A Global Method for Structural Damage Detection
Part II: A Comparative Study and Verification

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Abstract

To identify structural damages many different methods have already been developed. Evaluating the performance of these methods is not a convenient task because they have been applied to different structures or constructed for specific purposes. Most of these methods use model-updating techniques, as a tool, to detect and assess damage. On the other hand some methods, including Energy Index Method, use the concept of strain energy to detect damage. This paper tries to compare the performance of Energy Index method with the performance of a model-updating-based model. In order to facilitate the comparison of various damage identification methods a structure proposed by the IASC-ASCE Task Group on Structural Health Monitoring is considered as the benchmark structure. Finally, the effects of measurement noise and incompleteness of data on the performance of the proposed algorithm are investigated.

Keywords: Damage Assessment, Noisy Incomplete Measurement, Benchmark Structure, Energy Index. Model Updating.

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1. Introduction

Damage identification is relatively a new merging field of study in civil engineering. It has been attracting a lot of attention among a diverse group of researchers. As a result of its popularity, there are a considerable number of methods and algorithms for damage detection at our disposal. Many papers, theses and reports that address damage detection and related issues have already been published [1-9]. Each of these documents contains a literature survey and covers the development of the theory relevant to its scope. However, these different damage identification methods have not been applied to the same structure yet. Besides, a multitude of disparate evaluation criteria makes it also more difficult to compare and to contrast the merits of these various techniques against each other.

Due to size and complexity of a structure, it is impossible to record a specific measurement at all degrees of freedom. In addition, it is not possible to measure some degrees of freedom, such as rotational and internal degrees of freedom. On the other hand, in a real case, usually the measurements are contaminated by noise. Noise has a random nature and its magnitude depends on the sensors accuracy. In the presence of noisy measurements, damage detection algorithms will produce results different from those with noise-free data. Noise in the measurements might mislead an algorithm in identification of damaged elements and it may fail to localize the damage at all. Therefore, it is desirable to develop an algorithm which assesses the damage from noisy and spars data. Some authors have already used parameter estimation and system identification techniques as a tool to achieve such an algorithm. All of these researchers found that the number and locations of sensors significantly affect the quality of the estimation of parameters. But, there is no reliable method available yet to determine the optimal measurement location.

In this paper, Energy Index Method, which was developed by the authors and was presented in Part (I) of this paper, is modified by an iterative procedure to be able to identify the location and the magnitude of damage by using noisy incomplete measurements. Results show that the algorithm is not sensitive to noise for locating the damage but noise affects the quantification of damage severity. The efficiency of the proposed method is compared with the performance of the method presented by Pothisiri and Hjelmstad [10, 11] which is based on a model-updating technique. They employed the Output Error Estimator, (OEE), proposed by Banan and Hjelmstad [12] to detect the structural damages using incomplete noisy measurements. They tried to find the near-optimal location of measurements and successfully detected large damages for different levels of noise in measurement. But their algorithm is relatively slow and time consuming, especially when it is employed to identify structural damages in large, complex structures.

Finally, we will apply our Energy Index Method to the benchmark problem proposed by the IASC-ASCE Task Group on Structural Health Monitoring [13]. This problem has been used by some researchers to investigate the performance of their own proposed methods [14-21].

2. An Investigation on Noisy Incomplete Measurements

In general, Energy Index method tries to solve the following damage equation system to find damage location and severity using modal data (see part I of this paper):

$$
\begin{aligned}
&\boldsymbol{S}\boldsymbol{\delta}_e = \boldsymbol{r} \\
&s_{ie} = \tilde{\boldsymbol{q}}_{ie}^T \boldsymbol{k}_e \tilde{\boldsymbol{q}}_{ie}\,, \quad r_i = \tilde{\boldsymbol{Q}}_i^T \boldsymbol{K} \tilde{\boldsymbol{Q}}_i - \sum_{j=1}^{L} P_{ij} \tilde{Q}_{ij} \quad \text{(Static)} \\
&s_{ie} = \tilde{\varphi}_{ie}^T \boldsymbol{k}_e \tilde{\varphi}_{ie}\,, \quad r_i = \tilde{\boldsymbol{\Phi}}_i^T \boldsymbol{K} \tilde{\boldsymbol{\Phi}}_i - \tilde{\omega}_i^{\,2} \quad \text{(Dynamic)}
\end{aligned} \tag{1}
$$

where s_{ie}, the members of the system matrix $\boldsymbol{S}$, is the element strain energy of the *e*th element due to the *i*th deformation and r_i, the elements of the residual vector $\boldsymbol{r}$, is the difference between the total strain energies of the undamaged structure and the damaged structure due to the *i*th deformation. δ_e, the members of the vector $\boldsymbol{\delta}_e$, is the *e*th element energy index which varies between zero and one. The *e*th element is undamaged when δ_e is zero, and δ_e is equal to one if the *e*th element is completely lost. Therefore, Energy Index could be considered as a Damage Index. $\boldsymbol{k}_e$ is the *e*th element stiffness matrix of the undamaged structure, $\boldsymbol{K}$ and $\tilde{\boldsymbol{K}}$ are the global stiffness matrices of the undamaged structure and damaged structure, respectively. $\tilde{\boldsymbol{\Phi}}_i$ is the mode shape of the damaged structure; $\tilde{\varphi}_{ie}$ is the displacement vector applied to the *e*th element due to the *i*th mode shape. $\tilde{\boldsymbol{Q}}_i$ is the deformation of the damaged structure due to load case *i*; $\tilde{\boldsymbol{q}}_{ie}$ is the displacement vector applied to the *e*th element due to the *i*th load case.

When all degrees of freedom are not known, some members of the system matrix $\boldsymbol{S}$ and the residual vector $\boldsymbol{r}$ remain unknown. Thus, either model reduction or expansion algorithm must be utilized during the process of damage detection. It means either the degrees of freedom of the analytical model must be reduced to be equal to the same number of measurements, or the measured data are expanded so that it matches the analytical model. Reduction techniques yield matrices wherein the connectivity of the original finite element model is destroyed, and thus the physical meaning of the model will be lost through this process. However, the data expansion algorithms which do not suffer from this shortcoming have been used more widely and recommended by many researchers.

There are different methods such as Guyan Expansion, Model Coordinate Methods, Dynamic Expansion, Eigenvector Mixing and SEREP Expansion, which can be used to complete a vector of incomplete measurements. It has been shown that, for static measurements the Guyan Expansion method, Eqn. **Error! Reference source not found.**, and for dynamic measurements the Dynamic Expansion method, Eqn. **Error! Reference source not found.**, perform the best among these methods.

$$\boldsymbol{Q}_b = \tilde{\boldsymbol{K}}_{bb}^{+}\left(\overline{\boldsymbol{F}} - \tilde{\boldsymbol{K}}_{ba}\boldsymbol{Q}_a\right) \tag{2}$$

$$\boldsymbol{\Phi}_b = -\left(\tilde{\boldsymbol{K}}_{bb} - \tilde{\omega}^2 \boldsymbol{M}_{bb}\right)^{+}\left(\tilde{\boldsymbol{K}}_{ba} - \tilde{\omega}^2 \boldsymbol{M}_{ba}\right)\boldsymbol{\Phi}_a \tag{3}$$

In these equations, the superscript (+) indicates that the matrix may not be square and the pseudo inverse should be used and the subscripts *a* and *b* are associated with measured and unmeasured degrees of freedom, respectively.

Because the members of stiffness matrix are unknown, the system of energy equations and data expansion equations must be solved simultaneously as shown in Fig.1. Where in this figure *i* is the number of iteration, ε_1 and ε_2 are user defined thresholds and *N* is the maximum number of iteration which must be defined by the user.

It is observed that the convergence of the algorithm is sensitive to the location and the number of measurements. In dynamic tests, when just few measurements corresponding to higher modes are used, through observing the performance of the algorithm one can conclude that the results are not reliable. However, if the deformed configurations which have smooth shapes and developed uniform strain energy in structural elements are used, the algorithm almost always converges to the correct solution.

3. Simulation Study for Noisy and Incomplete Data

The considered structure is a bridge truss illustrated in Fig.2. We assume that two structural members are damaged: members 22 and 46 with 30% and 50% damage severity, respectively. Assume that the measurements are sampled at certain discrete locations as shown in Fig.2. In the simulated static tests, we use five load cases which shown in Fig.2. We also assume that the natural frequencies and mode shapes of the first two modes of the structures are available. This information is used as our measured data. The results of the damage identification process are shown in Fig.3. It can be seen that the rate of convergence of the algorithm is very good. After 3 or 4 iterations all damaged members are successfully identified with their exact actual damage severity for both modal and static responses. The accuracy of results is sensitive to the location and the number of measurements. The results are not reliable if just few measurements corresponding to higher modes are used.

In a simulation environment, noisy measurement might be produced by using the concepts of either proportional error or absolute error. Proportional errors generate the largest error at the maximum value of the measurement, while absolute errors are added to the simulated measurements regardless of their magnitude. The actual error falls somewhere between these two types of errors. Herein, we add the proportional error to noise-free data as follows

$$\tilde{\boldsymbol{Q}} = \boldsymbol{Q}_F (1 + \varepsilon \xi) \tag{4}$$

where amplitude ε quantifies the level of noise and ξ is a random number in the range of [-1, 1]. Vectors $\boldsymbol{Q}_F$ and $\tilde{\boldsymbol{Q}}$ are the noise-free data and noisy measurements.

In our evaluation process, we employed four different levels of noise i.e. ε=1%, 3%, 5% and 10% for dynamic measurements. For each of the noise levels, we generate 100 different measurements data sets from the simulated noise-free response.

To evaluate the performance of Energy Index method two indicators are utilized here. First, the False-Negative Error Rate for actual damaged member, and second the False-Positive Error Rate for undamaged elements (Intact members). False-negative error rate for a damaged element is defined as the ratio of the number of the solutions that missed this element to the total number of the solutions. False-positive error rate for an intact element is defined as the ratio of the number of the solutions that predicted this element as damaged element to the total number of the solutions.

When the measurements are contaminated by 5% noise the false-negative error rate indicator of each damaged element for different levels of noise and the false-positive error rate indicators for undamaged elements (intact members) are shown in Table 1 and Table 2, respectively. One can observe that the false-positive error rate values are small. It means that if the measurement sets are sufficient, the algorithm can identify damaged member even with high levels of noise.

In this simulation, it is permitted that the damage index of each elements, δ_e, varies from zero to infinite value $[0, \infty)$. Then those solutions which have δ_e>1 are not considered. The result reveals that for noise levels up to 5% no solution is neglected. But for the measurements with 10% noise, 89 solutions are omitted. It means that these measurements are not suitable because they contaminated by high level of noise.

4. Comparative Study

In this section Energy Index method is compared with the method presented by Pothisiri and Hjelmstad [10, 11]. Their method is based on model updating technique and applied to the truss structure shown in Fig.4. In addition to the self-weight of the structural members shown in the Fig.4, we assume that the dead load of the structure is uniformly distributed along all 35 members with a mass density equal to 82.977 $kg.sec^2/m^2$.The mode shapes are assumed to be measured at a certain subset of degrees of freedom of the structural model as shown in Fig.4. Note that the measured degrees of freedom are those that identified in Ref. [10] as near-optimal subset location of measurement. They simulated two single damage cases in their report. Damage case 1: member 12 with 75% damage severity and case2: member 12 with 20% damage severity as a light damage. For each damage case, damage is simulated by reducing the cross-sectional area of a truss member.

Three different levels of noise in the measured mode shapes i.e., ε=5%, 10% and 20% are considered to simulate noisy measurements. Table 3 compares the results of the proposed algorithm and the result of the method presented in Ref. [10]. It is noteworthy that in Ref [10] the first six mode shapes were used for detecting damage while in our method we have just used the first mode shape. Besides, the inputs are not the same, but the level of noise is the same for both methods.

5. IASC-ASCE Benchmark Structure

The benchmark structure constructed in the Earthquake Engineering Research Laboratory at the University of British Colombia (UBC) is a 4-story, 2-bay by 2-bay steel-frame quarter-scale model structure. All details of this structure are available on IASC-ASCE Structural Health Monitoring Task Group web site at {http://wusceel.cive.wustl.edu/asce.shm}.

Two finite element models of this structure were developed under the auspices of the Task Group to generate the simulated response data: a 12-DOF and a 120 DOF Model.

The 120-DOF model was constructed to include the effects of model error in this benchmark study. This model is used to simulate the response measurements, while the 12-DOF shear building model used in the identification analysis. The results are qualitatively similar to those obtained using the experimental model of the structure, although they cannot be compared directly as the masses vary in terms of the distribution pattern and values [13].

Details of the first phase of IASC-ASCE SHM benchmark problem is presented in [22]. We have applied the Energy Index method to the case 1 of this phase benchmark problem which described as follows.

In this case two damage patterns are considered: (i) no stiffness for the brace members in the first story (i.e. the braces still contribute mass, but provide no resistance within the structure) and (ii) no stiffness in any of the braces of the first and third stories. A linear 12-DOF shear building is used to simulate the response measurements and identification analyses. A MATLAB based finite element analysis code available through the IASC-ASCE SHM Task Group web site is used to compute both mass and stiffness matrices. The model has mass and story stiffnesses with percent loss of story stiffnesses for each damage pattern as shown in Table 4. The excitations are applied one per floor (independent loading in the weak (y) direction at each floor) as approximating the effect of wind or other ambient excitation on the structure, and are modeled as independent filtered Gaussian white noise and generated using a sixth-order low-pass Butterworth filter with a 100 Hz Cutoff. Sixteen accelerometers, two in x and y directions per floor, return noisy sensor measurements (with 10% Root Mean Square noise). 1% modal damping is assumed in each mode.

The type of provided data which is required for the process of damage identification is the mode shapes and natural frequencies which must be obtained from the response data. Herein two steps are used to identify modal parameters; first Natural Excitation Technique (NExT), which its effectiveness has been demonstrated through the identification of structural modal parameters in various types of civil structures using ambient vibration, is used to find free response data from forced responses. Second Eigen-system Realization Algorithm (ERA) developed by Juang and Papa [23] is utilized to identify modal parameters from the free response data. Because it is quite effective for identification of lightly damped structures and is applicable to multi-input/multi-output systems.

The reference response channel is selected to be the acceleration of the fourth floor of the system. This channel is chosen as the reference to ensure that all of the modes would be observed in the data (it is not a node of any mode). Using a sampling frequency of 200 *Hz*, 90 seconds of data, and 4096-point frames with 50% overlapping is deemed appropriate for identification of modal parameters. The results are provided in Table 5. The maximum difference between the exact (Johnson et al. 2004) and identified natural frequency values (Table 5) is 1.71%. With these results, Energy Index method is applied to the benchmark structure and damage identification results are shown in Table 6. Maximum difference between actual and predicted damage in this table is 7.5%.

6. Conclusion

An iterative procedure is augmented to Energy Index method to identify the location and the magnitude of damage by using noisy incomplete measurements. The effects of measurement noise and incompleteness of data in damage detection process are studied. There are cases where actually damaged elements are detected as undamaged or actually undamaged elements are detected as damaged. But it is shown that the accuracy of results will be significantly improved when the level of noise in the measurements decreases. When the magnitude of damage is high, the algorithm is not sensitive to the noise and it successfully detects the damage with noise up to 20%. In the case of light damages the algorithm successfully identifies the damage with noise up to 5%. Based on the demonstrated behavior of the algorithm we expect that it potentially be suitable for detecting damage in complex structures with large inertia that only few numbers of their degrees of freedom and mode shapes are measurable and the measurements might be contaminated by reasonable amounts of noise.

Finally, Energy Index Method is applied to the benchmark structure sponsored by the IASC-ASCE Task Group on Structural Health Monitoring which is developed in order to facilitate the comparison of various damage identification methods. The algorithm successfully detects the damages of this benchmark structure.

In this research, numerical simulations were performed on structures where each structural element is modeled with a single stiffness parameter. Further investigations needed to be carried out to examine the behavior of the Energy Index method when applied to the structures with structural members are characterized by multiple stiffness parameters.

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Figure Captions

Fig. 1. Flowchart of the proposed algorithm for incomplete measurements.

Fig. 2. Cross-sectional properties and the layout of bridge truss.

Fig. 3. Predicted damages using proposed method for incomplete measurements.

Fig. 4. Cross-sectional properties and the layout of bridge truss.

Table Captions

Table 1. False-negative error rate indicators of damaged elements.

Table 2. False-positive error rate indicators of intact elements for 5% noise.

Table 3. Comparison of the results provided by the proposed algorithm and the algorithm presented by Pothisiri and Hjelmstad [10, 11].

Table 4. Horizontal story stiffness (*MN/m*) of Undamaged and Damaged 12-DOF model.

Table 5. Identified natural frequencies of the benchmark for different damage patterns.

Table 6. Damage identification results for benchmark structure.

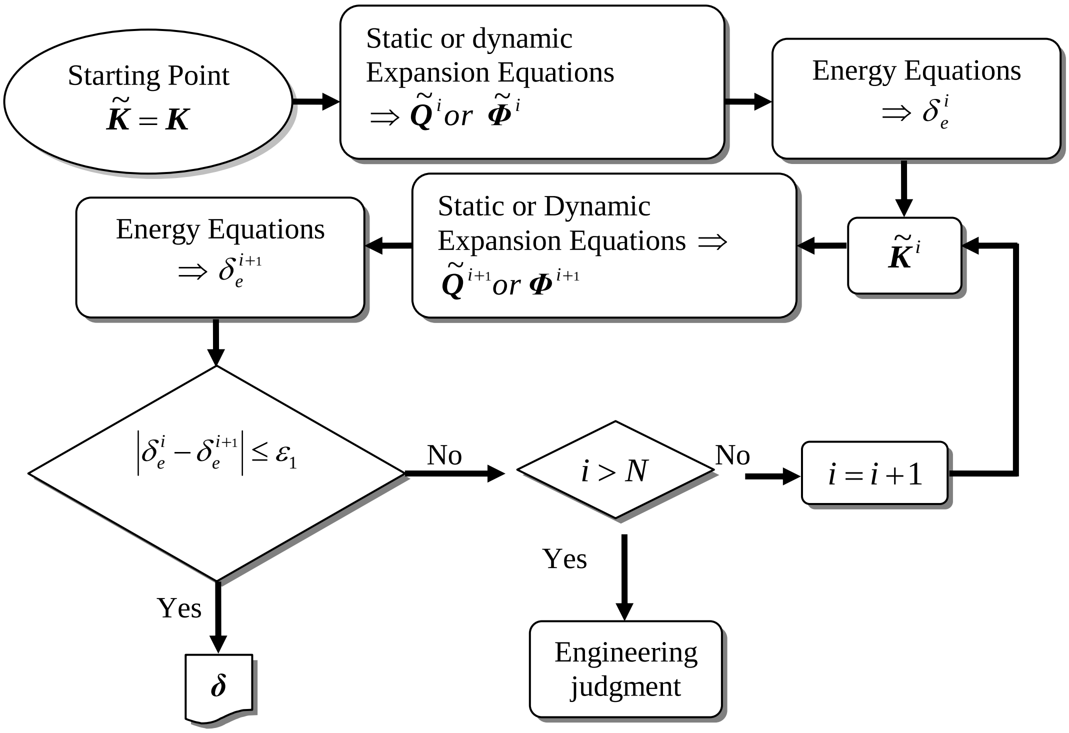
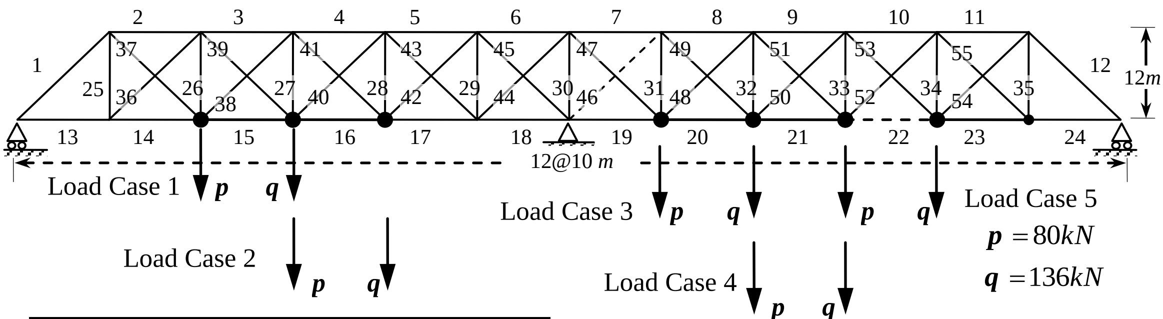


Fig. 1. Flowchart of the proposed algorithm for incomplete measurements.

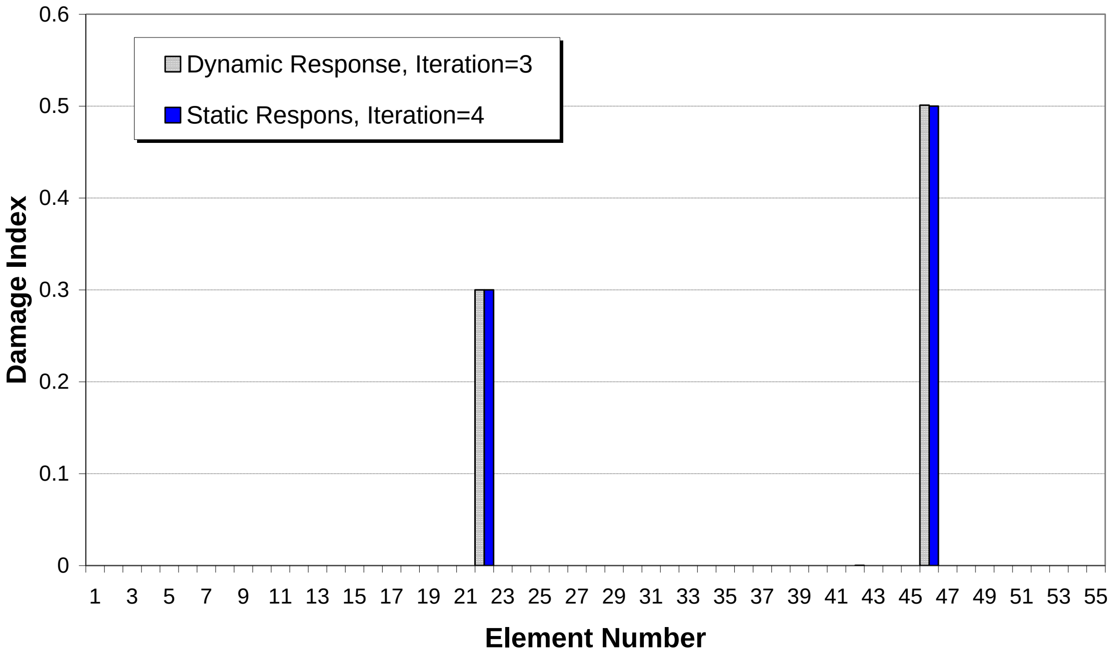


Member	Area (cm^2)	Member	Area (cm^2)
Top	250	Vertical	200
Bottom	300	Diagonal	220

Observation Point: ●

$\rho = 7.827E\text{-}08 \ {}^{kN \cdot S^2}\!/\!{}_{cm^4}$; $E = 19994.798 \ {}^{kN}\!/\!{}_{cm^2}$

Fig. 2. Cross-sectional properties and the layout of bridge truss.



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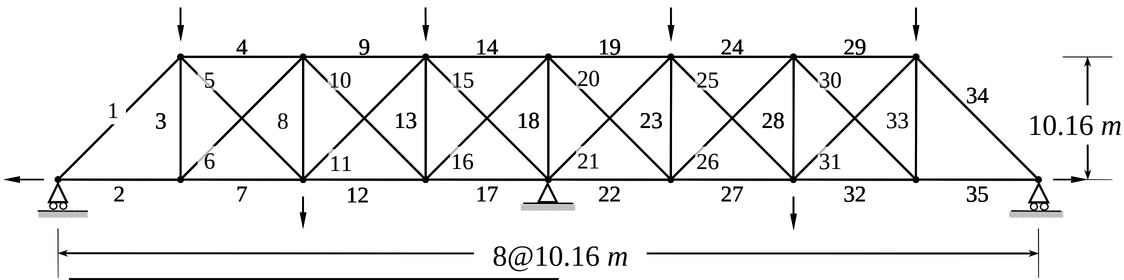

Members	Area (cm^2)	Mass ($Kg.Sec^2/m^2$)
Top	258.064	20.75148
Bottom	309.677	24.90183
Vertical	193.548	16.60122
Diagonal	206.451	15.52701

$E = 2\times10^{8}\ {}^{KN}\!/_{m^2}$

Measured DOFs: ↓ →

Fig. 4. Cross-sectional properties and the layout of bridge truss.

Table 1. False-negative error rate indicators of damaged elements

Noise Level	False-Negative Error Rate	
	Element 22	Element 46
1%	0%	0%
3%	1%	0%
5%	10%	6%
10%	18%*	0%*
*Rambling solutions are omitted.		

Table 2. False-positive error rate indicators of intact elements for 5% noise

Intact Element	F.P.E.R	Intact Element	F.P.E.R	Intact Element	F.P.E.R
1	0%	19	0%	38	0%
2	0%	20	3%	39	0%
3	0%	21	7%	40	0%
4	0%	23	0%	41	0%
5	0%	24	0%	42	0%
6	0%	25	0%	43	0%
7	0%	26	0%	44	0%
8	0%	27	0%	45	0%
9	0%	28	0%	47	0%
10	0%	29	0%	48	0%
11	0%	30	3%	49	0%
12	0%	31	0%	50	0%
13	0%	32	0%	51	0%
14	0%	33	0%	52	0%
15	0%	34	0%	53	0%
16	1%	35	0%	54	0%
17	0%	36	0%	55	0%
18	0%	37	0%		

Table 3. Comparison of the results provided by the proposed algorithm and the algorithm presented by Pothisiri and Hjelmstad [10, 11].

Damage Scenario	Simulated Damage	Noise Level	Proposed Algorithm	Pothisiri and Hjelmstad
1	$\delta_{12} = 75\%$	5%	$\delta_{12} = 81\%$	$\delta_{12} = [60\%, 100\%]$
		10%	$\delta_{12} = 83\%$	$\delta_{12} = [40\%, 100\%]$
		20%	$\delta_{12} = 91\%$	$\delta_{12} = [25\%, 100\%]$
2	$\delta_{12} = 20\%$	5%	$\delta_{12} = 50\%$	$\delta_{12} = [5\%, 30\%]$
		10%	Fail	Fail
		20%	Fail	Fail

Table 4. Horizontal story stiffness (*MN/m*) of Undamaged and Damaged 12-DOF model.

Element		**Mass**	**Undamaged**	**Damage Pattern (i)**		**Damage Pattern (ii)**	
Story	DOF	*kg*	Stiffness	Stiffness	Percent	Stiffness	Percent
1	x	3452.4	106.60	58.37	45.24%	58.37	45.24%
1	y	3452.4	67.90	19.67	71.03%	19.67	71.03%
2	x	2652.4	106.60	106.60	0	106.60	0
2	y	2652.4	67.90	67.90	0	67.90	0
3	x	2652.4	106.60	106.60	0	58.37	45.24%
3	y	2652.4	67.90	67.90	0	19.67	71.03%
4	x	1809.9	106.60	106.60	0	106.60	0
4	y	1809.9	67.90	67.90	0	67.90	0

Table 5. Identified natural frequencies of the benchmark for different damage patterns.

DOF	**Damage pattern**	**Natural Frequency** (*Hz*)			
		Mode 1	Mode 2	Mode 3	Mode 4
x-axis	(i)	9.91	28.97	47.47	60.10
	(ii)	9.62	24.93	46.94	54.37
y-axis	(i)	6.32	21.64	37.48	47.92
	(ii)	5.92	14.99	36.18	41.45

Table 6. Damage identification results for benchmark structure.

DOF	**Story**	**Damage pattern (i)**		**Damage pattern (ii)**	
		Predicted	Actual	Predicted	Actual
x-axis	1	41.81%	45.24%	41.98%	45.24%
	2	0	0	0	0
	3	0	0	45.13%	45.24%
	4	0	0	0	0
y-axis	1	66.26%	71.03%	69.48%	71.03%
	2	0	0	0	0
	3	0	0	69.50%	71.03%
	4	0	0	0	0

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