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Integrated Damage Identification System for Large Structures via Vibration Measurement

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ABSTRACT: *In this paper, an integrated damage identification system (IDIS) is proposed to locate and size damage in real structures. The application of the IDIS to real structures includes the measurement of modal responses, the construction of damage-detection models, and the implementation of measurements and m/odels into the damage-detection process. Firstly, the theory of the damage identification method is outlined. Secondly, the schematic and each component of the IDIS are described. Finally, the practicality of the IDIS is verified from experiments on two different bridge-models, a model plate-girder and a model truss.*

KEY WORDS: Nondestructive evaluation, system identification, damage detection, vibration test, plate-girder, truss.

1. Introduction

Undiscovered damage in critical members of a structure causes local or global structural failures and also results in catastrophic disasters, such as loss of lives, human suffering, and expenses of infrastructure properties. During the past decade, the structural safety assessment based on reliable techniques of damage identification has been important challenges to many research groups. Stubbs (1985), Chen and Garba (1988), Biswas et al.(1990), and Stubbs et al.(1992) are among those who have made successful attempts to detect damage in large structures using changes of modal parameters.

Despite those and other research efforts, many problems related to damage identification in bridge structures remained unsolved. A research need exists to practically measure and analyze motions and responses in bridges under service (Mazurek and DeWolf 1990). To overcome the difficulties in the practical use of the controlled instrumentation, researchers have made efforts on the use of the ambient vibration techniques. In the ambient ways, excitation sources may include winds, earthquakes, or moving vehicles. However, these methods require robust modal analysis techniques in order to extract the appropriate modal information but eliminate measurement errors by filtering out the noise induced under the ambient monitoring circumstances.

A research need exists to develop damage identification algorithms that can be applied to structures for which limited modal data are available (Kim and Stubbs 1995). In order to apply the damage identification algorithms to structures for which as-built modal data are not available, system identification techniques are required to construct baseline models of the structures. Research needs also exist to quantify the impact of model uncertainty and measurement errors on the accuracy of damage identification. Another research need is on the integration of the overall damage detection procedures. An integrated damage-detection system is related to four different stages: a monitoring scheme, an input interface, a damage-detection scheme, and an output interface. These procedures are integrated in a software system to produce the final results that are locations and magnitudes of damage.

The objective of this paper is to present an integrated damage identification system (IDIS) to locate and size damage in real structures. We focus on designing an integrated scheme that includes measuring modal responses, constructing damage-detection models, and implementing measurements and models to the damage-detection process. The development of the IDIS is needed to perform a damage-detection-oriented operation via vibration monitoring, mode extraction, and damage-detection. The following approaches are designed to meet the research goal. Firstly, the damage index method proposed by Kim et al.(1999) is summarized as the theory of approach. Damage-detection models that depend on the availability of modal data and modal sensitivities are formulated for the later use in the damage-detection process. Secondly, the schematic of the IDIS is designed and each component in the IDIS is described. Finally, the practicality of the IDIS is evaluated from experiments on two different bridge-models, a model plate-girder and a model truss.

2. Theory of Damage Identification Method

The nondestructive damage detection (NDD) methodology presented here was designed to yield information on location and severity of damage of a structure directly from monitoring changes in modal characteristics of the target structure. The modal characteristics of interest here are mode shapes and natural frequencies. Once two sets of modal parameters are measured for the as-built structure and its corresponding damaged state, the NDD method to be described here is used to predict damage location and to estimate the severity of the damage at that location of the structure (Kim and Stubbs 1995).

Consider a homogeneous, uniform cross-sectional, one-imensional beam with NE elements (in the finite element sense) and N nodes. Assume that the input-output relationship of the beam is linear. For i^{th} mode and j^{th} location of the system, the undamaged and damaged modal sensitivities, F_{ij} and F^*_{ij}, are related by the equation:

$$F^*_{ij} = F_{ij} + dF_{ij} \tag{1}$$

where dF_{ij} represents the change in the fraction of modal energy at the j^{th} member and for the i^{th} mode. On differentiating Eq. (1), the quantity dF_{ij} can be obtained from the expression:

$$dF_{ij} = \frac{K_{ij}}{K_i}\left[\frac{dK_{ij}}{K_{ij}} - \frac{dK_i}{K_i}\right] \tag{2}$$

In Eq. (2), K_i is the i^{th} modal stiffness of the arbitrary structure, K_{ij} is the contribution of j^{th} member to i^{th} modal stiffness, and dK_{ij} is the fractional change in K_{ij}.

$$K_i = \Phi_i^T \mathrm{C} \Phi_i \tag{3}$$

and

$$K_{ij} = \Phi_i^T \mathrm{C}_j \Phi_i \tag{4}$$

where Φ_i is the i^{th} modal vector, **C** is the system stiffness matrix, and C_j is the contribution of j^{th} member to the system stiffness matrix. Also, by noticing $K_i >> K_{ij}$, Eq. (2) is reduced to the following form:

$$dF_{ij} \cong \frac{dK_{ij}}{K_i} \tag{5}$$

The quantities in Eqs. (3) and (4) are expressed by separating variables as

$$K_{ij} = \gamma_{ij} E_j, \qquad K^*_{ij} = K_{ij} + dK_{ij} = \gamma^*_{ij} E^*_j \tag{6a,b}$$

in which $\gamma_{ij} = \Phi_i^T \mathrm{C}_{jo} \Phi_i$ and $\gamma^*_{ij} = \Phi_i^{*T} \mathrm{C}_{jo} \Phi^*_i$. The matrix C_{jo} involves only geometric quantities that can be read from structural information. Also from Eq. (6), dK_{ij} can be rewritten by

$$dK_{ij} = \gamma^*_{ij}(E_j + dE_j) - \gamma_{ij} E_j \tag{7}$$

On dividing both sides of Eq. (7) by K_i, substituting into Eq. (6), solving for the fractional change in the j^{th} member's stiffness by assuming the structure is damaged at a single location (to solve Eq. (7) in terms of a single unknown), then the resulting change in K_{ij} is only the function of E_j.

$$\frac{dK_{ij}}{K_i} \cong \frac{\gamma_{ij}}{\gamma_i}\frac{dE_j}{E_j} + \frac{d\gamma_{ij}}{\gamma_i} \tag{8}$$

in which

$$d\gamma_{ij} = \gamma^*_{ij} - \gamma_{ij}, \quad \gamma_i = \sum_{k=1}^{ne} \Phi_i^T C_{ko} \Phi_i \tag{9}$$

It follows readily that $dK_{ij} \approx dK_i / nd$ if the structure is damaged in nd multiple locations, in which the nd locations can be predicted. Then the fractional changes in modal stiffness are approximately related to the fractional changes in modal properties.

$$\frac{dK_{ij}}{K_i} \cong g_i(\lambda, \Phi) = \frac{1}{nd}\left[\frac{d\lambda_i}{\lambda_i} + \frac{dM_i}{M_i}\left(1 + \frac{d\lambda_i}{\lambda_i}\right)\right] \tag{10}$$

in which $g_i(\lambda, \Phi)$ is the dimensionless factor representing the systematic change in modal parameters of the i^{th} mode due to the damage.

By applying Eq. (10) to Eq. (8), the damage index for i^{th} mode and j^{th} location is given by

$$\beta_{ij} = \frac{E_j}{E^*_j} = \frac{\gamma^*_{ij}}{\gamma_i\, g_i(\lambda, \Phi) + \gamma_{ij}} = \frac{Num}{Den} \tag{11}$$

For a measured set of nm vibrational modes, we define the damage indication of the j^{th} member when the following numerically stable form is greater than one.

$$\beta_j = \sum_{i=1}^{nm} Num \Big/ \sum_{i=1}^{nm} Den \tag{12}$$

Once damage is located at the j^{th} member, damage severity of the same member is estimated directly from Eqs. (8) and (10).

$$\alpha_j = dE_j / E_j = 1/\beta_j - 1, \quad \alpha_j \geq -1 \tag{13}$$

in which the severity of damage is indicated as stiffness reduction in the jth member if the above indication is less than zero.

3. Integrated Damage Identification System (Idis)

The overall scheme of the IDIS was designed as shown in Fig. 1. It consists of several components in which four independent schemes are integrated for the completeness of the system. The four sequential schemes include a structure scheme to design experiments, a response scheme to measure structural responses, a modal scheme to identify modal parameters, and a damage-detection scheme to predict locations and magnitudes of damage. A practical modal test scheme is designed by arranging an ambient traffic cart, transducers, a signal analyzer, and a system of modal analysis softwares. Also, a software code for the damage detection algorithm is programmed to facilitate the damage prediction process as a part of the IDIS.

In the structure scheme of the IDIS, we define the structural geometry and constraint conditions to plan both monitoring scheme and damage-detection model (DDM). The DDM is defined as a mathematical representation of a structure with degrees of freedom limited to sensor readings. The layout of sensor stations and excitation sources are considered in this scheme. Then the requirement for the structure scheme is that it should satisfy the monitoring system and the DDM at the same time (i.e., the monitoring scheme as the robust data supplier to the DDM).

In the response scheme of the IDIS, we define the control of the excitation and the measurement of the structural responses (Ewins 1986). The ambient traffic vibration is used as the excitation source. In the laboratory experiment, we use a Lionel-type model-train passing through the model bridge under controlled speeds. Also, a SA-390 signal analyzer with eight channels is used for measuring analog time-dependent signals from accelerometers, processing analog to digital conversion, and calculating digitized frequency responses.

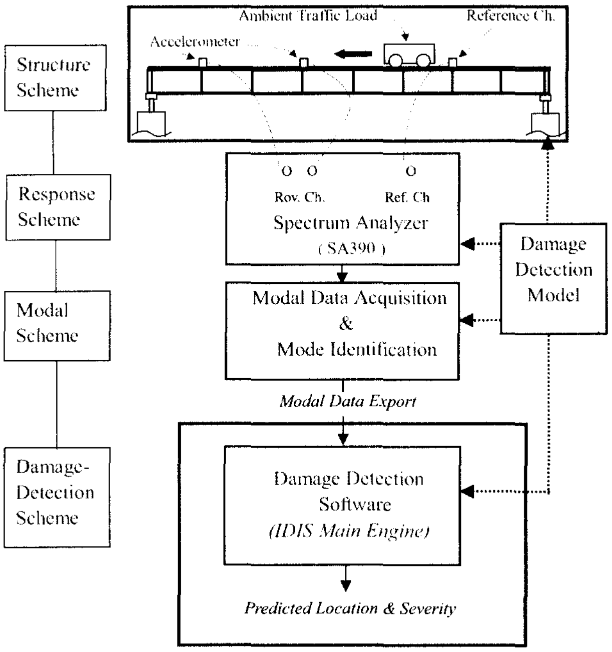


Fig. 1 Schematic of Integrated Damage Identification System (IDIS)

In the ambient test, one accelerometer is always positioned on one location as a reference channel. By placing active accelerometers, a set of locations (or DOFs) is measured at a single pass of the model train. The passes controlled by constant speeds are continued to complete the modal test. In addition to the ambient vibration test, two other excitation sources are examined to verify the ambient test results. Those are the impact test and the shaker test. A Dytran 5801 smart hammer is used in the impact test. A VTS-100 electromagnetic shaker is used in the shaker test.

In the modal scheme of the IDIS, we define the identification of the appropriate modes and modal parameters for the later use (Randall 1987). The STAR software by the Spectral Dynamics is employed to extract the modal parameters. The STAR includes the following four steps: firstly, structural geometry is defined (this should identical to the structural scheme of the IDIS); secondly, measurements (digitized frequency response data) are transferred from SA-390; thirdly, modal parameters are identified (resonance peaks in FRFs are identified by the operator); and finally, extracted modal parameters are transmitted.

The digitized frequency response data out of the response scheme are received via a Visual Basic interface and the modal parameters analyzed from this model are exported into the damage-detection scheme via another Visual Basic interface in Window environment. In the damage-detection scheme of the IDIS, we define the acquirement of modal responses, the geometric parameters from the structural scheme, the computation of modal sensitivities, and the selection of algorithms for damage localization and severity estimation.

For laboratory experiments, we selected one damage-detection model for each bridge-type involved. As the DDM of a model plate-girder bridge, we selected a one-dimensional Euler-Bernoulli beam model (Kim et al. 1999). As the DDM of a model truss bridge, we selected a three-dimensional truss model (Kim and Stubbs 1995). A computer software DDM-JTK, coded in Fortran and linked to the Visual Basic interfaces, was programmed and utilized in the damage detection process. As the final output from the IDIS, the predicted locations and magnitudes of damage are visualized on the structural model.

4. Experiment on Model Plate- Girder Bridge

The test structure was a single-span, stainless steel, model plate-girder (See Fig. 2). We conducted controlled laboratory experiments on the structure to measure changes in modal parameters caused by structural degradation. The structure was simply supported: a set of pin supports at the left edge and a set of roller supports at the other edge. Fourteen, equally spaced stations were selected along the deck of the model bridge as shown in Fig. 3.

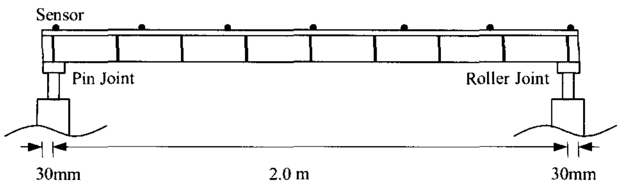
We performed a finite element analysis and three different types of experimental modal tests (the impact test, the shaker test, and the ambient traffic test) in order to verify the practicality of the ambient vibration method. Modal parameters of the undamaged state were measured for the initial four bending modes. The experimentally measured frequencies and the corresponding FEM results are listed in Table 1. (Mode shapes of the four modes are shown in Fig. 4). It shows that the ambient vibration test is consistent with both the FEM analysis and the two other methods.

Table 1 Natural Frequencies of Model Plate-Girder from FEM Analysis and Experimental Tests

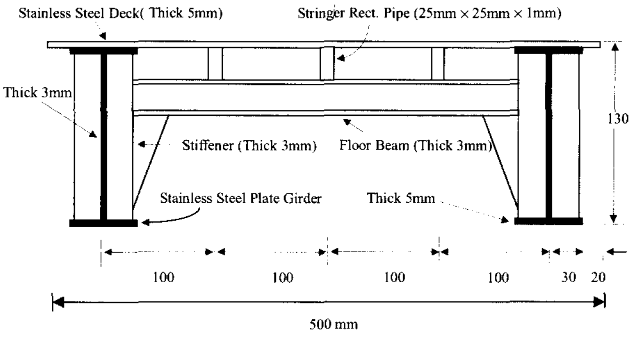
Mode No.	Natural Frequency (Hz)						
	FEM Analysis	Experimental Test					
		Impact	Div.	Shaker	Div.	Ambient	Div.
1	67.01	69.07	3.1	70.58	5.3	67.50	0.7
2	97.51	98.15	0.6	97.93	0.4	95.00	2.6
3	215.60	208.96	3.1	208.05	3.5	210.0	2.6
4	299.82	279.02	6.9	277.72	7.4	275.0	8.3

Table 2 Pre- and Post-damage Frequencies of Model Plate-Girder by Ambient Vibration Test

Damage Case	Damage Scenario	Natural Frequency (Hz)			
		Mode 1	Mode 2	Mode 3	Mode 4
Reference	-	67.50	95.00	210.0	275.0
Case 1	1-kg weight	66.90	94.50	209.5	275.0
Case 2	3-kg weight	66.20	94.10	209.1	274.5
Case 3	5-kg weight	65.60	93.30	208.8	274.2



(a) Model Bridge Schematic



(b) Deck and Plate-Girders

Fig. 2 Schematic of Model Plate-Girder

Next, we performed a set of damage detection tests. Three known damage scenarios were inflicted in the structure by adding a 1-kg, a 3-kg, or a 5-kg weight-mass, respectively, to the front girder at 0.99-m location (near the center of the bridge). Ambient

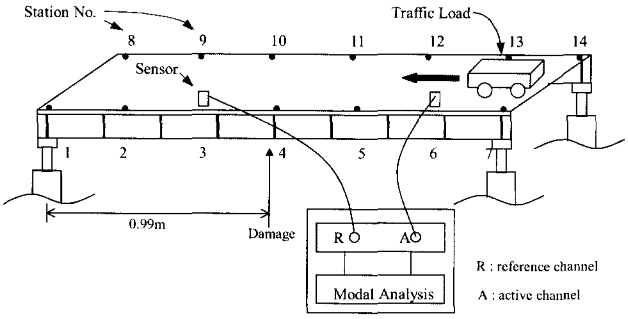
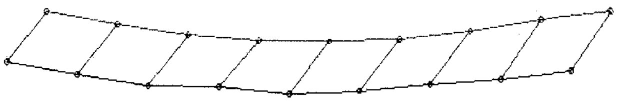
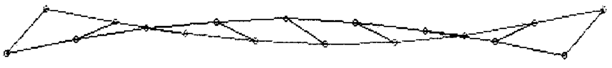


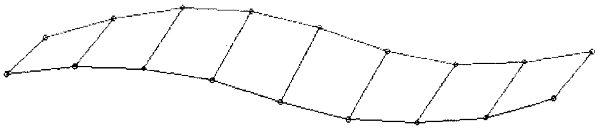
Fig. 3 Test Set-Up in Model Plate-Girder



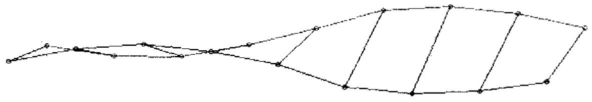
(a) Mode 1



(b) Mode 2



(c) Mode 3



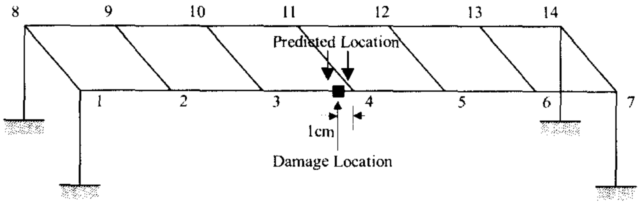
(d) Mode 4

Fig. 4 Initial Four Mode Shapes of Model Plate-Girder by Ambient Vibration Test forces from lightweight traffic carts (model trains) excited the structure. The extracted modal parameters of the model bridge are listed in Table 2 and shown in Fig. 4.

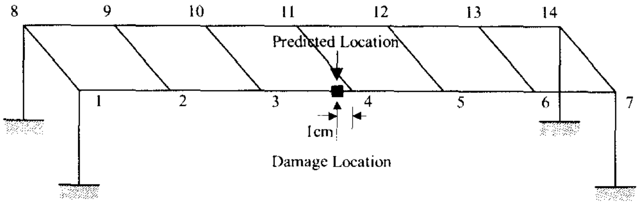
In the ambient test, one accelerometer was kept positioned on Station 6 as a reference channel. As active channels, one set of seven accelerometers was placed on Stations 1-7 on one side of the bridge and moved to Stations 8-14 on the other side of the bridge. The sensors measured the vertical motions at the fourteen stations (Fig. 2). The passes controlled by a constant speed of about 2 km/h were continued to complete the test. Both in the impact test and in the shaker test, the vertical excitation was applied to Station 6.

As the DDM, an Euler-Bernoulli beam model consists of 200 elements of equal size in each girder. The modal displacement functions, which fulfil the DDM, were generated using the cubic-spline interpolation over the measured mode shapes. We established a classification criterion for damage localization. For the measured set of modes, the locations of damage are selected on the basis of a rejection of hypotheses in the statistical senses. The criterion corresponds to a one-tailed test at a confidence level of 97.7%. Note that the detailed explanation on the damage-detection model and the classification criterion are described in Kim et al (Kim et al. 1999).

By applying the sequence of the IDIS in the model plate-girder bridge, we predicted potential locations and magnitudes of damage as shown in Fig. 5. In all three scenarios, damage was correctly localized with relatively high accuracy.



(a) Damage Scenario 1



(b) Damage Scenarios 2 & 3

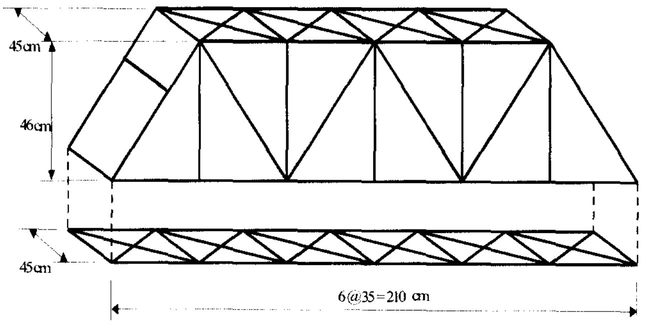
Fig. 5 Damage Prediction in Model Plate-Girder

5. Experiment on Model Truss Bridge

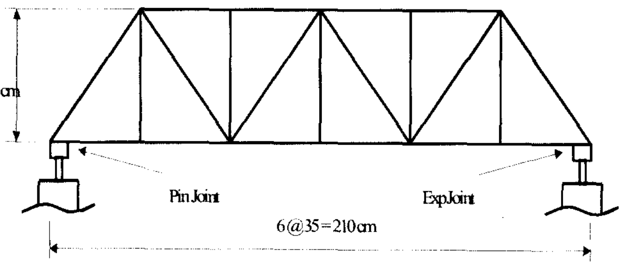
The test structure was a single-span, steel, model truss bridge. As shown in Fig. 6, it consists of 24 joints and 74 truss members connecting those joints. The geometrical properties of the 74 members are based on the shapes in Fig. 7. Type 1 includes twelve lower cord members and seven lower lateral members. Type 2 includes eight upper cord members, ten vertical members, and five upper lateral members. Type 3 includes twelve diagonal members and twenty cross-bracing members. The structure was simply supported: a set of pin supports at the left edge and a set of roller supports at the other edge. Three accelerometers, which are glued on an aluminum cube (1cm x 1cm x 1cm) oriented, respectively, toward the x-direction, y-direction, and z-direction, were placed on each joint (Fig. 8).

Table 3 Natural Frequencies of Model Truss from FEM Analysis and Experimental Tests

Mode No.	Natural Frequency (Hz)						
	FEM Analysis	Experimental Test					
		Impact	Div.	Shaker	Div.	Ambient	Div.
1	56.45	59.59	5.6	60.72	7.5	55.94	0.9
2	108.62	109.92	1.2	110.65	1.8	108.44	0.2
3	146.50	147.50	0.7	147.20	0.5	145.31	0.8
4	167.97	167.96	0.1	168.50	0.3	169.69	1.0



(a) 3-D View of Model Truss



(b) Geometry and Constraint Conditions

Fig. 6 Schematic of Model Truss

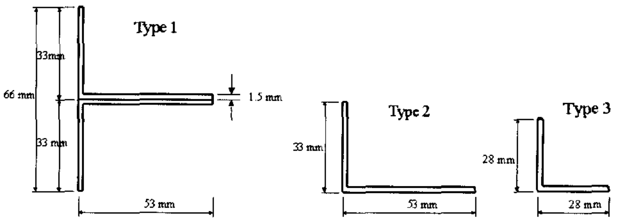


Fig. 7 Geometric Shapes of Truss Members

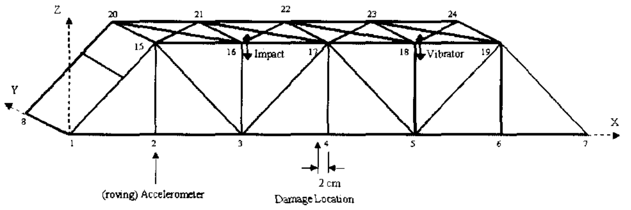
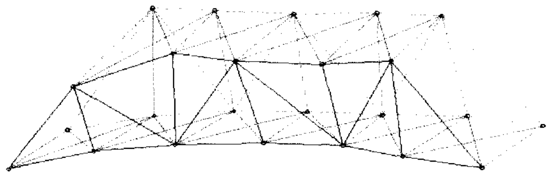
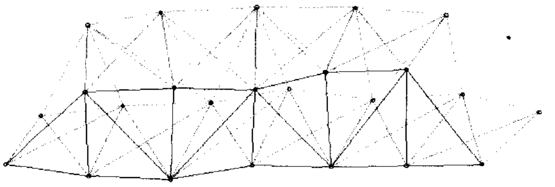


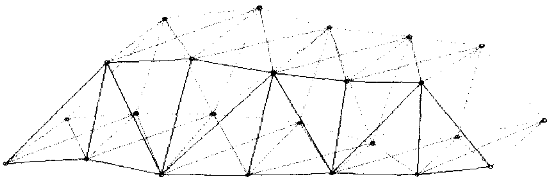
Fig. 8 Test Set-Up in Model Truss



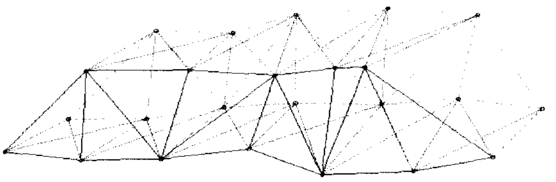
(a) Mode 1



(b) Mode 2



(c) Mode 3



(d) Mode 4

Fig. 9 Initial Four Mode Shapes of Model Truss by Ambient Vibration Test

We performed a finite element analysis and the three types of experimental modal tests (the impact test, the shaker test, and the ambient vibration test). Modal parameters of the undamaged state were measured for the initial four modes. The experimentally measured frequencies and the corresponding FEM results are listed in Table 3. (Mode shapes of the four modes are shown in Fig. 9). It shows that the ambient test is consistent with both the FEM analysis and the two other methods.

Next, we performed a single damage detection test. A known damage scenario was inflicted in the structure by adding a 1-kg weight-mass at Joint 4 (Fig. 8). Ambient forces from a model train excited the structure. The extracted modal parameters of the model bridge are listed in Table 4 and shown in Fig. 9. The DDM was a truss model of 74 elements and the modal displacements of elements were computed from the measured mode shapes. By applying the sequence of the IDIS to the test structure, we predicted potential locations and sizes of damage in the test structure. Damage was predicted in two members as shown in Fig. 10. The one is Joint 4Joint 11 and the other is Joint 3-Joint16. Compared to the inflicted location that is Joint 4, the first one shows relatively correct prediction considering that we detect damage in a correct truss-member using modal data measured at a joint of the member. But the second one shows false-alarm. A few other elements connecting Joint 4 should be alarmed but failed. A few more modes may be needed to improve damage localization prediction.

Table 4 Pre- and Post-Damage Frequencies of Model Truss by Ambient Vibration Test

Damage Case	Damage Scenario	Natural Frequency (Hz)			
		Mode 1	Mode 2	Mode 3	Mode 4
Reference	-	55.94	108.44	145.31	169.69
Case 1	1-kg weight near Joint 4	55.28	107.36	140.54	163.64

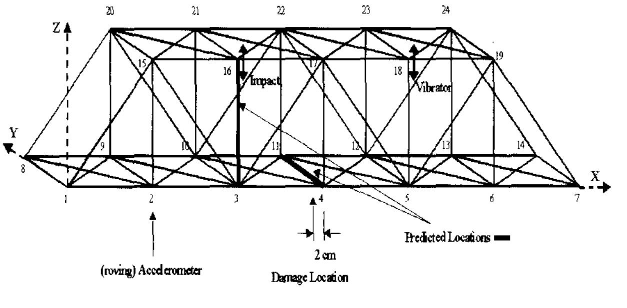


Fig. 10 Damage Prediction in Model Truss

6. Conclusion

An integrated damage identification system (IDIS) based on vibration-based system identification techniques was developed to locate and size damage in real structures. The application of the IDIS to real structures included the measurement of modal responses, the construction of damage-detection models, and the implementation of measurements and models into the damage-detection process. The research goal was achieved in three parts. Firstly, the damage index method proposed by Kim et al. (1999) was implemented as the theory of approach. Secondly, the schematic of the IDIS was designed and each component in the IDIS was described. Finally, the practicality of the IDIS was experimentally verified using two different bridge-models, a model plate-girder and a model truss.

For the two bridge-models, the practicality of the ambient vibration method was verified by performing a finite element analysis, the impact test, the shaker test, and the ambient traffic test. In both model-bridges, resonant frequencies measured from the ambient vibration test were consistent with both the FEM analysis and the results of two other methods. By applying the sequence of the IDIS to the model plate-girder, the inflicted locations in all three scenarios were correctly predicted. By applying the same sequence of the IDIS to the model truss, the inflicted location in a single damage scenario was correctly predicted.

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