Real-time fast damage detection of shear structures with random base excitation

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Abstract: This paper validates the use of two jerk energy-based damage localization methods, proposed for the regular test with pulse excitation in earlier work, in real-time damage detection of shear structures with random base excitation. First, a 20-story shear structure numerical model is considered to provide numerical validation with random base excitation. Then, performance of the two methods in damage detection is experimentally validated through a laboratory-scale 6-story shear structure model. Both experimental and numerical results of single and multiple damage cases with different levels of stiffness loss indicate that the two jerk energy-based methods can also be used in real-time damage detection of shear structures with random base excitation. The two jerk energy-based methods perform well in the presence of high noise level; moreover, they are model-free that avoid establishing the structural finite element model and model updating.

Keywords: fast damage detection, damage localization, random base excitation, shear structures, jerk energy, curvature difference

1. Introduction

In the past two decades, research on damage detection, localization and quantification based on the vibration data has increased significantly. Vibration-based damage detection methods can detect structural damage quickly and cost-effectively, they are promising [1]. Some review papers [2-6] of vibration-based damage detection methods have been published, including damage localization methods and damage quantification methods. These vibration-based methods have made good progress, in which some are used for the regular test with pulse excitation [7], some are used for real-time health monitoring with ambient excitation [8-10].

Considerable research has been devoted to the extraction of damage detection features based on different dynamic parameters [11-12] and finite element (FE) model updating [13], challenges remain in the application of real life and complex structures: (i) Many FE model-based methods [14-16] have been developed and they have made good progress. However, Bagchi et al. [16] pointed out that the use of a FE model presents some problems in the application of vibration-based damage detection methods; Fan and Qiao [5] stated that considerable computational cost in numerical analysis makes model-based methods not suitable for real-time damage detection; moreover, these methods are influenced by the accuracy of FE models. (ii) Some mode shape-based techniques do not require detailed FE models compared with those FE model-based methods and they can be used in real-time structural health monitoring [17]. Rahmatalla and Eun [18] studied a damage detection method based on the distribution of constraint forces from measured flexural strain; Reynders and De Roeck [19] studied a local flexibility-based damage localization and quantification method; Talebinejad et al. [17] conducted a numerical study of using four different mode-based damage detection methods including the enhanced coordinate modal assurance criterion, damage index method, mode shape curvature method, and modal flexibility index method

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on a cable-stayed bridge. However, because the measured mode shapes are highly influenced by noise contamination [5, 18, 20], the anti-noise ability of these methods is still required to be heightened. Hopefully, these methods can be well used with the development of the modal parameters identification techniques. (iii) Many model-free methods, which avoid establishing a FE model and the model updating, focus on the analysis of the time history of responses directly [21-23]. However, it is still an open question that how to extract the most appropriate feature from the response signals [24].

In our opinion, research of vibration-based damage detection should be explored along the following directions in order to be used well in engineering with consideration of their research status: (i) Damage detection methods with low-dependence on accuracy of structural FE models and model-free damage detection methods should be given priority to the development. That is because engineering structures are very complicated with many uncertainties in materials, construction, structural connection parts, and so on; moreover, some structural parts are difficult to be well established in the FE model, for example the boundary conditions can not be guaranteed the same as the real structure; as a result, some assumptions are introduced. Thus, obtaining an accurate FE model is very difficult and time-consuming. Model-free methods avoid tremendous work in FE model developing and updating. (ii) The hybrid damage detection methods of global and local methods should be adopted in engineering, i.e. the vibration-based damage detection methods (global methods) and non-destructive evaluation methods (local methods) should be combined to detect a structure. Generally, an accurate FE model is required in the damage quantification; it is recommended that damage localization is implemented based on the global methods while damage quantification is considered based on the local methods. (iii) The methods with high anti-noise ability are imperative because the structural responses often have high noise. The inherent anti-noise ability of a damage detection method is required to be improved; at the same time, the anti-noise ability can also be improved by using the mean result of multiple identifications based on different sets of data. (iv) Pulse excitation is commonly used for regular tests; while real-time structural health monitoring methods focus on random excitation mainly. And the real-time damage detection methods are more valuable compared with the regular test methods.

Consider the above first three points, two model-free damage localization methods used in regular test with pulse excitation, termed the Mean Normalized Curvature Difference of Waveform Jerk Energy (MNCDWJE) and the Curvature Difference Probability Waveform Jerk Energy (CDPWJE), have been proposed and validated with pulse excitation in the earlier work [25]. The damage localization results indicate they have good accuracy and they are robust to measurement noise. However, refer to the fourth point, the earlier work only focuses on performances of the two jerk energy-based methods in structures with pulse excitation; their performances in real-time damage detection is still required to be validated.

In the mechanical engineering, aerospace engineering and some other industrial fields, there are some shear structures which receive random excitation in their base all the time when they are in service. The main purpose of this manuscript is to provide a real-time structural health monitoring method for these shear structures. Therefore, the possibility of employing the two jerk energy-based methods in real-time damage detection of shear structures with random base excitation is investigated in this paper. Numerical simulation and experimental validation are conducted for both single and multiple damage cases. The remainder of this paper is organized as follows. Section 2 provides a brief introduction of the proposed two jerk energy-based damage localization methods. Section 3 investigates numerical simulations, in which several single and multiple damage cases of

a 20-story shear structure numerical model are considered, and the influence of data length on damage detection results is discussed. Section 4 examines the experimental validation, in which several experimental damage cases are conducted through a 6-story laboratory-scale shear structure model. Section 5 provides the conclusion.

2. Two Jerk Energy-based Damage Localization Methods

Two jerk energy-based damage localization methods are proposed for regular tests with pulse excitation in earlier work [25], i.e. the MNCDWJE and CDPWJE methods. In this section, the two methods are briefly presented for completeness.

For a discrete set of sampled points given by $a_1, a_2, \dots, a_N$ (signal a), which are accelerations in this study, the jerk energy-based damage feature JE at measured node k is defined as follows [25]

$$JE_k = \log \sum_{x=1}^{N-1} (j_x^k)^2 = \log \sum_{x=1}^{N-1} \left(\frac{a_{x+1} - a_x}{\Delta t} \right)^2 \quad (1)$$

where k represents the measured node number, Δt is the sampling interval, $\log$ is natural logarithm. Waveform of the Jerk Energy (WJE) is created through connecting JE values at every measured node. Then the “curvature” of WJE can be similarly computed through Equation (2),

$$C_k = \frac{JE_{k-1} - 2JE_k + JE_{k+1}}{h^2} \quad (2)$$

where C_k is the curvature at the node k , JE_k is evaluated at the node k , h is the distance between two adjacent measurement locations. For measured nodes 1, 2, 3, $\dots$, i , consider its element numbering sequence is 1, 2, 3, $\dots$, i , then the element numbering sequence can be considered as a clockwise closed loop and it can be seen in Fig. 1 (taking $i = 20$ for example). Therefore, C_1 and C_i are calculated based on the following Equations: $C_1 = \frac{JE_i - 2JE_1 + JE_2}{h^2}$ and $C_i = \frac{JE_{i-1} - 2JE_i + JE_1}{h^2}$.

Thus, elements at all measured nodes including measured nodes 1 and i can be detected.

Fig. 1. The i measured node clockwise closed loop model (here $i = 20$).

The curvature difference value of WJE before and after damage at node k is defined as follows:

$$(C_{\Delta}^k)_{rs} = (C_r^k)_{\text{before}} - (C_s^k)_{\text{after}} \quad (3)$$

where $(C_r^k)_{\text{before}}$ refers to the curvature at node k for the r^{th} response record before damage and $(C_s^k)_{\text{after}}$ refers to the curvature at node k for the s^{th} response record after damage.

2.1. The MNCDWJE damage localization method

The first method employs the mean normalized curvature difference of WJE to localize the damage. After $(C_{\Delta}^k)_{rs}$ values are obtained based on Equation (3), the damage can be localized as follows.

- 1) Normalize the $(C_{\Delta}^k)_{rs}$ for each pair of responses such that the maximum value is one, i.e.,

$$(C_{\Delta}^k)_{rs}^* = (C_{\Delta}^k)_{rs} / \max_k[(C_{\Delta}^k)_{rs}] \quad (4)$$

2) Calculate the mean of the normalized curvature difference μ_k for the available response histories, and the first damage index is then defined as

$$(DI_1)_k = \mu_k = \frac{1}{RS} \sum_{r=1}^R \sum_{s=1}^S (C_{\Delta}^k)_{rs}^* \quad (5)$$

$$\text{Damaged elements} = \{(DI_1)_k \geq \delta\} \quad (6)$$

As a rule of thumb, $RS \geq 10$ and generally $RS = 20$. The threshold level δ is determined based on the signals from the undamaged structure; more detailed information of setting δ can be found in Section 3.2.

2.2. The CDPWJE damage localization method

For the second method, after the normalized curvature difference $(C_{\Delta}^k)_{rs}^*$ is obtained at all nodes, three steps should be performed to localize the damage.

1) Determine how many of the normalized curvature values take values greater than and equal to δ in one identification, i.e. if the normalized curvature value at measured node k is greater than and equal to δ , Γ_{rs}^k is 1; otherwise, Γ_{rs}^k takes value of zero:

$$\Gamma_{rs}^k = H\{(C_{\Delta}^k)_{rs}^*\} \quad (7)$$

where $H(\cdot)$ is the Heaviside step function, δ is the same with Equation (6), and $(C_{\Delta}^k)_{rs}^*$ is defined in Equation (4).

2) The second damage index DI_2 , also called damage probability, is defined based on RS identifications as follows:

$$(DI_2)_k = \frac{1}{RS} \sum_{r=1}^R \sum_{s=1}^S \Gamma_{rs}^k \quad (8)$$

3) The element with damage probability no less than a probability threshold is considered as damaged element, i.e.,

$$\text{Damaged elements} = \{(DI_2)_k \geq \rho\} \quad (9)$$

where ρ is a probability threshold, which is determined based on the signals from the undamaged structure also, as discussed in Section 3.5.

3. Numerical Simulations with Random Base Excitation

To examine the performances of the proposed two jerk energy-based methods in the real-time damage detection of shear structures, a 20-story shear structure numerical model is selected as research object to consider several single and multiple damage cases.

3.1. Numerical research object

As shown in Fig. 2, consider a 20-story shear structure consisting of 20 lumped masses $m_1, m_2, \dots, m_{20}$; stiffnesses of the 20 stories are $k_1, k_2, \dots, k_{20}$, respectively; 20 viscous dampers with damping constants $c_1, c_2, \dots, c_{20}$; and the random excitation acting on its base. Assuming $k_1 = k_2 = \dots = k_{20} = 500 \text{ kN/m}$, $m_1 = m_2 = \dots = m_{20} = 600 \text{ Kg}$, and the modal damping factor $\zeta = 0.02$.

Fig. 2. The model of a 20-story lumped mass shear structure ($i = 20$).

Consider the basic equation of motion

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{P}(t) \quad (10)$$

in which $\mathbf{P}(t) = \{p_1(t), p_2(t), \dots, p_i(t)\}^T$. With the matrices $\mathbf{K}$ and $\mathbf{M}$, the system damping matrix $\mathbf{C}$ can be defined using $\mathbf{K}$ and $\mathbf{M}$ based on Rayleigh damping,

$$\mathbf{C} = a_0\mathbf{M} + a_1\mathbf{K} \quad (11)$$

$$\begin{bmatrix} a_0 \\ a_1 \end{bmatrix} = \frac{2\zeta}{\omega_1 + \omega_n} \begin{bmatrix} \omega_1\omega_n \\ 1 \end{bmatrix} \quad (12)$$

in which ω_1 is the first frequency, ω_n (i.e. the n th frequency) is the highest frequency one concerned.

Then the state space matrices $\mathbf{As}$, $\mathbf{Bs}$, $\mathbf{Cs}$ and $\mathbf{Ds}$ of the shear structure with random base excitation are expressed as follows,

$$\mathbf{As} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix} \quad (13)$$

$$\mathbf{Bs} = [0 \quad \dots \quad 0 \quad -1 \quad \dots \quad -1]^T \quad (14)$$

$$\mathbf{Cs} = [-\mathbf{M}^{-1}\mathbf{K} \quad -\mathbf{M}^{-1}\mathbf{C}] \quad (15)$$

$$\mathbf{Ds} = [0 \quad \dots \quad 0]^T \quad (16)$$

where $\mathbf{As}$ is system matrix, $\mathbf{Bs}$ is input matrix, $\mathbf{Cs}$ is output matrix, $\mathbf{Ds}$ is transmission matrix. With $\mathbf{As}$, $\mathbf{Bs}$, $\mathbf{Cs}$ and $\mathbf{Ds}$, the acceleration of every story can be obtained from the SIMULINK model, in which the Band-limited white noise modulus is selected to simulate the random base excitation. Note that in the SIMULINK modulus of “Band-limited white noise”, the seed before and after damage cannot be the same in order to simulate different random excitation. Then with the given sampling frequency and sampling time, the acceleration of every story can be obtained from the SIMULINK model shown in Fig. 3(a). Fig. 3(b) shows the acceleration response at the 2nd story of the intact model. A band-limited noise with different noise levels is added to the acceleration signals according to Equation (17),

$$\tilde{\mathbf{a}} = \mathbf{a} + \mathbf{n} = \mathbf{a} + \mu\boldsymbol{\sigma}_a\mathbf{r} \quad (17)$$

where $\tilde{\mathbf{a}}$ and $\mathbf{a}$ are accelerations with and without noise, $\mathbf{n}$ is the noise; $\boldsymbol{\sigma}_a$ is standard deviation of the accelerations; μ is noise level; $\mathbf{r}$ is a vector containing normally distributed random numbers.

Fig. 3. Numerical model of the 20-story shear structure with random base excitation: (a) the SIMULINK model; (b) an acceleration response signal at the 2nd story.

3.2. Damage cases and determination of the threshold δ

Damage cases: As shown in Table 1, five damage cases including single and multiple damage cases are considered to validate the feasibility of two jerk energy-based methods in real-time damage detection with random base excitation, in which the damage of a story is simulated by reducing its stiffness. To verify that the methods are robust enough against noise, a band-limited white noise with levels of 5%, 10%, even 20% of the acceleration signal is added to the acceleration to simulate measurement noise. The sampling frequency is 50 Hz.

Table 1. Numerical damage cases of the 20-story shear structure with random base excitation.

	Damage case number	Description of damage cases	Excitation
Single damage cases	1	1rd story: 5% stiffness reduction	Random base excitation
	2	10th story: 5% stiffness reduction	
	3	20th story: 5% stiffness reduction	
Multiple damage cases	4	7th and 12th stories: 5% stiffness reduction	Random base excitation
	5	6th, 11th and 16th stories: 5% stiffness reduction	

Determination of the threshold δ : The threshold δ is a value greater than the mean normalized curvature difference μ_k of undamaged cases, in which μ_k (Equation (5)) is calculated based on accelerations of the intact structure with random base excitation. Fig. 4 shows μ_k results in some undamaged cases with different noise levels, in which δ is determined to be 0.30 for this model.

Fig. 4. Results of mean normalized curvature difference (μ_k) in undamaged cases with random base excitation.

3.3. Damage detection processes based on the two methods

Taking damage case 4 for example, its damage detection process using the proposed two jerk energy-based methods is illustrated in Fig. 5. The first row in Fig. 5 shows 20 waveforms of JE before and after damage with different random excitation; the second row shows curvature values of the waveforms in first row, one can see curvature values decrease at the 6th and 11th stories; the third row shows 20 curvature difference results; the fourth row shows the normalized curvature difference values of curvature difference values in the third row, one can see the normalized curvature difference values at the 6th and 11th stories are always positive and mostly greater than the others while the remainder normalized curvature difference values are sometimes positive and sometimes negative. After 20 normalized curvature difference waveforms are obtained, final damage detection results using the two methods can be shown in the 1st row, 1st column of Fig. 7 and Fig. 10 respectively. One can see both results of damage case 4 show a rule that the result values at the location 6 and 11 are always greater than the threshold level when the 7th and 12th stories are damaged. If this is a rule for all stories, the damage locations can be obtained.

Fig. 5. Results of damage case 4 (7th and 12th stories are damaged) based on 20 sets of data (5% noise level) with different random base excitation.

3.4. Damage detection results based on the MNCDWJE method

With 20 identifications using different sets of data based on the MNCDWJE methods, the damage detection results of single damage cases 1~3 and multiple damage cases 4~5 with 5%, 10% and 20% noise levels are summarized in Fig. 6 and Fig. 7, respectively. From these results, one can find a rule that when the i th story is damaged, the result value at the location before the measured node i in the clockwise closed loop model in Fig. 1 is always greater than the threshold level; for example in damage cases 1 and 2, the results show story 20, story 9 is abnormal respectively when story 1, story 10 is damaged. According to this rule, correct damage locations can be obtained.

Fig. 6. Damage detection results of single damage cases using the MNCDWJE method with random base excitation ($i\#$ represents i th story).

Fig. 7. Damage detection results of multiple damage cases using the MNCDWJE method with random base excitation.

3.5. Damage detection results based on the CDPWJE method

Determination of the probability threshold ρ : ρ is observed from the damage probability results of undamaged cases. According to the CDPWJE method, damage probability results of undamaged case with different noise levels are shown in Fig. 8, in which 60% is determined as the probability threshold.

Fig. 8. Damage probability results of the undamaged case with random base excitation.

Based on the CDPWJE method, the damage detection results of single damage cases 1~3 and multiple damage cases 4~5 with 5%, 10% and 20% noise levels are summarized in Fig. 9 and Fig. 10 respectively, in which all results show the same rule as that in results based on the MNCDWJE method. Therefore, all results also show correct damage locations.

Fig. 9. Damage detection results of single damage cases using the CDPWJE method with random base excitation.

Fig. 10. Damage detection results of multiple damage cases using the CDPWJE method with random base excitation.

3.6. About the data length used in the two methods

In the process of numerical simulation, it is found that the accuracy of damage detection results is influenced by data length; the longer the data length, the smaller damage that can be localized successfully. For the 20-story model in this section, when the sampling time of the accelerations is no less than 1000s, damage of 5% stiffness reduction can be localized based on the proposed two methods with no more than 20% noise level. The conclusion is that it is better to employ longer data in order to identify smaller damage. In the present example, damage detection always employs the accelerations in past 1000s; as a result, the real-time structural health monitoring can be implemented 1000s later than the beginning of data acquisition.

4. Experimental validation

This section validates the use of two jerk energy-based methods (MNCDWJE and CDPWJE) in real-time damage detection of a laboratory-scale shear structure model with random base excitation. Here, the two proposed methods have been experimentally verified through tests on a 6-story shear structure model (Fig. 11) that was designed and built in Smart Structures Technology Laboratory at the University of Illinois at Urbana-Champaign. Each story is 210mm in height, 260mm in width; the lumped mass of each storey is 2.17 kg. The section of the spring steel column is 50mm in width, and 1.27mm in thickness (i.e. 0.05inch, which is the standard thickness of spring steel in US). Another several spring columns with reduced thickness of 0.042 inch are prepared also. The damage of a story is simulated by installing a (left/right) column with reduced thickness to replace the original one.

Fig. 11. The 6-story shear structure model on the shaking table.

4.1. Data acquisition

The flowchart of experimental setup for the shaking table test is shown in Fig. 12, in which the VIBPILOT system can send excitation signals and collect responses. The random signals are sent from VIBPILOT system (Fig. 12) to the controller to control the shaking table (Fig. 11). The lateral acceleration responses of the 6 stories are collected from the VIBPILOT system with 6 accelerometers having the sensitivity of about 100mV/g. The frequencies of the model are 1.719, 5.156, 8.344, 11.06, 13.19 and 14.59 Hz, respectively; and the cut frequency is 15 Hz. The sampling

time is 300s. The experimental model shown in Fig. 11 is excited with a random excitation from a shaking table at the base of the model. For every damage case, repeat the random base excitation 4 times before damage to obtain 4 different responses in intact status and 5 times after damage to obtain 5 different responses in damaged status; thus, every damage case has 20 sets of data before and after damage. Fig. 13 shows the acceleration responses on every story of the intact shear structure model with random base excitation.

Fig. 12. Experimental setup of the shaking table test for real-time damage detection.

Fig. 13. Accelerations on every story of the intact shear structure model with random base excitation.

4.2. Determination of the two thresholds

The thresholds δ and ρ are determined based on the accelerations from the intact structure. Consider one group of acceleration signals from the intact structure is the base signal, and then different levels of noise is added in the base signal. Thus, multiple groups of acceleration signals can be obtained and these signals can be used as signals of the undamaged cases. Then, Fig. 14 shows several results based on signals of the intact laboratory-scale model after multiple identifications, in which δ and ρ are determined to be 0.30 and 60% respectively.

Fig. 14. Determining the two thresholds with experimental data of the intact structure with random base excitation: (a) mean normalized curvature difference results; (b) damage probability results.

4.3. Experimental damage detection results

In simulation section, all the numerical results show a rule that the damage detection result value at the location before the measured node i in the clockwise closed loop model in Fig. 1 is always greater than the threshold level when the i th story is damaged; according to this rule, correct damage locations can be obtained in simulation. Here, the rule is examined in experiments.

Four experimental damage cases in Table 2 are considered. With 20 sets of acceleration signals before and after damage, damage detection results with the MNCDWJE and CDPWJE methods are shown in Fig. 15 and Fig. 16 respectively, in which all the damaged stories can be localized successfully according to the same rule as that in simulation. Therefore, all the experimental damage detection results of the shear structure model with random base excitation are correct.

Table 2. Experimental damage cases of the shear structure model with random base excitation.

	Damage case NO.	Damage	Excitation
Single damage case	1E	The left column of the 5th story is replaced by one with thickness of 0.042 inch	Random base excitation from a shaking table
	2E	The left column of the 6th story is replaced by one with thickness of 0.042 inch	
Multiple damage cases	3E	The left columns of the 3th and 6th stories are replaced by one with thickness of 0.042 inch respectively	
	4E	The left column of the 4th and 6th stories are replaced by one with thickness of 0.042 inch respectively

Fig. 15. Experimental damage detection results using the MNCDWJE method with random base excitation. **Fig. 16.** Experimental damage detection results using the CDPWJE method with random base excitation.

5. Conclusions

The present work investigates the possibility of real-time damage detection of shear structures with random base excitation by employing two damage localization methods MNCDWJE and CDPWJE. For this purpose, the numerical studies of a 20-story shear structure model and experimental studies of a laboratory-scale 6-story shear structure model are conducted. All damage detection results of single and multiple damage cases indicate the two proposed jerk energy-based methods are feasible. With accelerations from a structure before and after damage, the proposed two jerk energy-based methods don't require a numerical model; compared with some model-based damage detection methods, the present time series-based methods are performed simply and fast, which greatly reduce the workload of model developing and updating and the computation time.

Moreover, the two methods have strong anti-noise ability. In all, the proposed two jerk energy-based methods can be well used in real-time damage detection with random base excitation.

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References

- [1] H. Monajemi, H.A. Razak, Z. Ismail, Damage detection in frame structures using damage locating vectors, *Measurement* 46 (2013) 3541-3548.
- [2] H. Sohn, C.R. Farrar, F.M. Hemez, D.D. Shunk, D.W. Stinemates, B.R. Nadler, J.J. Czarnecki, A Review of Structural Health Monitoring Literature: 1996-2001. Los Alamos National Laboratory Report. LA-13976-MS (2004) 1-311.
- [3] L. Wang, T.H.T. Chan, Review of vibration-based damage detection and condition assessment of bridge structures using structural health monitoring. The Second Infrastructure Theme Postgraduate Conference: Rethinking Sustainable Development: Planning, Engineering, Design and Managing Urban Infrastructure, 2009, Queensland University.
- [4] J.J. Sinou, A review of damage detection and health monitoring of mechanical systems from changes in the measurement of linear and non-linear vibrations. *Mechanical Vibrations: Measurement, Effects and Control*. R.C. Sapri (Ed.), 2009, Nova Science Publishers 643-702.
- [5] W. Fan, P.Z. Qiao, Vibration-based Damage Identification Methods: A Review and Comparative Study, *Structural Health Monitoring* 10(1) (2011) 83-111.
- [6] D.N. Thatoi, H.C. Das, D.R. Parhi, Review of Techniques for Fault Diagnosis in Damaged Structure and Engineering System, *Advances in Mechanical Engineering* (2012) 327569.
- [7] Y.H. An, J.P. Ou, Experimental and numerical studies on model updating method of damage severity identification utilizing four cost functions, *Structural Control and Health Monitoring* 20 (2013) 107-120.
- [8] L.F.F. Miguel, L.F.F. Miguel, J. Kaminski Jr, J.D. Riera, Damage detection under ambient vibration by harmony search algorithm, *Expert Systems with Applications* 39 (2012) 9704-9714.
- [9] Z.D. Xu, K.Y. Wu, Damage Detection for Space Truss Structures Based on Strain Mode under Ambient Excitation, *Journal of Engineering Mechanics* 138(10) (2012) 1215-1223.
- [10] Y.H. An, J.P. Ou, J. Li, B.F. Spencer Jr, Stochastic DLV Method for Steel Truss Structures: Simulation and Experiment, *Smart Structures and Systems* (2014) 14(2) 105-128.
- [11] Z. Ismail, Z.C. Ong, Honeycomb damage detection in a reinforced concrete beam using frequency mode shape regression, *Measurement* 45 (2012) 950-959.
- [12] Z. Ismail, Application of residuals from regression of experimental mode shapes to locate multiple crack damage in a simply supported reinforced concrete beam, *Measurement* 45 (2012) 1455-1461.
- [13] A. Teughels, G.D. Roeck, Damage Detection and Parameter Identification by Finite Element Model Updating, *Archives of Computational Methods in Engineering* 12(2) (2005) 123-164.

- [14] C.P. Fritzen, K. Bohle, Parameter Selection Strategies in Model-Based Damage Detection, Structural Health Monitoring 2000, Stanford University, Palo Alto, California (1999) 901-911.
- [15] K.C. Park, G.W. Reich, Model-Based Health Monitoring of Structural Systems: Progress, Potential and Challenges Structural Health Monitoring 2000 Stanford University, Palo Alto, California (1999) 82-95.
- [16] A. Bagchi, J. Humar, H.P. Xu, A.S. Noman, Model-Based Damage Identification in a Continuous Bridge Using Vibration Data, Journal of Performance of Constructed Facilities 24(2) (2010) 148-158.
- [17] I. Talebinejad, C. Fischer, F. Ansari, Numerical Evaluation of Vibration-Based Methods for Damage Assessment of Cable-Stayed Bridges, Computer-Aided Civil and Infrastructure Engineering 26 (2011) 239-251.
- [18] S. Rahmatalla, H.C. Eun, A damage detection approach based on the distribution of constraint forces predicted from measured flexural strain, Smart Materials and Structures 19 (2010) 105016.
- [19] E. Reynders, G.D. Roeck, A local flexibility method for vibration-based damage localization and quantification, Journal of Sound and Vibration 329(23) (2010) 67-83.
- [20] Q.D. Huang, P. Gardoni, S. Hurlebaus, A probabilistic damage detection approach using vibration-based nondestructive testing, Structural Safety 38 (2012) 11-21.
- [21] Z. Hou, M. Noori, R.S. Amand, Wavelet-based approach for structural damage detection, Journal of Engineering Mechanics 126(7) (2000) 677-683.
- [22] P. Omenzetter, J.M.W. Brownjohn, Application of time series analysis for bridge monitoring, Smart Materials and Structures 15(1) (2006) 129-138.
- [23] D. Posenato, P. Kripakaran, D. Inaudi, I.F.C. Smith, Methodologies for model-free data interpretation of civil engineering structures, Computers & Structures 88(7-8) (2010) 467-482.
- [24] A. Shi, X.H. Yu, Structural damage detection using artificial neural networks and wavelet transform, 2012 IEEE International Conference on Computational Intelligence for Measurement Systems and Applications (2012) 7-11.
- [25] Y.H. An, H.K. Jo, B.F. Spencer Jr, J.P. Ou, A Damage Localization Method based on the “Jerk Energy”, Smart Materials and Structures 23(2) (2014) 025020.