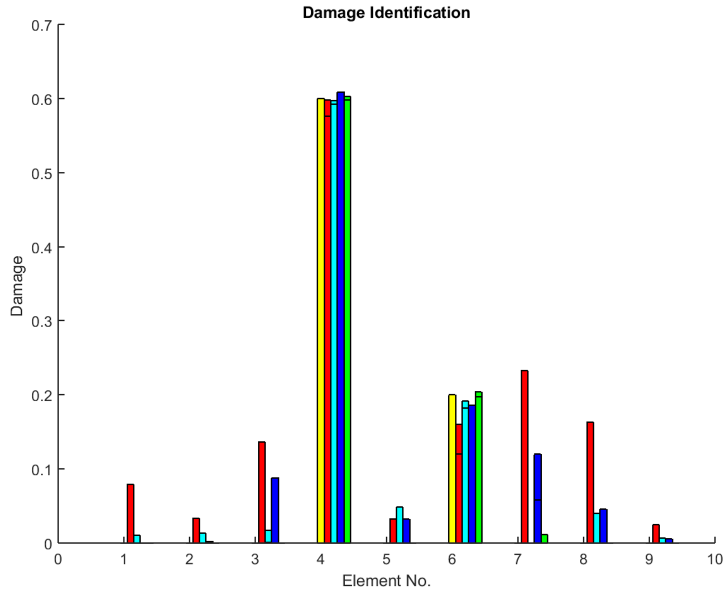

Figure 3.30. Damage detection of example 1 - scenario 2 using objective function 2 noise=0

CS DE PSO SBO

B.2.2. with noise ratio =0.05

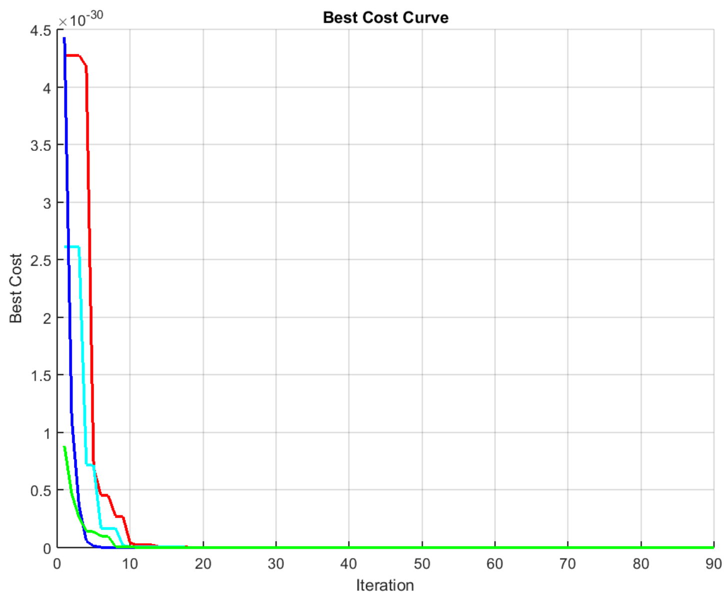

Figure 3.31. Best cost of algorithms of example1- scenario 2 using objective function 2 noise=0.05

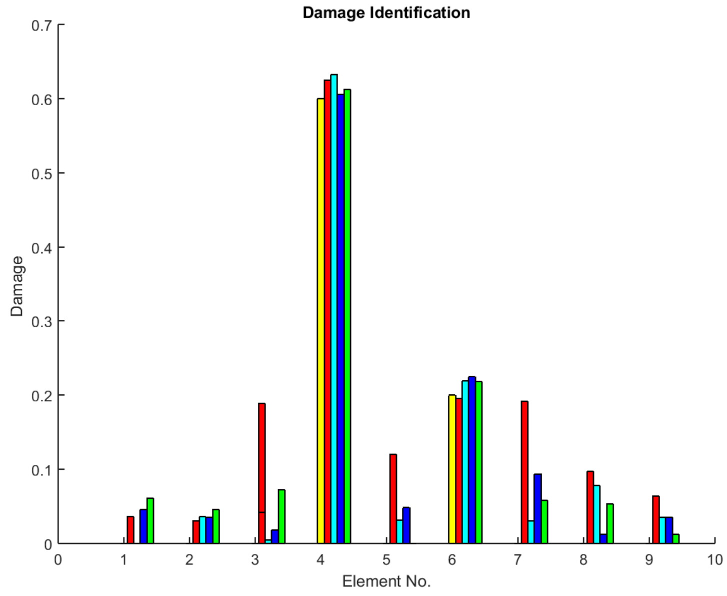

Figure 3.32. Damage detection of example 1 - scenario 2 using objective function 2 noise=0.05

CS DE PSO SBO

B.2.3. with noise ratio =0.1

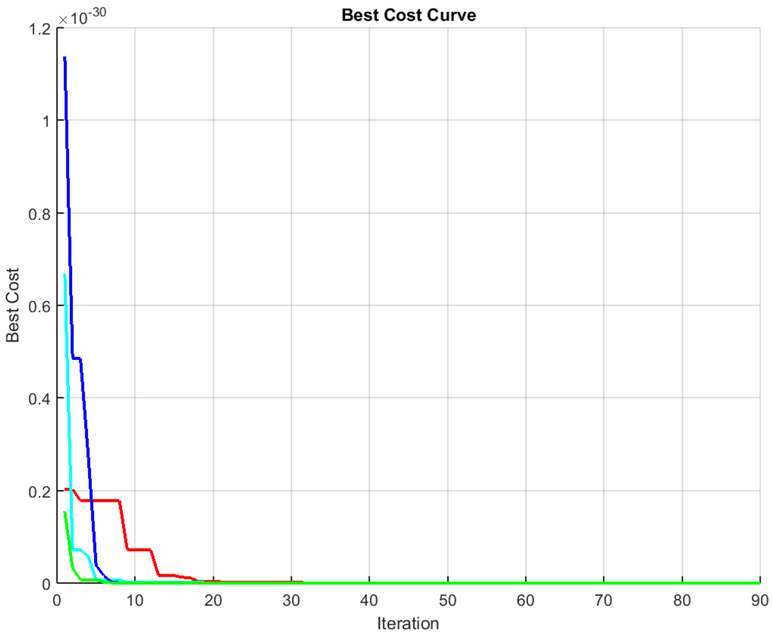

Figure 3.33. Best cost of algorithms of example1- scenario 2 using objective function 2 noise=0.1

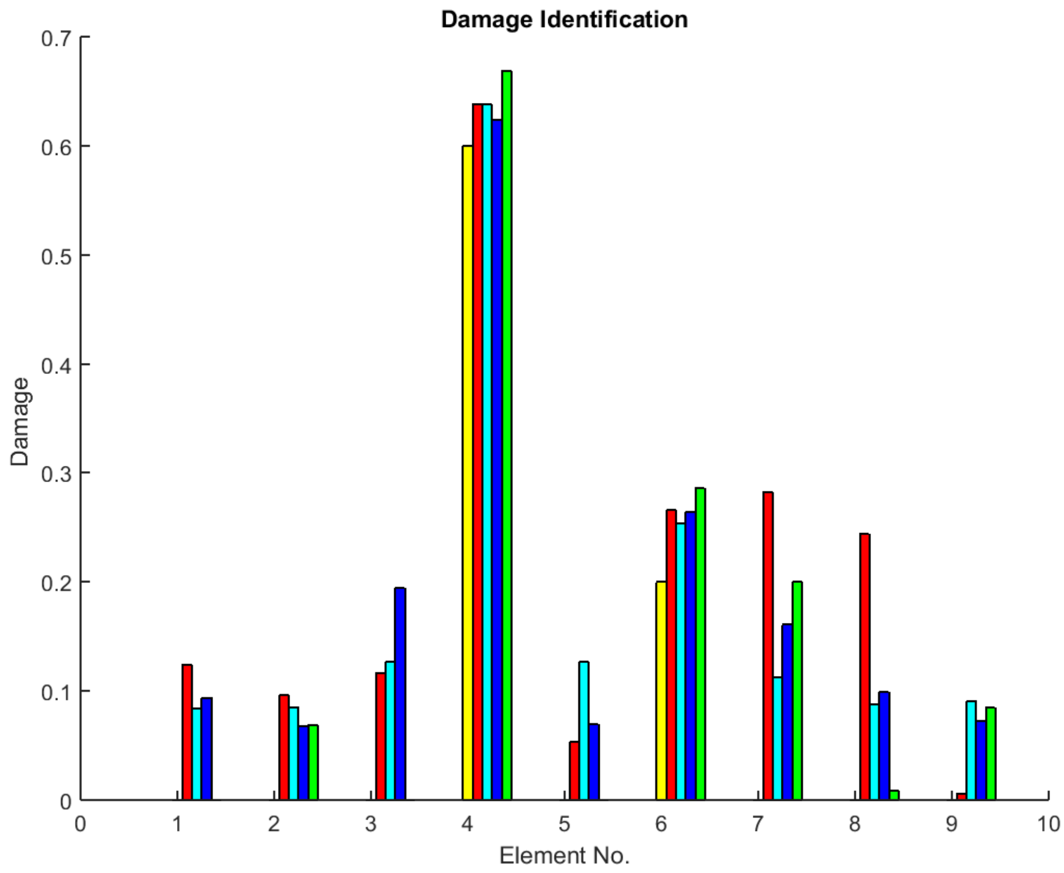

Figure 3.34. Damage detection of example 1 - scenario 2 using objective function 2 noise=0.1

CS DE PSO SBO

Observation5: using SBO, DE algorithm to solve the objective function F2 in example 1 damage scenario 2 gives a clear indication of the position of the damaged element in the truss and guide the algorithm to define the position and determine the severity of damage but the other algorithms need more iteration as shown in figure 3.31. but when applying the noise, it gives an acceptable performance to detect the position and severity of damage as shown in figure 3.33 and as shown in figure 3.35.

B.3. objective function (F3)

B.3.1. with noise ratio =0

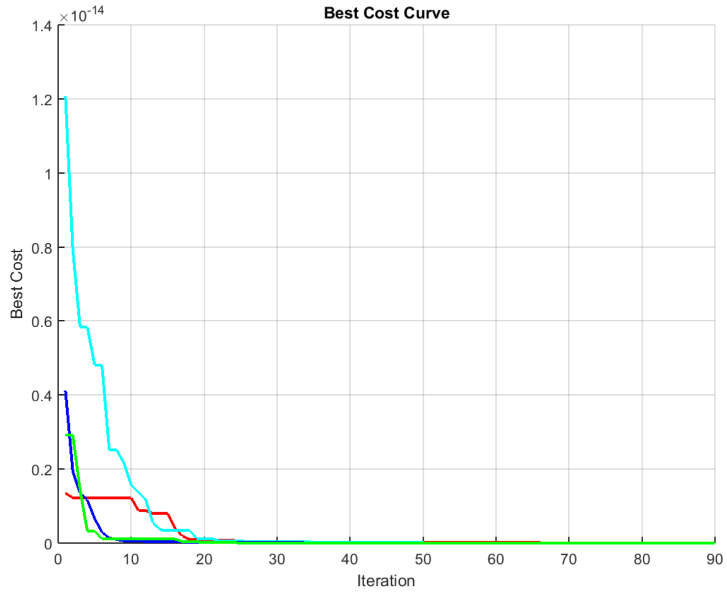

Figure 3.35. Best cost of algorithms of example1-damage scenario 2 using objective function 3 noise=0.0

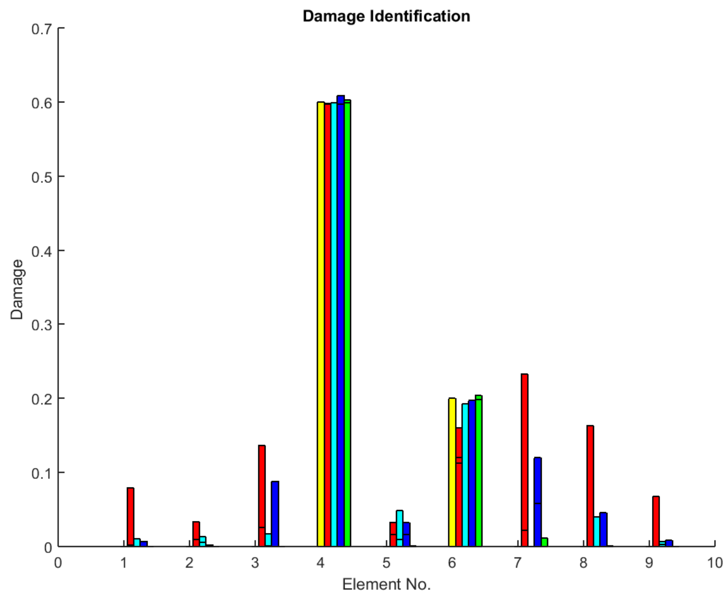

Figure 3.36. Damage detection of example 1 - damage scenario 2 using objective function 3 noise=0.0

CS DE PSO SBO

B.3.2. with noise ratio =0.05

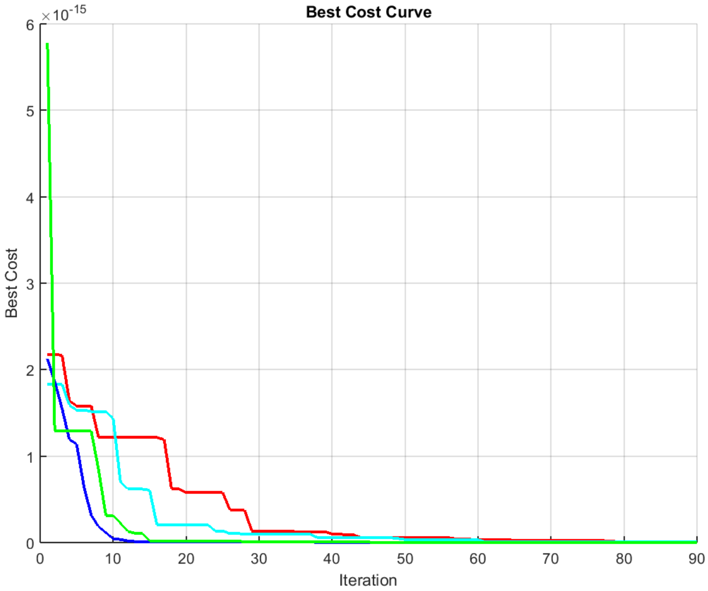

Figure 3.37. Best cost of algorithms of example1- damage scenario 2 using objective function 3 noise=0.05

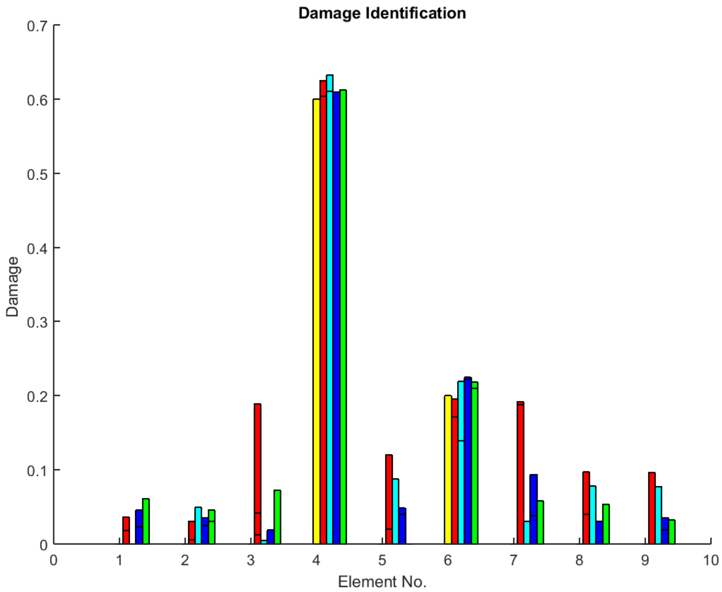

Figure 3.38. Damage detection of example 1 - damage scenario 2 using objective function 3 noise=0.05

CS DE PSO SBO

B.3.3. with noise ratio =0.1

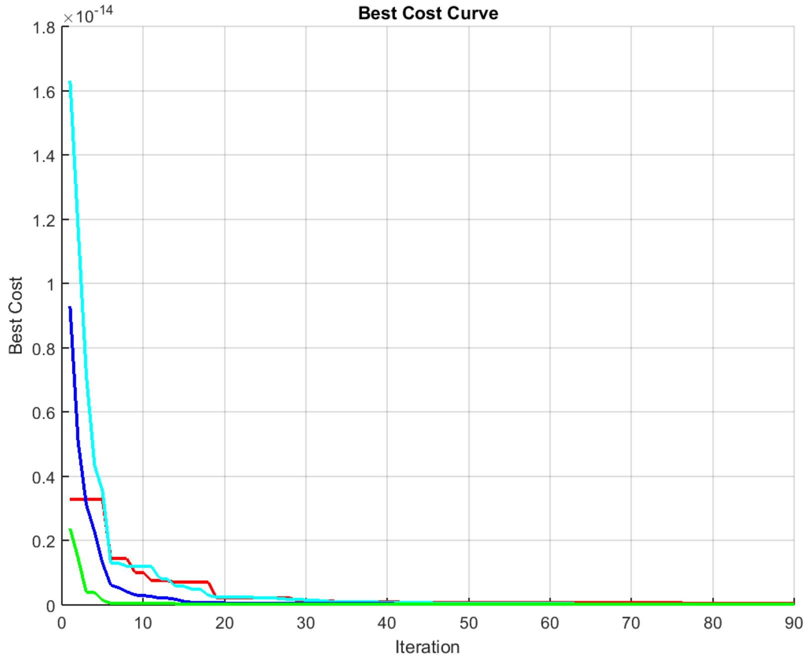

Figure 3.39. Damage detection of example 1 - damage scenario 2 using objective function 3 noise=0.1

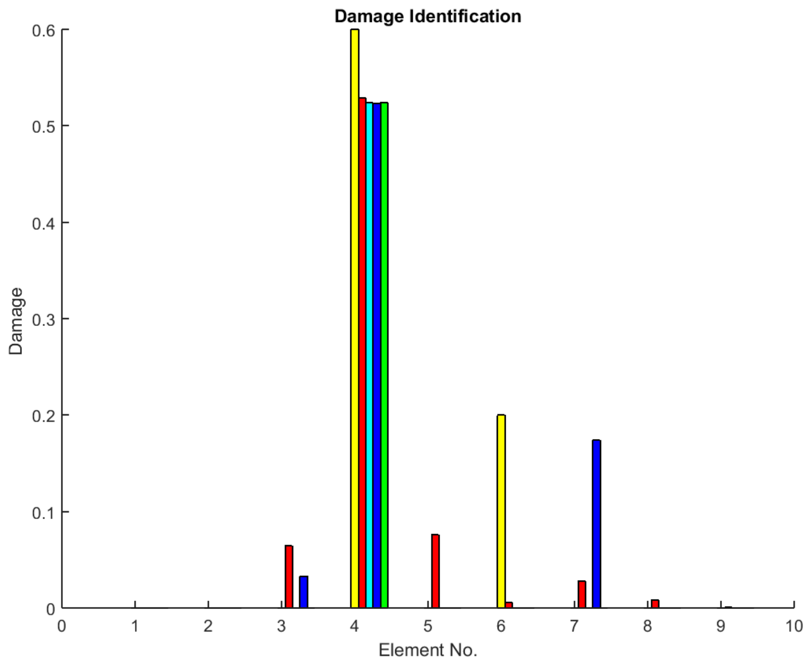

Figure 3.40. Damage detection of example 1 - damage scenario 2 using objective function 3 noise=0.1

CS DE PSO SBO

Observation6: using SBO, DE algorithm to solve the objective function F3 in example 1 damage scenario 2 gives a clear indication of the position of the damaged element in the truss and guide the algorithm to define the position and determine the severity of damage but the other algorithms need more iteration as shown in figure 3.37. but when applying the noise, it gives an acceptable performance with 0.05 noise as shown in figure 3.39 and misleading the position and severity of damage with noise 0.1 and figure 3.41

Example 2:

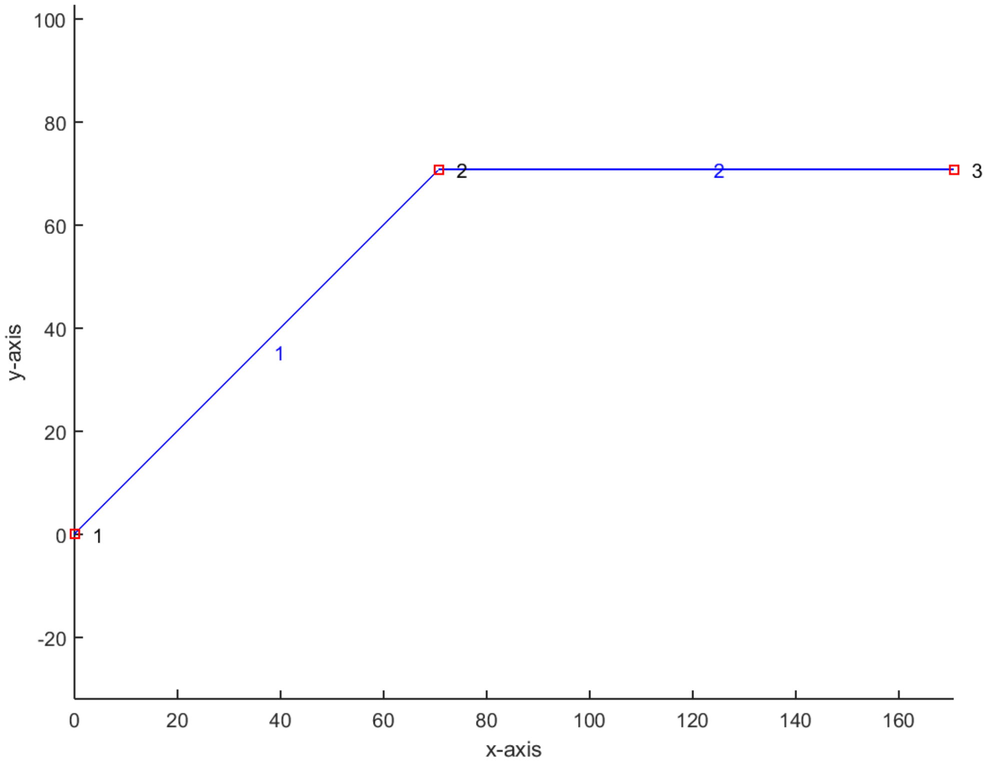

Figure 3.41. Structure of example 2

Table 3.6. The parameters of algorithms

Algorithm	The parameters
CS	Number of initial population =20 The probability to discover the eggs by host birds =0. 25 Lower bound =0 Upper bound =1 Maximum iteration =20
DE	Number of initial population =20 Crossover Probability=0.2 Lower bound =0 Upper bound =1 Maximum iteration =20
SPO	C1=2, C2=2, W=0.8. Initial population =20. Lower bound =0 Upper bound =1 Maximum iteration =20
SBO	Parameter values of á = 2. Parameter values of z= 0.2. The mutation probability is 0.5. A number of initial population =20. Lower bound =0 Upper bound =1 Maximum iteration =20

Table 3.7. Structural properties of example 2

Structure property	property value
Structure type	2D frame
Node number	3
Element number	2
Mass type	consistent
Modulus of elasticity	$1x10^7$ lb/in^2
Moment of inertia	100 in^4
Mass density	0.7 lb/in^3
Cross-section area	6 in2
Boundary condition (Constraint)	Joint 1 → fix Joint 3 → fix

Table 3.8. Damage scenario of example 2

Damage scenario	elements	Damage %
1	element 1	0.7
2	element 1 , 2	0.4 ,0.6 respectively

A. Damage scenario 1

Table 3.7.shows the frequencies values of healthy structure, the frequencies are given by the textbook and the frequencies for damage scenario of the structure, respectively. The corresponding mode shapes are shown in figure 3.43 .and figure 3.44.

Table 3.9. The first 3 frequencies for Damage scenario 1

Order	Healthy structure frequencies values by FE	Healthy structure frequencies values by [38]	Damage structure frequencies values by FE
1	25.269 rad/s	25.26 rad/s	16.867 rad/s
2	31.251 rad/s	31.24 rad/s	25.245 rad/s
3	64.897 rad/s	64.90 rad/s	53.531 rad/s

In this example using the first mode shape and frequency in calculation

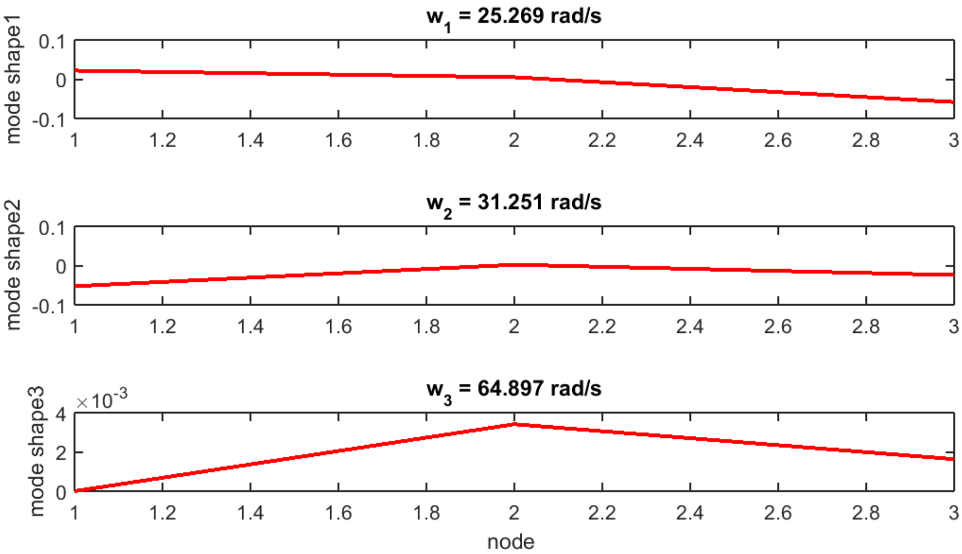

Figure 3.42. Mode shape of healthy structure of example 2 damage scenario 1

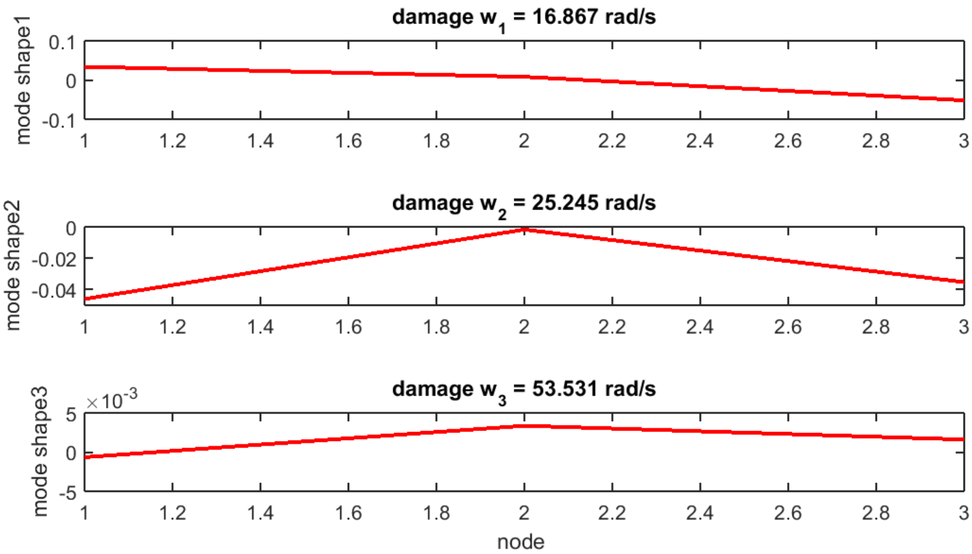

Figure 3.43. Mode shape of damage structure of example 2 damage scenario 1

A.1 objective function (F1)

A.1.1 with noise ratio =0

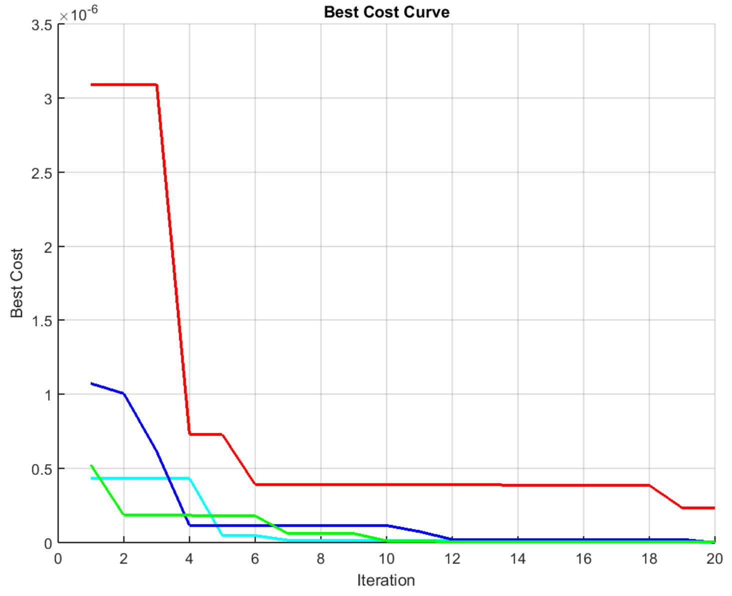

Figure 3.44. Best cost of algorithms of example 2- damage scenario 1 using objective function 1 noise=0.0

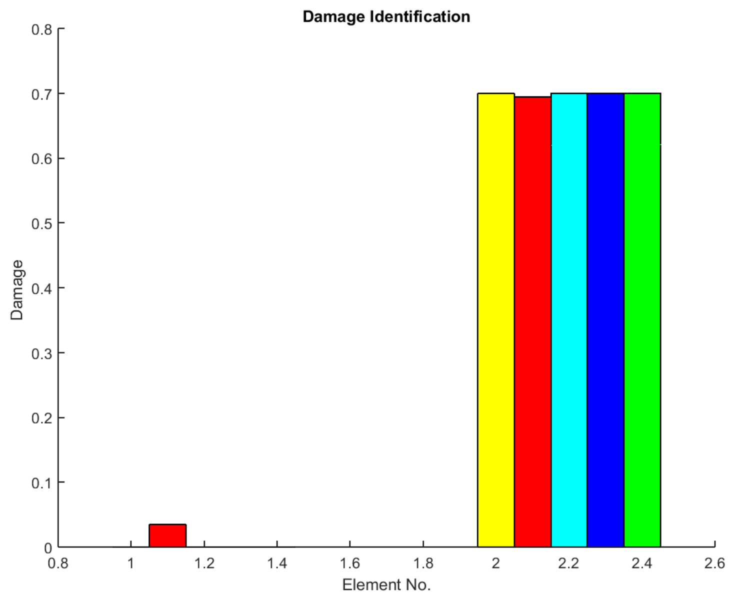

Figure 3.45. Damage detection of example 2-damage scenario 1 using objective function 1 noise=0.0

CS DE PSO SBO

A.1.2 with noise ratio =0.05

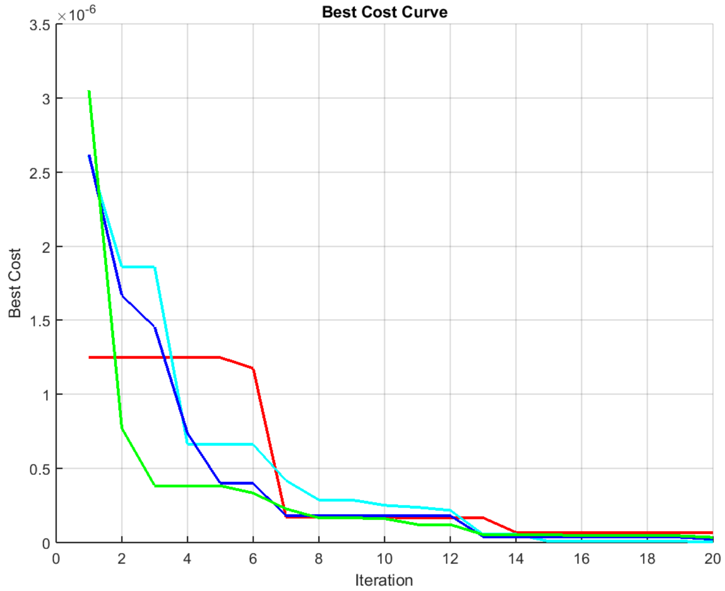

Figure 3.46. Best cost of algorithms of example1-damage scenario 1 using objective function 1 noise=0.05

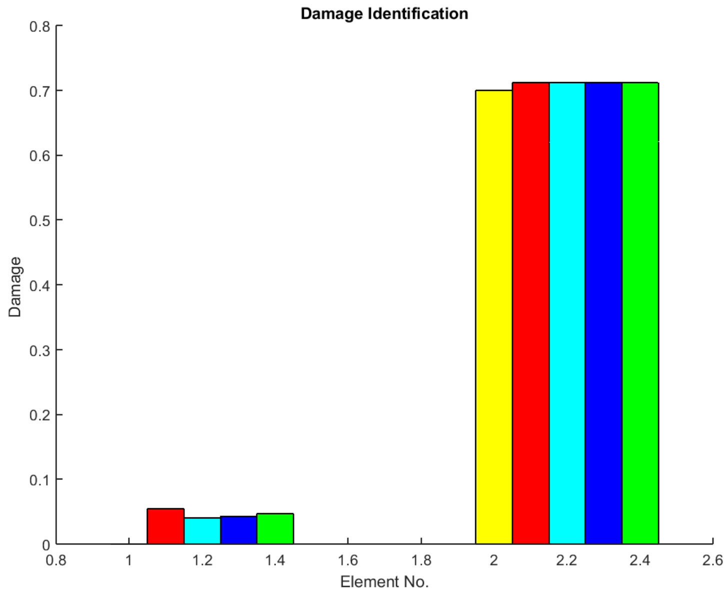

Figure 3.47. Damage detection of example 2-damage scenario 1 using objective function 1 noise=0.05

CS DE PSO SBO

A.1.3 with noise ratio =0.1

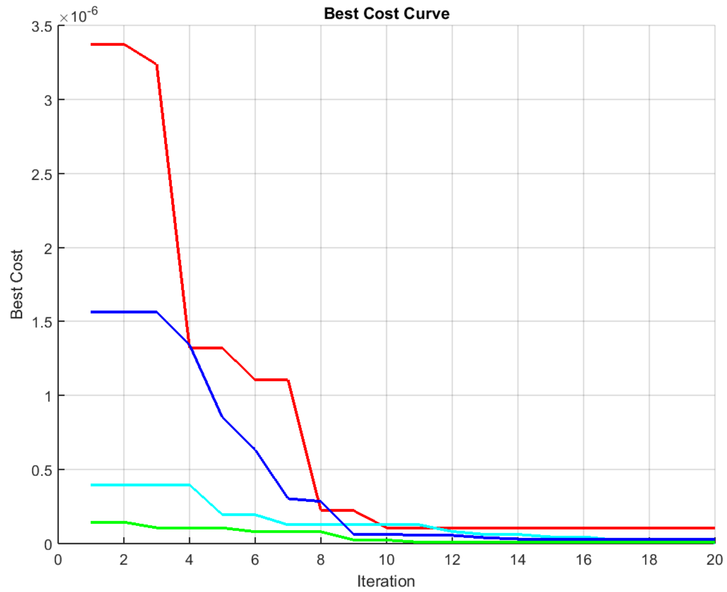

Figure 3.48. Best cost of algorithms of example 2-damage scenario 1 using objective function 1 noise=0.1

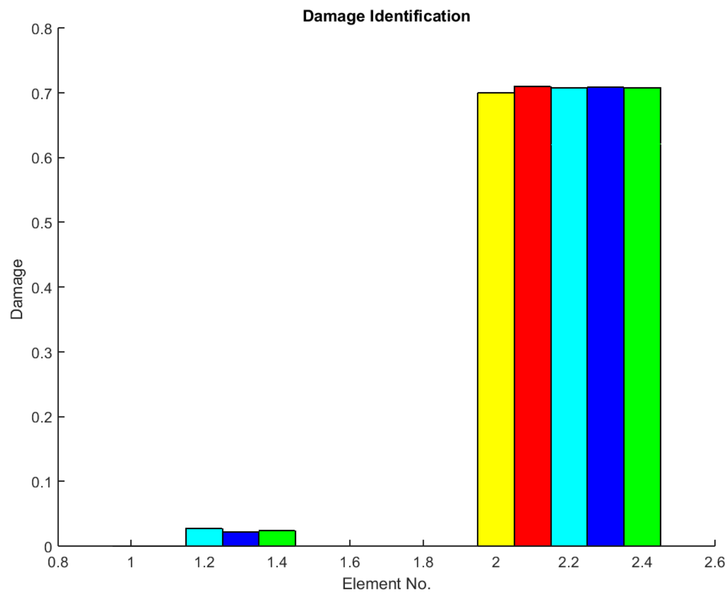

Figure 3.49. Damage detection of example 2-damage scenario 1 using objective function 1 noise=0.1

CS DE PSO SBO

<u>Observation7</u>: using SBO, DE, CS, PSO algorithm to solve the objective function F1 in example 2 damage scenario 1 gives a clear indication of the position of the damaged element in the beams and guide the algorithm to define the position and determine the severity of damage as shown in figure 3.46. but when applying the noise, it gives an acceptable performance with noise as shown in figure 3.48 and figure 3.50

A.2. Objective function (F2)

A.2.1. with noise ratio =0

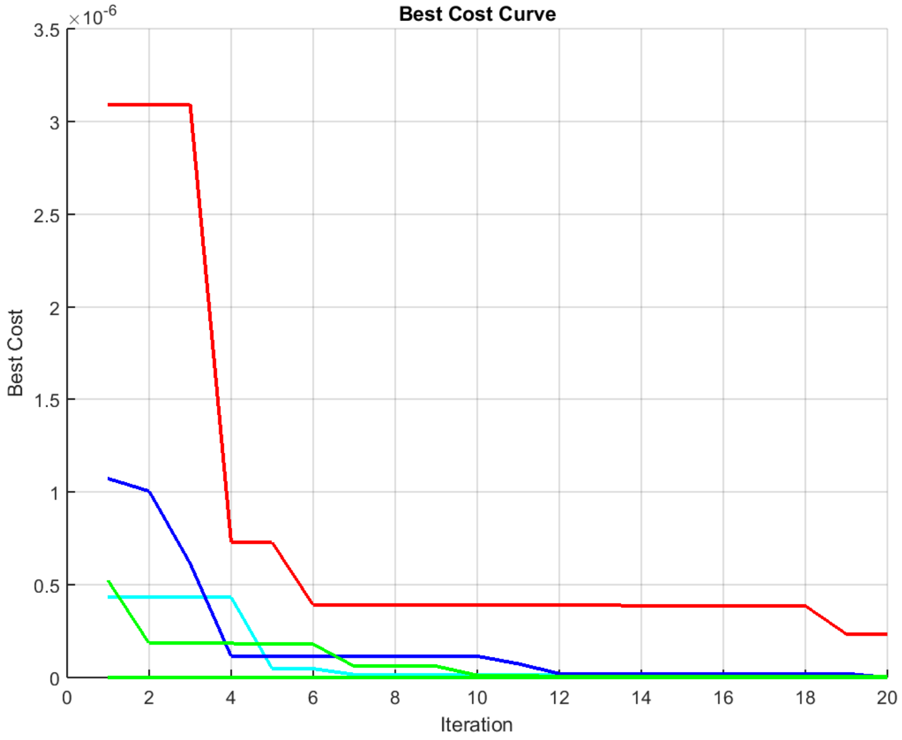

Figure 3.50. Best cost of algorithms of example 2-damage scenario 1 using objective function 2 noise=0.0

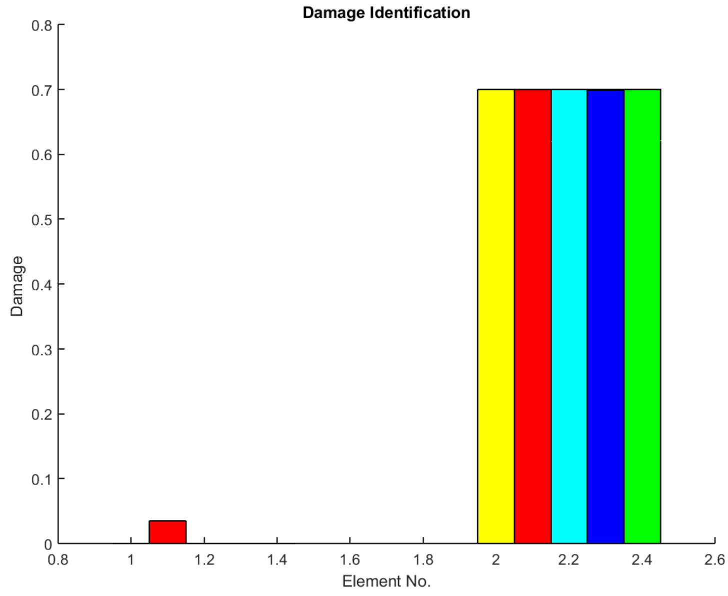

Figure 3.51. Damage detection of example 2-damage scenario 1 using objective function 2 noise=0.0

CS DE PSO SBO

A.2.2. with noise ratio =0.05

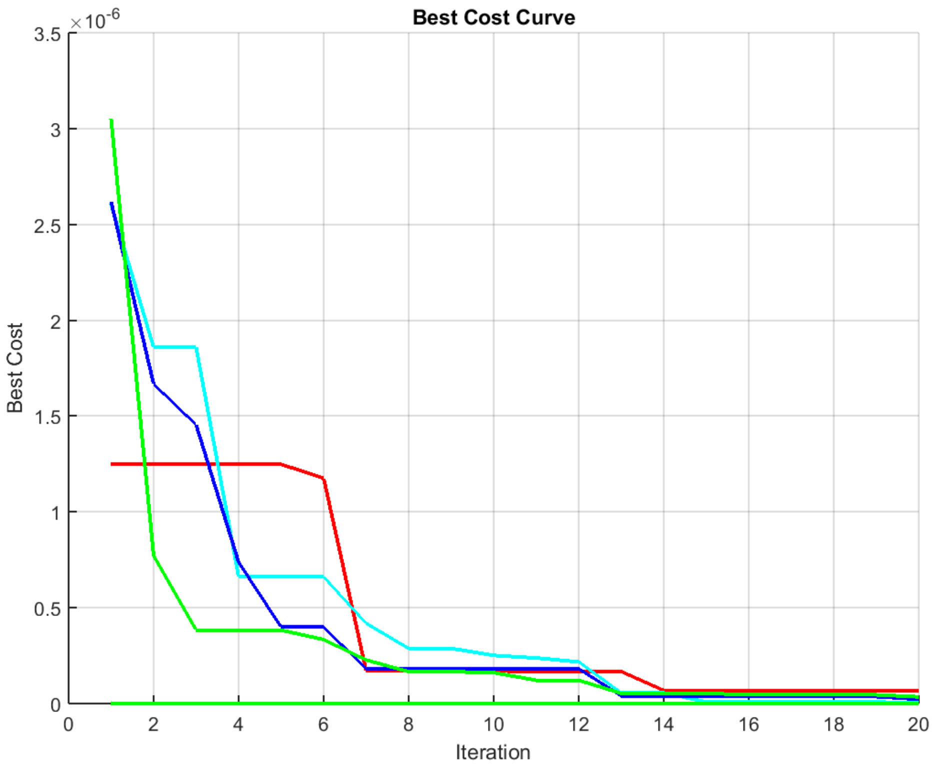

Figure 3.52. Best cost of algorithms of example 2-damage scenario 1 using objective function 2 noise=0.05

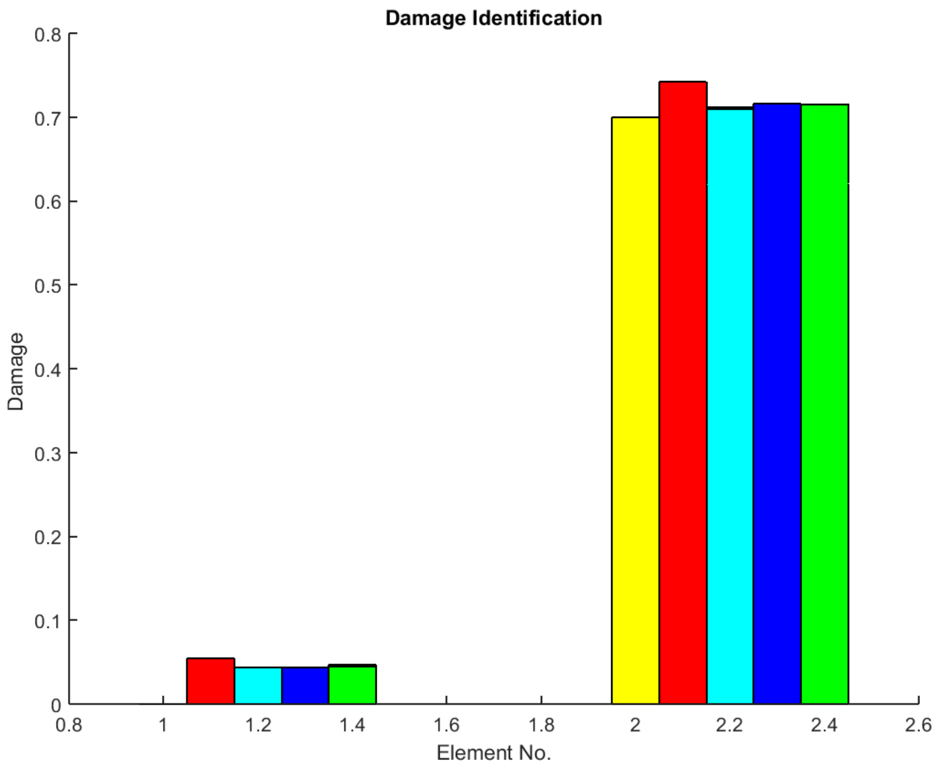

Figure 3.53. Damage detection of example 2-damage scenario 1 using objective function 2 noise=0.05

CS DE PSO SBO

A.2.3. with noise ratio =0.1

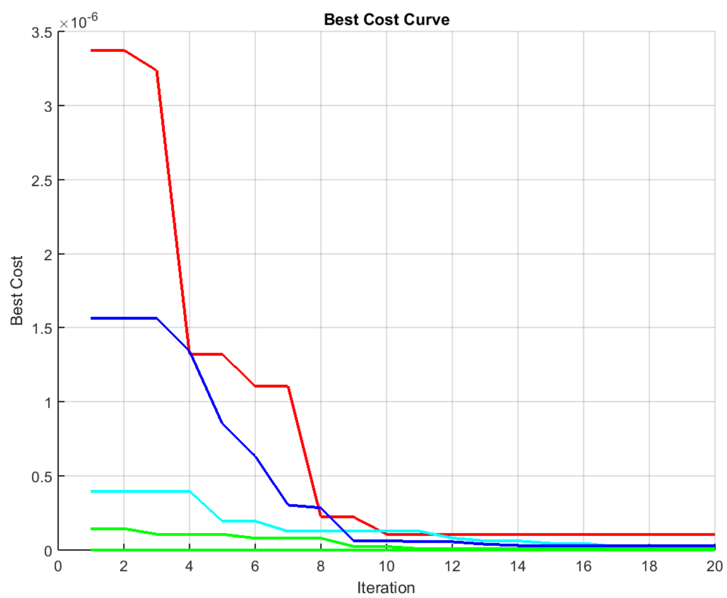

Figure 3.54. Best cost of algorithms of example 2-damage scenario 1 using objective function 2 noise=0.1

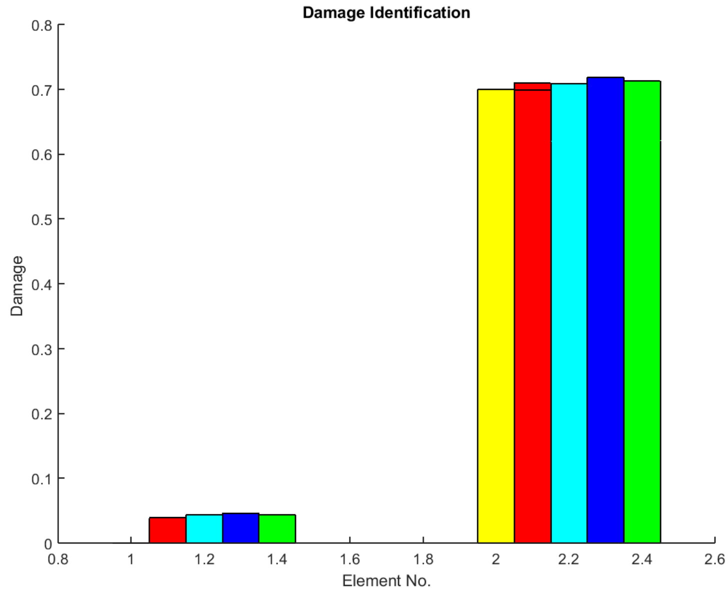

Figure 3.55. Damage detection of example 2-damage scenario 1 using objective function 2 noise=0.1

CS DE PSO SBO

Observation8: using SBO, DE, CS, PSO algorithm to solve the objective function F2 in example 2 damage scenario 1 gives a clear indication of the position of the damaged element in the beams and guide the algorithm to define the position and determine the severity of damage as shown in figure 3.52 but when applying the noise, it gives an ecceptable performance with noise as shown in figure 3.54 and figure 3.56

A.3. objective function (F3)

A.3.1. with noise ratio =0

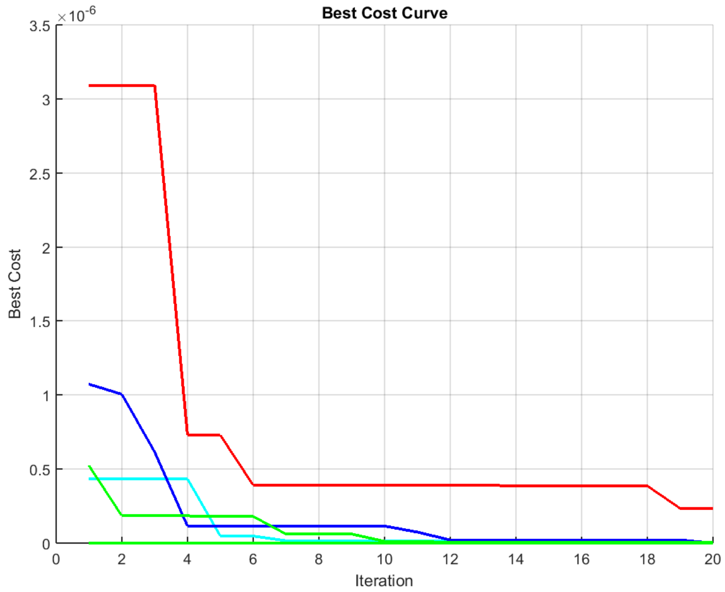

Figure 3.56. Best cost of algorithms of example 2-damage scenario 1 using objective function 3 noise=0.0

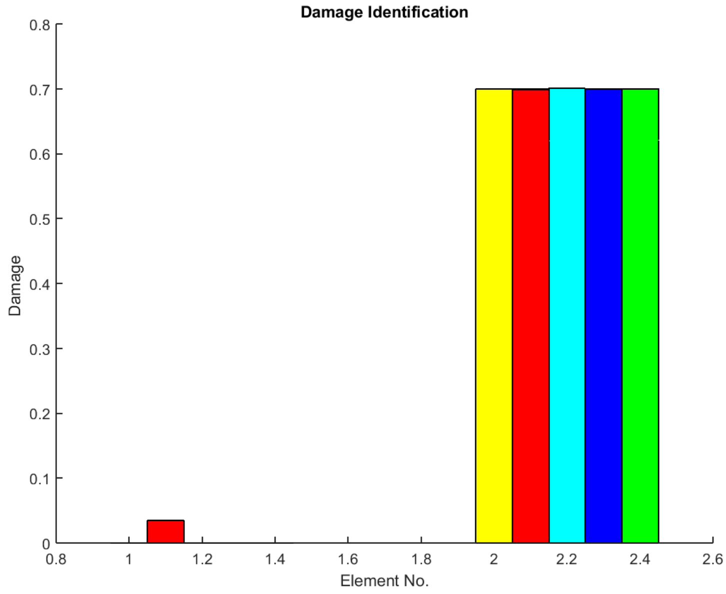

Figure 3.57. Damage detection of example 2-damage scenario 1 using objective function 3 noise=0.0

CS DE PSO SBO

A.3.2. with noise ratio =0.05

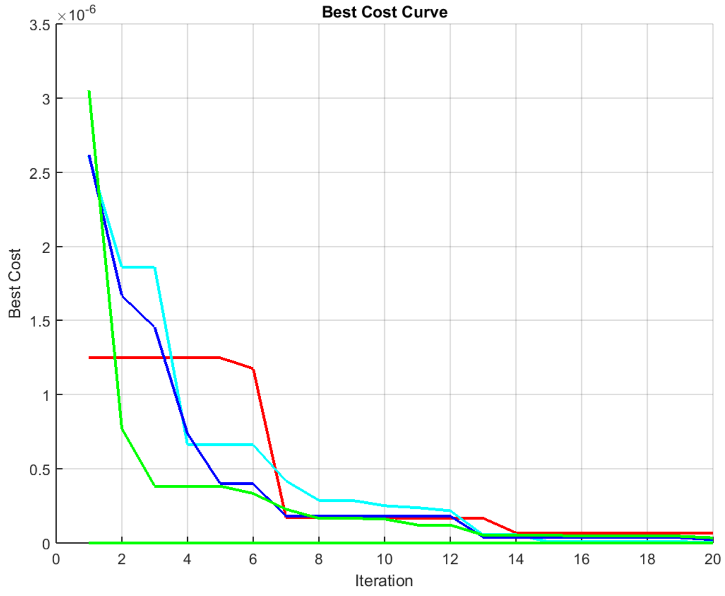

Figure 3.58. Best cost of algorithms of example 2-damage scenario 1 using objective function 3 noise=0.05

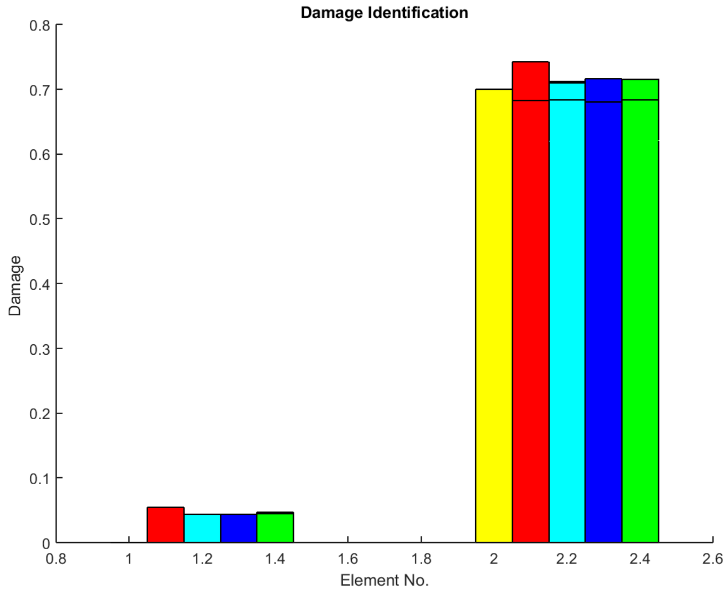

Figure 3.59. Damage detection of example 2-damage scenario 1 using objective function 3 noise=0.05

CS DE PSO SBO

A.3.3. with noise ratio =0.1

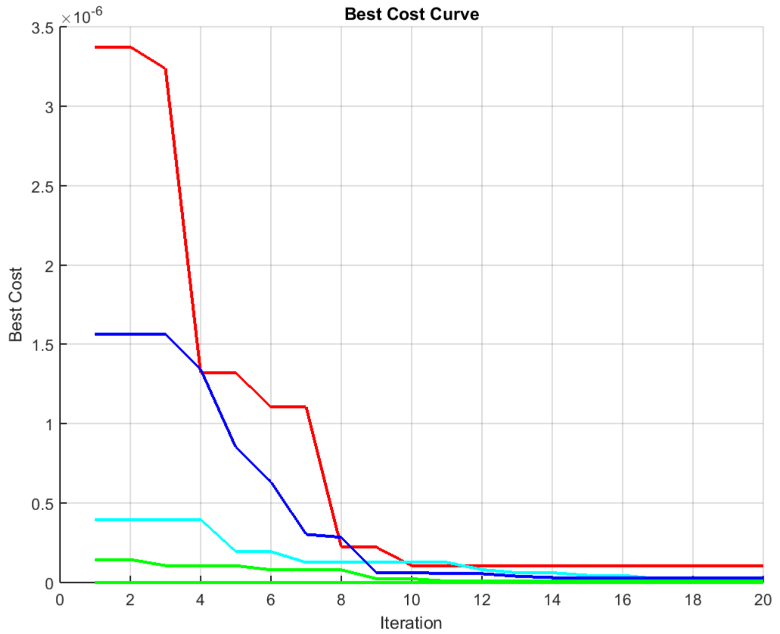

Figure 3.60. Best cost of algorithms of example 2-damage scenario 1 using objective function 3 noise=0.1

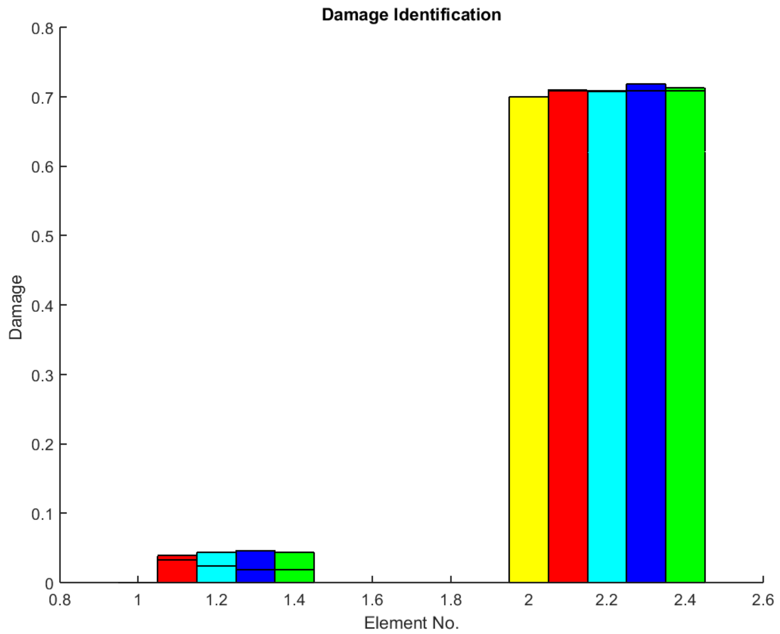

Figure 3.61. Damage detection of example 2-damage scenario 1 using objective function 3 noise=0.1

CS DE PSO SBO

<u>Observation9</u>: using SBO, DE, CS, PSO algorithm to solve the objective function F3in example 2 damage scenario 1 gives a clear indication of the position of the damaged element in the beams and guide the algorithm to define the position and determine the severity of damage as shown in figure 3.58. but when applying the noise, it gives an acceptable performance with noise as shown in figure 3.60 and figure 3.62

B. Damage scenario 2

Table 3.8.shows the frequencies values of healthy structure, the frequencies are given by the textbook and the frequencies for damage scenario of the structure, respectively. The corresponding mode shapes are shown in figure 3.63.and figure 3.64.

Table 3.10. The first 3 frequencies for Damage scenario 2

order	Healthy structure frequencies values by FE	Healthy structure frequencies values by [38]	Damage structure frequencies values by FE
1	25.269 rad/s	25.26 rad/s	17.453 rad/s
2	31.251 rad/s	31.24 rad/s	25.107 rad/s
3	64.897 rad/s	64.90 rad/s	46.044 rad/s

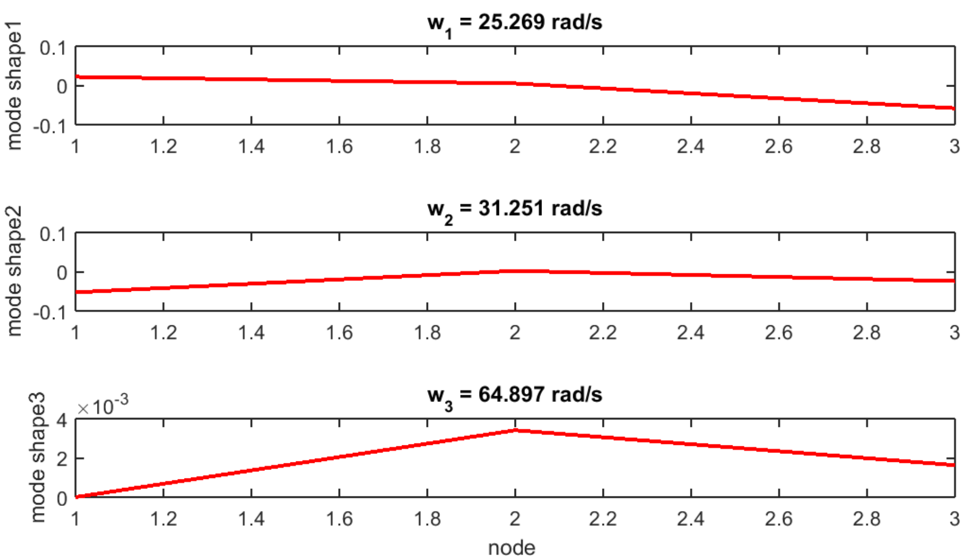

Figure 3.62. Mode shape of healthy structure of example 2 damage scenario 2

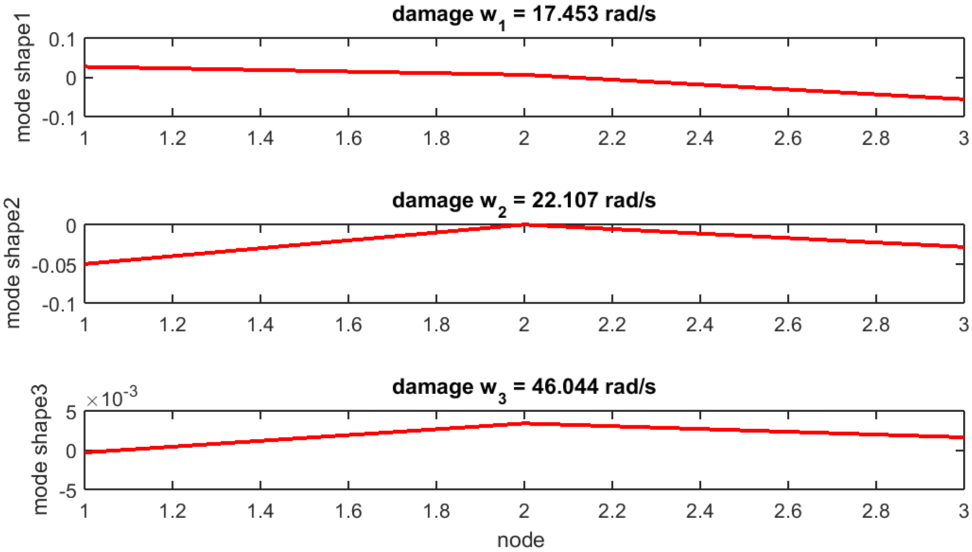

Figure 3.63. Mode shape of damage structure of example 2 damage scenario 2

B.1. Objective function (F1)

B.1.1. with noise ratio =0

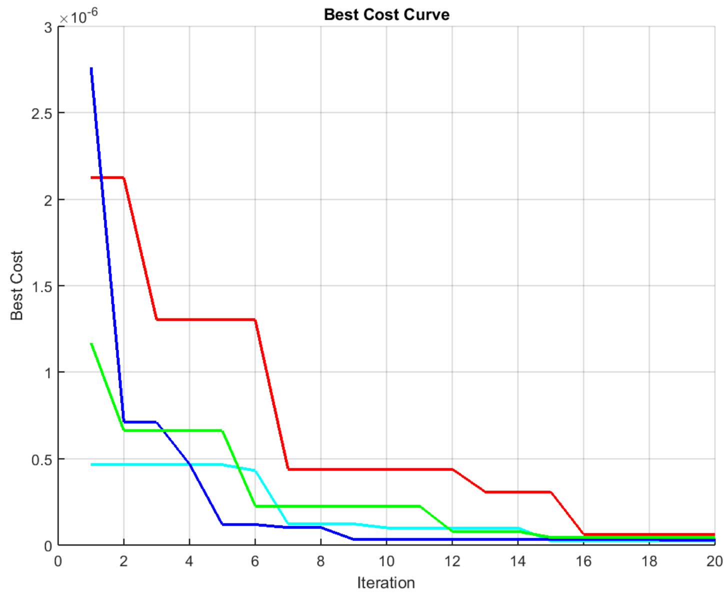

Figure 3.64.Best cost of algorithms of example 2-damage scenario 2 using objective function 1 noise=0.0

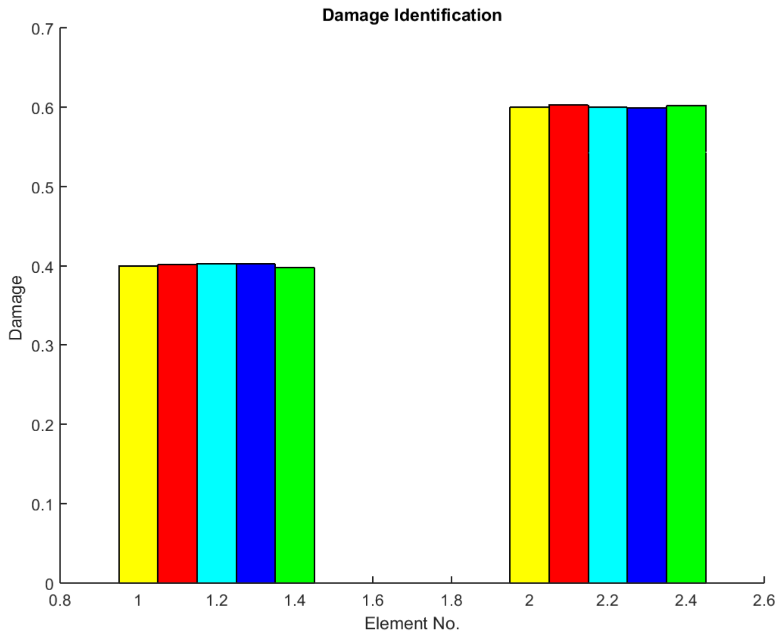

Figure 3.65. Damage detection of example 2-damage scenario 2 using objective function 1 noise=0.0

CS DE PSO SBO

B.1.2 with noise ratio =0.05

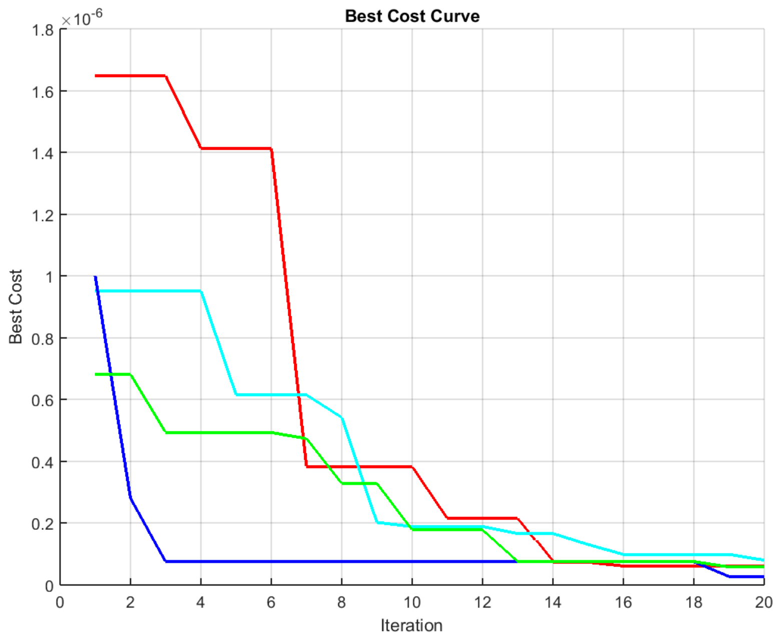

Figure 3.66. Best cost of algorithms of example 2-damage scenario 2 using objective function 1 noise=0.05

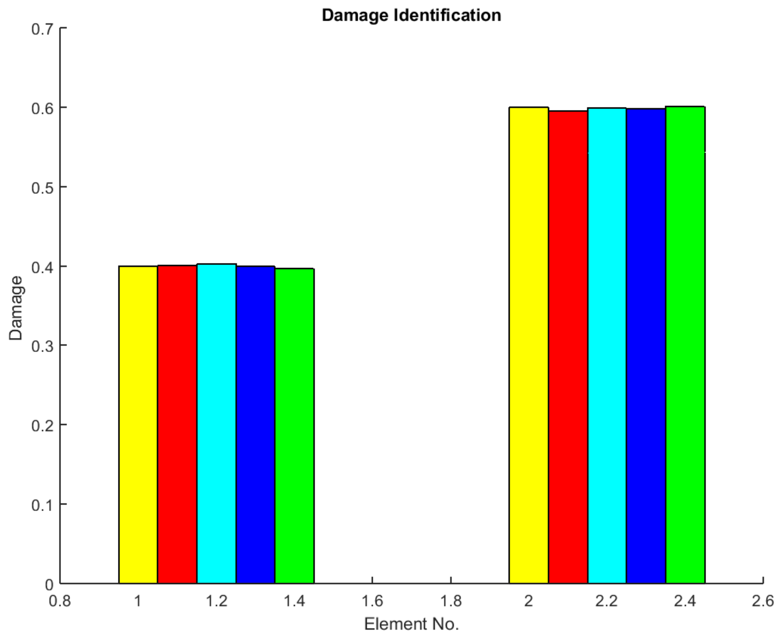

Figure 3.67. Damage detection of example 2-damage scenario 2 using objective function 1 noise=0.05

CS DE PSO SBO

B.1.3 with noise ratio =0.1

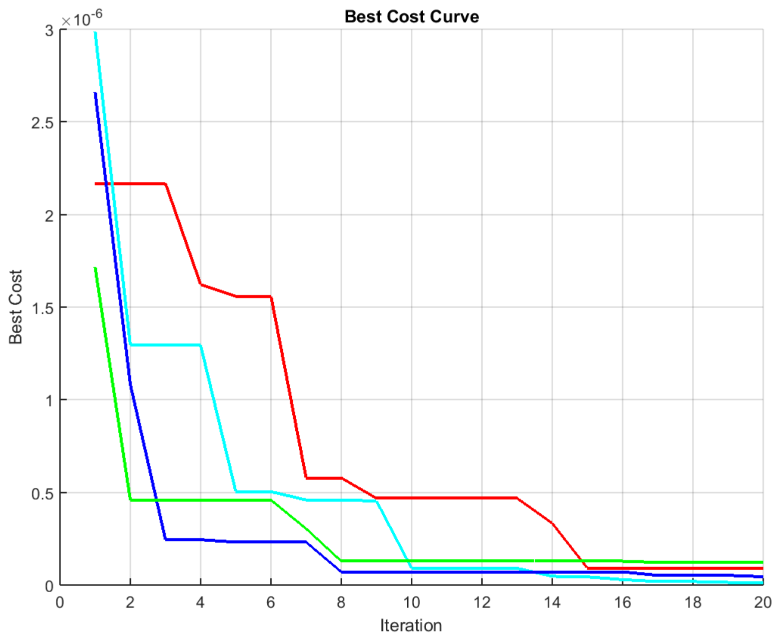

Figure 3.68. Best cost of algorithms example 2-damage scenario 2 using objective function 1 noise=0.1

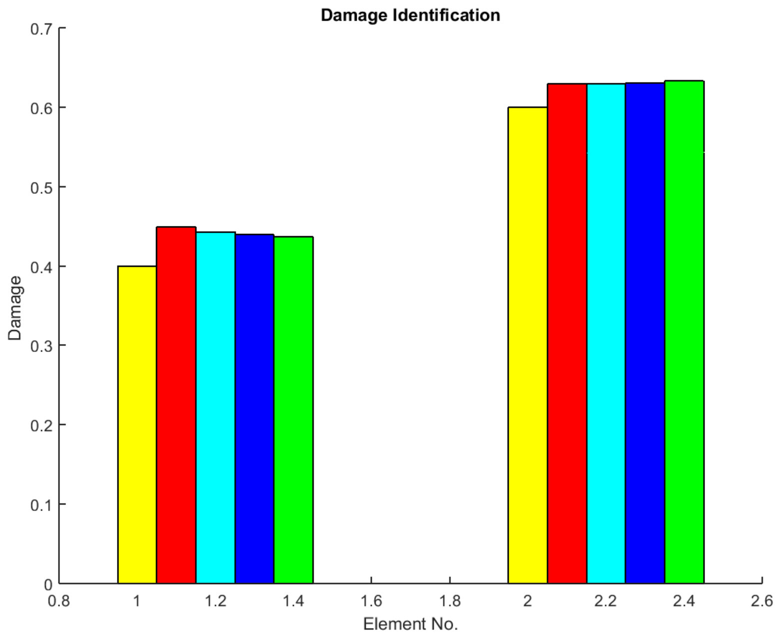

Figure 3.69. Damage detection of example 2-damage scenario 2 using objective function 1 noise=0.1

CS DE PSO SBO

<u>Observation10</u>: using SBO, DE, CS, PSO algorithm to solve the objective function F1in example 2 damage scenario 2 gives a clear indication of the position of the damaged element in the beams and guide the algorithm to define the position and determine the severity of damage as shown in figure 3.66. but when applying the noise, it gives an acceptable performance with noise as shown in figure 3.68 and figure 3.70

B.2. The objective function (F2)

B.2.1. with noise ratio =0

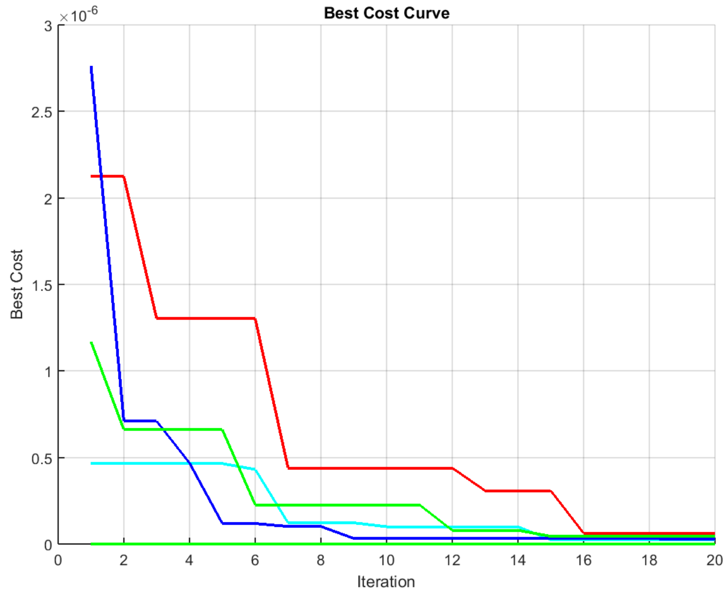

Figure 3.70. Best cost of algorithms of example 2-damage scenario 2 using objective function 2 noise=0.0

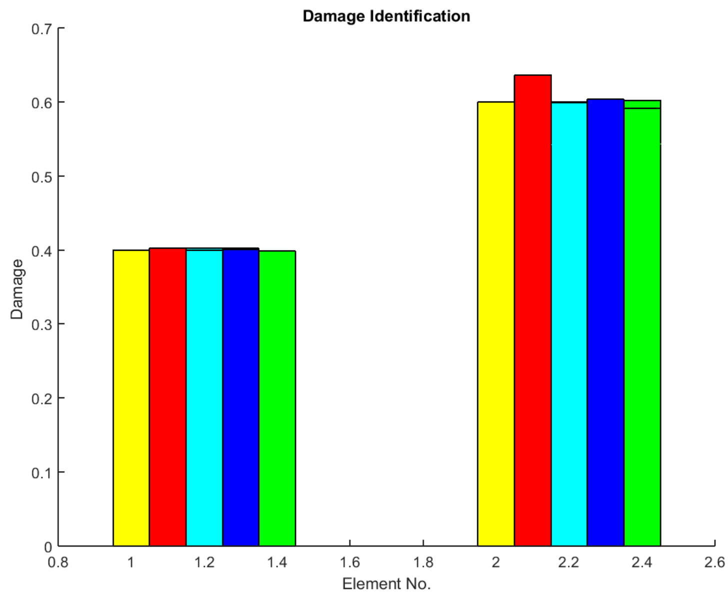

Figure 3.71. Damage detection of example 2-damage scenario 2 using objective function 2 noise=0.0

CS DE PSO SBO

B.2.2. with noise ratio =0.05

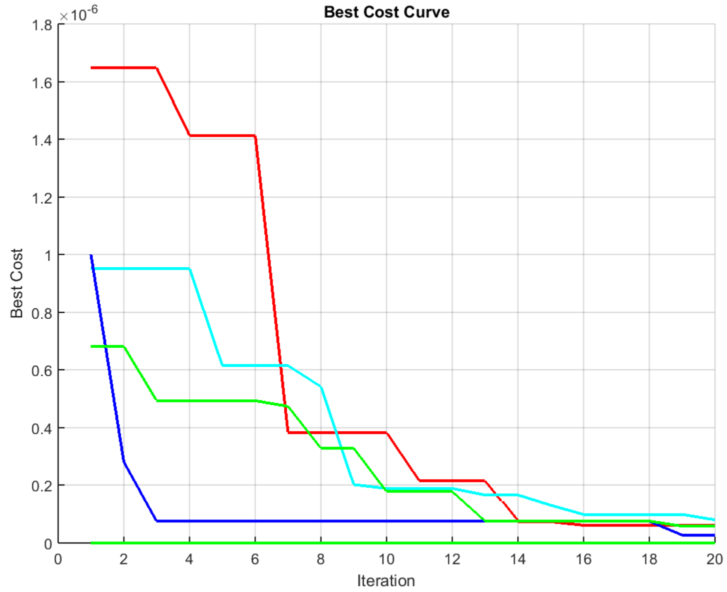

Figure 3.72. Best cost of algorithms of example 2-damage scenario 2 using objective function 2 noise=0.05

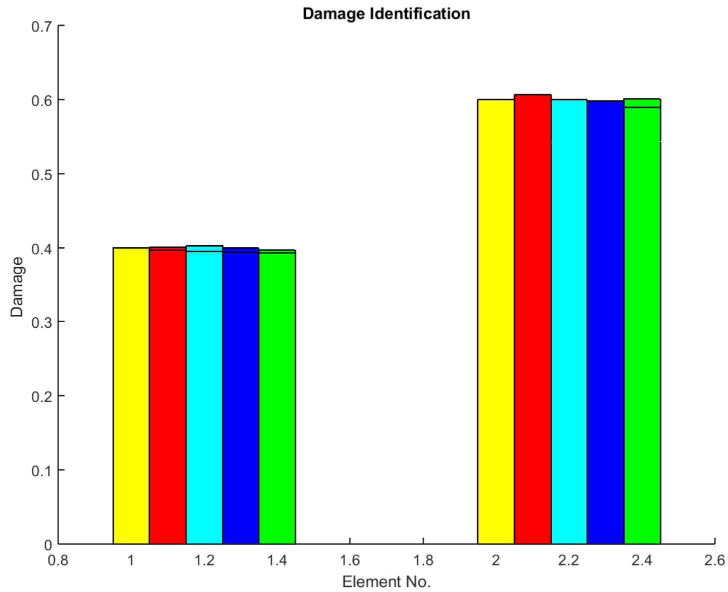

Figure 3.73. Damage detection of example 2-damage scenario 2 using objective function 2 noise=0.05

CS DE PSO SBO

B.2.3. with noise ratio =0.1

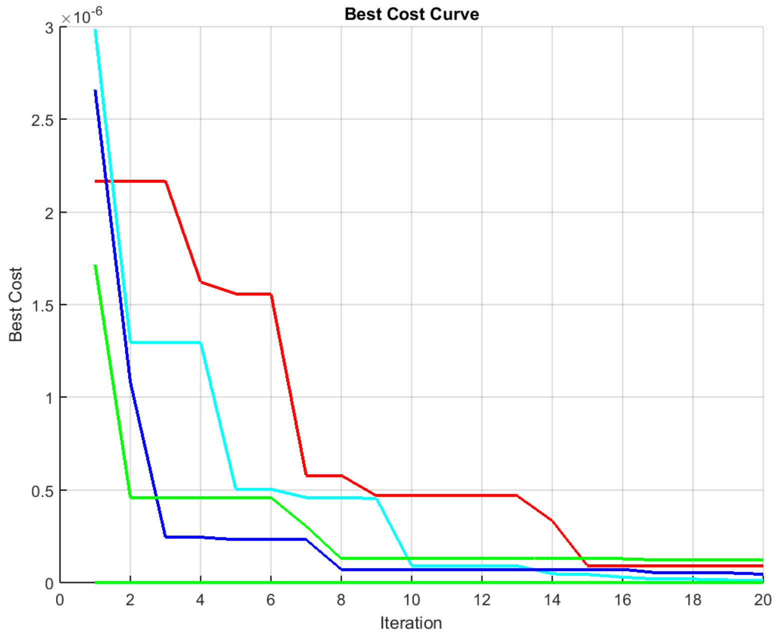

Figure 3.74. Best cost of algorithms of example 2-damage scenario 2 using objective function 2 noise=0.1

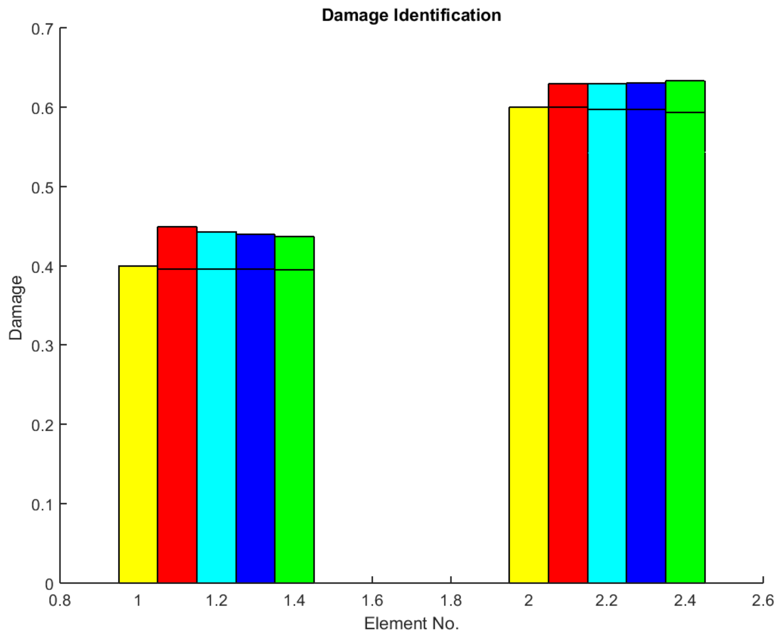

Figure 3.75. Damage detection example 2-damage scenario 2 using objective function 2 noise=0.1

CS DE PSO SBO

Observation11: using SBO, DE, CS, PSO algorithm to solve the objective function F2in example 2 damage scenario 2 gives a clear indication of the position of the damaged element in the beams and guide the algorithm to define the position and determine the severity of damage as shown in figure 3.72. but when applying the noise, it gives an acceptable performance with noise as shown in figure 3.74 and figure 3.76

B.3. the objective function (F3)

B.3.1. with noise ratio =0

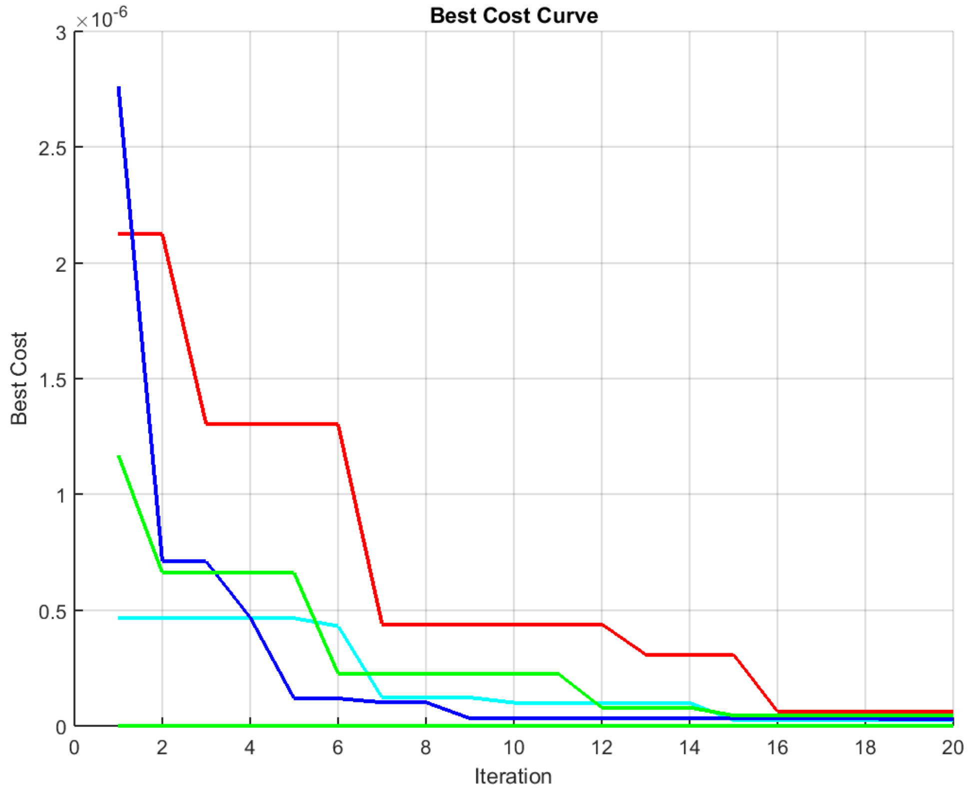

Figure 3.76. Best cost of algorithms of example 2-damage scenario 2 using objective function 3 noise=0.0

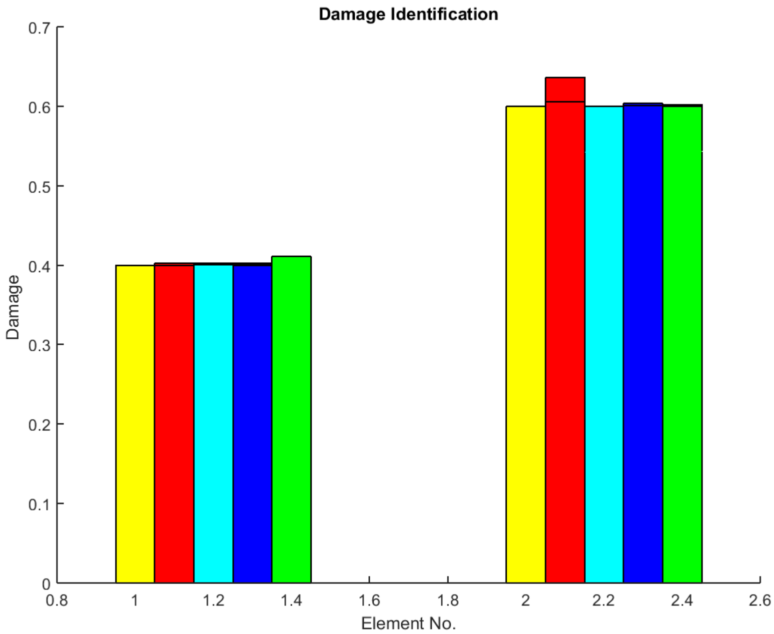

Figure 3.77. Damage detection of example 2-damage scenario 2 using objective function 3 noise=0.0

CS DE PSO SBO

B.3.2. with noise ratio =0.05

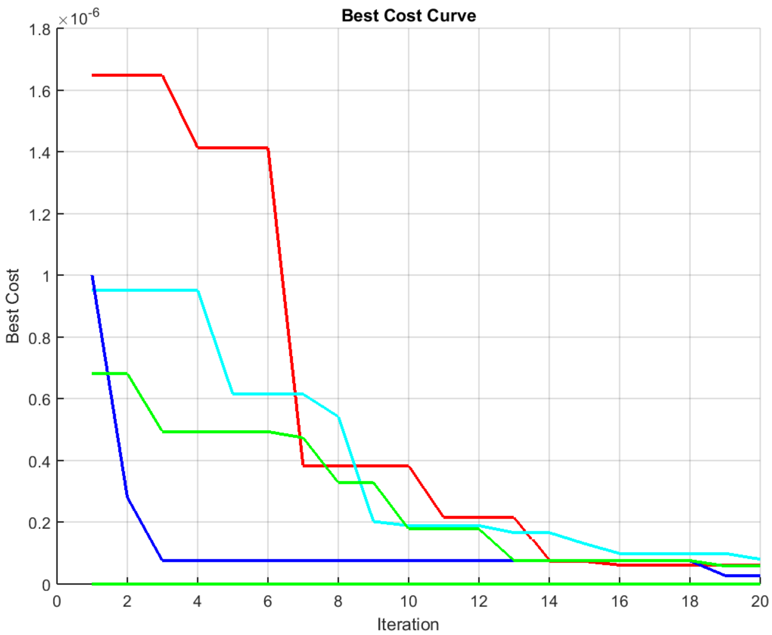

Figure 3.78. Best cost of algorithms of example 2-damage scenario 2 using objective function 3 noise=0.05

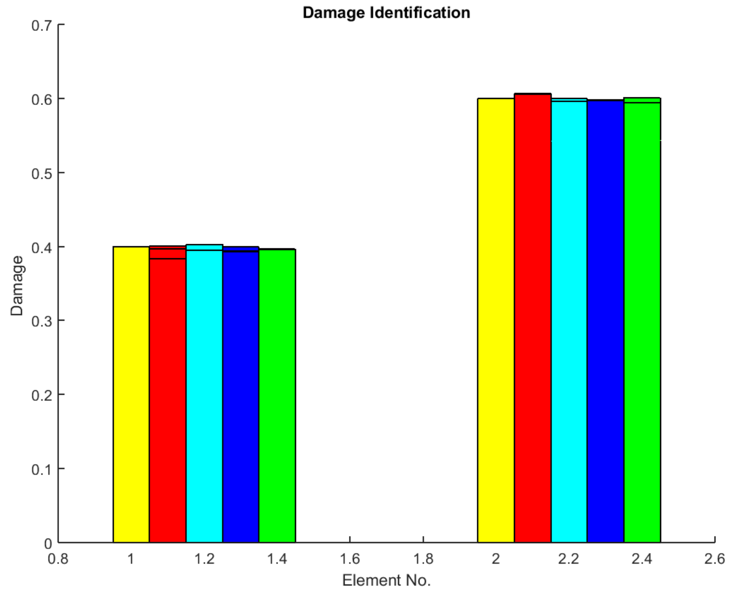

Figure 3.79. Damage detection of example 2-damage scenario 2 using objective function 3 noise=0.05

CS DE PSO SBO

B.3.3. with noise ratio =0.1

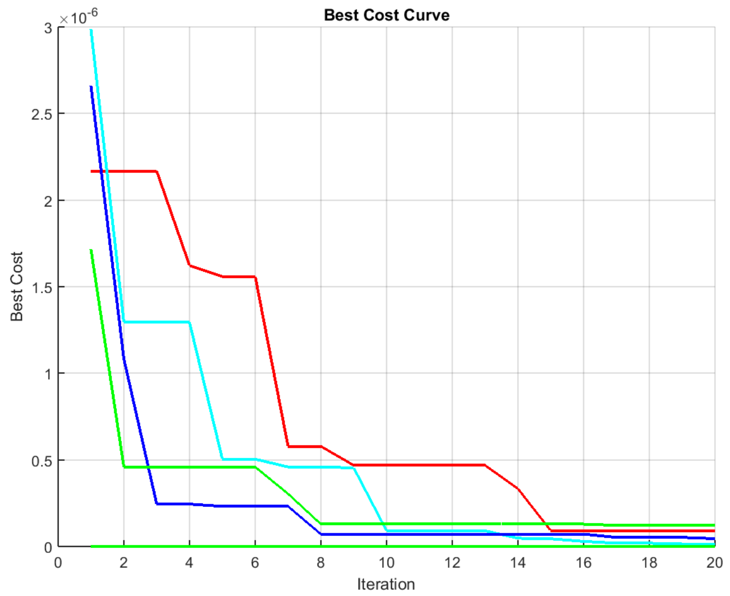

Figure 3.80. Best cost of algorithms of example 2-damage scenario 2 using objective function 3 noise=0.1

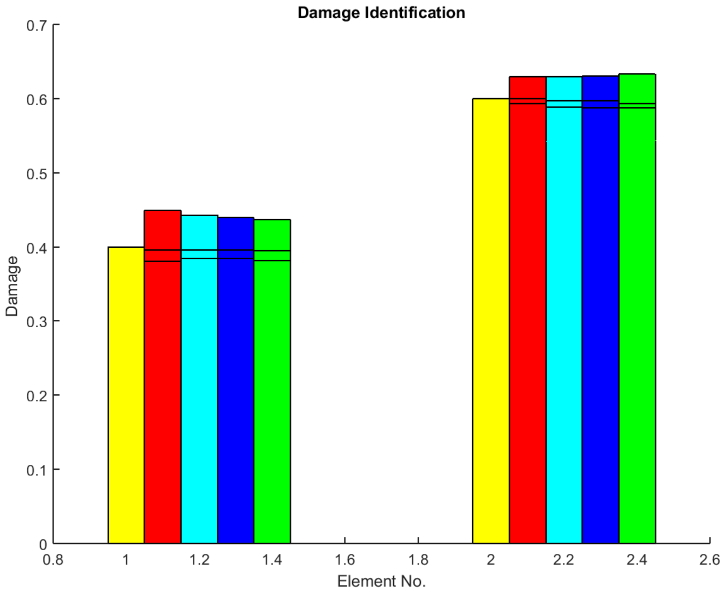

Figure 3.81. Damage detection of example 2-damage scenario 2 using objective function 3 noise=0.1

CS DE PSO SBO

Observation12: using SBO, DE, CS, PSO algorithm to solve the objective function F3in example 2 damage scenario 2 gives a clear indication of the position of the damaged element in the beams and guide the algorithm to define the position and determine the severity of damage as shown in figure 3.78. but when applying the noise, it gives an acceptable performance with noise as shown in figure 3.80 and figure 3.82

CHAPTER 4

DISCUSSIONS AND CONCLUSIONS

4.1 Discussions

The problem of minimization was implemented to solve the problem of damage detection using The Satin bowerbird optimization method. Other methods were also used to compare its efficiency, namely Cuckoo Optimization, The Differential Evolution, and Particle Swarm Optimization. The efficiency of candidate algorithms depends largely on their mathematical model. Therefore, there is a different behavior of competition algorithms based on the objective function used and their mathematical model.

In this thesis, the damage detection is examined using a flexible matrix with a few low-frequency and mode shapes using minimizing objective functions that are used to determine the unrestricted optimization problem. These objective functions are based on a change in the dynamic properties of the experimental model and the numerical model of the structure. Due to experimental data is not available, damage scenarios are assumed using the numerical model of the structure. In order to demonstrate the efficiency of the SBO to damage detection, the 2D structures have been considered with various damage scenarios as test examples. Structural damage scenarios were detected in one element damaged, two elements damaged of the structure. To ensure that the experimental measurements error in the simulation was taken into account, random noise was applied at the initial frequencies. However, the data with 10% noise lead to a slight impact on algorithms efficiency. To compare all the algorithms quantitatively, the maximum iteration must be set for all algorithms the same. Using maximum iteration equals has advantages to ensure the convergence of the algorithm guided by objective functions are reached to the goal and take in consideration that the complexity of the problem increase with the number of elements increased.

Results are shown that the flexibility matrix is sensitive to damages in the structure. Damage was able to be detected in two different types of structures; a 2D steel truss, 2D frame, showing that the method and algorithms are robust to detect damage.

The results have explained that the SBO algorithm has good performance when using all candidate objective functions which are affected in a different way with the noise existence. However, the CS and DE have good performance but the SBO can be considered as the superior algorithm used to solve the problem.

The first objective function using the maximum element in the difference of the flexibility matrices can detect the presence of damage, position, and rate of damage in the structural elements and can lead to accurate damage rate values but it showed a very sensitive to noise than others.

The second objective function using the maximum element in the difference of the flexibility matrices can provide much better results than first in detecting the presence of damage, position, and rate of damage in the structural elements.   it showed a less sensitive to noise than first objective function.

The third objective function using the flexibility matrix error residual criterion can provide much better results than first in detecting the presence of damage, position, and rate of damage in the structural elements. It showed a less sensitive to noise than first objective function.

4.2 Conclusions

Above all, it became clear that the Satin bowerbird optimization improved to be appropriate to deal with damage detection problem and has shown superior efficiency to others. And the second and third objective functions showed good performance when considering measurement noise in the damage detection and simulated case studies.

4.3 Future Work

The performances of the optimization algorithms will be compared with a reference model of many building systems based on real experimental tests such as steel frames, concrete floor slabs, bridges and towers and testing the ability of this methodology to achieve the damage detection in any of these structural elements.

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