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Model updating and damage detection in multi-story shear frames using Salp Swarm Algorithm

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Abstract. This paper studies damage detection as an optimization problem. A new objective function based on changes in natural frequencies, and Natural Frequency Vector Assurance Criterion (NFVAC) was developed. Due to their easy and fast acquisition, natural frequencies were utilized to detect structural damages. Moreover, they are sensitive to stiffness reduction. The method presented here consists of two stages. Firstly, Finite Element Model (FEM) is updated. Secondly, damage severities and locations are determined. To minimize the proposed objective function, a new bio-inspired optimization algorithm called salp swarm was employed. Efficiency of the method presented here is validated by three experimental examples. The first example relates to three-story shear frame with two single damage cases in the first story. The second relates to a five-story shear frame with single and multiple damage cases in the first and third stories. The last one relates to a large-scale eight-story shear frame with minor damage case in the first and third stories. Moreover, the performance of Salp Swarm Algorithm (SSA) was compared with Particle Swarm Optimization (PSO). The results show that better accuracy is obtained using SSA than using PSO. The obtained results clearly indicate that the proposed method can be used to determine accurately and efficiently both damage location and severity in multi-story shear frames.

Keywords: changes in natural frequencies; natural frequency vector assurance criterion; salp swarm; optimization; finite element model updating; damage detection

1. Introduction

Damage detection has drawn researchers' attention through recent decades, since damages influence optimal performance of structures and may cause human disasters. Structural damages occur due to several factors such as erosion, cracks or holes. Local stiffness or mass of a structure can be affected by damages. Dynamic characteristics such as natural frequencies are dependent on distribution of the mass and stiffness; Therefore they are used in damage detection. Damage detection techniques based on modal properties such as natural frequencies, mode shapes, mode shape curvature, strain energy, mode flexibility, and Modal Assurance Criterion (MAC) have received a great deal of consideration in present-day literature of this field (Zare Hosseinzadeh *et al*. 2017, Yang and Wang 2010). Natural frequencies were used for structural damage detection because of their simple and fast acquisition. Additionally, measurement of mode shapes is more difficult than that of frequencies, needing more sensors (Wang *et al*. 2015a, Humar *et al*. 2006).

Some of the earliest articles are compiled on application of natural frequencies in structural damage detection (Hassiotis 2000, Wang *et al*. 2000, Patil and Maiti 2003, Choubey *et al*. 2006).

Xu *et al*. (2007) presented an iterative algorithm used to detect locations and severity of damages in beam-like structures, using only changes in a number of their first natural frequencies. The proposed method is validated by experimental and numerical examples of cantilever beams with several damage cases. Vakil-Baghmisheh *et al*. (2008) utilized a Binary Genetic Algorithm (BGA), a Continuous Genetic Algorithm (CGA) and objective function based on differences between measured and calculated natural frequencies for crack detection and depth identification in cantilever beams. Average of errors made in predicted location and depth (BGA) were 1.02% and 1.98%, respectively. When CGA was used, error rates were changed to 0.73% and 1.11%. The average rates of errors for experimental predicted location and depth (BGA) were 10.57% and 11.19%, respectively. When CGA was implemented, error rates were changed to 10.21% and 10.39%. Majumdar *et al*. (2012) presented a damage assessment method for truss structures using changes in a number of first natural frequencies and Ant Colony optimization. Esfandiari *et al*. (2013) investigated natural frequency-based structural damage detection method using experimental and numerical examples. Their results showed that natural frequency-based methods are not efficient enough to find accurate solutions, making other types of modal properties necessary to be applied in order to obtain suitable results. Kaveh and Zolghadr (2015) utilized improved Charged System Search optimization algorithm for damage detection in truss structures. Two objective functions were used in their study. The first objective function involved changes in natural frequencies. The second one involved changes in natural frequencies and

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mode shapes. Dahak *et al*. (2017) proposed a simple method to locate single damages in cantilever beams. In their study, cantilever beams were discretized into several zones, and damaged zone was located only by classifying normalized frequencies of the beams. Moreover, the proposed method was validated using experimental measurements of cantilever beams. Zhu *et al*. (2017) proposed a structural damage detection approach based on a new optimization algorithm called Bird Mating. The method was proposed in time-frequency domain, where a hybrid objective function is presented through minimizing the differences between measured and calculated natural frequencies. An efficient study for Finite Element Model (FEM) updating in large-scale steel truss bridge using Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) was conducted by Tran-Ngoc *et al*. (2018). Tiachacht *et al*. (2018) have presented a new damage detection approach for planar truss and 3D frame structures, using GA and Modified Cornwell Indicator (MCI). MCI is thereby used as an objective function to compare between measured and calculated indicators. Khatir *et al*. (2019) performed a two-stage method for damage assessment in beam-like structures using two-dimensional Isogeometric Analysis, newly developed damage indicator based on normalized Modal Strain Energy, and Teaching-Learning-Based optimization algorithm. Nobahari *et al*. (2019) developed a new and fast strategy relying on an evolutionary algorithm and an objective function based on residual force vector, as well as an efficient approach based on Truss Element Damage Index. The proposed method includes a two-step procedure. Firstly, they locate possible damaged elements. Secondly, they detected damaged locations and severities. Khatir *et al*. (2018b) utilized a new fast method for crack detection in Carbon Fibre Reinforced Polymer composite structures using proper orthogonal decomposition method, radial basis function, and Cuckoo search algorithm.

Some other efficient studies on damage detection and severity identification are also conducted (Ghodrati Amiri *et al*. 2013, Hosseinzadeh *et al*. 2014, Hosseinzadeh *et al*. 2016a, Hosseinzadeh *et al*. 2016b, Rasouli *et al*. 2015, Khatir *et al*. 2018a, Zenzen *et al*. 2018, Khatir and Wahab 2019). What the said studies have in common is that they have used optimization algorithms and static/dynamic measurements in objective functions.

Amezquita-Sanchez presented a comprehensive study of vibration-based signal processing techniques for civil structures such as bridges and buildings (Amezquita-Sanchez and Adeli 2016). As a comparative study of signal processing methods for structural health monitoring, the article includes four non-parametric and five parametric signal processing techniques. Non-parametric techniques include Fourier transform, periodogram estimation of power spectral density, wavelet transform, and empirical mode decomposition using Hilbert-Huang transform. Parametric techniques, on the other hand, include pseudo spectrum estimation using multiple signal categorization, empirical wavelet transform, approximate Prony method, matrix pencil method, and estimation of signal parameters by rotational invariance technique (Qarib and Adeli 2016).

Noori *et al*. (2018) utilized a wavelet packet transform-based method of damage detection in steel bridges. Strain data were collected by strain sensors and were transformed into modified wavelet packet energy to detect location and severity of the damage. The proposed method was robust to noise. Therefore, the location of the damage could be detected with a noise level of up to 30%. Rahami *et al*. (2018) utilized a signal processing approach for damage assessment in multi-story shear frames. The proposed method uses integration of wavelet transform and fast Fourier transform as means of signal processing, and Hilbert transform in order to estimate final modal parameters, aiming to characterize location and severity of damages. There are a number of more recent papers on damage detection using wavelet (Parrany 2019, Zhu *et al*. 2019, He *et al*. 2019).

There are numerous Degrees Of Freedom (DOFs) in large-scale structures, while measurement of responses at all DOFs is impossible (Kourehli *et al*. 2013). Therefore some researchers developed damage detection methods using incomplete modal data. Lin *et al*. (2014) introduced a damage identification method for seismically excited buildings (with focus on shear buildings) which used incomplete measurements. Sun and Büyüköztürk (2016) investigated a probabilistic approach for updating Bayesian model using incomplete modal data. Ghannadi and Kourehli (2018) studied different FEM reduction techniques. Application of model reduction methods for structural connections can be also mentioned (Yin *et al*. 2017). As another solution to overcome measurement limitations, DeVore *et al*. (2015) have introduced substructure identification as a methodology of direct recognition of local stiffness changes by measured responses, in order to improve damage detection process. Structural damage detection techniques based on statistical moments of dynamic responses have been recently developed. The said method is robust to noise. An experimental investigation of this approach was performed by Xu *et al*. (2009). Their results were compared with analytical values and found to be satisfactory.

Wang *et al*. (2018) developed a damage detection strategy based on Laplace Transform-based Spectral Element Method (LTSEM) and strain statistical moment. The dynamic measurements of the structure were analyzed by LTSEM. Then, the strain statistical moment was employed as a failure indicator. Yang *et al*. (2019) have introduced damage detection techniques based on statistical moment by incorporating the fourth-order displacement statistical moments with the eighth-order acceleration statistical moments. This fusion of statistical moment was found to be highly accurate with anti-noise properties. Some other efficient studies in this field have been presented by Wang *et al*. (2014) and Xiang *et al*. (2014).

The present paper proposes a new damage detection approach. This method consists of FEM updating and damage detection procedures. A new objective function based on changes in natural frequencies and Natural Frequency Vector Assurance Criterion (NFVAC) was developed. Moreover, in order to minimize the objective function, a new bio-inspired optimization algorithm called Salp Swarm was employed. Moreover, the performance of Salp Swarm Algorithm (SSA) was compared with PSO. The proposed method was applied to three experimental shear

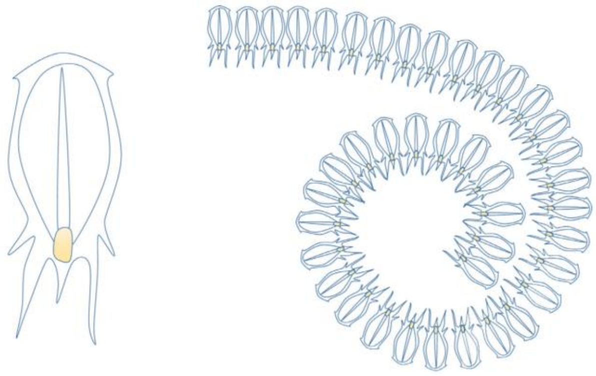


Fig. 1 (left) salp, (right) salps chain (Mirjalili *et al*. 2017)

```
Initialize the salp population xi (i = 1, 2, ..., n) considering ub and lb
while (end condition is not satisfied)
Calculate the fitness of each search agent (salp)
F=the best search agent
Update c1 by Eq (2)
 for each salp (xi)
        if (i==1)
                Update the position of the leading salp by Eq (1)
        else
                Update the position of the follower salp by Eq (4)
        end
    end
    Amend the salps based on the upper and lower bounds of variables
end
return F
```

Fig. 2 The pseudo code of SSA (Mirjalili *et al*. 2017)

frames with different damage severity and locations.

2. Salp Swarm algorithm

Salps are species of Salpidae family with a transparent barrel-shaped body (Mirjalili *et al*. 2017). Their body tissue and movement mechanism is similar to jelly fish, such that water is pumped through the body to generate propulsion as a movement force forward.

One of the most significant behaviors of salps inspiring optimization studies is swarming. Salps live in deep ocean waters and usually form a swarm called salp chain. Salps and their chain are demonstrated in Fig. 1. The logic behind this behavior is not obviously known, but some researchers believe that it is an attempt to achieve better movement in water and higher chance of foraging, through rapid orderly changes in their movements.

2.1 Mathematical model inspired by moving salp chains

To obtain a mathematical model of salp chains, their population is classified into two groups:

a) leaders b) followers.

The leader is a salp at the front end of the chain, whereas the rest of them are followers. The leader guides the swarm and the followers follow the one in front of them. Similar to other swarm-based algorithms, the position of salps is determined in an n-dimensional search space, where *n* is the number of variables of a given problem.

Consequently, the positions of all salps are collected in a two-dimensional matrix called *x*. It is often assumed that there is a food source called *F* in the search space as the swarm's target. To update the position of the leader, the following equation is used

$$x_j^1 = \begin{cases} F_j + c_1\left(\left(ub_j - lb_j\right)c_2 + lb_j\right) & c_3 \geq 0 \\ F_j - c_1\left(\left(ub_j - lb_j\right)c_2 + lb_j\right) & c_3 < 0 \end{cases} \tag{1}$$

where x indicates the position of the first lead in the j^{th} dimension, F_j is the food source location in the j^{th} dimension, ub_j represents the upper bound of j^{th} dimension, lb_j indicates the lower bound of j^{th} dimension, and c_1, c_2, and c_3 are random numbers. Eq. (1) indicates that the leader only updates its position with respect to food source.

c_1 coefficient is a significant parameter in SSA, since it balances exploration and exploitation determined as follows

$$c_1 = 2e^{-\left(\frac{4l}{L}\right)^2} \tag{2}$$

where l and L represent the current iteration and maximum number of iterations. c_2 and c_3 parameters indicate uniformly random numbers generated in the interval [0,1]. To update the position of the followers, the following equation is used

$$x_j^i = \frac{1}{2}at^2 + v_0 t \tag{3}$$

where $i \geq 2$, x_j^i is the position of i^{th} following salp at j^{th} dimension. t and v represent time and initial speed, respectively. Also in Eq. (3), $a = \frac{v_{final}}{v_0}$ where $v = \frac{x - x_0}{t}$. Time interval in optimization is iteration, and the discrepancy between iterations is equal to 1 while substituting v_0=0, Eq. (3) is hence rewritten as follows

$$x_j^i = \frac{1}{2}(x_j^i + x_j^{i-1}) \tag{4}$$

where $i \geq 2$, x_j^i represents the position of i^{th} followingsalp at j^{th} dimension. Fig. 2 illustrates the pseudo codeof SSA.

3. Particle Swarm optimization

PSO is a population-based optimization algorithm formulated by Eberhart and Kennedy (1995).

The PSO algorithm was based on swarm intelligence and has been employed widely in recent years. The PSO algorithm is based on two equations. Eq. (5) updates the position of a particle and Eq. (6) updates the velocity of a particle (Tran-Ngoc *et al*. 2018).

$$x^i(t+1) = x^i(t) + v^i(t+1) \tag{5}$$

$$v^i(t+1) = wv^i + C_1 r_1 (p^i(t) - x^i(t)) + C_2 r_2 (G_{best} - x^i(t)) \quad (6)$$

Where $x^i(t)$, and $x^i(t+1)$ indicate the position vectors of particle i at time t and t+1, respectively. v is the velocity vector of particle, w represents the inertia weight parameter. C_1, C_2 indicate the cognition learning factor and the social learning factor, respectively, r_1 and r_2 are random numbers in the range of (0,1), $p^i(t)$ is the best position of each particle, and G_{best} is the best position of all particles. When the objective function is minimum, the G_{best} is achieved.

4. FEM updating and damage detection methodology

In this paper, the damage detection method is apportioned into two parts. Firstly, the initial FEM of structures is updated by experimental measurements. This means that stiffness matrix is calibrated with experimental models. Second, severity and location of the damage is determined by updated FEM from the first part.

4.1 FEM updating

Objective function for FEM updating is as follows

$$\begin{aligned} Minimize: fun(x) = &\left(\frac{1}{n}\sum_{i=1}^{n}\left|\left(f_i^{ex} - f_i^{nu}\right)^2\right|\right)^{0.5} \\ &+\left(1 - NFVAC(F^{ex}, F^{nu})\right) \end{aligned} \quad (7)$$

In Eq. (7), f_i^{ex}, f_i^{nu} represent experimental and numerical natural frequencies of the i[th] mode, respectively. n is the total number of DOFs. Similar to the definition of MAC, NFVAC was defined as follows

$$NFVAC\left(F^{ex}, F^{nu}\right) = \frac{\left|\left\{F^{ex}\right\}^T \left\{F_j^{nu}\right\}\right|^2}{\left(\left\{F^{ex}\right\}^T \left\{F^{ex}\right\}\right)\left(\left\{F^{nu}\right\}^T \left\{F^{nu}\right\}\right)} \quad (8)$$

where $\{F^{ex}\}$ is the Natural Frequency Vector (NFV) of the experimental measurement and $\{F^{nu}\}$ is NFV of thenumerical calculation (Yang and Wang 2010). Also, NFV was defined as follows

$$F = \begin{Bmatrix} f_{i=1} \\ \vdots \\ f_{i=n} \end{Bmatrix}_{n\times 1} \quad (9)$$

In order to minimize Eq. (7), a vector of stories sizes should be found in the interval of 0 and 1, which are shown in Eq. (10) and Eq. (11).

$$Find: x = \{d_1, \ldots, d_{nst}\}^T \quad (10)$$

$$Bound: 0 \le d_u \le 1 \quad (11)$$

By substituting the values from Eq. (10) in Eq. (12), updated stiffness matrix was obtained.

$$\left[K_{up}\right] = \sum_{u=1}^{nst}(1 \pm d_u)k_u \quad (12)$$

where d_u is update parameter for each story which is between zero and one. K_{up} and k_u represent stiffness matrix of updated structure and story stiffness before updating, respectively. nst is the total number of stories. The eigenvalue equation was solved by K_{up}, therefore f^{up} was obtained. up superscript represents updated natural frequencies.

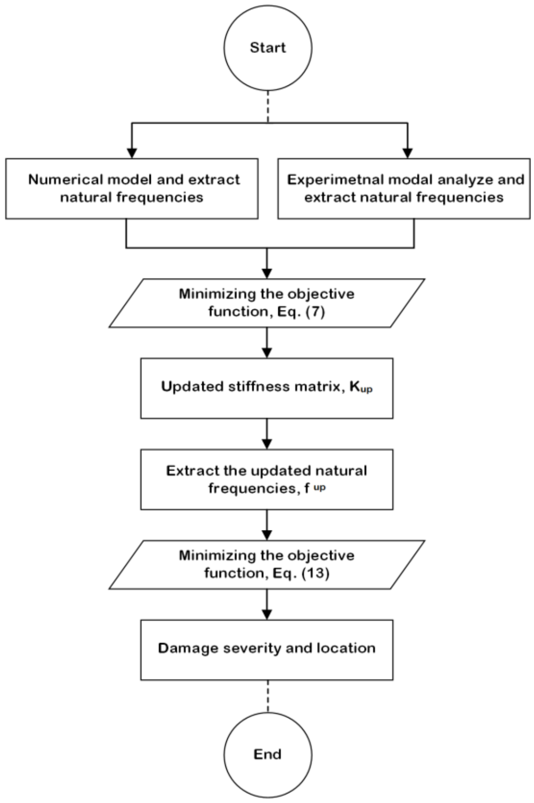


Fig. 3 Flowchart of the damage detection approach

4.2 Damage detection

The objective function for damage detection is as follows

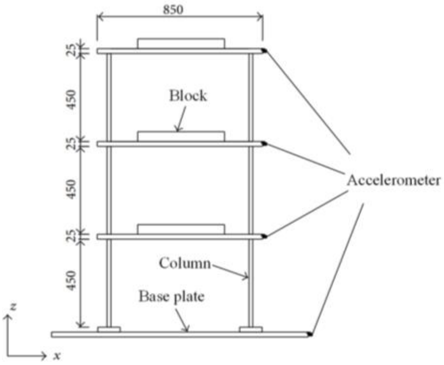
$$\begin{aligned} Minimize: fun(x) = &\left(\frac{1}{n}\sum_{i=1}^{n}\left|\left(f_i^{ex} - f_i^{up}\right)^2\right|\right)^{0.5} \\ &+\left(1 - NFVAC(F^{ex}, F^{up})\right) \end{aligned} \quad (13)$$

In Eq. (13), f_i^{ex}, f_i^{up} represent experimental natural frequencies with known damage state and updated natural frequencies of the structure to be investigated. Also, F^{ex} and F^{up} indicate NFV of structure with known damage state and updated NFV of the structure to be investigated. The flowchart of the proposed method can be briefly shown in Fig. 3.

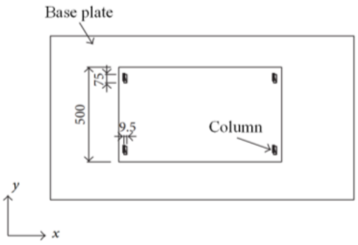
5. Experimental validation

Competence of the method proposed here is validated through three experimental examples. The first one relates to a three-story shear frame with two single damage cases in the first story. The second relates to a five-story shear frame with single and multiple damage cases in the first and third stories. The last example relates to a large-scale eight-story

(a) Experimental configuration of shear frame



(b) Dimensions of front view



(c) Dimensions of top view

Fig. 4 Experimental configuration and dimensions of three-story shear frame (Wang *et al*. 2015b, Chen *et al*. 2014)

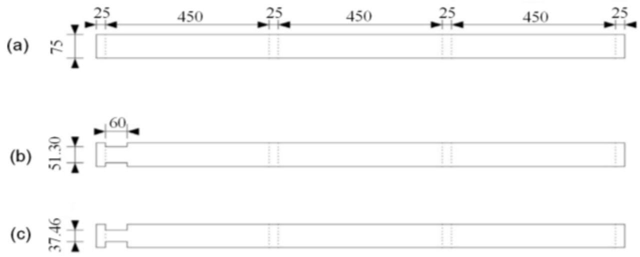
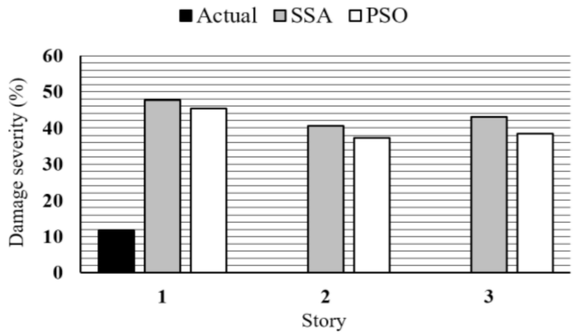
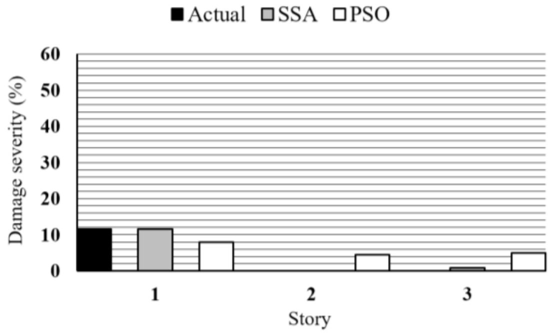


Fig. 5 Columns used in three-story shear frame: (a) undamaged case, (b) first damaged case, (c) second damaged case (Wang *et al*. 2015b)



(a) Damage detection before FEM updating



(b) Damage detection after FEM updating

Fig. 6 Results of damage detection for three-story shear frame - first damaged case

shear frame with minor damage case in the first and third stories. Additionally, the parameters of SSA, the number of iterations and the number of search agents, are 1000 and 170.

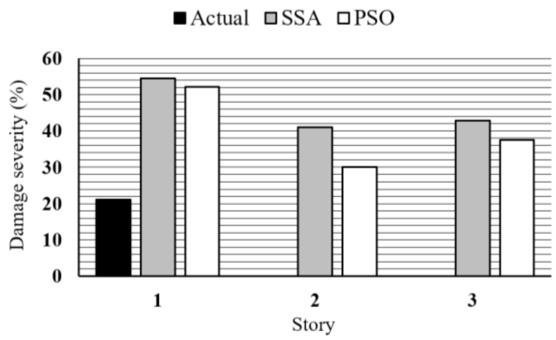
5.1 Three-story shear frame

A three-story shear frame is assembled using three steel plates (850 mm×500 mm×25 mm) and four steel columns (75 mm×9.5 mm) as shown in Fig. 4 (Wang *et al*. 2015b). Total dimensions of this frame in height, length and width are 1450 mm, 850 mm and 500 mm, respectively. The plates and columns are connected by welding providing rigid connections. Thickness of the plates is greater than the height of the columns cross-section. Thus, the floors will not rotate when the story drifts and that is the reason why the frame can be considered as a shear frame. The feet of columns are welded to the base plate with 20 mm thickness, attached to a 3×3 m^2 shaking table with eight bolts to provide rigid connection between the frame and the ground. All floors are equipped with a B&K 4370 accelerometer to acquire frame acceleration response data in x-direction. Additional blocks of 135 kg mass are distributed on each story as lumped mass. Theoretical stiffness of the first, second and third stories are 4.84×10^5 N/m, 5.74×10^5 N/m and 5.95×10^5 N/m, respectively.

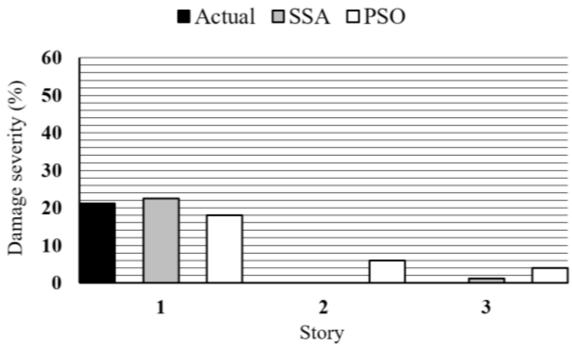
Table 1 Experimental natural frequencies (Hz) of three-story shear frame (Wang *et al*. 2015b)

Mode	Undamaged case	First damaged case	Second damaged case
1	3.369	3.259	3.113
2	9.704	9.485	9.302
3	14.282	14.209	14.136

Ground excitation is exerted to simulate white noise acceleration time history. Frequency range of this band limited white noise is 1-30 Hz. The peak acceleration value is limited to 0.05g, duration of excitation is approximately 180 s, and sampling frequency is 300 Hz. Two different



(a) Damage detection before FEM updating



(b) Damage detection after FEM updating

Fig. 7 Results of damage detection for three-story shear frame-second damaged case

Table 2 Natural frequencies (Hz) of three-story shear frame before and after FEM updating (undamaged case)

Mode	Experimental (Wang *et al*. 2015b)	Initial FEM	Updated FEM
1	3.369	4.407	3.369
2	9.704	12.693	9.704
3	14.282	18.680	14.282

damage cases are examined during this test. In the first case, the width of the first story columns was decreased to 51.30 mm within the height of 60 mm from the feet. In the second case, the width of the columns was decreased to 37.46 mm within the height of 60 mm from the feet, which represents the first and second damage cases. Fig. 5 (a), (b) and (c) show the columns of experimental shear frame in undamaged, first and second damaged cases, respectively.

Figs. 6 and 7 illustrate the detected and actual damage cases. To show the sensitivity analysis and FEM updating performance, damage detection results are presented before and after FEM updating. It is visible that damage detection procedure is more effective using the proposed FEM updating.

The three natural frequencies (including undamaged and damaged cases) are listed in Table 1. Updated natural frequencies for undamaged case are presented in Table 2.

Tables 3 and 4 also represent detected and actual values for the first and second damaged cases, respectively. Average errors between results of SSA and actual values are 0.290% and 0.876% for the first and second damaged cases, respectively. When PSO was implemented, average errors were changed to 4.367% and 4.200%, respectively.

Table 3 Comparison between detected and actual results from three-story shear frame-first damaged case

Story	1	2	3
Actual	11.6%	0%	0%
SSA	11.53%	0%	0.8%
Error	-0.07%	0%	0.8%
PSO	8%	4.5%	5%
Error	-3.6%	4.5%	5%
Wang *et al*. (2015b)	13.2%	0%	0%
Error	1.6%	0%	0%

Table 4 Comparison between detected and actual results of three-story shear frame-second damaged case

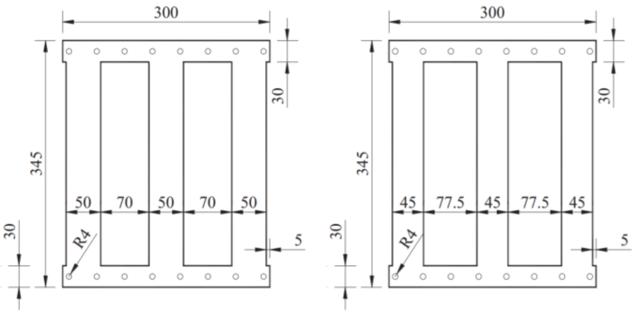
Story	1	2	3
Actual	21.1%	0%	0%
SSA	22.54%	0%	1.19%
Error	1.44%	0%	1.19%
PSO	18.5%	6%	4%
Error	-2.6%	6%	4%
Wang *et al*. (2015b)	23.9%	0%	0.5%
Error	2.8%	0%	0.5%

Fig. 8 Experimental configuration of a five-story shear frame (Koo *et al*. 2011)

These values were calculated as 0.533% and 1.100% by Wang *et al*. (2015b).

5.2 Five-story shear frame

A five-story shear frame was tested on a shaking table to validate competence of the proposed methods, as shown in Fig. 8 (Ghodrati Amiri *et al*. 2013, Koo *et al*. 2011). The structure with a random load was excited by the shaking table for 900 s. Five accelerometers were used in this experiment. Sampling frequency for this experiment was 20 Hz. This measurement was repeated eight times for each undamaged and damaged cases to evaluate uncertainty of the modal data. Theoretical values of mass and stiffness for each story were 16.09 kg and 11.89 kN/m, respectively.



(a) undamaged case (b) damaged case

Fig. 9 Columns used in five-story shear frame (Hosseinzadeh *et al*. 2014)

Table 5 Experimental natural frequencies (Hz) of five-story shear frame (Koo *et al*. 2011)

Mode	Undamaged case	First damaged case	Second damaged case
1	1.245	1.214	1.201
2	3.706	3.634	3.602
3	5.912	5.84	5.77
4	7.620	7.58	7.54

Table 6 Natural frequencies (Hz) of five-story shear frame before and after FEM updating (undamaged case)

Mode	Experimental (Koo *et al*. 2011)	Initial FEM	Updated FEM
1	1.245	1.231	1.245
2	3.706	3.595	3.706
3	5.912	5.666	5.912
4	7.620	7.279	7.620

Table 7 Comparison between detected and actual results from five-story shear frame-first damaged case

Story	1	2	3	4	5
Actual	10%	0%	0%	0%	0%
SSA	11.63%	0%	0.005%	0%	0%
Error	1.63%	0%	0.005%	0%	0%
PSO	8.9%	0%	2%	2.5%	4%
Error	-1.1%	0%	2%	2.5%	4%

Two damaged cases were considered for this structure as follows:

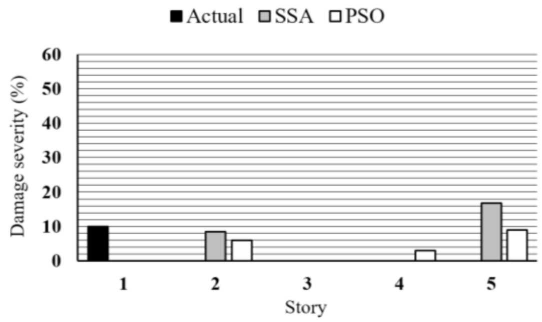
a) Damage in the first story with a 10% decrease in story stiffness

b) Damages in the first and third stories with a 10% decrease in stories stiffness

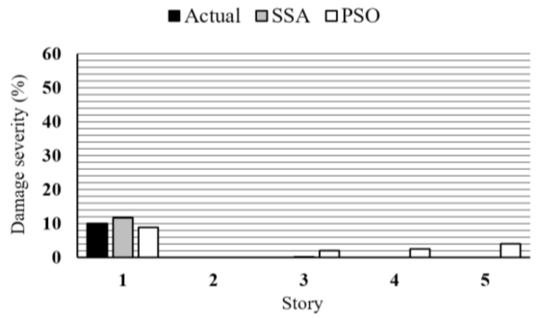
Fig. 9 illustrates columns of the five-story shear frame before and after the damages.

The four natural frequencies (including undamaged and damaged cases) are listed in Table 5. Updated natural frequencies are presented in Table 6.

Tables 7 and 8 represent detected and actual damage severity values for first and second damaged cases, respectively. The average errors between the results of SSA and actual values are 0.327% and 1.208% for the first and second damage cases, respectively. When PSO was implemented, average errors were changed to 1.920% and 4.296%, respectively.

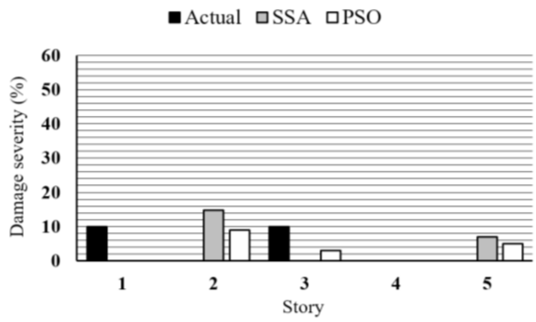


(a) Damage detection before FEM updating

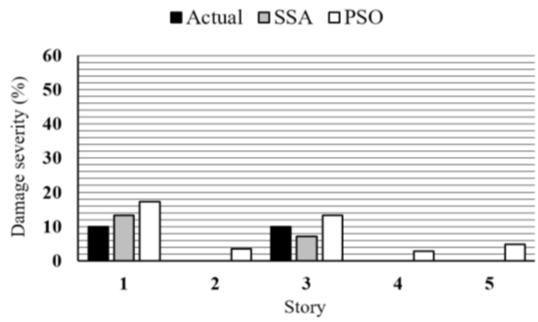


(b) Damage detection after FEM updating

Fig. 10 Results of damage detection for five-story shear frame-first damaged case



(a) Damage detection before FEM updating



(b) Damage detection after FEM updating

Fig. 11 Results of damage detection for five-story shear frame-second damaged case

Figs. 10 and 11 illustrate detected and actual damage cases. Results show the importance of FEM updating procedure in structural damage detection.

5.3 Eight-story shear frame

An eight-story shear frame (see Fig. 12) was excited by

Table 8 Comparison between detected and actual results from five-story shear frame-second damaged case

Story	1	2	3	4	5
Actual	10%	0%	10%	0%	0%
SSA	13.22%	0%	7.18%	0%	0%
Error	3.22%	0%	-2.82%	0%	0%
PSO	17.3%	3.45%	13.2%	2.78%	4.75%
Error	7.3%	3.45%	3.2%	2.78%	4.75%

Table 9 Experimental natural frequencies (Hz) of eight-story shear frame (Su *et al*. 2017)

Mode	Undamaged case	Damaged case
1	1.052	1.007
2	3.112	3.057
3	5.179	5.089
4	7.123	6.981
5	8.921	8.825
6	10.469	10.407
7	11.725	11.572
8	12.512	12.441

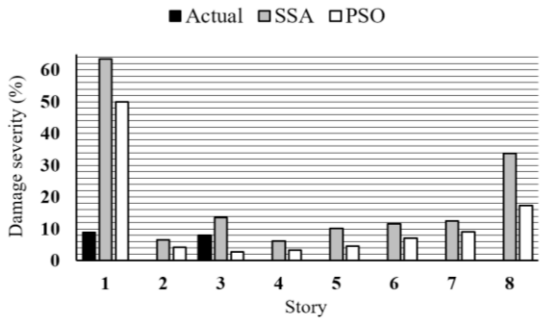
Fig. 12 Eight-story shear frame in the laboratory (Su *et al*. 2017)

a shaking table (Su *et al*. 2017) to validate competence of the proposed method for damage detection in full-scale structures. Dimensions of the frame in height, length and width are 8.5, 1.8 and 1.2 meters, respectively. The total mass of the shear frame is about 4.519 tons. The damaged case was constructed of cutoff plates in the first and third stories as shown in Fig. 13. Theoretical stiffness of the first and third stories was reduced to 8.864% and 8.008%, respectively. The eight-story shear frame was subjected to base excitations of the 1999 Chi-Chi earthquake in Taiwan. The sampling rate for this experiment was 200 Hz.

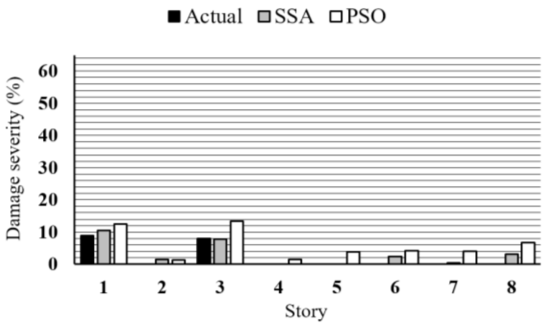
The eight natural frequencies (including undamaged and damaged cases) are listed in Table 9. Updated natural frequencies are presented in Table 10.

Fig. 14 illustrates detected and actual damaged cases. Results show efficiency of the two-stage method of updating and damage detection. It is visible that damage detection procedure is more effective using the proposed FEM updating.

Fig. 13 A damaged plate (Su *et al*. 2017)



(a) Damage detection before FEM updating



(b) Damage detection after FEM updating

Fig. 14 Results of damage detection for eight-story shear frame-damaged case

Table 10 Natural frequencies (Hz) of eight-story shear frame before and after FEM updating (undamaged case)

Mode	Experimental (Su *et al*. 2017)	Initial FEM	Updated FEM
1	1.052	1.236	1.051
2	3.112	3.665	3.112
3	5.179	5.970	5.179
4	7.123	8.071	7.123
5	8.921	9.897	8.921
6	10.469	11.387	10.469
7	11.725	12.488	11.725
8	12.512	13.165	12.512

Table 11 represents detected and actual values for damaged cases respectively. The average error between the result of SSA and the actual value was 1.140%. When PSO was implemented, average error was changed to 3.838%.

Table 11 Comparison between detected and actual results from eight-story shear frame-damaged case

Story	1	2	3	4	5	6	7	8
Actual	8.864%	0%	8.008%	0%	0%	0%	0%	0%
SSA	10.455%	1.423%	7.811%	0%	0%	2.331%	0.436%	3.143%
Error	1.591%	1.423%	-0.197%	0%	0%	2.331%	0.436%	3.143%
PSO	12.510%	1.315%	13.443%	1.514%	3.869%	4.217%	4.003%	6.703%
Error	3.646%	1.315%	5.435%	1.514%	3.869%	4.217%	4.003%	6.703%

6. Conclusions

A new optimization-based damage detection method is introduced by this study. This method consists of FEM updating and damage identification by minimizing a sensitive objective function. Objective function includes changes in natural frequencies and Natural Frequency Vector Assurance Criterion (NFVAC). Minimization of objective function was carried out using a new bio-inspired technique called Salp Swarm Algorithm (SSA). In the meantime, one of the population-based optimization algorithms called Particle Swarm Optimization (PSO) was compared with SSA.

To validate the proposed approach, three experimental shear frames were investigated. Results of these experimental examples are as follows:

• For a three-story shear frame, the average errors between the results of SSA and actual values were 0.290% and 0.876% for the first and second damage cases, respectively. When PSO was implementd, Average errors were changed to 4.367% and 4.200%, respectively. In previous studies (Wang *et al*. 2015b), these values were calculated to be 0.533% and 1.100%, respectively.

• For a five-story shear frame, the average errors between the results of SSA and actual values for the first and second damage cases were 0.327% and 1.208%, respectively. When PSO was implemented, Average errors were changed to 1.920% and 4.296%, respectively.

• For an eight-story shear frame, the average error between the result of SSA and actual value is 1.140%. When PSO was implemented, Average error was changed to 3.838%.

The results have clearly shown that the proposed method can detect the locations and severities of damage using SSA, objective function includes changes in natural frequencies and NFVAC, and FEM updating. Moreover, The results show that better accuracy is obtained using SSA than using PSO.

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