DEVELOPMENT OF A MODEL UPDATING TECHNIQUE USING SOFT COMPUTING

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Abstract

The structural models, do not necessarily predict the measured data sufficiently accurately. Because of this, there is a need for these models to be updated to better reflect the measured data. This paper introduces computational intelligence techniques to update finite element models. The model updating is formulated as a constrained optimization problem and solved using a recently developed meta-heuristic algorithm called Artificial Bee Colony (ABC) algorithm. A MATLAB code is developed using the model-updating formulations presented in this paper. Numerical simulation studies are carried out by solving for the proposed model updating technique by using pseudo-experimental data of an 8 storey framed structure and also the experimental data of ASCE three storey benchmark structure. Studies presented in this paper clearly indicate the effectiveness of the proposed computational intelligence-based model updating technique.

Keywords: *MATLAB, Artificial Bee Colony (ABC), Finite element models, ASCE three storey benchmark structure*

1. Introduction

Model updating of civil engineering structures has a great significance in the area of active and semi-active control of structures and structural health monitoring. Model updating is typically performed by updating the structural stiffness and mass matrices in order to obtain good matching of the responses obtained from the analytical structure from the corresponding experimental model. In view of the importance of model updating in engineering structures research is being carried out actively from past three decades. New and innovative techniques are being developed and reported regularly in the literature. This is clearly manifested from the huge haul of literature with several special issues of journals and conference proceedings [Chang (2003), Beck and Wu (2006)]. Model updating is typically being carried out using experimentally identified natural frequencies, mode shapes, frequency response functions etc. Since civil engineering structures are mammoth, the finite elements of these structures will obviously have a large number of degrees of freedom. This poses a serious problem for model updating as the number of unknown variables in the form element stiffness and or mass matrices increases. One alternative is to handle this problem is parameterization, using which we can reduce the number of unknown variables in the model updating process. However, the parameterization is usually carried out based on the user's discretion. Here the user’s experience comes into the picture. Hence, with parameterization, the process of model updating become subjective. Alternative formulations for model updating has been attempted in the literature by applying the orthogonality concepts, connectivity and/or boundary condition to correct/update the analytical model with Lagrange multiplier or generalized inverse method [Wei (1990), Farhat and Hemez (1993), Lin et al. (1995), Hua et al.(2009a,2009b)].In these type of approaches, the, stiffness and mass matrices obtained using the finite element idealisation of the structure are modified in order to correlate the natural frequencies and mode shapes obtained from the numerical model with the experimental model. Recently computational intelligence algorithms are being popularly used in the majority of civil engineering applications including structural system identification, structural health monitoring and also vibration control. Keeping this in view in the present work an attempt has been made to develop a computational intelligence-based model updating algorithm. In the present work, the modelling updating procedure is formulated as a constrained optimization problem and solved using the recently developed meta-heuristic algorithm called Artificial Bee Colony (ABC) algorithm. The proposed model updating algorithm is formulated in such a way that the natural frequencies and mode shapes are correlated and the mass and stiffness orthogonality is maintained. Numerical simulation studies have been carried out using framed structures. An eight-storey framed structure is employed by generating pseudo-experimental data in order to verify the proposed model updating procedure. Later the experimental data available in the literature related to ASCE three storey benchmark structure is used to demonstrate the effectiveness of the proposed algorithm.

2. METHODOLOGY

The following are the steps involved in the model updating process, which are common to every model irrespective of their type, properties, conditions etc.:

Step-1: Collect the corresponding response data after conducting the experiment from the experimental model.

Step-2: Develop a mathematical tool using the standard mathematical formulation that defines the experimental model using a computer program.

Step-3: Calculate the error between the experimental and analytical response data. If the error is very large, then re-conduct the experiment. Otherwise, select a proper optimization tool.

Step-4: Vary different parameters of the model (Material or Geometric) in the optimization process within their acceptable ranges and run the optimization process.

Step-5: Input these parameters in the mathematical tool developed and calculate the error again.

Step-6: If the error reduced, then update the numerical model with the optimal parameters obtained and this updated numerical model can be used for simulating the experimental model.

Step-7: If the error is not reduced, then there might be some problem with the experimentation or computation and it is suggested to repeat those steps again. The flow of computations are shown below

Formulation details

The dynamic equilibrium equation for any finite element idealisation can be written as

$$M\ddot{x}(t) + C\dot{x}(t) \;\; Kx(t) = F(t) \tag{1}$$

With initial conditions x (0) = x_0 and x (0) = x_0

Where matrices M, K and C represent mass, stiffness and damping respectively. x is displacement, $\dot{x}$ is the velocity and $\ddot{x}$ is the acceleration vector

A free vibration problem can be formulated by assuming that the dynamic response is harmonic in nature. Accordingly substituting

$$\left.\begin{aligned} x &= \phi \sin\omega t \\ \dot{x} &= \phi\omega \cos\omega t \end{aligned}\right\} \tag{2}$$

$$\ddot{x} = -\phi\omega^2 \sin\omega t$$

Accordingly substituting the equations (2) in equation (1), and setting damping and also the external force to zero, the following relationship can be obtained.

$$K\phi = \omega^2 M\phi \quad \text{or} \quad K\phi = \lambda M\phi \tag{3}$$

It should be mentioned here that the damping in equation (1) is set to zero and the force vector is also set to zero as the objective function is to obtain undamped free vibration.

Solving Equation (4) by using any popular Eigensolver, the Eigenvalues representing the natural frequencies ($\sqrt{\omega^2}$) and Eigen vectors representing the mode shapes of the structure can be obtained.

It is well known that the structural modes are orthogonal to stiffness and mass.

$$\phi^T M\phi = I \quad ; \quad \phi^T K\phi = \mathrm{diag}\left(\omega_1^2, \omega_2^2, ..., \omega_n^2\right) \equiv \lambda \tag{4}$$

M represents mass matrix and K represents the stiffness matrix.

Formulation of objective function for model updating

As mentioned earlier, the proposed model updating procedure is formulated as an optimization problem and solved using recently developed meta-heuristic called ABC algorithm. The fitness or objective function is formulated as follows

$$OBJ = \sum_{i=1}^{NF} ABS(\omega_i^E - \omega_i^A) + \sum_{i=1}^{NF}[1 - MAC(\Phi_i^E, \Phi_i^A)] + \sum_{i=1}^{NP} ABS(POV_i^E - POV_i^A) + \sum_{i=1}^{NP}[1 - MAC(POM_i^E, POM_i^A)] \tag{5}$$

With the following constraints

The details related to proper orthogonal decomposition with the following constraints.

$$\left.\begin{aligned} &[\overline{\phi}_i^A]^T [M] [\overline{\phi}_i^E] \neq 0 \\ &[\overline{\phi}_i^A]^T [K] [\overline{\phi}_i^E] \neq 0 \text{ where } i = 1, 2, 3.......m \end{aligned}\right\} \tag{6}$$

Sum of non-diagonal elements of matrix $[[\overline{\phi}_i^A]^T [M] [\overline{\phi}_i^E]]$ are ≈ 0.

Sum of non-diagonal elements of matrix $[[\overline{\phi}_i^A]^T [K] [\overline{\phi}_i^E]]$ are ≈ 0.

Where NF is the number of natural frequencies, superscript, E represents experimental, superscript, A represents analytical. POM and POV represent the proper orthogonal modes and proper orthogonal vectors respectively. These POMs and POVs can be obtained using proper orthogonal decomposition. Similarly, MAC is the Model assurance criteria. The proper orthogonal decomposition and also the model assurance criteria are discussed in the next section

Proper orthogonal decomposition

POD Kerschen and Golinval(2002) provides a substratum for the spectral decomposition of a spatiotemporal signal and its property of mean-square optimality provides an efficient denotes of capturing the ascendant components of a high dimensional signal through a few ascendant scales of fluctuations called Proper Orthogonal Modes.

The acceleration response function at the i^{th} (i= 1 to k time steps) step obtained at n spots looks like

$$\ddot{v}(t_i) = \begin{bmatrix} \ddot{v}_1(t_i) \\ \vdots \\ \ddot{v}_n(t_i) \end{bmatrix} \qquad (7)$$

The matrix of the response correlation $R_{uu} \in R^{nxn}$ in the time domain got to be $R_{uu}=\langle \ddot{v}(t)\ddot{v}^T(t)\rangle$, where $\langle . \rangle$ represents time averaging operator. Further, its spectral decomposition is acquired as $R_{uu} = \sum_{i=1}^{n} \lambda_i \phi_i \phi_i^T$ where λ_i represents eigenvalues of R_{uu} and ϕ_i represents eigenvectors which form an orthonormal basis. The first few ascendant modes known as the proper orthogonal modes have the greatest amount of energy and required to be selected. If E= $\sum_{j=1}^{n} \lambda_j$ is the total energy content in the data, then $\sum_{j=1}^{p} \frac{\lambda_j}{E}$ □ K is the p modes need to capture K energy of the measured accelerations. λ_i are the proper orthogonal values (POVs) and ϕ are the proper orthogonal modes(POMs).

Model assurance criterion

The model assurance criterion (MAC) is used to estimate the degree of correlation between the analytical mode shapes and experimental mode shapes. The value of MAC is in between 0 and 1.

MAC can be calculated by the following formula,

$$MAC_{jk} = \frac{\left|\{\phi_{mj}\}^T \{\phi_{ak}\}\right|^2}{[\{\phi_{ak}\}^T\{\phi_{ak}\}]\,[\{\phi_{mj}\}^T \{\phi_{mj}\}]} \qquad (8)$$

Here, MAC is modal assurance criterion;

$\{\phi_{mj}\}$ represents experimental mode shapes.

$\{\phi_{ak}\}$ represents analytical mode shapes.

A value of MAC close to 1 suggests that the two mode shapes are well correlated, while a value close to 0 indicates that the mode shapes are poorly correlated.

Artificial bee colony (abc) algorithm

The Artificial Bee Colony(ABC) algorithm is a swarm predicated meta-heuristic algorithm. This method was founded by Karaboga in 2005 for optimizing numerical problems.

In ABC model, the colony consists of three components. They are1) Employed bees, 2)Onlookers and 3) Scouts. It is postulated that the number of employed bees is equal to the number of the sources of the food situated around the hive. Employed bees go to their food source and come back to hive and dance on this area. The employed bee whose food source has been forsaking becomes a scout and commences to probe for finding an incipient aliment source. Onlookers watch the dances of employed bees and operate food sources based on dances.

The following are the steps of the algorithm:-

- Food sources are produced initially for all the employed bees.
- REPEAT
    - Each employed bee peregrinates to a food source in her memory and finds the nearest source, then determines its nectar amount and dances in the hive.
    - Each onlooker watches the dance of employed bees and selects one of their sources based on the dances, and then peregrinates to that source. After selecting a neighbour around that, she determines its nectar amount.

- ○ Food sources which are deserted are determined and are superseded with the new food sources discovered by scouts.
- ○ The best food source, so far found is stored.

- Till the requirements are met.

The flow chart of the ABC algorithm is shown in Figure 1.

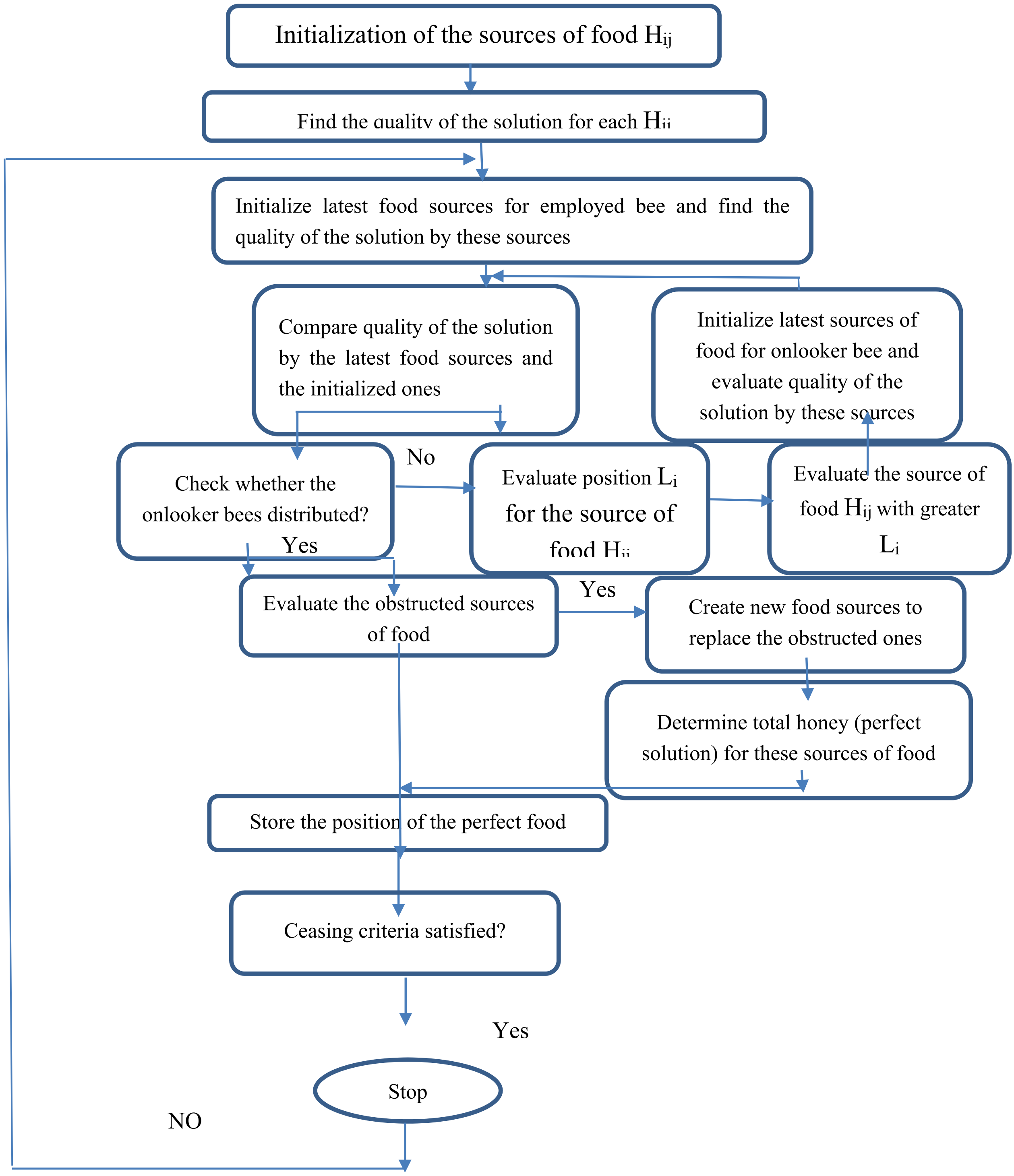

Figure 1: Flow chart of ABC algorithm

Numerical studies

A MATLAB code is developed for the proposed model updating technique discussed in the earlier sections. Numerical simulation studies have been carried out by solving an 8 storey framed structure shown in Figure 2. In order to simulate model updating procedure analytical stiffness and mass matrices of the framed structure are multiplied by a random stiffness factor ranging from 0.8 to 1.0. The resulting responses are assumed as experimental data and model updating procedure is carried out accordingly.

In this example, an 8 DOF framed structure is taken into consideration. The stiffness, damping, masses of the storeys are given below. The frame is idealised as a shear building model. In order to alter the model for the purpose of demonstrating the updating model procedure. The mode shapes and the mode frequencies obtained from this model is assumed as to be the experimental modal data. The modal frequencies (in Hz) of the actual system, the updated model, and the analytical model with a varied number of observed modes are shown in Table 1 below.

Natural frequencies for 8-DOF:

Structural properties of the 8-DOF system.

Stiffness for level 1 is 5529 KN/m and for level 2-8 is 2723 KN/m

Masses for level 1–7 is 49.48kg and for level 8 is 45.06kg

Damping for all level is 1%.

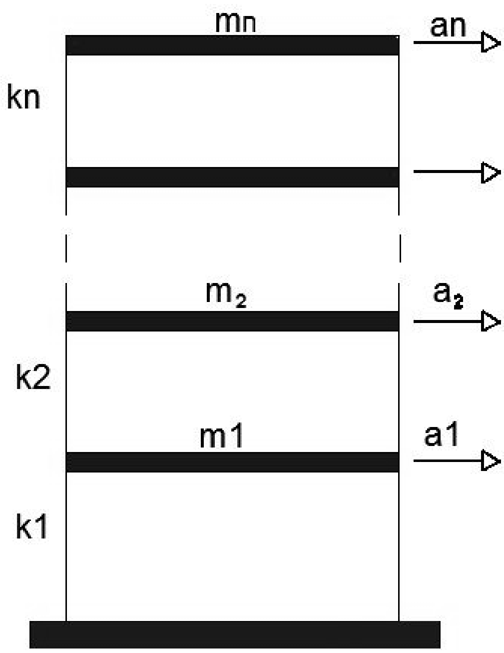

Figure 2. Eight storey framed structure

Table1: Performance of the proposed model updating technique-comparison of natural frequencies of eight storey framed structure

Pseudo-experimental frequency	**Numerical model frequency**	**Percentage change**
(Hz)	(Hz)	(%)
0.2205	0.2182	1.04
0.6189	0.6103	1.39
1.0005	1.0033	-0.28
1.4259	1.4296	-0.26
1.7755	1.7768	-0.07
1.9404	1.9412	-0.04
2.0949	2.0830	0.57
2.2607	2.2256	1.55

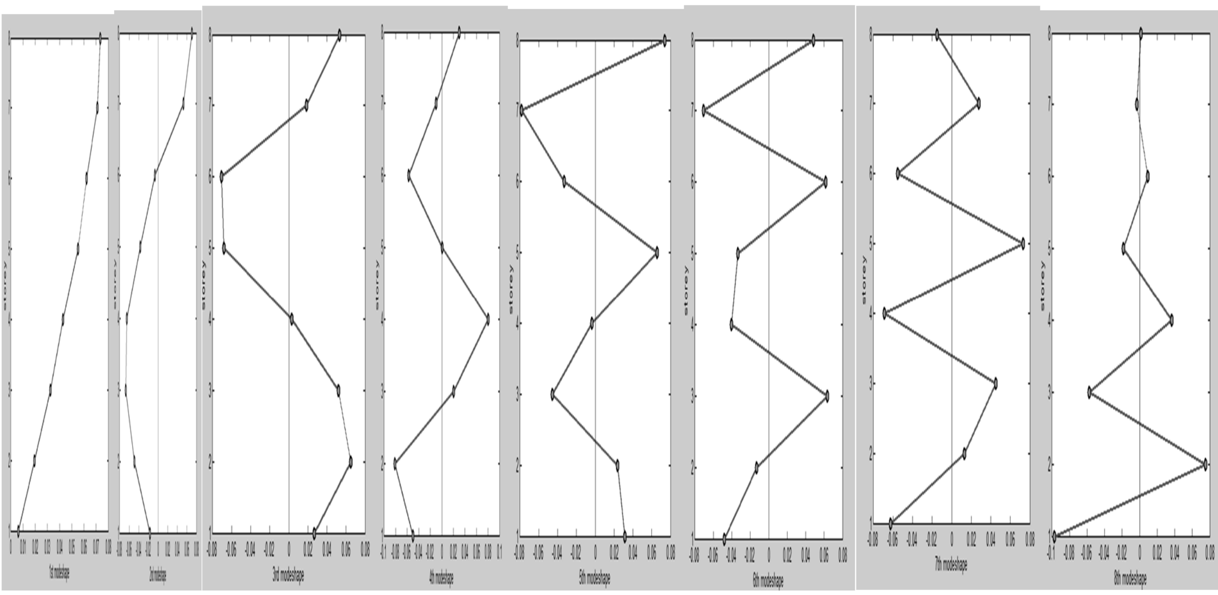

Figure 3: Numerical Example 1: Comparison of mode shapes:

The IASC-ASCE SHM benchmark structure is a four-storey, two-bay by two-bay steel frame quarter-scale model structure fabricated at the earthquake engineering research laboratory at the University of British Columbia (UBC).the plan dimensions of the scaled-down model is 2.5 m x 32.5 m and the height is 3.6 m. Further details about this model can be found in Johnson *et al*(2004). An analytical model of the structure is shown in Figure 4.

The shear building model is utilized for the SHM benchmark problem to get the simulated data. In the present model, the floor beams and floor slabs move as rigid bodies. Therefore there is one DOF's per floor. The natural frequencies obtained using the proposed model updating procedure are compared with the experimental natural frequencies and are shown in Table 2. The experimental mode shapes are compared with the theoretical mode shapes obtained using the proposed model updating technique is shown in Figure 5. It can be observed from the results furnished in Table 2 and Figure 5, that there is a very close agreement in the values clearly demonstrating the effectiveness of the proposed model updating procedure.

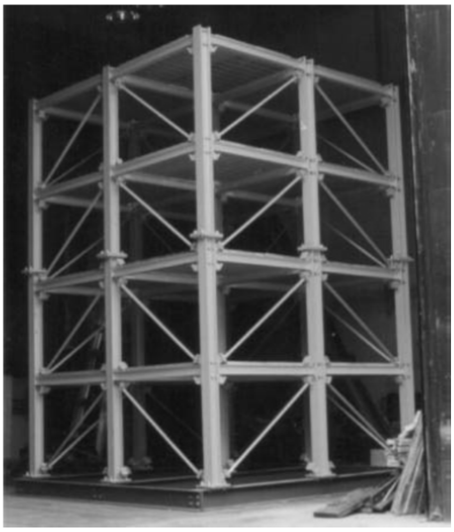

Figure 4. IASC-ASCE SHM benchmark structure

Table 2: Comparison of natural frequencies obtained using the model updating technique with the experimental data

Frequencies (Hz) taken From the experimental data of IASCE-ASCE Benchmark	**Analytical Frequencies (Hz) obtained using the proposed model updating technique**	**Error %**
9.4156	9.4147	0.096
25.5579	25.4107	0.576
38.6830	38.6472	0.093
48.0317	47.9509	0.168

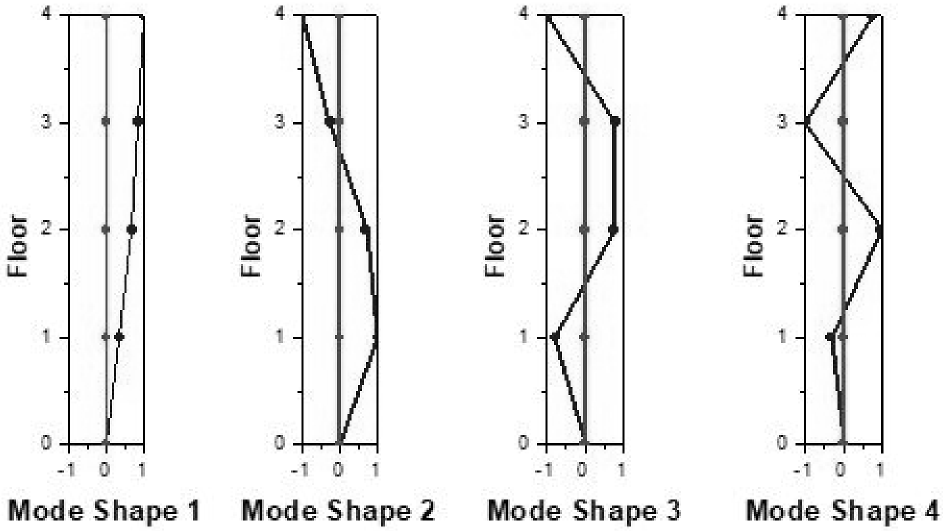

Figure 5: Comparison of experimental mode shapes with the theoretical mode shapes obtained using the proposed model updating technique

4. Conclusion

In this paper, a model updating technique using soft computing technique is presented. The problem of model updating is formulated as a constrained optimization problem and solved using a metaheuristic algorithm. In this paper, a recently developed Artificial Bee Colony (ABC) algorithm is employed for solving the constrained optimization problem. Numerical simulation studies have been carried out by solving two frame examples to demonstrate the effectiveness of the proposed model updating procedure. Among them, one is the IASC-ASCE benchmark experimental structure. The numerical investigations presented in this paper clearly demonstrate the effectiveness of the proposed model updating procedure and reemphasizes the utility of computational intelligence technique in the field of structural engineering

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