Bridge-vehicle coupled vibration response and static test data based damage identification of highway bridges

Jinsong Zhu*[1,2] and Qiang Yi[1,2]

[1]*School of Civil Engineering, Tianjin University, Tianjin 300072, China*
[2]*Key Laboratory of Coast Civil Structure Safety (Ministry of Education), Tianjin University, Tianjin 300072, China*

(Received July 25, 2012, Revised January 25, 2013, Accepted March 6, 2013)

Abstract. In order to identify damage of highway bridges rapidly, a method for damage identification using dynamic response of bridge induced by moving vehicle and static test data is proposed. To locate damage of the structure, displacement energy damage index defined from the energy of the displacement response time history is adopted as the indicator. The displacement response time histories of bridge structure are obtained from simulation of vehicle-bridge coupled vibration analysis. The vehicle model is considered as a four-degree-of-freedom system, and the vibration equations of the vehicle model are deduced based on the D'Alembert principle. Finite element method is used to discretize bridge and finite element model is set up. According to the condition of displacement and force compatibility between vehicle and bridge, the vibration equations of the vehicle and bridge models are coupled. A Newmark-β algorithm based professional procedure VBAP is developed in MATLAB, and used to analyze the vehicle-bridge system coupled vibration. After damage is located by employing the displacement energy damage index, the damage extent is estimated through the least-square-method based model updating using static test data. At last, taking one simply supported bridge as an illustrative example, some damage scenarios are identified using the proposed damage identification methodology. The results indicate that the proposed method is efficient for damage localization and damage extent estimation.

Keywords: bridge; analysis of vehicle-bridge coupled vibration; static test; damage identification; energy index

1. Introduction

In recent years, there has been increasing interest in methods for predicting and estimating the location and extent of damage in bridge structures. Generally, the existing approaches proposed in this field are classified as two major categories, i.e., the dynamic identification methods using dynamic test data and the static identification methods using static test data. Dynamic identification methods due to its non-destructive nature, continuous monitoring, digital processing and other advantages are gaining more attention of scholars. Various dynamic damage identification methods have been proposed by utilizing parameters as natural frequencies (Salawu 1997, Roy *et al.* 2006, Mehrjoo *et al.* 2008), mode shapes (Roy *et al.* 2006, Mehrjoo *et al.* 2008),

*Corresponding author, Associate Professor, E-mail: jszhu@tju.edu.cn

modal damping (Curadelli *et al.* 2008), curvature mode shapes (Li 2010), and modal strain energies (Li 2010, Lee *et al.* 2006, Hu *et al.* 2011) , etc.

To avoid the false positives of damages in the deterministic identification method induced by uncertainties in measurement noise, Zhang *et al.* (2011) proposed a probabilistic method to identify damages of the structures with uncertainties under unknown input. The proposed probabilistic method is developed from a deterministic simultaneous identification method of structural physical parameters and input based on dynamic response sensitivity. A procedure for damage detection has been outlined using modal-based approach in finite element framework in reference (Dutta *et al.* 2004). A damage detection strategy based on the energy of acceleration response is proposed based on the relationship between the frequency response functions (FRFs) of acceleration responses and mode shapes (Xu *et al.* 2007). Kim *et al.* (2008) proposed a methodology for damage identification based on a time domain approach, considering the coupled vibration between a bridge and a moving vehicle, including the effect of roadway surface roughness. A damage identification approach using train-induced responses and sensitivity analysis is proposed for the non-destructive evaluation of railway bridges in reference (Zhan *et al.* 2011). The dynamic responses of railway bridges under moving trains composed of multiple vehicles are calculated by a train–bridge dynamic interaction analysis and the stiffness variation of the bridge element is used as an index for damage identification. A method for damage detection of a simply supported concrete bridge in time domain is presented using the interaction forces from the moving vehicles as excitation (Zhu *et al.* 2007). The vehicle-bridge interaction forces and the structural damage in the bridge deck are identified from the measured responses in sequence of iteration without prior knowledge of the moving loads. Lu *et al.* (2011) proposed a method to identify both damages in bridge and the vehicular parameters from the structural dynamic responses. A dynamic response sensitivity-based finite element model updating approach is used to identify both the structural damages and the vehicular parameters in their method.

Compared with the dynamic identification techniques, the static ones have been developed less maturely and the corresponding literature is intensive. According to the displacement continuity conditions, a damage identification model for the structure is established by Fu *et al*. (2010). By approaching the calculated deflection value to the measured one and making the relative rotation angle of the node the least, the static damage identification method based on the displacement continuity is proposed and the multi-objective optimization method is used to provide the solution.

Wang *et al.* (2001) presented a structural damage identification algorithm using static test data and changes in natural frequencies. Based on the support vector machine, a new method for static damage identification is proposed in reference (Fu *et al.* 2010). This method divides the damage identification into three steps: the judgment of the damage occurrence, the identification of damage location and the recognition of the damage degree.

Combining dynamic identification method and static identification method, a damage detection methodology using dynamic response of bridge induced by moving vehicle and static test data is proposed in the present study. The displacement response time histories of bridge structure are obtained from simulation of vehicle-bridge coupled vibration analysis. The vehicle model is considered as a four-degree-of-freedom system, the vibration equations of the vehicle model are deduced based on the D'Alembert principle. Finite element method is used to discretize bridge and finite element model is set up. According to the condition of displacement and force compatibility between vehicle and bridge, the vibration equations of vehicle and bridge models are coupled. A Newmark-β algorithm based professional procedure vehicle-bridge coupled vibration analysis program (VBAP) is developed in MATLAB, which is used to analyze the vehicle-bridge system coupled vibration. After the damage is located by employing the displacement energy damage index, the damage extent is estimated through the least-square-method based model updating using static test data. At last, taking one simply supported bridge as an illustrative example, some damage scenarios are identified using the proposed damage identification methodology.

2. Vehicle-bridge coupled system

2.1 Vehicle model

The vehicle used herein is modeled as shown in Fig. 1. The vehicle body is modeled as a rigid body having a mass m_2 and a moment of inertia J around the centroid axis. Similarly, each bogie frame is considered as a rigid body. The mass of two axles are m_1 and m_3. The spring stiffness and damping coefficient of the connection between vehicle body and wheels are k_2, c_2 and k_3, c_3; The spring stiffness and damping coefficient of the interaction between wheels and the bridge are k_1, c_1 and k_4, c_4.

As depicted in Fig. 1, there are 8 displacement parameters in total. Among them, z_1 and z_2 are displacement of bridge in the position where wheels contact bridge, y_c and θ can be expressed by

$$y_c = (y_2 l_2 + y_3 l_1)/l \tag{1}$$

$$\theta = (y_3 - y_2)/l \tag{2}$$

Thus there are four independent degrees in this model, which are expressed as vector

$$Y_V = [y_1 \quad y_2 \quad y_3 \quad y_4]^T \tag{3}$$

Mechanical analyzing for each rigid body of the vehicle model, vehicle vibration equations are derived according to D'Alembert principle

$$M_V \ddot{Y}_V + C_V \dot{Y}_V + K_V Y_V = F_V \tag{4}$$

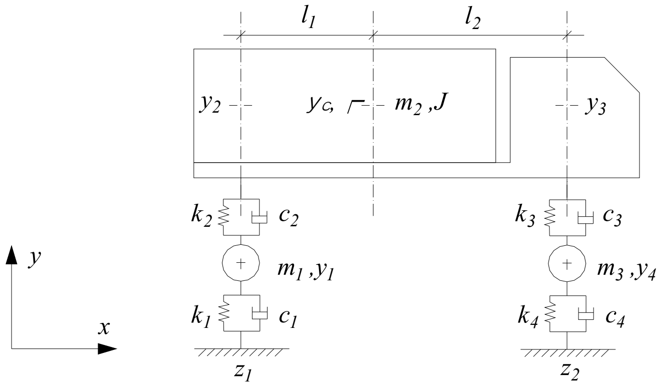


Fig. 1 Model of vehicle

where, $M_V = \begin{bmatrix} m_1 & 0 & 0 & 0 \\ 0 & \frac{m_2 l_2}{l} & \frac{m_2 l_1}{l} & 0 \\ 0 & -\frac{J}{l} & \frac{J}{l} & 0 \\ 0 & 0 & 0 & m_3 \end{bmatrix}$, $K_V = \begin{bmatrix} k_1 + k_2 & -k_2 & 0 & 0 \\ -k_2 & k_2 & k_3 & -k_3 \\ k_2 l_1 & -k_2 l_1 & k_3 l_2 & -k_3 l_2 \\ 0 & 0 & -k_3 & k_3 + k_4 \end{bmatrix}$,

$C_V = \begin{bmatrix} c_1 + c_2 & -c_2 & 0 & 0 \\ -c_2 & c_2 & c_3 & -c_3 \\ c_2 l_1 & -c_2 l_1 & c_3 l_2 & -c_3 l_2 \\ 0 & 0 & -c_3 & c_3 + c_4 \end{bmatrix}$, $F_V = \begin{Bmatrix} f_1 + k_1 z_1 + c_1 \dot{z}_1 \\ f_2 \\ f_3 \\ f_4 + k_4 z_2 + c_4 \dot{z}_2 \end{Bmatrix}$. f_1 and f_4 in the vector F_V are the external loads applied on the wheels (only the weight of the wheels are considered); f_2 is the external load acting on the mass center of the vehicle (only the weight of the vehicle body is taken into account); f_3 is the torque acting on the mass center of the vehicle, which is assumed as 0.

2.2 Roadway profile

The roadway profile is usually assumed to be a zero-mean stationary Gaussian random process and can be generated through trigonometric series method based on a power spectral density function such as (Au *et al.* 2001)

$$r(x) = \sum_{k=1}^{N} \alpha_k \cos(2\pi\omega_k x + \theta_k) \tag{5}$$

$$\alpha_k^{\ 2} = 4S(\omega_k)\Delta\omega \tag{6}$$

$$\omega_k = \omega_l + (k - \frac{1}{2})\Delta\omega \tag{7}$$

$$\Delta\omega = (\omega_u - \omega_l)/N \tag{8}$$

where, α_k is the amplitude of the cosine wave, θ_k is the random phase angle with uniform probability distribution in the interval [0, 2π], x is the global coordinate measured from the left end of the bridge, N is the total number of terms used to build up the road surface roughness and ω_k is the frequency within the interval [ω_l, ω_u]. In the interval [ω_l, ω_u], the power spectral density function $S(\omega_k)$ is defined as (Honda *et al.* 1982)

$$S(\omega_k) = \alpha\omega_k^{\ -\beta}, \omega_l < \omega_k < \omega_u \tag{9}$$

where the parameter α is a spectral roughness coefficient which is assigned according to ISO 8608 (1995) and the exponent, β, is taken to be 1.94.

2.3 Analysis of vehicle-bridge coupled vibration

The equations of motion for a bridge under external loads can be written as follows

$$M_B \ddot{Y}_B + C_B \dot{Y}_B + K_B Y_B = F_B \tag{10}$$

where, $\ddot{Y}_B$, $\dot{Y}_B$ and Y_B denote bridge acceleration, velocity and displacement vectors respectively. M_B, C_B and K_B represent general mass, damping and stiffness matrices of bridge respectively. F_B is the force vector acting on the bridge.

The structure system damping assumed as Rayleigh damping (Leitão *et al.* 2011) is expressed by mass and stiffness matrix, as shown in Eq. (11)

$$C_B = \alpha_0 M_B + \beta_0 K_B \tag{11}$$

The parameters α_0 and β_0 are computed, respectively, by

$$\beta_0 = \frac{2(\xi_2\omega_{02} - \xi_1\omega_{01})}{\omega_{02}\omega_{02} - \omega_{01}\omega_{01}} \tag{12}$$

$$\alpha_0 = 2\xi_1\omega_{01} - \beta_0\omega_{01}\omega_{01} \tag{13}$$

where, ω_{01} and ω_{02} are the first and second nature frequencies of structure, ξ_1 and ξ_2 are the first and second modal damping ratios of structure.

Assuming that wheels always cling to the deck when vehicle moving through bridge, the interaction forces between wheels and bridge can be expressed as

$$f_i(t) = k_i\Delta_i(t) + c_i\dot{\Delta}_i(t) \tag{14}$$

where, subscript i indicates the ith wheel, $\Delta_i(t)$ is the vertical displacement of the ith wheel relative to the deck at time t, as shown in Eq. (15)

$$\Delta_i(t) = y_i(t) - z_i(t) - r_i \tag{15}$$

where $y_i(t)$ is the vertical displacement of the ith wheel at time t, $z_i(t)$ is the vertical displacement of bridge in the position where the ith wheel contact the bridge at time t and r_i is the irregularity function value in the position where the ith wheel contact the bridge.

According to the condition of displacement and force compatibility between vehicle and bridge, the vibration equations of vehicle model and bridge model are coupled. A Newmark-β algorithm based professional procedure is developed in MATLAB to solve this coupled and time-varying second-order ordinary differential equations and the dynamic responses of vehicle and bridge can be obtained. Fig. 2 is the flowchart of this procedure.

3. Damage detection algorithm

3.1 Displacement energy damage index

In the present study, an energy damage index is used to identify and locate damage in structure. This damage index is based on the energy of the displacement response time history. Dynamic response of the structure at its intact state is obtained from simulation of vehicle-bridge coupled vibration analysis, and dynamic response of the structure at its damaged state is captured through an array of sensors attached to the structure. The energy of the displacement response time history is then established by

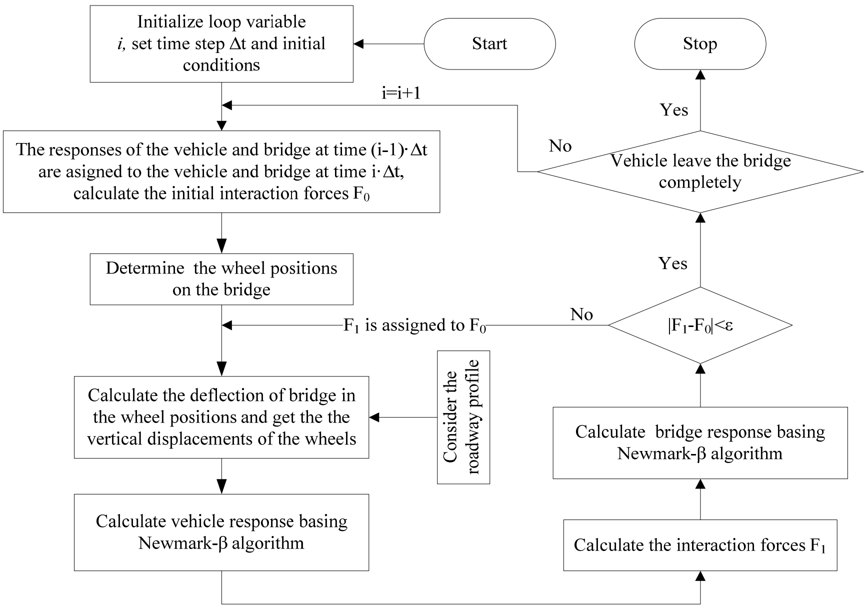


Fig. 2 Simulation procedure of vehicle-bridge coupled vibration

$$E = \int_0^{t_0} y^2(t)dt \tag{16}$$

Then, the displacement energy damage index for each sensor is defined as

$$DI = \left| \frac{E_{Healthy} - E_{Damaged}}{E_{Healthy}} \right| \times 100\% \tag{17}$$

where, $E_{Healthy}$ and $E_{Damaged}$ are the energy of displacement response time histories at intact and damaged states of bridge, respectively. The above damage index provides a scalar value, which is the percentage difference in the structural energies at its intact and damaged states. Once *DI* is calculated for each sensor, the relatively higher index values are identified as indicators for the existence of damage, thereby the existence and location of damage are identified accordingly.

3.2 Damage extent estimation

When the damage location is detected by employing the damage index described above, the estimation of damage extent is the next significant step. The mass and damping matrices of a bridge are assumed to be immune to the damage. It is also assumed that the damage causes a change in the bending rigidity to simplify the derivation. The basic idea of the estimation of damage extent in this study is to update the finite element model of the bridge using static test data and obtain parameter changes of damaged elements. Static test is carried out on bridge structure firstly and the number of damage determines testing times. The way of loading can be chosen from following ways arbitrarily:

(1) Load at mid span and change load to carry out another static test;

(2) Keep the load value and change loading position to carry out another static test.

Measure the vertical displacements at a quarter point, midpoint and three quarter point of main girder. Then, update the finite element model of bridge using least square method based on static test data to estimate damage extent. For updating the finite element model, it is an estimating parameter changes progress of damage elements. The least square method is selected to identify parameters in the present study.

$\{P\}$ is the parameter vector of damaged elements

$$\{P\}=\{EI_1 \quad EI_2 \quad \cdots \quad EI_i \quad \cdots\}^T, i=1,2\cdots n \tag{18}$$

where, i is the order number of damage element, n is the total number of damage elements, EI_i is the bending rigidity of the *ith* damage element. Making every parameter unit change, the influence parameter α_{ji} of EI_i and state variable S_j could be obtained from numerical simulation. Then, the influence matrix can be defined as

$$[A_s]=\begin{bmatrix} \alpha_{11} & \alpha_{12} & \cdots & \alpha_{1n} \\ \alpha_{21} & \alpha_{22} & \cdots & \alpha_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \alpha_{m1} & \alpha_{m2} & \cdots & \alpha_{mn} \end{bmatrix} \tag{19}$$

where, n is the total number of damaged elements, m is the total number of state variables. To ensure that all parameters can be estimated, there should be $m \geq n$.

$\{S_t\}$ is assumed as the measured value of state variables, and $\{S_a\}$ is the calculation value of state variables. The difference of $\{S_t\}$ and $\{S_a\}$ can be calculated as

$$\{\Delta S\}=\{S_t\}-\{S_a\} \tag{20}$$

$\{\Delta P\}$ is assumed as the vector of the parameter to be estimated, then

$$[A_s]\{\Delta P\}=\{\Delta S\} \tag{21}$$

Generally, the number of elements in $\{\Delta P\}$ is less than the number of elements in $\{\Delta S\}$, so Eq. (21) is contradictory equations which could be solved by least square method. The least square solution of Eq. (21) is

$$\{\Delta P\}=\left([A_s]^T[A_s]\right)^{-1}[A_s]^T\{\Delta S\} \tag{22}$$

A weighting matrix $[\rho]$ is introduced to reflect the reliability of every element in $\{S_t\}$, and thus Eq. (21) can be expressed as

$$[\rho][A_s]\{\Delta P\}=[\rho]\{\Delta S\} \tag{23}$$

When $[\rho]$ is a unit matrix, Eq. (23) is the same as Eq. (21). The least square solution of Eq. (23) is

$$\{\Delta P\}=\left([A_s]^T[\rho]^2[A_s]\right)^{-1}[A_s]^T[\rho]^2\{\Delta S\} \tag{24}$$

After $\{\Delta P\}$ is calculated, one time model updating is completed. In order to achieve desired accuracy, it is necessary to repeat this process for several times. After model updating is completed, the damage extent of damage element could be calculated by

$$De_i = \frac{\Delta EI_i}{EI_i} \times 100\%, i = 1,2 \cdots n \tag{25}$$

where, i is the order number of damage element, n is the total number of damage elements, ΔEI_i is the total change of the bending rigidity of the *ith* damage element.

In order to update model through iteration, a program named DEE (Damage Extent Estimation) was developed in MATLAB. Fig. 3 is the flow chart of this program.

3.3 Procedure of the proposed damage detection method

It is assumed that the parameters of the intact bridge and vehicle model are estimated initially by experiments. Then, the damage identification method proposed in the present study can be performed as following steps:

(1) Measure the roadway profile at the bridge, which will be used in simulation of bridge-vehicle coupled vibration to get the dynamic response of bridge at intact state.

(2) Get the dynamic response of bridge at intact state through simulation of bridge-vehicle coupled vibration analysis.

(3) Measure the dynamic displacement response of bridge at its damaged state at each sensor when the test vehicle moving through bridge.

(4) Calculate the displacement energy damage index for each sensor and detect the location of damage.

(5) Select an appropriate static test plan according to the number of damage for static testing.

(6) Estimate the damage extent using the program DEE.

(7) Report the result of damage identification.

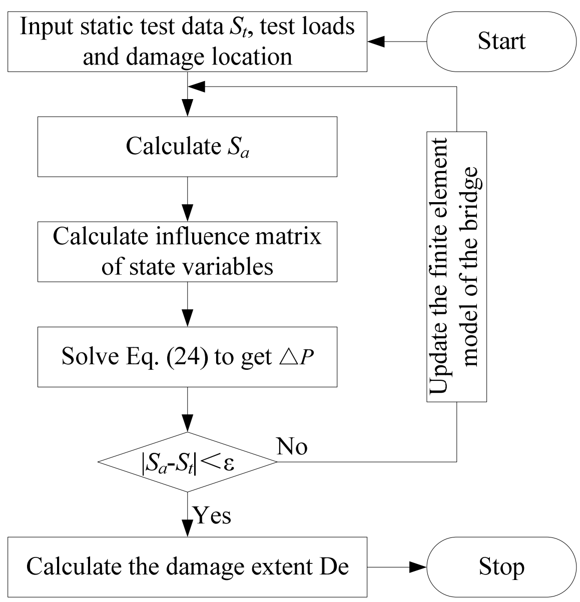


Fig. 3 Flowchart of DEE

4. Numerical simulation

4.1 Numerical model and damage scenarios

The bridge used in following studies is a simply supported girder bridge as shown in Fig. 4. The properties of the bridge are: flexural rigidity $EI = 2.5 \times 10^{10}$ N·m^2, linear density $\rho A = 5000$ kg/m and L = 30m. The first three natural frequencies of the bridge are 3.90 Hz, 15.61 Hz and 35.13 Hz, respectively. The modal damping ratio is taken as 0.02 for the first two modes to calculate the two coefficients α_0 and β_0 in the Rayleigh damping. In the finite element model, the bridge deck is modeled as an Euler-Bernoulli beam with 8 elements. Seven sensors are distributed evenly along the beam to measure the displacement responses. The moving speed of the vehicle is 30 km/h and class ‘Good’ road surface roughness is used in all the study cases below. The characteristics of the vehicle model as depicted in Fig. 1 are listed in Table 1 (Wu *et al.* 2010).

The elements of the bridge are assumed to successively suffer damage of a reduction in element flexural rigidity with extents between 5% and 20%. Following damage scenarios are defined:

(1) Signal damage

Every element suffers damage with extents 5%, 10%, 15% and 20%.

(2) Multi-damage

For multiple damages, there are so many damage scenarios. Several scenarios are selected as listed in Fig. 5. The value in the Fig. 5 is the damage extent of the element.

4.2 Damage detection

At each damage scenario, the dynamic displacement responses of the bridge at damaged state taken from the simulation are assumed as measured data. Fig. 6 shows the displacements of the bridge when element 4 suffers different extents of damage. As shown in this figure, the displacements of the bridge increase when element 4 is more seriously damaged. Fig. 7 shows the displacements of the bridge at multi-damage scenario DM-4. The distribution of maximum displacements of the bridge midpoint under different damage scenarios are shown in Fig. 8. For the single damage scenario, the following observations can be made from Fig. 8:

(1) The maximum displacements of the bridge increase when the damage extends.

(2) When the damage extent keeps unchanged, the maximum displacement decreases with the distance between the damaged element and the midpoint.

(3) For two elements symmetrically located to the midpoint, the same damage causes the same maximum displacement of the midpoint.

Table 1 Parameters of vehicle model

Parameters	Values	Parameters	Values
m_1(kg)	1500	m_3(kg)	1000
m_2(kg)	17500	J(kg·m^2)	1.45×10^5
k_1(N/m)	4.60×10^6	c_1(N/m/s)	4.30×10^3
k_2(N/m)	4.23×10^6	c_2(N/m/s)	4.00×10^4
k_3(N/m)	2.47×10^6	c_3(N/m/s)	3.00×10^4
k_4(N/m)	3.74×10^6	c_4(N/m/s)	3.90×10^3
l_1(m)	1.7	l_2(m)	2.5

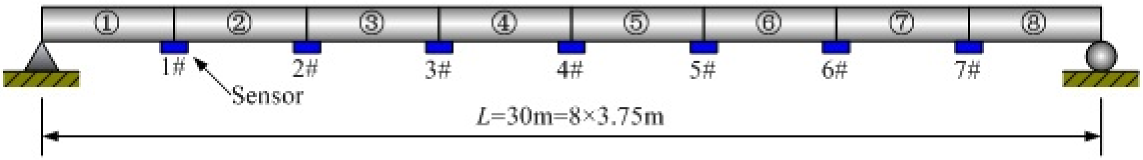
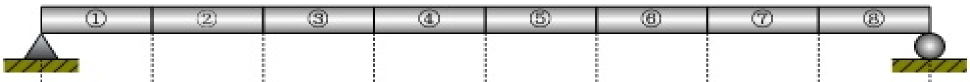
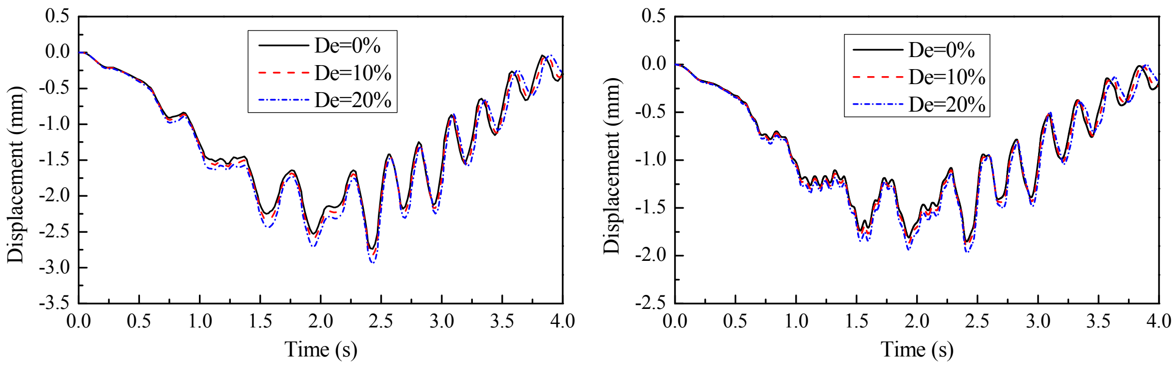


Fig. 4 Layout of the simply supported girder bridge



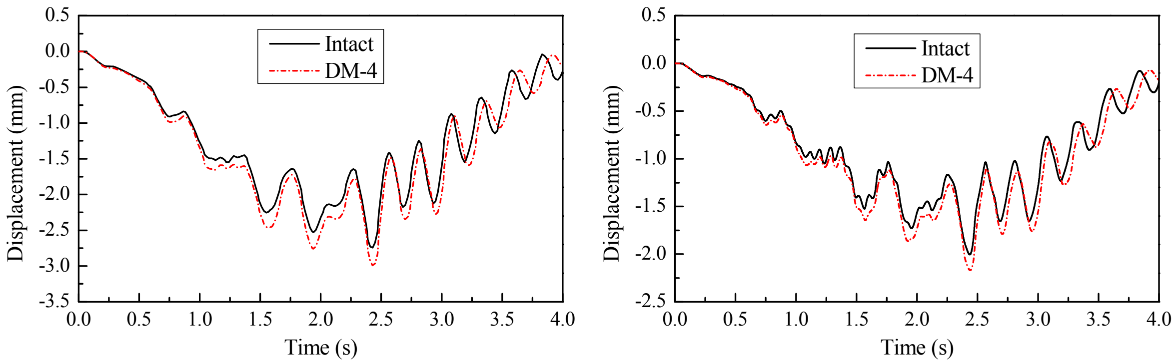
	①	②	③	④	⑤	⑥	⑦	⑧
DM-1	0.2	0	0	0	0.2	0	0	0
DM-2	0	0.2	0	0	0.2	0	0	0
DM-3	0	0	0	0.2	0.2	0	0	0
DM-4	0	0	0	0.2	0	0	0.2	0
DM-5	0.2	0	0	0	0.1	0	0	0
DM-6	0	0	0	0.2	0.1	0	0	0
DM-7	0	0	0.2	0	0	0.2	0	0
DM-8	0	0	0.1	0	0	0.2	0	0

Fig. 5 Multi-damage scenarios



(a) at Sensor 4# (b) at Sensor 2#

Fig. 6 Displacement responses of the bridge when element 4 suffers different extent damages



(a) at Sensor 4# (b) at Sensor 6#

Fig. 7 Displacement responses of the bridge at DM-4

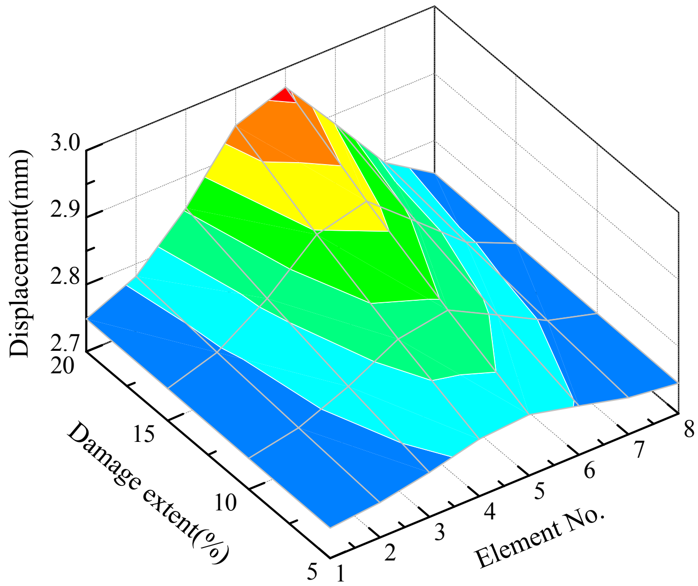


Fig. 8 Maximum displacements of the midpoint under different single damage scenarios

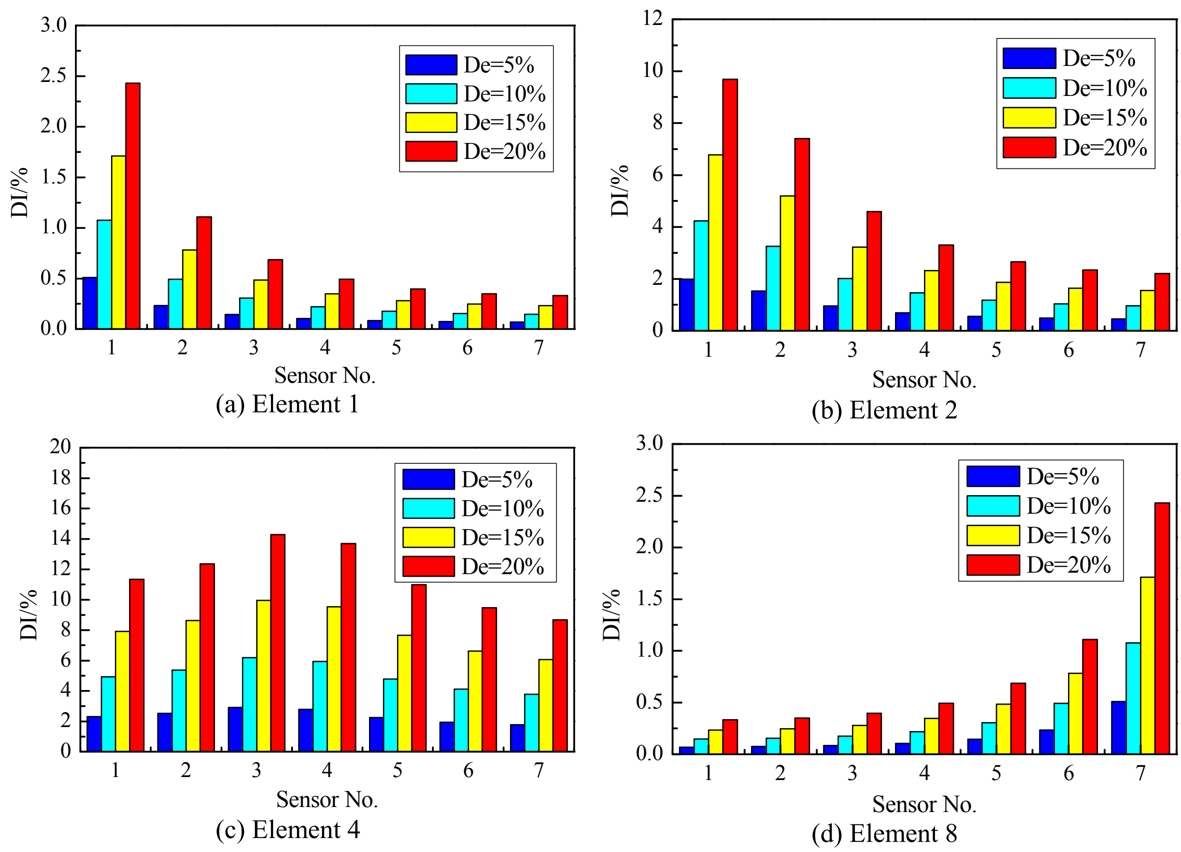


Fig. 9 Damage indices at each measuring point when elements suffer different extent damages

Fig. 9 shows the damage indices at each measuring point when elements suffer damage with different extents. From these figures, the following observations can be obtained:

(1) At each single damage scenario, the damage indices at the sensors close to the damage are higher than the others, thereby the existence and location of damage are identified accordingly.

(2) Damage index increases when element is more seriously damaged.

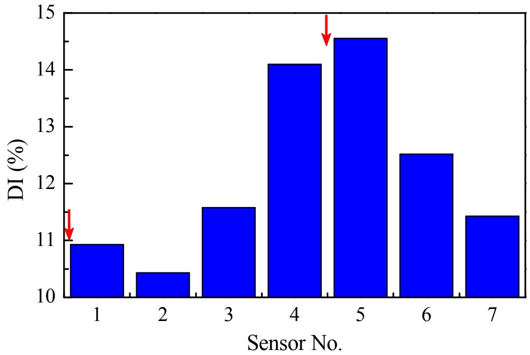
Fig. 10 presents damage indices at each measuring point when bridge suffers different multi-damage scenarios listed in Fig. 5. Compared Fig. 9 with Fig. 10, the definite differences of the damage indices distribution between single damage scenarios and multi-damage scenarios are found. Generally speaking, damage indices at multi-damage scenarios are larger than the values at single damage scenarios, and multiple peak values would appear corresponding to the number of damage location at multi-damage scenarios. One exception is shown in Fig. 10(c), there is only one peak value located at Sensor 4# measuring point, however, Fig. 10(c) shows damage index distribution at one multi-damage scenario. Also, only one peak value located at Sensor 3# measuring point is found in Fig. 9(c). But the damage indices distribution in Fig. 9(c) and Fig. 10(c) are definitely different. So, it is effective to distinguish multi-damage and single damage though damage indices. As shown in Fig. 10(a) and Fig. 10(d), the distributions of damage indices in the two figures are very similar when damage locations of two figures are same and damage extents of them are different. So, it is feasible to identify damage location at multi-damage scenario using the displacement energy damage index.

White noise is added to the calculated responses of the bridge at damaged state to simulate the polluted measurements with (Zhu *et al.* 2007)

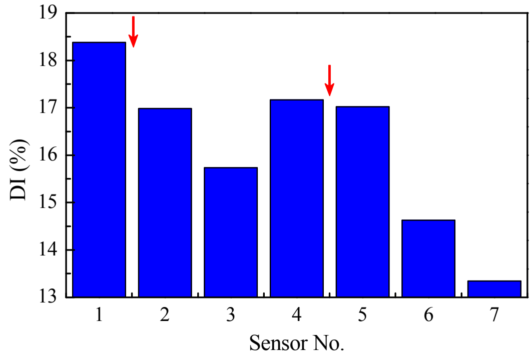
$$U = U_a + E_p N_{noise} \sigma(U_a) \tag{26}$$

where, U_a and U are the polluted and the original displacements, respectively. E_p is the noise level. N_{noise} is a standard normal distribution vector with zero mean value and unit standard deviation. $\sigma(U_a)$ is the standard deviation of the original displacements. 1%, 5% and 10% levels noise are added to simulate the measured responses in the following studies in order to demonstrate the robustness of the presented damage index.

Damage indices with different levels noise at some damage scenarios are shown in Fig. 11. As depicted in Fig. 11, through damage index values are influenced by noise the damage location can be identified through the distribution of damage index yet.

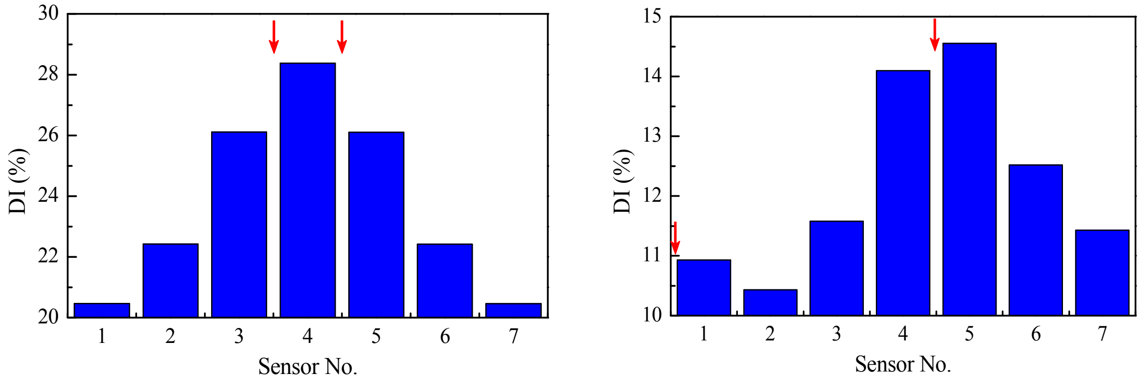


(a) DM-1



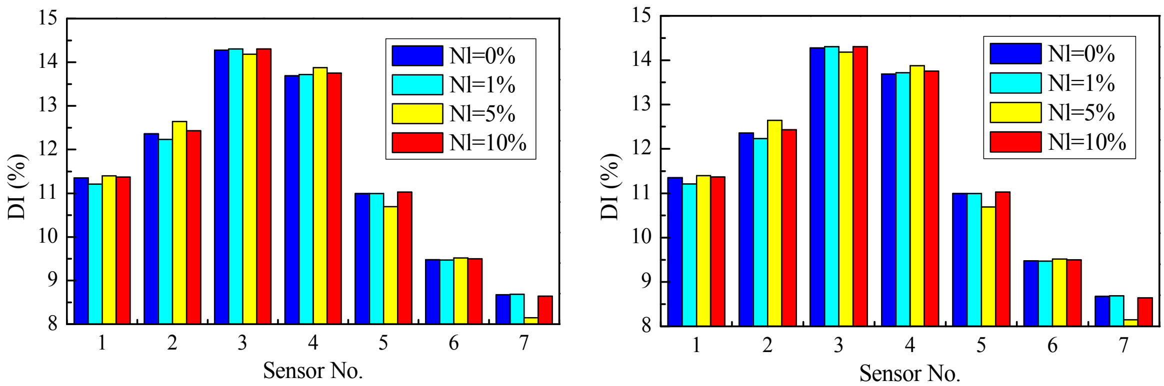
(b) DM-2

Fig. 10 Damage indices at multi-damage scenarios (The exact locations of damage are marked with arrows (↓))



(c) DM-3 (d) DM-5

Fig. 10 Continued



(a) No.4 element damage with 20% extent (b) DM-4

Fig. 11 Damage indices at different noise levels ('Nl' denotes noise level)

4.3 Damage extent estimation

After damage location was identified, damage extent is estimated using program DEE. The first loading way described above is selected and two vehicles with weight of 15 ton and 20 ton respectively are used to carry out static test. Displacements at Sensor 2#, 4# and 6# are measured in each test and totally 6 displacement values are obtained. In the following studies, all displacements are calculated using ANSYS and assumed as measured data. Input load values, test data and damage location into the program DEE and some damage extent estimation results are listed in table 2. Table 2 demonstrates that the proposed method can identify damage location and estimate damage extent within an error of less than 3%. The accuracy of damage extent estimation would be influenced by the static test measuring error, thus high-precision measuring instruments would be better.

Table 2 Results of damage extent estimation

Damage scenarios	Element No.	Ex.(%)	De.(%)	Err.(%)
DS-1	1	10	9.98	-0.20
DS-2	2	20	20.39	1.95
DS-3	4	5	4.97	-0.60
DS-4	7	15	15.08	0.53
DM-1	1	20	20.41	2.03
	5	20	19.99	-0.06
DM-2	2	20	20.00	0.00
	5	20	20.01	0.06
DM-3	4	20	20.00	0.00
	5	20	20.00	0.00
DM-4	4	20	20.01	0.06
	7	20	20.00	0.00
DM-5	1	20	19.94	-0.29
	5	10	10.02	0.22
DM-6	4	20	20.05	0.24
	5	10	9.95	-0.53
DM-7	3	20	19.99	-0.03
	6	20	19.99	-0.03
DM-8	3	10	9.99	-0.12
	6	20	20.00	0.00

Note: the 'Ex.' and 'De.' denote exact damage extent value and estimated damage extent value, the 'DS' and 'DM' denote single damage scenario and multi-damage scenario respectively, whereas the 'Err.' is the error between the exact damage extent and the estimated one.

5. Conclusions

A method of bridge damage identification using vehicle-induced bridge vibration data and static test data has been proposed in the present study. The displacement energy damage index based on the bridge vibration data is used to detect the location of the damage. The dynamic responses of bridge at intact state are obtained from simulation of vehicle-bridge coupled vibration analysis and the dynamic responses of bridge at damaged state are measured through sensors attached on the bridge. When the damage is located, model updating method based static test data is used to estimate the damage extent. The above studies and observations reveal that the presented damage identification algorithm is effective. It provides a method for extending engineering choice in damage identification of bridge structures.

Acknowledgments

This work reported here was supported by the National Science Fund of China (51178305) and the Key Projects in the Science & Technology Pillar Program of Tianjin (11ZCKFSF00300). Any opinions, findings and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect those of the sponsor.

Reference

Au, F.T.K., Cheng, Y.S. and Cheung, Y.K. (2001), "Effects of random road surface roughness and long-term deflection of prestressed concrete girder and cable-stayed bridges on impact due to moving vehicles", *Computers and Structures*, **79**(8), 853-872.

Curadelli, R.O., Rier, J.D., Ambrosini, D. and Amani, M.G. (2008), "Damage detection by means of structural damping identification", *Engineering Structures*, **30**(12), 3497-3504.

Dutta, A. and Talukdar, S. (2004), "Damage detection in bridges using accurate modal parameters", *Finite Elements in Analysis and Design*, **40**(3), 287-304.

Fu, C.Y., Li, Q. and Shan, D.S. (2010), "Static damage identification based on displacement continuity", *Bridge Construction*, **2**, 18-20, 36. (in Chinese)

Fu, C.Y, Shan, D.S. and Li, Q. (2010), "The static damage identification method based on the support vector machine", *China Railway Science*, **31**(5), 47-53. (in Chinese)

Honda, H., Kajikawa, Y. and Kobori, T. (1982), "Spectra of road surface roughness on bridges", *Journal of structural division*, ASCE, **108**(ST9), 1956-1966.

Hu, H.W., Wu, C.B. and Lu, W.J. (2011), "Damage detection of circular hollow cylinder using modal strain energy and scanning damage index methods", *Computers and Structures*, **89**(1-2), 149-160.

ISO 8608(1995), "Mechanical vibration-Road surface profiles Reporting of measured data", ISO.

Kim, C.W. and Kawatani, M. (2008), "Pseudo-static approach for damage identification of bridges based on coupling vibration with a moving vehicle", *Structure and Infrastructure Engineering*, **4**(5), 371-379

Lee, J.J. and Yun, C.B. (2006), "Damage diagnosis of steel girder bridges using ambient vibration data", *Engineering Structures*, **28**(6), 912-925.

Leitão, F.N., da Silva, J.G.S., da S. Vellasc, P.C.G., de Andrade, S.A.L. and de Lima, L.R.O. (2011), "Composite (steel-concrete) highway bridge fatigue assessment", *Journal of Constructional Steel Research*, **67**(1), 14-24.

Li, Y.Y. (2010), "Hypersensitivity of strain-based indicators for structural damage identification: a review", *Mechanical Systems and Signal Processing*, **24**(3), 653-664.

Lu, Z.R. and Liu, J.K. (2011), "Identification of both structural damages in bridge deck and vehicular parameters using measured dynamic responses", *Computers and Structures*, **89**(13-14), 1397-1405.

Mehrjoo, M., Khaji, N., Moharrami, H. and Bahreininejad, A. (2008), "Damage detection of truss bridge joints using Artificial Neural Networks", *Expert Systems with Applications*, **35**(3), 1122-1131.

Roy, S., Chakraborty, S. and Sarkar, S.K. (2006), "Damage detection of coupled bridge deck-girder system", *Finite Elements in Analysis and Design*, **42**(11), 942-949.

Salawu, O.S. (1997), "Detection of structural damage through changes in frequency: a review", *Eng. Struct.*, **19**(9), 718-723.

Wang, X., Hu, N., Fukunaga, H. and Yao, Z.H. (2001), "Structural damage identification using static test data and changes in frequencies", *Engineering Structures*, **23**(6), 610-621.

Wu, S.Q. and Law, S.S. (2010), "Dynamic analysis of bridge with non-Gaussian uncertainties under a moving vehicle", *Probabilistic Engineering Mechanics*, **26**(7), 281-293

Xu, Z.D. and Wu, Z.S. (2007), "Energy damage detection strategy based on acceleration responses for long-span bridge structures", *Engineering Structures*, **29**(4), 609-617.

Zhang, K., Li, H., Duan, Z.D. and Law, S.S. (2011), "A probabilistic damage identification approach for structures with uncertainties under unknown input", *Mechanical Systems and Signal Processing*, **25**(4), 1126-1145.

Zhan, J.W., Xia, H., Chen, S.Y. and Roeck, G.D. (2011), "Structural damage identification for railway bridges based on train-induced bridge responses and sensitivity analysis", *Journal of Sound and Vibration*, **330**(4), 757-770.

Zhu, X.Q. and Law, S.S. (2007), "Damage detection in simply supported concrete bridge structure under moving vehicular loads", *Journal of Vibration and Acoustics*, **129**(1), 58-65.