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VIBRATION-BASED DAMAGE DETECTION WITH STRUCTURAL MODAL CHARACTERISTICS

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Abstract. A challenging problem in structural health monitoring systems is the requirement of a systematic, effective method for damage localisation and assessment severity of structures, based on vibration data measured by sensors. To address this issue, a novel technique, referred to as damage estimator with modal parameters of structure before and after damage, is applied to detect the location and estimate the severity of existing damage of complex structures. Specifically, a series of experimental tests using a scaled offshore platform model of a 4-story jacket type has been conducted to verify the efficiency of proposed approach, with white noise excitations applied to the top plate of test model. For 6 scenarios of damage conditions simulated by bolt adjustment in the 3rd layer, vibration-based impulse data are induced by an impact hammer and recorded to analyse the variations of modal parameters. Upon the investigation, the results highlight that damage estimator is capable of tracking damage orientation and severity longitudinally, using data from only the fundamental mode shape before and after damage. However, detection accuracy declines considerably for small-scale damages.

Keywords: health monitoring, damage localisation, severity assessment, damage estimation, offshore platform, structural modal.

1. Introduction

Damage in a structure can be defined as a reduction of its load-bearing capacity. Due to a variety of unforeseen conditions and circumstances, it will never be possible or practical to design and build a structure with a 0 % probability of failure (Idichandy, Ganapathy 1987). Structures are always accumulating damage from environmental loadings such as wind, snow and ice. Rain and moisture cause steel structures to corrode and affect the reliability and the life of a structure. In Sept 2000, a lightning mast collapsed in Baltimore Gas and Electric Co (BGE), Texas. The mast collapsed prematurely, causing a power outage and damage to a surrounding structure.

Therefore, there are needs for periodic inspections to qualify the safety of civil structures in service and take some measures to monitor and evaluate their performance, such as serviceability, reliability and durability, for the purpose of judging the existence, determining the location, estimating the severity and evaluating the consequences of a certain damage to the structure.

A central capability for the structural health monitoring system is a timely and effective response to damage. Damage detection is basically destructive or non-destructive in nature. Destructive damage detection is originally characterised by manual, visual inspection. However, poor visibility condition and concealment of damages by structure organism growth make the use of this method in damage detection unreliable (Crohas, Lepert 1982).

Conventional non-destructive tests with purely physical approaches and localised experimental measures, including penetrant testing, magnetic particle, eddy current, ultrasonic and radiographic testing, have drawn significant interest of researchers and engineers over past 2 decades (Doebling *et al.* 1998). However, they have several limitations for large structures. Firstly, they have a limited depth of penetration. Secondly, damage location must be known partly or the whole in advance and the structure needs to be tested. Lastly, there is no way to easily determine the structural health of the boundaries and joints.

By far, advanced process in computer science and information technology helps damage detection from traditional reactive management toward on-line proactive solutions for damage detection and treatment in a huge structure (Peeters *et al.* 2001). Since the physical variation of structure must result in the change of structural modal parameters (Pandey, Biswas 1994), so a structural damage at a special position has different effect on modal characteristics like frequency response function and vibration mode shapes (James *et al.* 1995), and the changes just provide the message to detect the damage.

Specifically, several automatic approaches, such as those based on perturbation theory and structure equation of motion to describe the relationship between damage and variation in modal parameter under damage, are performed to model the dynamic response and classify the abnormal conditions of huge structure from large patterns of collected modal data so as to estimate the benefits and risks of their serviceability as well as the identification of damage according to the variation of physical parameter according to the variation of modal characteristics of pre-damage and post-damage of a structure.

The realisation of such requirement has led to the application of modern vibration-based modal analysis techniques during damage detection. Saadat *et al.* (2007) presented an intelligent parameter varying (IPV) technique to evaluate structural damage. Ni *et al.* (2000) employed the probabilistic technique to identify the damage in the cable-stayed Ting Kau Bridge by simulation.

Stubbs *et al.* (1995) are the pioneers to apply the sensitivity analysis method in structural damage detection. In the forthcoming investigation they (Kim, Stubbs 1995; 2002) proposed a new structural damage indicator based on modal strain energy (MSE) properties of members and tested them via a numeral bridge model. Juang *et al.* (1985) proposed Eigensystem Realization Algorithm (ERA) and the results are efficient for highly damped structures and applicable to multi-input/output systems. Ryue *et al.* (2007) used the chaotic excitation signal as input to detect cracks in a beam.

Above all, vibration-based damage detection (VBDD) methods use damage-induced changes to the dynamic properties of a structure to detect, locate, and sometimes quantify the extent of damage and have significant advantages: 1) there is no need for unit-mass, normalisation of mode shapes, which could not be obtained, if modal parameters are extracted under unknown excitation; 2) application can be extended to online structural health monitoring system etc.

Despite various research efforts, however, many problems related to traffic infrastructure quality monitoring remain unsolved today (Kashevskaya 2007). Farrar *et al.* (1998) pointed out that most of present damage methods are effective for relatively simple structures on the assumption that the structure is dominated by flexural vibrations, though they show a high efficiency in laboratory experiment. In fact, many cases deal with complex structures, such as huge bridge, offshore, and steel building.

Therefore outstanding needs remain to locate and estimate the damage severity of complex structures: 1) in structures with only few available modes and many members, 2) in structures for which baseline modal responses are not available, and 3) in the environment of uncertainty associated with modelling, measurement, and processing errors.

Upon urgent requirement, the purpose of this paper is to present a novel vibration-based non-destructive damage detection (NDD) method to locate and estimate severity of damage in structures. It is organised as follows: Section 2 addresses the general sensitivity algorithms proposed by Kim and Stubbs. Section 3 formulates an improved NDD methodology to enhance its accuracy in damage localisation and severity estimation on the basis of the limits analysis in the existing NDD approach. Section 4 provides details on the feasibility check of the proposed NDD methodology in an offshore experimental environment. The paper concludes with general remarks about the method and its evaluation in Section 5.

2. Mathematical model and estimation

A novel method via MSE is addressed via vibration test to locate and evaluate the structural damage from the aspect of mathematical construction and real implementation.

2.1. Damage description

The equations of motion for any n-DOF dynamic system can be expressed by:

$$K\varphi = \lambda M\varphi, \tag{1}$$

where K – the stiffness matrix, M – the mass matrix, λ – the eigenvalue, and φ – the mode shape matrix.

For a linear, skeletal structure with n elements and m nodes, let λ_i and λ_i^* be the i^{th} eigenvalue before and after damage, respectively. Then, its corresponding i^{th} eigenvalue satisfies:

$$K\varphi_i = \lambda_i M\varphi_i, \tag{2a}$$

$$K^*\varphi_i^* = \lambda_i^* M^*\varphi_i^*. \tag{2b}$$

From Eq (1), the i^{th} damaged eigenvalue is:

$$\lambda_i^* = \lambda_i + \Delta\lambda_i = \frac{\left(K_i + \Delta K_i\right)}{\left(M_i + \Delta M_i\right)}, \tag{3}$$

where $\Delta\lambda_i$, ΔK_i and ΔM_i – the changes in the i^{th} eigenvalue, stiffness and mass, individually.

On expanding and reorganising Eq (3), we adopt:

$$\frac{\Delta K_i}{K_i} = \frac{\Delta\lambda_i}{\lambda_i} + \frac{\Delta M_i}{M_i}\left(1 + \frac{\Delta\lambda_i}{\lambda_i}\right), \tag{4}$$

where $\frac{\Delta K_i}{K_i}$ – the fractional change of the i^{th} modal stiffness.

In an actual structure in service, damage may often affect its stiffness distribution but not the mass matrix of the system excepting the mass one. Thus Eq (12) can be further simplified to:

$$\frac{\Delta K_i}{K_i} = \frac{\Delta\lambda_i}{\lambda_i}. \tag{5}$$

It can be seen that damage is a function of modal parameters and can be calculated directly or by an experimental measurement.

2.2. Modal strain energy approach

To a pre-damaged and post-damaged structure, its MSE for the i^{th} mode satisfies:

$$MSE_i = \varphi_i^T K \varphi_i, \tag{6a}$$

$$MSE_i^* = \varphi_i^{T*} K^* \varphi_i^*. \tag{6b}$$

Thus the MSE contribution of the j^{th} member to the i^{th} modal element is defined as:

$$MSE_{ij} = \varphi_i^T k_j \varphi_i, \tag{7a}$$

$$MSE_{ij}^* = \varphi_i^{T*} k_j^* \varphi_i^*, \tag{7b}$$

where k_i – the stiffness matrix of j^{th} member to the i^{th} modal element. Here the quantities k_j and k_j^* are:

$$k_j = E_j k_{j0}, \tag{8a}$$

$$k_j^* = E_j^* k_{j0}, \tag{8b}$$

where the scalars E_j and E_j^* – parameters representing the stiffness of the j^{th} undamaged and damaged members determined by material properties, respectively. The matrix k_{j_0} involves only geometric quantities and it can represent a beam or plate elements.

Then Eqs (7) and (8) are combined into the following expression:

$$MSE_{ij} = \varphi_i^T E_j k_{j0} \varphi_i, \tag{9a}$$

$$MSE_{ij}^* = MSE_{ij} + \Delta MSE_{ij} = \varphi_i^{T*} E_j^* k_{j0} \varphi_i^*, \tag{9b}$$

where ΔMSE_{ij} – the change in the contribution of the j^{th} member to the i^{th} modal strain energy induced by structural damage.

Suppose $\gamma_{ij} = \varphi_i^T k_{i0} \varphi_i$ and $\gamma_{ij}^* = \varphi_i^{T*} k_{i0} \varphi_i^*$, thus Eq (4) is further simplified into:

$$MSE_{ij} = \gamma_{ij} E_j, \tag{10a}$$

$$MSE_{ij}^* = \gamma_{ij}^* E_j^*. \tag{10b}$$

Let the modal characteristics associated with a subsequently damaged structure be characterised the change of MSE distribution in Eqs (6)–(10). Then for a damaged structure the change in MSE of the i^{th} mode and the j^{th} member can be defined as:

$$\Delta MSE_{ij} = \gamma_{ij}^* E_{ij}^* - \gamma_{ij} E_j. \tag{11}$$

If ΔE denotes the reduction in stiffness before and after damage, Eq (11) is thus expressed by:

$$\Delta MSE_{ij} = \gamma_{ij}^*(E_j + \Delta E_j) - \gamma_{ij} E_j. \tag{12}$$

Considering that the stiffness matrix of total structure is just integrated by each structural element together, therefore it yields:

$$K = \sum_{i=1}^{ne} k_j, \tag{13}$$

where *ne* – the total element number of structure.

On substituting Eqs (8a), (10a) and (13) into Eq (1a) and by rearranging, we obtain

$$MSE_i = \sum_{j=1}^{ne} \varphi_i^T E_j k_{j0} \varphi_i = \gamma_i E_j. \tag{14}$$

Then dividing both sides of Eq (12) by MSE_i ($MSE_i = \gamma_i E_j$), it reaches:

$$\frac{\Delta MSE_{ij}}{MSE_i} = \frac{\gamma_{ij}^*(E_j + \Delta E_j) - \gamma_{ij} E_j}{\gamma_i E_j}, \tag{15}$$

subject to:

$$\frac{E_j}{E_j + \Delta E_j} = \frac{\frac{\gamma_{ij}^*}{\gamma_i}}{\frac{\gamma_{ij}}{\gamma_i} + \frac{\Delta MSE_{ij}}{MSE_i}}. \tag{16}$$

Eq (16) provides the direct insight into the damage via MSE and some theoretical considerations for damage identification by data mining.

2.3. Estimator consideration

Assuming that the structure is damaged at a single location and its induced change in k_{ij} is only the function of E_j, it follows readily that $\Delta MSE_{ij} = \Delta MSE_i$. Thus

$\Delta MSE_{ij} = \frac{\Delta MSE_i}{nd}$, if *nd* elements are damaged totally. It should be noticed that *nd* can be located here.

According to Eq (5), the change of modal strain energy is related to proportional to the structural frequency. Therefore, by substituting Eq (12) into Eq (11), a new estimator to localise the damage for the i^{th} mode and j^{th} location is defined as $\frac{E_j}{\left(E_j + \Delta E_j\right)}$ and represented by:

$$\beta_{ji} = \frac{\gamma_{ij}^*}{\gamma_i\left(\frac{\Delta\lambda_i}{nd\lambda_i}\right) + \gamma_{ij}} = \frac{\varphi_i^{T*} k_{j0} \varphi_i^*}{\sum_{j=1}^{ne} \varphi_i^T k_{j0} \varphi_i \left(\frac{\Delta\lambda_i}{nd\lambda_i}\right) + \varphi_i^T k_{j0} \varphi_i}. \tag{17}$$

The quantities of numerator and denominator in Eq (17) are expanded by E_j, so we obtain:

$$\beta_{ji} = \frac{\varphi_i^{T*} k_{j0} \left(E_j^* - \Delta E_j\right) \varphi_i^*}{\sum_{j=1}^{ne} \varphi_i^T k_{j0} E_j \varphi_i \left(\frac{\Delta\lambda_i}{nd\lambda_i}\right) + \varphi_i^T k_{j0} E_j \varphi_i}. \tag{18}$$

Then the undamaged modal sensitivity of the i^{th} mode and the j^{th} member is described as:

$$\beta_{ji} = \frac{MSE_{ij}^* - MSE_{ij}^{**}}{MSE_i\left(\frac{\Delta\lambda_i}{nd\lambda_i}\right) + MSE_{ij}}, \tag{19}$$

where $MSE_{ij}^{**} = \varphi_i^{T*} k_{j0} \Delta E_j \varphi_i^*$.

For *nm* vibration modes, a damage estimator β_j for the j^{th} member is yielded by:

$$\beta_j = \frac{1}{nm} \sum_{i=1}^{nm} \frac{MSE_{ij}^* - MSE_{ij}^{**}}{MSE_i\left(\frac{\Delta\lambda_i}{nd\lambda_i}\right) + MSE_{ij}}, \tag{20}$$

where damage location is indicated by the reduction in modal strain energy in the j^{th} member, if $\beta_j > 1$. Here influence of experimental noise is decreased, compared with that acquired by a single modal parameter.

Let the fractional change in the stiffness of the j^{th} member be given by the severity estimator α_j, then:

$$\alpha_j = \left|\frac{E_j^* - E_j}{E_j}\right| = \left|\beta_j^{-1} - 1\right|. \tag{21}$$

According to Eq (1), the stiffness matrix of damaged structure is expanded as:

$$K^* = K + \sum_{n=1}^{N} \alpha_n K_n, \tag{22}$$

where α_n – the damage severity of the n^{th} damaged element, N – the total number of damaged elements and taking the relation between K and λ before and after damaged into consideration, it yields:

$$\sum_{n=1}^{N} \alpha_n K_n = K\left(\frac{\lambda_j^*}{\lambda_i} - 1\right). \tag{23}$$

Let assume $B = \sum_{n=1}^{N} K_n$ and $C = K\left(\frac{\lambda_j^*}{\lambda_i} - 1\right)$, then Eq (23) is transferred into $B \cdot \alpha = C$. Thus damage severity can be approximated by least-square theory as:

$$\hat{\alpha} = \left(B^T B\right)^{-1} B^T C. \tag{24}$$

This method means information on the location and severity of damage deeply and directly from the changes in mode shapes of structure. Its appealing features include: 1) damage can be located and sized by a few modes, despite of members contained in structure; 2) damage can be easily estimated without solving a series of tedious equations of system; and 3) disposal procedure is simple and on-line operation is feasible.

3. Methodology performance

A laboratory experiment, in Ocean University of China, Qingdao, P. R. China, is performed on an offshore platform to testify the method performance for damage localisation and severity assessment.

3.1. Experimental model

A 1:20-scaled modular of jacket type offshore platform, launched in Bohai hay, China, is chosen as the test object. The platform has a trapezoid section conductor and 4 non-grouted vertical piles, and the level of connection point is 2,4 m. 5 links are welded in inner of each main leg at the level of 0,6 m, 1,2 m and 1,8 m respectively in order to centralise the piles during piling as well as to reduce the space the piles and main legs in accordance with the design code. Table 1 shows the scale of main structure in platform.

Fig 1a presents the real structure of platform model, which is fabricated of steel cube and fixed to a foundation.

Table 1. Scale of the platform

ID	Cross-section	Position
1	ϕ 18 × 2,5	Column of 1 layer
2	ϕ 14 × 2,5	Column of 2–4 layers
3	ϕ 10 × 2	Beam
4	ϕ 10	Horizontal brace of 1–3 layers
5	ϕ 8 × 1,5	Vertical brace of 1–4 layers
6	20	Plate

At the top of the experimental model, a 20 mm-thick steel plate is equipped to simulate the upside weight of real offshore platform.

Correspondingly, Fig 1b gives the 3-dimensional finite element model (FEM) by ANSYS 6.0. For the column, beam and brace, BEAM4 element is used; for the top steel plate, SHELL63 element is used; and MASS21 element is launched to simulate the lumped mass outside the top plate. Thus there are 20 nodes, 1 SHELL63 element, 4 MASS21 elements and 50 BEAM4 elements, totally. Then modal analysis is performed for FEM to generate the modal parameters, so as to compare with the measured results.

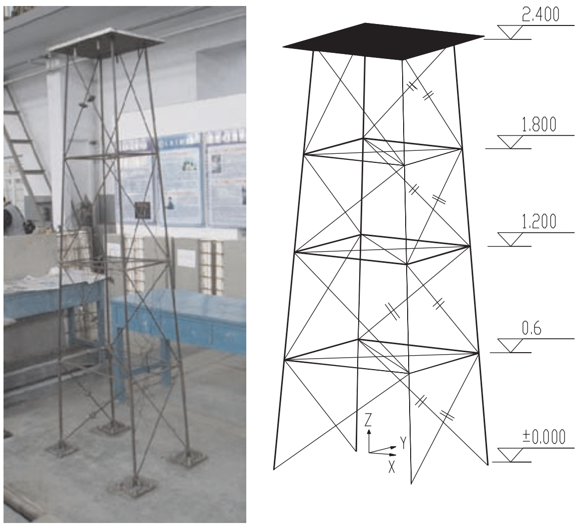
4.2. Damage state simulation

Generally, structural damage state is simulated by physical approaches, such as crack, cut, gap, partly rupture of structure etc, just like measures used in I-40 Bridge test and Fan's (Fan *et al.* 2007) investigation. Different from the past destroyed patterns, there are several spliced connections on members that will simulate the damage in member and damage degree is controlled by the bolt, as described by Fig 2.

The member is damaged partly, if the partial bolts are removed while the shim is not removed. If 4 bolts and shim in a spliced connection are removed, the member is damaged completely. Then, the damage of a member recovers, if the bolts and shim are reinstalled.

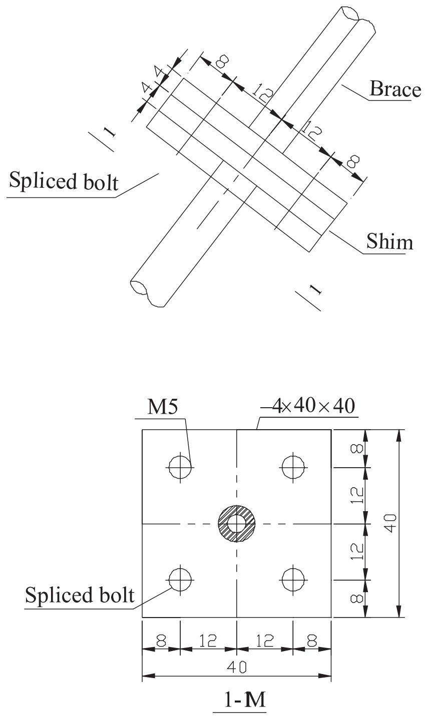
Table 2 gives 6 scenarios of damage state in the 3rd layer of platform frame, 1,2–1,8 m above water, induced at a particular position, dealing with 3 typical damage conditions: damage in column, damage in brace, and damage in beam.

Fig 3 focuses on the detailed insight into the distribu-



a b

Fig 1. Experimental model of platform: a – real structure; b – FEM structure



a

b

Fig 2. Internal structure of damage simulation position: a – spliced connection; b – cross-section

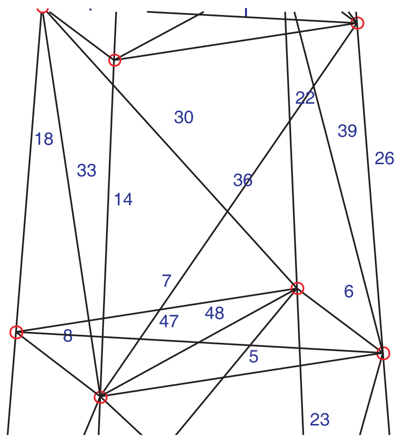


Fig 3. Damaged element distribution

Table 2. Damage case in brace of offshore platform

Case	Element	Simulation way
undamaged	–	–
1	14	Broken
2	6	Broken
3	39	Broken
4	39	2 bolts removed
5	36, 39	3 bolts removed
6	6, 36	1 bolt removed

tion of damaged elements at the 3rd layer of experimental platform model.

Auto-Regressive Moving Average (ARMA) method is processed to modal identification of the offshore platform model and the identified mode shape is normalised to unit for maximum. Table 3 describes the modal frequencies induced by 2 patterns.

It can be seen in Table 3 that the 1st and 2nd frequency errors between analysis and measurement are less than 10 %. However, the 3rd frequency errors are about 15 %, which indicates that there exist distinct parameter errors between FEM and physical experiment model and structural scale has significant influence on modal characteristics (Zhou *et al.* 2007).

4.3. Data collection

The experimental instrument includes 36 capacitive accelerometers (Model 2220-005, Silicon Designs Inc, USA), installed at each intersection point between beams and columns in both *X* and *Y* directions with 8 accelerometers on the top of each layer, for response measurement, an impact hammer (LC-YD-302, Sinocera Piezotronics Inc, China) for exerting impulse force and a measurement system (PL16-DCB8, Integrated Measurement and Control Cooperation, Germany) for data acquisition. Fig 4 is a photo of the experiment spot.

Table 3. The 1st 3 mode frequencies of structure

Case	1st mode *Y* bending	2nd mode *X* bending	3rd mode *Z* torsion	Acquired pattern
Undamaged	18,76	24,85	34,23	FEM
	17,05	24,77	34,20	Measured
1	14,23	23,95	33,14	FEM
	12,98	23,73	33,12	Measured
2	18,76	24,85	34,22	FEM
	17,05	24,65	34,15	Measured
3	16,34	24,85	30,40	FEM
	14,65	24,77	30,35	Measured
4	18,01	24,85	32,66	FEM
	16,85	24,77	32,42	Measured
5	18,26	24,85	30,94	FEM
	16,63	24,77	30,76	Measured
6	18,65	24,85	33,96	FEM
	16,96	24,77	33,80	Measured

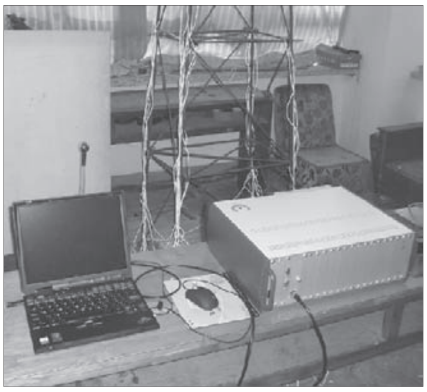


Fig 4. Set of experiment model

The impacts in both *X* and *Y* directions are applied at the middle of the top plate to generate the 1st bending torsional modal of axial and lateral directions, respectively. For each case, the member is damaged and the responses to these impulses are recorded.

4.4. Experiment discussion

Flexural vibration-induced damage generally occurs in the pile member of offshore platform and the axial case. On the other hand, it appears in subordinate members, including horizontal and slanted braces. While the structure suffers damage, signal always shows a change both from the damaged members and some related members.

Assuming estimator β_j complies with normal distribution, the standardised estimator Z_j is defined as:

$$Z_j = \frac{\beta_j - \bar{\beta}}{\alpha\beta}, \tag{25}$$

where $\bar{\beta}$, σ_β – the mean of estimator and the standard deviation of estimator, respectively.

Suppose, Z_j is a threshold, characterising the statistical distribution of estimator. Then damage is considered to occur in the j^{th} element, if $Z_j > Z_c$. Otherwise, the j^{th} element is not damaged. Here, $P_c = 2$ means that the level of credibility is 97,7 %.

In case 1, damage state is simulated in pipe member 14 by bolt adjustment. However, brace elements 18 and 36 are also indicated in damage case, as in Fig 5, by the method (Farrar, Jauregui 1998), which means that the localisation of structural damage is overestimated, according to the statistical assumption. Fig 6 indicates that the accuracy of this proposed method is satisfied in localisation of structural damage. For elements, change of estimator for element 14

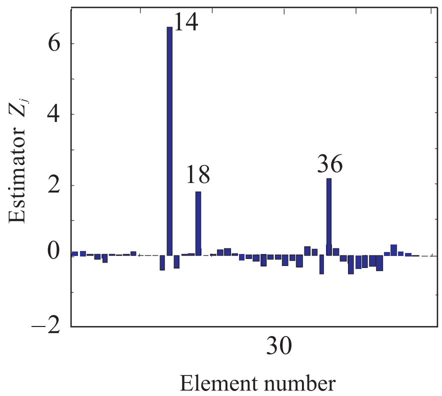


Fig 5. Damage estimator for case 1 via normal method

is much larger than others. Thus element 14 is surely damaged.

In other 5 cases, this proposed estimator is used to detect the structural damage, and other 4 scenarios of damage position can be successfully identified from Figs 6–10, except for case 6. It proves that when braces are broken, damage positions and extents are evaluated accurately, despite of completely damaged member or partly damaged member.

In case 6, however, damage cannot be detected accurately from Fig 11, because of small-scale damage condition simulated by only one bolt removed from spliced connection and 3 bolts remained. Thus brace is damaged slightly and induces few changes in modal characteristics. Then, the measurement error and noise cover the change of mode parameters and lead to an unavailable identification.

The similar standardised measure is utilised for severity estimator α_j. Table 4 gives the satisfied severity evalua-

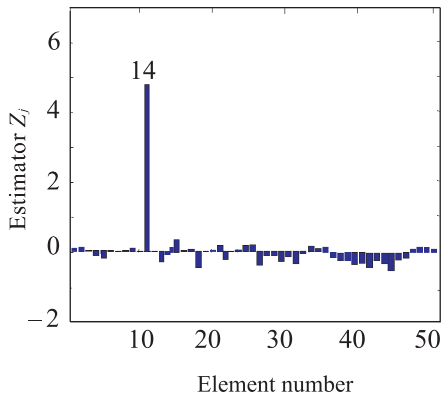


Fig 6. Damage estimator for case 1 via proposed method

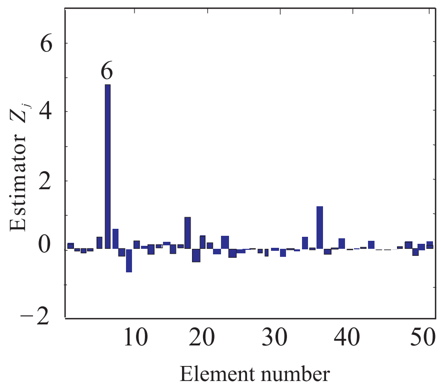


Fig 7. Damage estimator for case 2

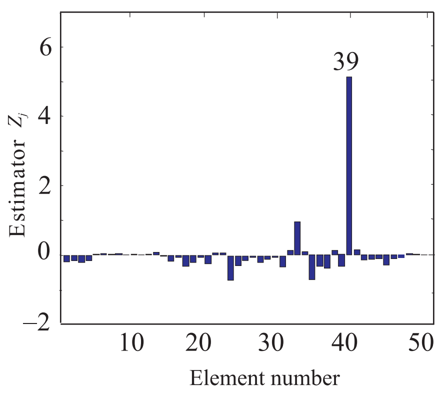


Fig 8. Damage estimator for case 3

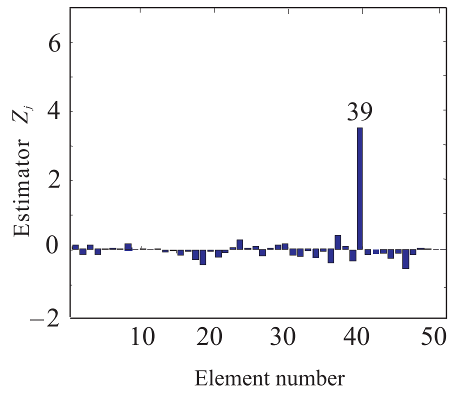


Fig 9. Damage estimator for case 4

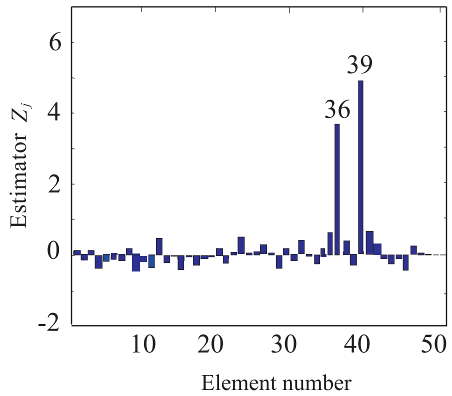


Fig 10. Damage estimator for case 5

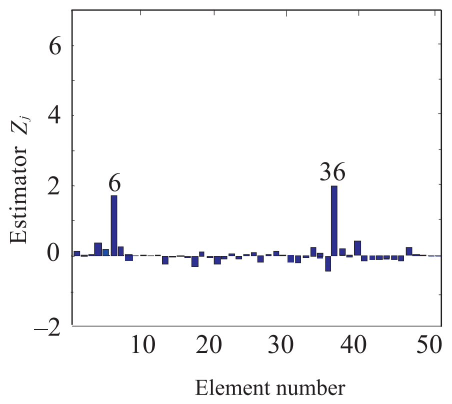


Fig 11. Damage estimator for case 6

Table 4. Evaluation of damage extent

Case	Damaged element	Damage extent / %	
		Real value	Measurement
1	14	100	85,6
2	6	100	73,3
3	39	100	76,5
4	39	50	40,1
5	36, 39	75, 75	62.5, 65.4
6	6, 36	25, 25	13.8, 16.2

tion results. But the identification of case 6 also certificates that a more effective methodology needs further investigation for other conditions, such as small scale damage, complex composite etc.

5. Conclusions

A considerable amount of experience obtained by the construction of a novel approach to locate and evaluate the damage in structure, has led to the following recommendations.

1. An improved method, based on the modal strain energy, is proposed to improve the localisation performance for structural health monitoring. Experimental test with a platform frame verifies that damage can be detected and localised longitudinally.

2. Compared with other NDD methods, the estimator, using data for only the fundamental mode shape before and after damage, no matter how many nodes and elements the investigated structure has. It is easy to operate the feasibility work on line.

3. Damage identification is related to structure scale and damage degree. Thus the declination of estimator in case 6 proves that damage ability is obviously affected by the actual condition. There has no obvious effect on simple structures and large-scale damage. However, there exist significant differences for complex structures. Sometimes, damage degree is overestimated and damage location is judged falsely.

4. For future research it would be of interest to investigate the influence and elimination of noise for damage detection as well as effective detection technique for small-scaled damage so as to construct a practical health monitoring system for a huge civil engineering work.

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