트러스 구조물 내 손상부위 추적에 관한 실험적 검증

Experimental Verification of Nondestructive Damage Detection in a Truss Structure

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Abstract

In this paper, a damage detection method using mode shapes of truss structures is presented. The theory is formulated based on the changes in the modal strain energy in a truss type structures due to damage. To examine the feasibility, the theory is applied to an experimental data of a 1:6 scale model of a typical hexagonal truss structure. The experiment consists of 17 damage scenarios subjected to three different types of damage. The damage evaluation results show that the proposed method detects successfully damage in truss elements and also show that the performance of proposed method can be significantly impacted by the noise in the measurement data for small damage.

요 지

본 논문에서는 모드형상을 이용한 트러스 구조물의 손상탐지 방법을 소개하였다. 트러스 부재에 대한 손상탐지 이론은 손상 전과 손상 후의 모달 변형에너지의 차이점을 이용하여 정립하였으며, 이론의 타당성을 조사하기 위하여 1:6 축척의 6각형 트러스 구조물의 실험 데이터에 이론을 적용하였다. 손상 실험은 총 17가지의 시나리오로 구성되어 있으며, 손상 타입은 3가지로 구성되어있다. 17가지 실험 데이터에 대한 손상평가 결과, 본 연구에서 제안한 방법으로 트러스 부재의 손상을 성공적으로 탐지할 수 있었으며, 비교적 작은 손상의 경우 계측 데이터의 노이즈가 손상탐지 성능에 많은 영향을 미친다는 것을 확인하였다.

Keywords : Damage Detection, Truss Structures, Mode Shapes, Modal Strain Energy

핵심 용어 : 손상탐지, 트러스 구조물, 모드형상, 모달 변형에너지

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1. Introduction

Preventing deterioration while maintaining the serviceability of structures has emerged as a prominent problem in structural engineering. To date, numerous nondestructive damage evaluation (NDE) methods have been proposed and developed using various experimental and theoretical techniques. Some of the well known experimental techniques include ultrasonics, radiography, magnetic particle, dye penetrant, and eddy current.[1] These techniques have been applied to small-scale systems and a specific portion of large-scale structures. However, since these "local" methods can only be applied to the detection of damage on a local scale and to accessible portions of the structure, alternative methods that can be applied to the entire structure, the so-called global NDE methods using dynamic responses of a structure, are gaining acceptance. The basic idea behind these vibration-based global methods is that changes in the physical properties of a structural system alter the dynamic response characteristics of the structure.

During the past decade, a great deal of research has been conducted in the area of NDE of structural systems via changes in their vibrational characteristics.[2~4] The NDE methods developed to date can be classified into four levels, according to the specificity of the information provided by a given approach:[5] (i) Level I methods, i.e. those methods that only identify if damage has occurred,[6] (ii) Level II methods, i.e. those methods that identify if damage has occurred and simultaneously determine the location of damage,[7] (iii) Level III methods, i.e. those methods that identify if damage has occurred, determine the location of damage as well as estimate the severity of damage,[8] (iv) Level IV methods, i.e. those methods that identify if damage has occurred, determine the location of damage, estimate the severity of damage, and evaluate the impact of damage on the structure. In many studies, the resonant frequencies were used to identify damage and estimate the amount of damage.[2),(8] The shifts of frequencies, however, are very difficult to measure when a small amount of damage is introduced to a relatively large/massive structure. However, the changes of mode shapes are more sensitive to damage than those of frequencies. One potential solution to this problem is the damage index method. This method has been corroborated using numerically simulated data[9] and field data on a full-scale plate girder bridge[10]. To date, no evidence of the performance of the method with regard to truss structures has been reported.

The objective of this study is to examine the feasibility of NDD theory in truss type structures. In this paper, to explore the systematic use of modal parameters (i.e., mode shapes) in NDE on such a large/complex structure, especially on a 3-D truss type structure, the following tasks are performed: first, the nondestructive damage detection theory is formulated; second, the theory is applied to an experimental data of a 1:6 scale model of a hexagonal truss structure; and third, the feasibility of the damage detection method is investigated and discussed.

2. Nondestructive Damage Detection Theory

Let the fraction of the strain energy, F_{ij}, for a typical element j and mode i of a truss structure be given by

$$F_{ij} = \frac{k_j(\Delta_{ij})^2}{\sum_{j=1}^{NE} k_j(\Delta_{ij})^2} \quad (1)$$

where k_j represents the stiffness of j^{th} element, Δ_{ij} represents the deformation of j^{th} element in i^{th} mode, and NE is the number of elements. Let the corresponding parameter of a damaged structure be characterized by asterisk, then Eq. (1) becomes

$$F^*_{ij} = \frac{k^*_j(\Delta^*_{ij})^2}{\sum_{j=1}^{NE} k^*_j(\Delta^*_{ij})^2} \quad (2)$$

where $F_{ij}*$ and F_{ij} are related by

$$F^*_{ij} = F_{ij} + dF_{ij} \quad (3)$$

If we set $A = k_j(\Delta_{ij})^2 = \frac{A_jE_j}{L_j}(\Delta_{ij})^2$ and $B = \sum_{j=1}^{NE} k_j(\Delta_{ij})^2 = \sum_{j=1}^{NE} \frac{A_jE_j}{L_j}(\Delta_{ij})^2$, and assume that the structure is damaged in only a single location, then from Eq. (1)

$$dF_{ij} = \frac{dA}{B} - \frac{AdB}{B^2} = \frac{A}{B}\left(\frac{dA}{A} - \frac{dB}{B}\right) \quad (4)$$

Since dA=dB and B >> A, the second term dB/B can be neglected. If we set $X=k_j$, $Y=(\Delta_{ij})^2$, and $dK=dk_j$, then Eq. (4) can be rewritten as

$$dF_{ij} = \frac{1}{B}\left[\frac{\partial A}{\partial X}\frac{\partial X}{\partial K}dK + \frac{\partial A}{\partial Y}\frac{\partial Y}{\partial K}dK\right] \quad (5)$$

where $\frac{\partial A}{\partial X} = (\Delta_{ij})^2$, $\frac{\partial X}{\partial K} = 1$, $\frac{\partial A}{\partial Y} = k_j$,

and $\frac{\partial Y}{\partial K} = \frac{\partial((\Delta_{ij})^2)}{\partial K} = \frac{\partial\left((\frac{P}{K})^2\right)}{\partial K} = \frac{-2(\Delta_{ij})^2}{k_j}$

in which the force $P = k_j(\Delta_{ij}) = K(\Delta_{ij})$.

On substituting $B, \frac{\partial A}{\partial X}, \frac{\partial X}{\partial K}, \frac{\partial A}{\partial Y}$,

and $\frac{\partial Y}{\partial K}$ into Eq. (5), we obtain

$$dF_{ij} = -F_{ij}\frac{dK}{k_j} \quad (6)$$

Substitute Eq. (6) into Eq. (3) and solve for damage index β_j

$$\beta_j = \frac{k_j}{k^*_j} = \frac{\frac{f^*_{ij}}{f_{ij}} + 1}{2} \quad (7)$$

where $f_{ij} = (\Delta_{ij})^2 / \sum_{j=1}^{NE}(\Delta_{ij})^2$ and

$f^*_{ij} = (\Delta^*_{ij})^2 / \sum_{j=1}^{NE}(\Delta^*_{ij})^2$.

In field application of Eq. (7), however, a false indication of damage may result if the element is at or near a node point of i^{th} mode, because the modal energy of that element is very small relative to that of other elements. To overcome this limitation, we simply add unity to both side on the term $f_{ij}*/f_{ij}$. This scheme is equivalent to one to one mapping from domain Ω(0, 1) to Ω(1, 2). Then Eq. (7) can be rewritten as:

$$\beta_j = \frac{\frac{f^*_{ij}+1}{f_{ij}+1} + 1}{2} \quad (8)$$

The following expression will be the convenient form of damage index β_j if several modes(NM) are used

$$\beta_j = \frac{\dfrac{\left(\sum_{i=1}^{NM} f_{ij}^{*}\right)+1}{\left(\sum_{i=1}^{NM} f_{ij}\right)+1}+1}{2} \tag{9}$$

Next, we establish the criteria for damage localization based on statistical reasoning. The values, β_1, β_2, β_3,..., β_{NE} for each element, are considered as realization of a random variable. The standardized damage indicator is given by

$$Z_j = \frac{\beta_j - \mu_\beta}{\sigma_\beta} \tag{10}$$

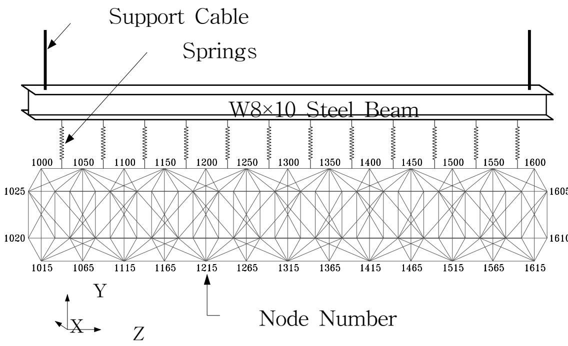
where μ_β and σ_β represent mean and standard deviation of the damage index, β_j, respectively.

The final step in damage localization is classification. Classification analysis addresses itself to the problem of assigning an object to one of a number of possible groups on the basis of observations made on the objects. There are two groups: undamaged elements and damaged elements. The observations made on the objects are the β_j's. Many techniques are available to accomplish the classification of objects. In this paper, the method of classification utilizes the Neyman-Pearson criteria.[11] Let Ho be the hypothesis that structure is not damaged at member j, and let H_1 be the hypothesis that structure is damaged at member j. The following decision rules may be used to assign damage to member j: (1) choose H_1 if $Z_j \geq \lambda$ and (2) choose Ho if $Z_j < \lambda$ where λ is a threshold which assigns a level of significance.

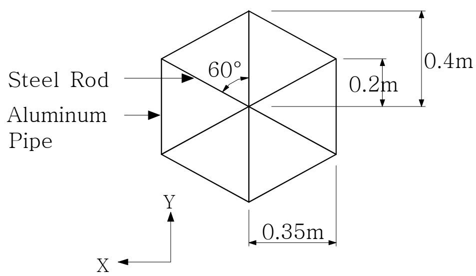
3. Application to a Laboratory Model of a Truss Structure

3.1 Description of the space truss

Carrasco et al.[12] conducted an experiment on a three-dimensional 1:6 scale model of a typical hexagonal truss to be used in the construction of the Space Station Freedom. The experimental data included mode shapes and frequencies for the undamaged and damaged cases. A schematic of the test set-up for the truss structure is shown in Fig. 1(a).



(a) Test Setup



(b) Cross Section

Fig. 1 Schematic of the Truss Structure

The test structure was suspended using twelve soft springs from a W8x10 steel beam which was in turn suspended from a mezzanine ceiling of the laboratory. The W8x10 beam was suspended with two steel cables attached at each end. The springs have an average stiffness coefficient of 0.063 kN/m. The structure is 4.83m long and consists of twelve evenly spaced bays. The model has a total of 300 elements and 91 nodes.

A typical cross-section of the truss is shown in Figure 1(b). All elements, excluding the elements contained inside the hexagon, are aluminum pipes with an outside radius of 8.56mm and a wall thickness of 2.2mm. The elements contained within the hexagon are threaded steel rods with a radius of 3.2mm.

3.2 Summary of the test

The experiment consisted of 17 damage scenarios and the structure was subjected to three different types of damages (see Table 1). Type I damage corresponded to a 180° x 1.6mm wide cut located at the center of the element. Type Ⅱ damage corresponded to the removal of 1/3 of the top half of the element. The removed section was located at the center of the damaged element. Type Ⅲ damage corresponded to a complete cut through the center of the element.

Fig. 2 shows a collection of all elements that were damaged. Mode shapes from the 17 damage scenarios and 5 undamaged baselines were measured. In each case, it was determined that there were five fundamental vibrational modes for the truss structure that could be used for the purpose of damage detection.

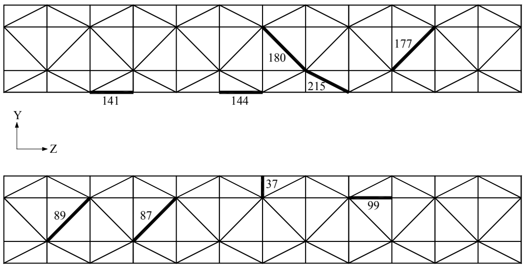


Fig. 2 Inflicted damage locations for damage scenarios 1-17

Table 1 Inflicted Damage

Damage Case	Baseline	Damaged Element(s)	Type of Damage
1	1	89	Type I
2		87	Type I
3		215	Type I
4		141	Type Ⅲ
5	2	89	Type Ⅲ
6	3	87	Type Ⅲ
7		180	Type Ⅲ
8		215	Type Ⅲ
9	4	141	Type Ⅲ
10		144	Type Ⅲ
11		37	Type Ⅲ
12		87, 89	Type Ⅲ
13	5	87, 215	Type Ⅲ
14		89, 144	Type Ⅲ
15		37, 180	Type Ⅲ
16		177	Type Ⅱ
17		99, 177	Type Ⅱ

The selected modes can be described as follows: (1) the first bending in the X-direction; (2) the first bending in the Y-direction; (3) the first torsion; (4) the second bending in the X-direction; and (5) the second bending in the Y-direction. A visualization of these modes is provided in Fig. 3. The apparatus, test set-up, data collection, and analysis of the measured data are described in great detail in the reference.[12]

3.3 Damage detection

The location of potential damage in a given structure is implemented in the following manner. First, the damage index for each element j is calculated using Eq. (9). Note that in this example all five modes are simultaneously used for the damage localization. Next, the normalized damage indicator, Z_j, is calculated using Eq. (10). Finally, pre-assigned decision rules are applied if the structure is damaged or not damaged at element j: (a) the element is damaged if $Z_j \geq 3$; (b) the element is not damage if $Z_j < 3$. In this study, damage threshold value to be $\lambda=3$ which assigns a 99% significance level. The damage localization results for the 17 damage cases are shown in Fig. 4 through Fig. 20. Table 2 summarizes results of the predicted damage locations.

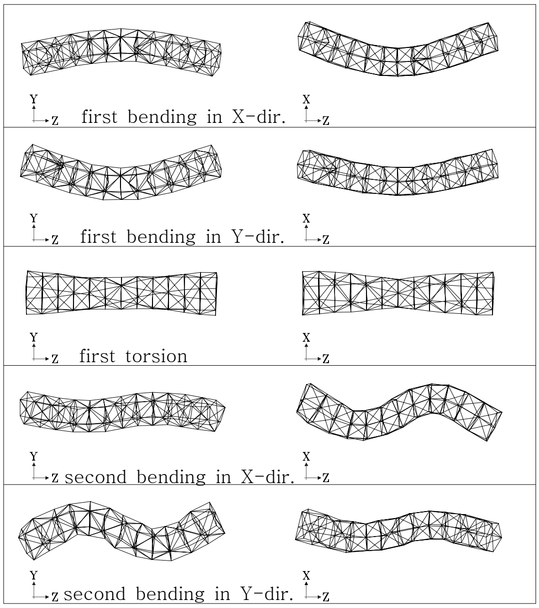


Fig. 3 Measured mode shapes for baseline structure

Table 2 Damage Location for Laboratory Experiment

Damage Scenario		Damage Location(s)	
Case	Damage Type	Inflicted	Predicted
1	Type I	89	100,294,296,299
2	Type I	87	57,58,72
3	Type I	215	137,294,296
4	Type III	141	1,103,225,227,228
5	Type III	89	57,58,89,259
6	Type III	87	87
7	Type III	180	180,295,296,298,299
8	Type III	215	215,286
9	Type III	141	57,58,141,255,256,257
10	Type III	144	144
11	Type III	37	-
12	Type III	87,89	87,89
13	Type III	87,215	87,215
14	Type III	89,144	89,144
15	Type III	37,180	26,180,295,296,298,299
16	Type II	177	177,289,292
17	Type II	99,177	99,177,296

Table 3 Performance of Method for the Laboratory Experiment

Damage Type	Number of Damage Location	Number of Correctly Predicted Locations (%)	Number of False Positives (%)	Number of False Negatives (%)
I	4	0 (0%)	15 (1.3%)	4 (100%)
II	3	3 (100%)	3 (0.5%)	0 (0%)
III	15	13 (87%)	18 (0.5%)	2 (13%)
Total	22	16 (73%)	36 (0.7%)	6 (27%)

The performance of the method is summarized in Table 3 according to the type of damage. The performance of the method is a function of the number of damaged locations. Here three indicators are utilized to evaluate the performance of this method. These include (1) the probability of localization, (2) the false positive error rate, and (3) the false negative error rate. The probability of localization is the rate of correct localization of at which we correctly localize a damaged member. The false positive error rate can be defined as the ratio of the number of locations that we incorrectly designate as being damaged to the total number of locations that are indeed not damaged. The false negative error rate can be defined as the ratio of damaged locations that are missed to the total number of damaged locations. In an ideal situation, the probability of localization should be unity, and the false positive and the false negative rates should be zero. In the present application, the consequence of a false negative is much greater than that of a false positive.

The probability of localization varies from zero to one. For the Type I damage (Damage Cases 1 to 4), which corresponded to a 180° x 1.6mm wide cut located at the center of the element, the proposed method fails to detect the correct locations of damage. Note that Type I damage was inflicted at Members 87, 89, 141, and 215. These locations of damage were repeated in Type III damage (completely cut at the center of the element) where perfectly detected (see Table 2). The poor performance on smaller damage cases (Type I damage) might be attributed to the noise contained in the mode shapes. In other words, the noise level of the measurement system exceeds the level of damage. For the Type II damage (Damage Cases 16 and 17), the proposed method correctly finds all damage locations. For the Type III damage (Damage Cases 5 to 15), there are two locations of false negative error at Member 37 (Damage Cases 11 and 15). Note that Member 37 is one of the hexagonal member in the middle of the structure. This location has very low strain energy and the sensitivity calculated by Eq. (1) is negligible. In overall, 16 locations are correctly detected for the 22 inflicted locations.

4. Summary and Conclusions

The objective of this study was to examine the feasibility of the nondestructive damage detection theory in large/complex structures via systematic use of modal parameters (i.e., mode shapes). The theory was formulated to localize the damage in 3-D truss type structures. The theory was applied to an experimental data of a 1:6 scale model of a typical hexagonal truss which subjected to three different types of damage.

From the results obtained, the following conclusions are drawn: (1) the nondestructive damage detection scheme proposed in this study can be applied successfully to truss type structures; (2) damage detection results might be better if several modes are used simultaneously; and (3) the experimental study shows that the performance of proposed method might be significantly impacted by the noise in the measurement data, especially when small amount of damage is introduced.

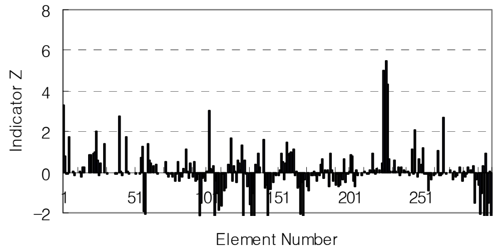


Fig. 7 Damage Localization Result for Case 4

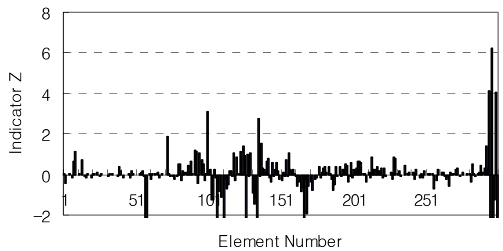


Fig. 4 Damage Localization Result for Case 1

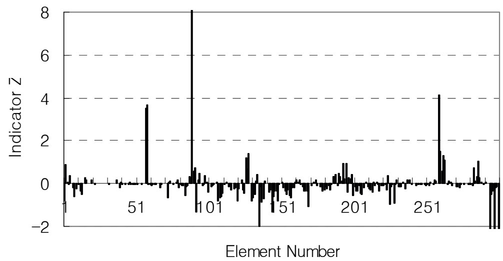


Fig. 8 Damage Localization Result for Case 5

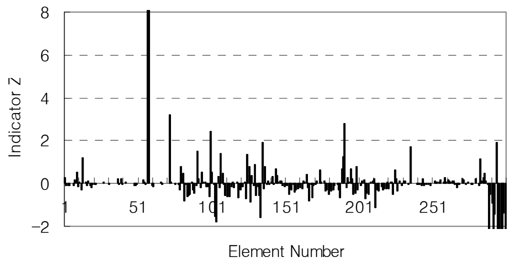


Fig. 5 Damage Localization Result for Case 2

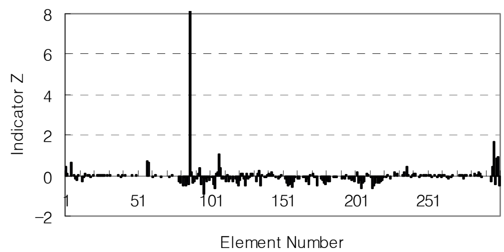


Fig. 9 Damage Localization Result for Case 6

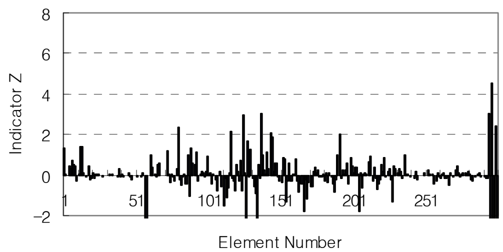


Fig. 6 Damage Localization Result for Case 3

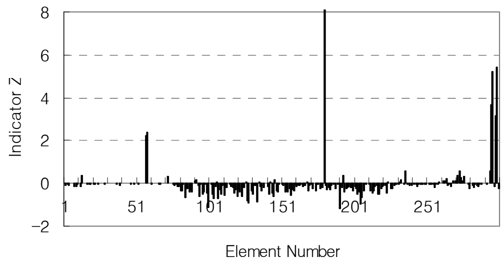


Fig. 10 Damage Localization Result for Case 7

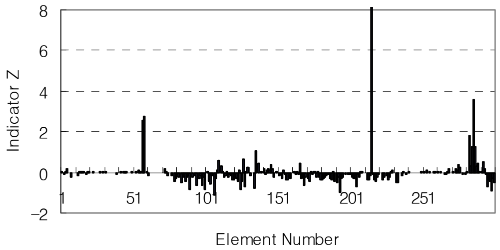


Fig. 11 Damage Localization Result for Case 8

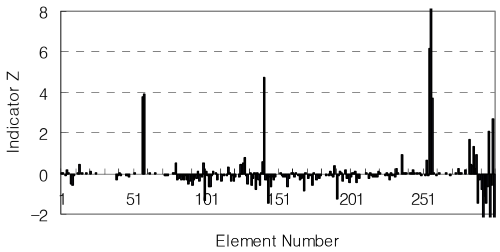


Fig. 12 Damage Localization Result for Case 9

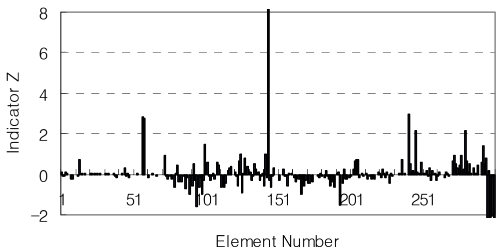


Fig. 13 Damage Localization Result for Case 10

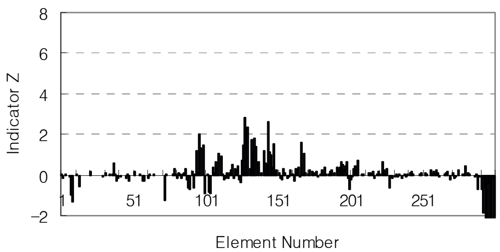


Fig. 14 Damage Localization Result for Case 11

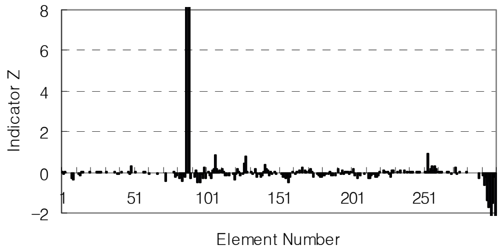


Fig. 15 Damage Localization Result for Case 12

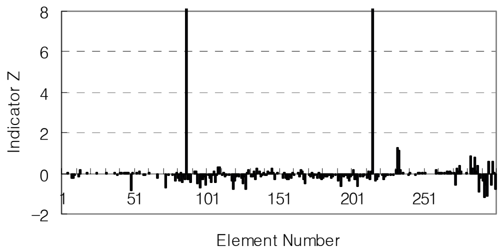


Fig. 16 Damage Localization Result for Case 13

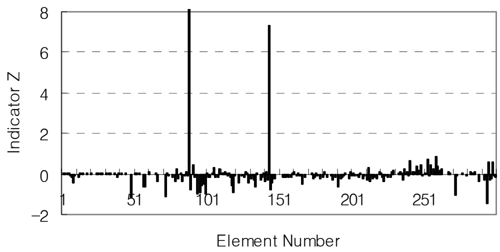


Fig. 17 Damage Localization Result for Case14

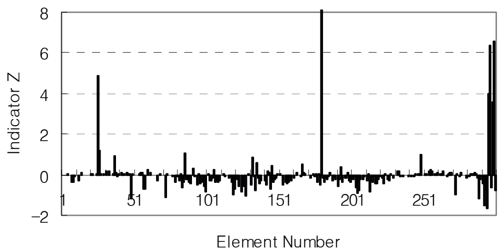


Fig. 18 Damage Localization Result for Case 15

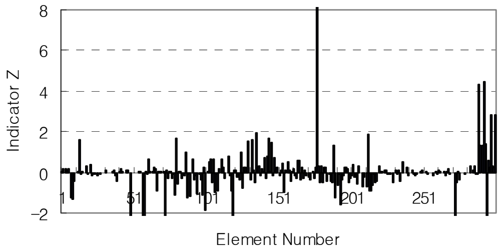


Fig. 19 Damage Localization Result for Case 16

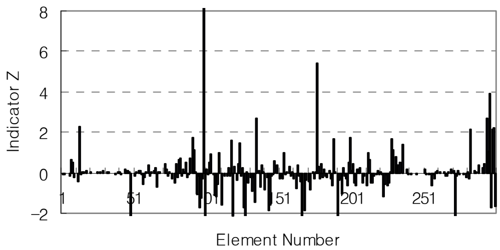


Fig. 20 Damage Localization Result for Case 17

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