Structural Engineering and Mechanics, Vol. 39, No. 2 (2011) 187-206 187
DOI: http://dx.doi.org/10.12989/sem.2011.39.2.187

Damage detection in truss bridges using vibration based multi-criteria approach

H.W. Shih, D.P. Thambiratnam and T.H.T. Chan*

School of Urban Development, Faculty of Built Environment and Engineering, Queensland University of Technology, Brisbane, Australia

(Received December 5, 2009, Accepted March 9, 2011)

Abstract. This paper uses dynamic computer simulation techniques to develop and apply a multi-criteria procedure using non-destructive vibration-based parameters for damage assessment in truss bridges. In addition to changes in natural frequencies, this procedure incorporates two parameters, namely the modal flexibility and the modal strain energy. Using the numerically simulated modal data obtained through finite element analysis of the healthy and damaged bridge models, algorithms based on modal flexibility and modal strain energy changes before and after damage are obtained and used as the indices for the assessment of structural health state. The application of the two proposed parameters to truss-type structures is limited in the literature. The proposed multi-criteria based damage assessment procedure is therefore developed and applied to truss bridges. The application of the approach is demonstrated through numerical simulation studies of a single-span simply supported truss bridge with eight damage scenarios corresponding to different types of deck and truss damage. Results show that the proposed multi-criteria method is effective in damage assessment in this type of bridge superstructure.

Keywords: truss bridges; damage assessment; finite element method; vibration; flexibility; strain energy

1. Introduction

Bridges are normally designed to have long life spans. Changes in load characteristics, deterioration with age, environmental influences and random actions may cause local or global damage to these structures. Continuous health monitoring of structures will enable the early identification of distress and allow appropriate retrofitting to prevent potential catastrophic structural failures. In recent times, structural health monitoring (SHM) has attracted much attention in both research and development. SHM defined by Housner *et al.* (1997) refers to the use of in-situ, continuous or regular (routine) measurement and analyses of key structural and environmental parameters under operating conditions, for the purpose of warning impending abnormal states or accidents at an early stage to avoid casualties as well as giving maintenance and rehabilitation advice. SHM encompasses both local and global methods of damage identification (Zapico and Gonzalez 2006). In the local case, the assessment of the state of a structure is done either by direct visual inspection or using experimental techniques such as those using acoustic emission, ultrasonic, magnetic particle inspection, radiography and eddy current. A characteristic of all these techniques

*Corresponding author, Professor, E-mail: tommy.chan@qut.edu.au

is that their application requires a prior localization of the damaged zones. The limitations of the local methodologies can be overcome by using vibration-based (VB) methods, which give a global damage assessment. Health monitoring techniques based on processing vibration measurements basically relate two types of characteristics: the structural parameters (mass, stiffness, damping) and the modal parameters (modal frequencies, associated damping values and mode shapes). As the dynamic characteristics of a structure, namely natural frequencies and mode shapes are known to be functions of its stiffness and mass distribution, variations in modal frequencies and mode shapes can be an effective indication of structural deterioration. Deterioration of a structure results in a reduction of its stiffness which causes the change in its dynamic characteristics. Thus, damage state of a structure can be inferred from the changes in its vibration characteristics (Doebling *et al*. 1996). Usually there are four different levels of damage assessment (Rytter 1993): damage detection (Level 1), damage localization (Level 2), damage quantification (Level 3), and predication of the acceptable load level and of the remaining service life of the damaged structure (Level 4). The amount of literature is quite large for treating single damage scenarios especially in simple structural elements, but limited for multiple damage scenarios. Also most existing methods are based only on a single parameter or criterion. Methods depending only on changes in frequencies and mode shapes, are limited in scope and may not be useful in several realistic situations. It is common to have more than one damage case giving a similar frequency-change characteristic ensemble. In the case of symmetric structures, the changes in natural frequency due to damage at two different symmetric locations are exactly the same. Alternatively, no changes in the mode shapes could be detected if the mode had a node point at the location of damage (Farrar and Cone 1994). There is thus a need for a more comprehensive method of damage assessment in structures.

Fast computers and sophisticated finite element (FE) programs have enabled the possibility of analyzing hitherto intractable problems in structural engineering while simplifying the analyses of other problems. Dynamic computer simulation techniques are used to develop and apply a multi-criteria procedure based on two non-destructive damage detection parameters, along with changes in natural frequencies, for damage assessment in truss bridges. These parameters are the modal flexibility and the modal strain energy, which are based on the vibration characteristics of natural frequencies and mode shapes and their variations with the health of the structure. The application of the approach is demonstrated through numerical simulation studies of a single-span simply supported truss bridge with eight damage scenarios corresponding to different types of deck and truss damage.

2. Recent studies on vibration-based (VB) damage assessment

Literature on the damage assessment of structures using numerical, experimental and theoretical procedures is quite vast. Most of the research pertains to damage assessment in structural members, while some treat a bridge or a building frame. Some of the most recent and relevant research is reviewed here, especially those on vibration based damage assessment methods and/or those pertaining to bridge structures.

Yan *et al*. (2007) comment that the development of vibration-based structural damage detection techniques can be divided into two types: (i) traditional types which use the vibration characteristics such as natural frequency, modal damping, modal strain energy or modal shapes and (ii) modern types which use online measured structural vibration response, and include wavelet analysis, genetic algorithm (GA) and artificial neural network (ANN). An extensive review of methods which directly use the vibration characteristics such as frequencies, mode shapes, damping, etc. to detect structural damage has been carried out by Araújo dos Santos *et al*. (2008). They also review model updating methods and infer that the vast amount of exiting knowledge can be applied to all kinds of structures and damages types. Structures in general have been treated by Fang and Perera (2009) who used a method based on the two parameters - power mode shape curvature and power flexibility, derived from power mode shapes obtained from signal power spectral densities to successfully detect structural damage in linear structures. Goldfeld (2009) assessed the stiffness distribution in structures with the aid of an inverse-problem algorithm. The identification procedure is based on an FE model of the structure with an unknown stiffness distribution and a subset of measured vibration frequencies and vibration modes. Two independent stiffness indicators -axial and flexural, applicable to a variety of structure types including frames, beams and trusses, were proposed. They were determined by using the axial strain and the curvature mode shapes respectively. Damage assessment in structural elements and frames has received considerable attention. The use of vibration based parameters in assessing the effect of repairs to reinforced concrete beams was studied by Baghiee *et al*. (2009). They carried out vibration tests on healthy, damaged and repaired reinforced concrete beams and assessed the capability of different parameters such as frequency, modal assurance criterion, coordinate modal assurance criterion and modal curvature in assessing the repair. El-Ouafi *et al*. (2009) proposed a damage diagnosis method for beams and slabs, which involved the calculation of an "error" based on vibration data relative to the current and reference states of the structure and demonstrated its ability to assess moderate degrees of damage. Ge and Lui (2005) proposed a method for determining the location and severity of damage in three structures, a beam, a frame and a plate, using the corresponding undamaged structure's stiffness and mass properties and the damaged structure's vibration properties. They pointed out that good results can be expected if suitable finite element models and reliable vibration data are available. A virtual-energy-based approach which estimates reduction of the strain energy of vibration modes to assess the damage of a reinforced concrete beam was proposed by Petryna *et al*. (2002). Finite element and Monte-Carlo techniques are used to solve the Eigenvalue problem with respect to randomly generated stiffness and mass matrices and determine the damage. The success of the method is demonstrated by comparing numerical and experimental results. Damage assessment in a reinforced concrete frame was treated by Curadelli *et al*. (2008) by evaluating the damage-sensitive damping coefficient using wavelet transforms. They carried out vibration measurements on the structure under ambient or controlled excitation and correlated damping with damage.

Damage in bridges has also received some attention using vibration based methods and other techniques. Ren and Sun (2008) adopted the wavelet transform combined with Shannon entropy to detect structural damage of a bridge model from measured vibration signals. Some damage features such as wavelet entropy, relative wavelet entropy and wavelet-time entropy are defined and investigated to detect and locate damage. The procedure is illustrated by a numerically simulated case and two laboratory test cases and the merits of these damage features are discussed. The integrity of shear connectors in a 1:3 scaled bridge model was assessed by Xia *et al*. (2007) adopting various vibration-based damage identification methods for different damage scenarios in the connectors. The results showed that a local approach was able to detect all the damage successfully and consistently and as this approach did not need any reference data for the structure, it could be applied to the prototype bridges. Modal parameters from ambient vibration, together with neural networks, were used by Lee and Yun (2006) to determine damage location and severity of steel girder bridges. The effectiveness of the proposed method was demonstrated through numerical analysis and experimental testing of a simply supported bridge model with multiple girders. Petryna *et al*. (2006) carried out a geometrically and physically nonlinear finite element analyses to simulate and assess structural damage and lifetime of an arch bridge. The degradation of structural performance was simulated and design, material and damage parameters were considered as random values to account for possible uncertainties. The numerical results on structural and material state of the bridge after 54 years of service life were predicted and compared with the actual state observed before demolition through vibration tests and examination of different structural elements respectively.

Optimisation techniques in combination with modal data have been used in damage assessment. Perera *et al*. (2007) presented the framework for damage identification problems using measured modal data formulated as a multi-objective optimization problem and describe the methodologies for solving such problems and compare their merits. Guan and Karbhari (2008) introduced an improved damage detection method in which the damage index does not rely on numerical differentiation, but is calculated using only modal displacement and modal rotation. A penalty-based minimization approach is used to find the unknown modal rotation using sparse and noisy modal displacement measurement. The feasibility of the procedure is confirmed through numerical simulation and experimental validation.

Forced vibration and wave propagation techniques have also been used for damage assessment. Zacharias *et al*. (2008) proposed a method for fatigue crack detection in beam-like structures based on nonlinear vibration. The nonlinear dynamic behavior of a cantilever beam with a fatigue crack under harmonic excitation is investigated both theoretically and experimentally and a relationship for crack size was established for damage assessment. Fernandes *et al*. (2008) compared the influence of damage on the vibration wave propagation features of a slender Euler-Bernoulli beam. In the vibration framework, the damage is assessed by considering changes in the reduced flexibility matrix of the structure. In the wave propagation framework, the presence of damage is perceived by an early echo output. A slender aluminium beam with an imposed damage scenario is considered for the numerical analysis. Both approaches showed sensitivity to damage and hence can be used for identification. Peng *et al*. (2008) developed a simple model to track non-linear phenomenon in cracked structures under sinusoidal excitation. This is then applied to analyze the crack-induced non-linear response of a finite element model of a beam to successfully indicate the existences and the sizes of cracks.

As evident from the above review and as also elaborated in Lee *et al*. (2004) a number of methodologies have been used to identify, locate and estimate the severity of damage in structures. The most common vibration-based (VB) damage detection techniques include (changes to) mode shapes, modal curvatures, flexibility curvatures, strain energy curvatures, modal strain energy, flexibility and stiffness matrices. Other techniques such as numerical model updating and artificial neural network have also been incorporated into some VB damage detection methods. It is noticed that those methods utilizing mode shapes are the most developed in terms of displaying the ability to identify, locate and estimate the severity of damage. The modal flexibility and modal strain energy parameters are chosen in this investigation as their corresponding algorithms can be applied to both truss and plate elements, which are the main load bearing elements of truss bridges. In a previous paper the application of these two parameters to beam and plate (flexural members) was demonstrated (Shih *et al*. 2009). The advantage of using the modal flexibility parameter is that the flexibility matrix is most sensitive to changes in the lower-frequency modes of the structures due to the inverse relationship to the square of the natural frequencies (Huth *et al*. 2005). Therefore, a good estimate of the modal flexibility can be made with the inclusion of the first few frequencies and their associated mode shapes. The advantage of using modal strain energy parameter is that only measured mode shapes are required in the damage identification without knowledge of the complete stiffness and mass matrices of the structure (Stubbs *et al.* 1995, Cornwell *et al*. 1999). Only the mode shapes of the first few modes and their corresponding derivatives are required in this proposed algorithm for accurate damage localization. By using both parameters simultaneously, the shortcomings of either of the two parameters can be compensated as they complement and supplement each other to guarantee that single and multiple damages are accurately detected. There is some literature on the application of these two parameters for damage detection in beam, plate or truss structures, but to the best of the authors' knowledge, none on the application to simultaneous damage in both deck and truss in a coupled truss-deck system. The objective of this paper therefore, is to evaluate the feasibility and capability of simultaneously using these two proposed parameters for damage assessment in truss bridges under a range of damage scenarios which includes single and multi damage in deck, truss and combined deck + truss.

3. Theory

3.1 Modal flexibility

The modal flexibility includes the influence of both the modes and natural frequencies. It is defined as the accumulation of the contributions from all available mode shapes and corresponding natural frequencies. It is found that modal flexibility is more sensitive to damage than the mode shapes and natural frequencies alone (Zhao and DeWolf 2002). Damage is a structure results in stiffness reduction and the flexibility increment in the corresponding elements near the damages. Increase in structural flexibility can therefore serve as a good indicator of the degree of structural deterioration.

Modal Flexibility, F_h of element x of a healthy structure can be obtained from as (Zhao and Dewolf 2006, Adewuyi and Wu 2010).

$$F_h = \left[\sum_{r=1}^{n} \frac{1}{\omega_r^2} \phi_{xr} \phi_{xr}^T \right] \tag{1}$$

Where

x = location

r and n = the mode and total number of modes considered (= 5 for present case) respectively

ϕ_{xr} = magnitude of modal vector of mode r at location x

ω is the circular natural frequency

F_h is a scalar. Since, the ω^2 term is in the denominator of Eq. (1).

This expression converges rapidly with increasing values of frequency and a few of the lower modes will provide a good estimate of the flexibility. A similar expression can be written for the modal flexibility F_d at the same location in the damaged structure. The change in the modal flexibility due to structural deterioration is given by Eq. (2) below.

Structural deterioration increases flexibility which can hence serve as a good indicator of the structural damage.

$$\Delta F = F_d - F_h \tag{2}$$

The complete derivation of this damage indicator is given in references (Huth *et al*. 2009, Paz and Leigh 2004).

3.2 Modal strain energy based damage index β

The modal strain energy based damage indicator β uses the change in modal strain of the undamaged and damaged structure to detect and locate damage in a structure (Sazonov *et al*. 2003, Shi *et al*. 2000, Wang *et al*. 2010). The modal strain energy U stored in a bar is as follows

$$\mathbf{U} = \frac{1}{2}\Phi^T\mathbf{K}\Phi \tag{3}$$

$$\mathbf{K} = \mathbf{EA/L} \tag{4}$$

where $\mathbf{K}$ is the stiffness matrix, Φ is the modal displacement shape, E is the modulus of elasticity, A is the cross-sectional area and L is the length of the prismatic bar (Paz and Leigh 2004).

The change of modal strain energy of a truss element is then given as follows

$$\beta = \Delta\mathbf{U} = \mathbf{U}_d - \mathbf{U}_h \tag{5}$$

or rewritten as $\beta = \frac{1}{2}\Phi_d^T\mathbf{K}_d\Phi_d - \frac{1}{2}\Phi_h^T\mathbf{K}_h\Phi_h$ (6)

where index '*h*' and '*d*' refer to the healthy and damaged state respectively. The complete derivations of the damage indicator for truss are given in references (Paz and Leigh 2004, Doebling *et al*. 1997).

The strain energy U for a plate of size $a \times b$ is given as follows

$$U = \frac{D}{2}\int_0^b\int_0^a\left(\left(\frac{\partial^2 w}{\partial x^2}\right)^2 + \left(\frac{\partial^2 w}{\partial y^2}\right)^2 + 2\nu\left(\frac{\partial^2 w}{\partial x^2}\right)\left(\frac{\partial^2 w}{\partial y^2}\right) + 2(1-\nu)\left(\frac{\partial^2 w}{\partial x\partial y}\right)^2\right)dxdy \tag{7}$$

where $D = Eh^3/12(1-\nu^2)$ is the bending stiffness of the plate, ν is the Poisson's ratio, h is the plate thickness, w is the transverse displacement of the plate, $\partial^2 w/\partial x^2$ and $\partial^2 w/\partial y^2$ are the bending curvatures, and $2\partial^2 w/\partial x\partial y$ is the twisting curvature of the plate (Cornwell *et al*. 1999). For a particular mode shape $\phi_i(x, y)$ of the undamaged structure, the strain energy U_i associated with that mode shapes is

$$U_i = \frac{D}{2}\int_0^b\int_0^a\left(\left(\frac{\partial^2 \phi_i}{\partial x^2}\right)^2 + \left(\frac{\partial^2 \phi_i}{\partial y^2}\right)^2 + 2\nu\left(\frac{\partial^2 \phi_i}{\partial x^2}\right)\left(\frac{\partial^2 \phi_i}{\partial y^2}\right) + 2(1-\nu)\left(\frac{\partial^2 \phi_i}{\partial x\partial y}\right)^2\right)dxdy \tag{8}$$

where $\partial^2\phi_i/\partial x^2$ and $\partial^2\phi_i/\partial y^2$ are the mode shape curvatures, $2\partial^2\phi_i/\partial x\partial y$ is the twisting mode shape curvature for the *i*-th mode of the plate. If the plate with area A is subdivided into N_x subdivisions in the x direction and N_y subdivisions in y the direction, then the energy U_{ijk} associated with sub-region jk for the *i*-th mode is given by

$$U_{ijk} = \frac{D}{2}\int_{b_k}^{b_{k+1}}\int_{a_j}^{a_{j+1}}\left(\left(\frac{\partial^2 \phi_i}{\partial x^2}\right)^2 + \left(\frac{\partial^2 \phi_i}{\partial y^2}\right)^2 + 2\nu\left(\frac{\partial^2 \phi_i}{\partial x^2}\right)\left(\frac{\partial^2 \phi_i}{\partial y^2}\right) + 2(1-\nu)\left(\frac{\partial^2 \phi_i}{\partial x \partial y}\right)^2\right)dxdy \tag{9}$$

or rewritten in a discretized form as

$$U_{ijk} = \frac{D}{2}[(\phi''_{xi\cdot jk})^2 + (\phi''_{yi\cdot jk})^2 + 2\nu(\phi''_{xi\cdot jk})(\phi''_{yi\cdot jk}) + 2(1-\nu)(\phi''_{xyi\cdot jk})]A_{jk} \tag{10}$$

and

$$U_i = \sum_{k=1}^{N_y}\sum_{j=1}^{N_x} U_{ijk} \tag{11}$$

The fractional energy at location jk is defined as

$$F_{ijk} = \frac{U_{ijk}}{U_i} \quad \text{and} \quad \sum_{k=1}^{N_y}\sum_{j=1}^{N_x} F_{ijk} = 1 \tag{12, 13}$$

Similar expressions can be written using the modes of the damaged structure ϕ_i^*, where the superscript * indicates damaged state. A ratio of parameters can be determined that is indicative of the change of stiffness in the structure as follows

$$f_{ijk} = \frac{\int_{b_k}^{b_{k+1}}\int_{a_j}^{a_{j+1}}\left(\left(\frac{\partial^2 \phi_i}{\partial x^2}\right)^2 + \left(\frac{\partial^2 \phi_i}{\partial y^2}\right)^2 + 2\nu\left(\frac{\partial^2 \phi_i}{\partial x^2}\right)\left(\frac{\partial^2 \phi_i}{\partial y^2}\right) + 2(1-\nu)\left(\frac{\partial^2 \phi_i}{\partial x \partial y}\right)^2\right)dxdy}{\int_0^b\int_0^a\left(\left(\frac{\partial^2 \phi_i}{\partial x^2}\right)^2 + \left(\frac{\partial^2 \phi_i}{\partial y^2}\right)^2 + 2\nu\left(\frac{\partial^2 \phi_i}{\partial x^2}\right)\left(\frac{\partial^2 \phi_i}{\partial y^2}\right) + 2(1-\nu)\left(\frac{\partial^2 \phi_i}{\partial x \partial y}\right)^2\right)dxdy} \tag{14}$$

or rewritten in a discretized form as

$$f_{ijk} = \frac{[(\phi''_{xi\cdot jk})^2 + (\phi''_{yi\cdot jk})^2 + 2\nu(\phi''_{xi\cdot jk})(\phi''_{yi\cdot jk}) + 2(1-\nu)(\phi''_{xyi\cdot jk})]A_{jk}}{\sum[(\phi''_{xi})^2 + (\phi''_{yi})^2 + 2\nu(\phi''_{xi})(\phi''_{yi}) + 2(1-\nu)(\phi''_{xyi})]A} \tag{15}$$

and an analogous term f_{ijk}^* can be defined using the damaged mode shapes. In order to account for all measured modes, the following formulation for the damage index (Cornwell *et al*. 1999) or MSEC, for sub-region jk is used

$$\beta_{jk} = \frac{\sum_{i=1}^{m} f_{ijk}^*}{\sum_{i=1}^{m} f_{ijk}} \tag{16}$$

4. Method

Initially a single-span truss bridge is developed as a finite element (FE) model and its modal response is obtained using the FE software package SAP2000. Additional FE models with eight damage scenarios are selected for investigation. The primary modal parameters of natural frequencies & mode shapes of the first five modes of these models, before and after damage in eight damage scenarios are extracted from the results of the FE analysis. These parameters are then used to determine the change of flexibility and the change of modal strain energy and thereby assess the structural health state of the bridge. The peak value of each damage parameter indicates the corresponding simulated damage location. The accuracy of the damage detection method is then evaluated through observations of the plots of the two parameters which are modal flexibility change & modal strain energy change. Detailed discussions on the finite element modelling of proposed structure are given as follows.

4.1 Finite element modelling of truss bridge

A truss bridge model is treated in this study and the general modelling scheme for bridge is depicted in Fig. 1. The superstructure used as the basis for the investigation is a zero-skew, single span truss bridge with 4 m wide deck consisting two steel truss girder spanning 18 m. The concrete slab thickness is 200 mm and the spacing between twin-girders is 3 m. Details of geometry and material properties for the bridge are listed in Table 1. The model is a nine-panel truss bridge with a

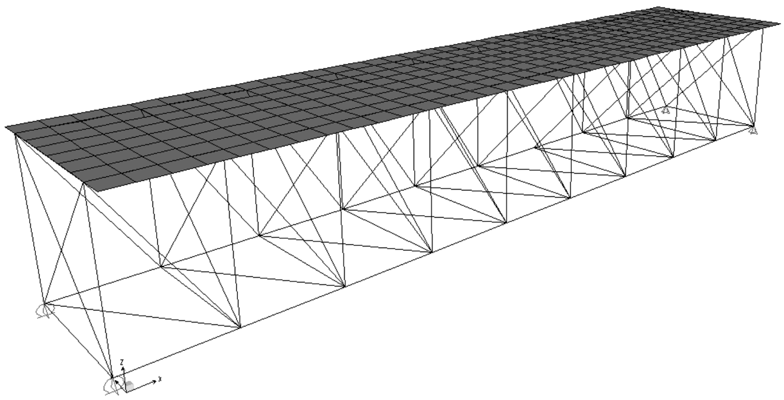


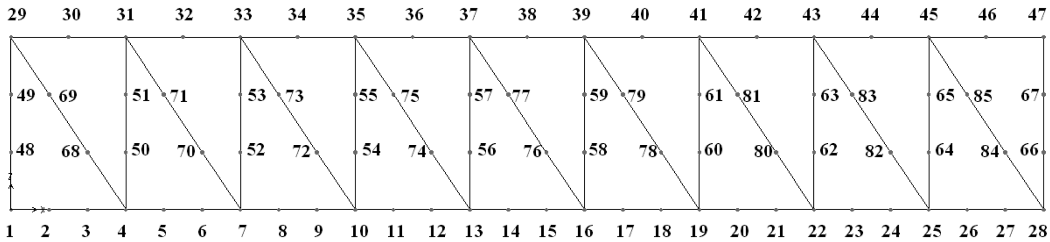
Fig. 1 Isometric view of truss model

Table 1 Geometric and material properties of deck and truss

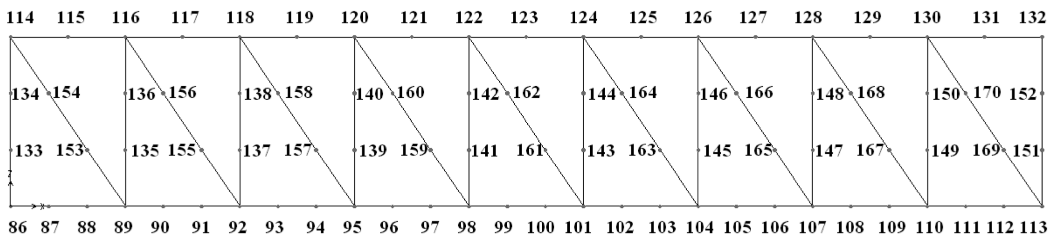
Structural member	Deck	Truss
Element type	Shell	Truss
Material	Concrete	Steel
Length	18 m	various
Width	4 m	100 mm
Depth	200 mm	6 mm
Poisson's ratio	0.2	0.3
Mass density	2400 kg/m^3	7800 kg/m^3
Modulus of elasticity	24 GPa	200 GPa

Table 2 Numbering system for truss members

Truss type	Element no.	
	Left truss panel	Right truss panel
Top chord member	130-147	28-45
Bottom chord member	103-129	1-27
Vertical member	148-177	46-75
Diagonal member	178-204	76-102

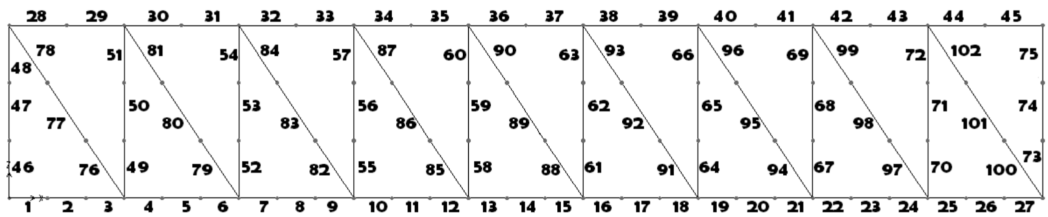


(a) Right truss panel

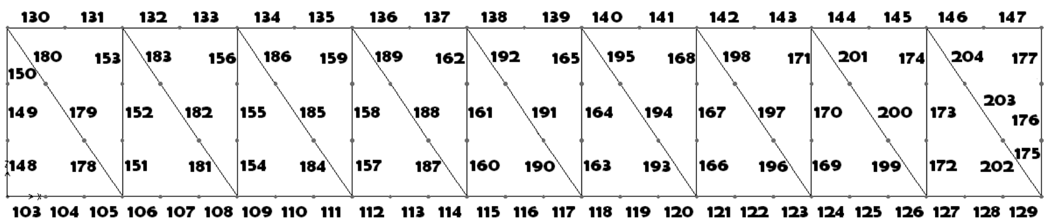


(b) Left truss panel

Fig. 2 Numbering system for truss nodes



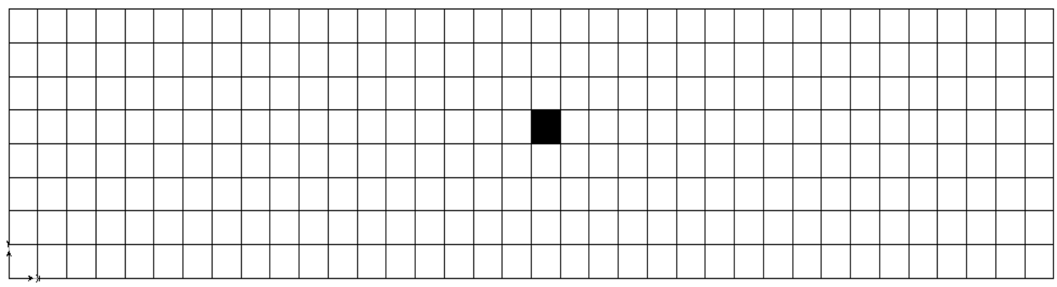
(a) Right truss panel



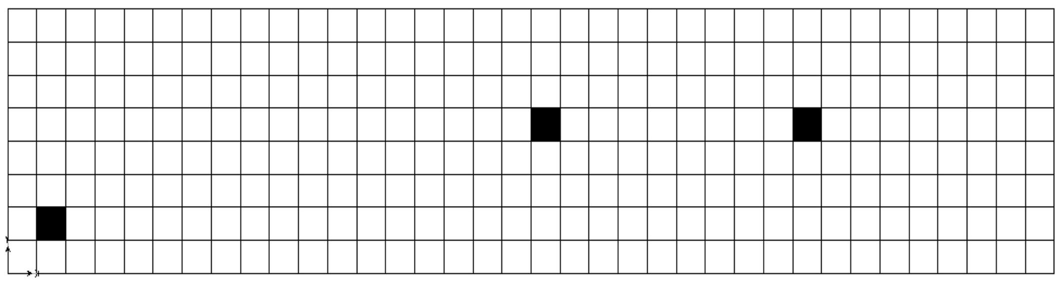
(b) Left truss panel

Fig. 3 Numbering system for truss members truss depth of 3 m and each panel having a width of 2 m. The numbering systems for truss members are shown in Table 2 and Figs. 2 to 3. Steel diagonal bracings in the vertical plane are installed between truss-girders at spacing of 2 m and bottom cross bracing are provided between the two truss panels to prevent lateral buckling failure of compression truss members. For finite element analysis, bridge deck is modelled with shell elements while truss panels and steel bracing are modelled with truss elements. The deck and each truss girder are divided into 288 and 102 elements respectively. It is assumed that there is a complete connection between the truss girders and slab. Twin girders having the same span are simply supported at their ends and rotations about all 3 axes are allowed in order to simulate the desired boundary condition.

A total of 8 damage cases are investigated for the damage assessment of this bridge. The first two damage cases D1 and D2 are simulated for deck damage, the next four damage cases D3-D6 for truss damage, and the last two damage cases D7 and D8 for deck and truss damage simultaneously. Damage on deck is simulated by reducing the elastic modulus (E) of selected elements with size of 500 mm × 500 mm while damage on the truss is simulated by reducing the cross-section area (A) of the selected truss members along one-third of their lengths. The corresponding reduced stiffness for the selected deck and truss damage elements are represented by 0.5E and 0.5A respectively. All damage scenarios of deck and truss are shown in Figs. 4-6. The truss damage configurations are listed in Table 3. In damage cases D1 and D2, a single damage and three damages are simulated on the deck respectively. In damage cases D3, D4 and D8, damage is simulated in right truss panel only, while in D5-D7, damage is simulated on right and left truss panels.

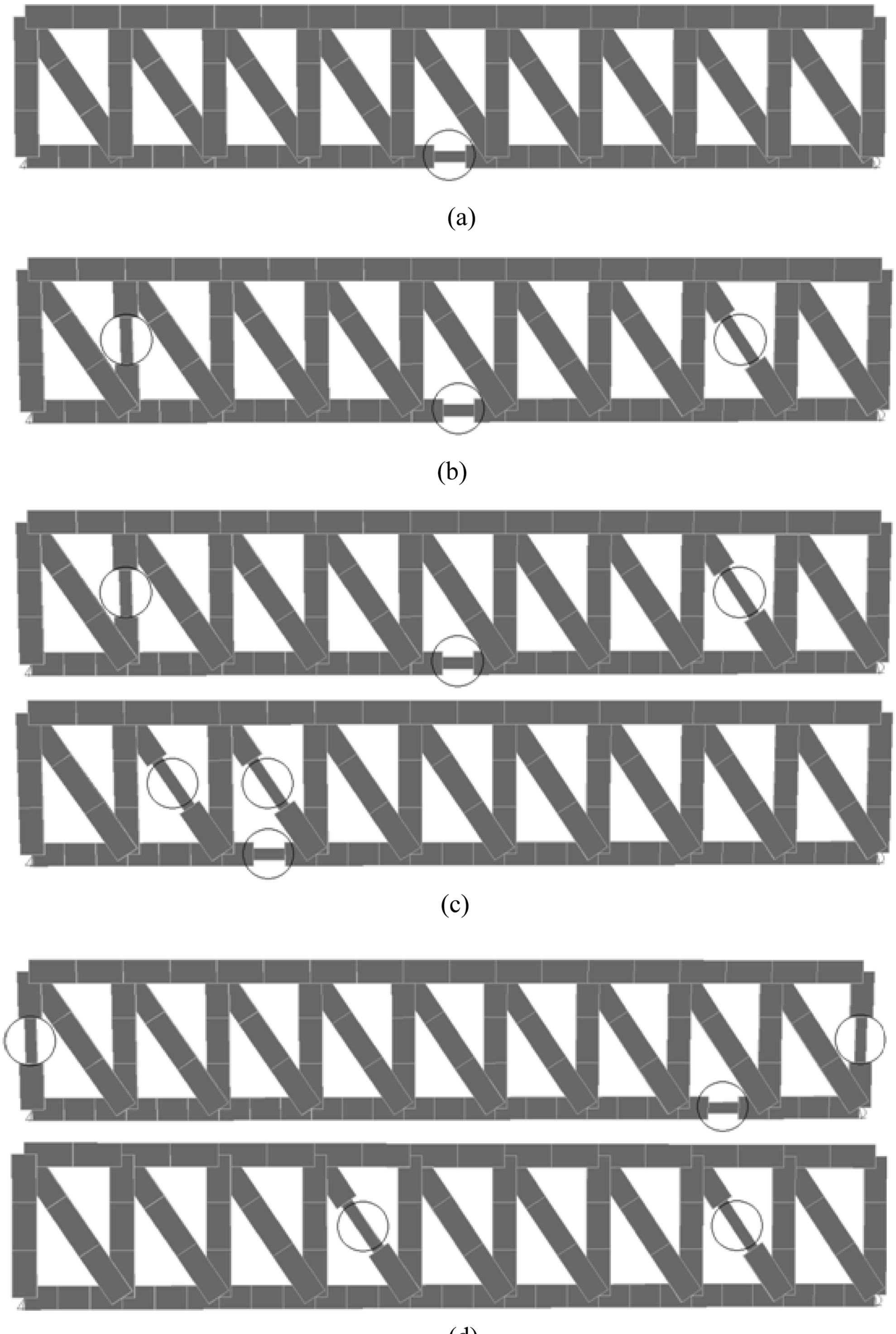


(a)



(b)

Fig. 4 Damage cases for deck: (a) D1, (b) D2



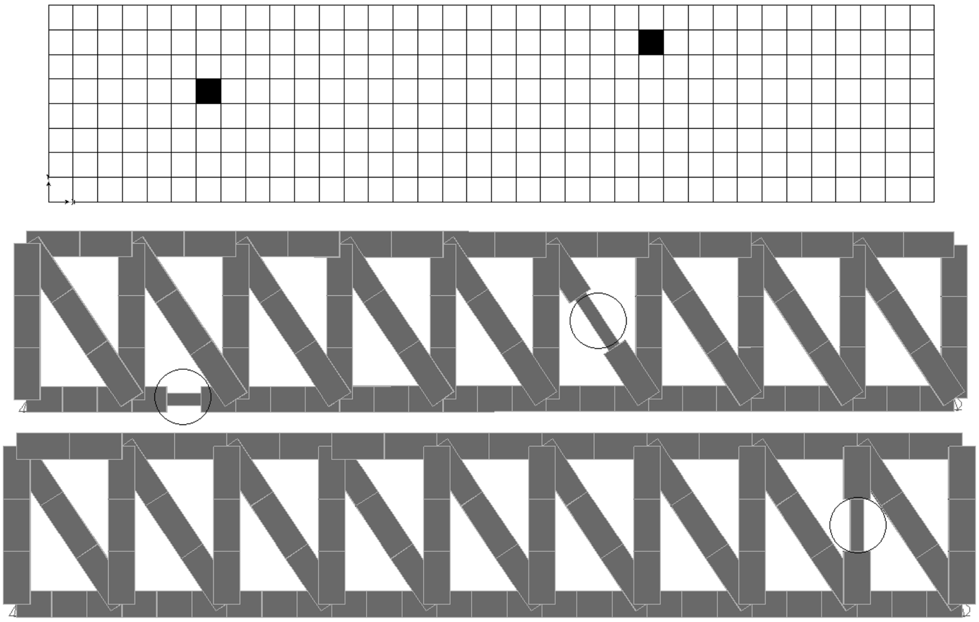
(a)

(b)

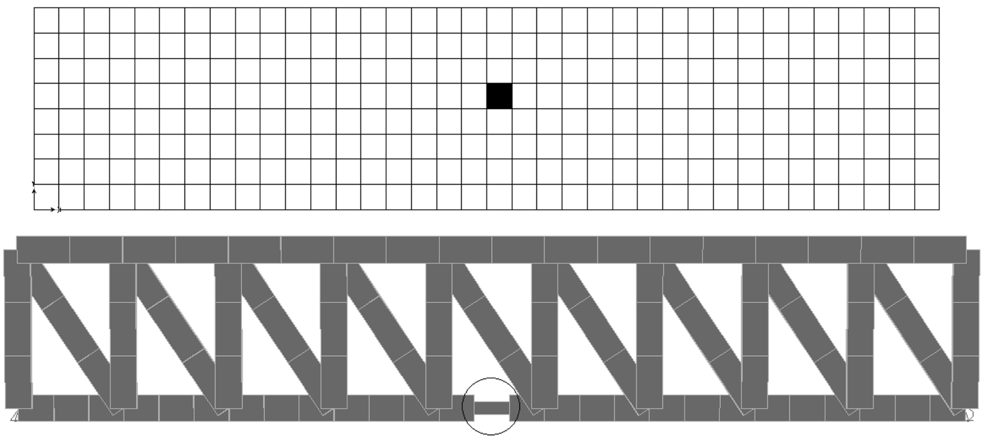
(c)

(d)

Fig. 5 Damage cases for truss girders: (a) D3, (b) D4, (c) D5, (d) D6



(a)



(b)

Fig. 6 Damage cases for deck and truss girders: (a) D7, (b) D8

Table 3 Truss damage configurations

Damage case	Left truss panel		Right truss panel	
	Element no.	Node no.	Element no.	Node no.
D3	-	-	14	14-15
D4	-	-	14,50,98	14-15,50-51,82-83
D5	110,182,185	93-94,155-156,157-158	14,50,98	14-15,50-51,82-83
D6	188,200	159-160, 167-168	23,47,74	23-24,48-49,66-67
D7	173	149-150	5,92	5-6, 78-79
D8	-	-	14	14-15

Table 4 Natural frequencies from FEM for truss bridges (Percentage changes wrt to the undamaged conditions are listed within brackets)

Damage case		Mode 1 f_1 (Hz)	Mode 2 f_2 (Hz)	Mode 3 f_3 (Hz)	Mode 4 f_4 (Hz)	Mode 5 f_5 (Hz)
Intact		7.90	12.05	15.63	17.95	22.55
Deck damage	D1	7.87 (0.49)	12.00 (0.42)	15.59 (0.24)	17.93 (0.10)	22.52 (0.12)
	D2	7.84 (0.81)	11.95 (0.85)	15.53 (0.63)	17.92 (0.16)	22.37 (0.79)
Girder(s) damage	D3	7.82 (1.12)	12.05 (0.03)	15.63 (0.01)	17.94 (0.04)	22.54 (0.05)
	D4	7.80 (1.30)	12.05 (0.05)	15.47 (0.98)	17.93 (0.06)	22.34 (0.93)
	D5	7.69 (2.70)	12.04 (0.12)	15.41 (1.36)	17.80 (0.81)	22.18 (1.66)
	D6	7.79 (1.42)	11.88 (1.44)	15.34 (1.82)	17.71 (1.32)	22.23 (1.42)
Deck & girder(s) damage	D7	7.85 (0.74)	11.97 (0.72)	15.44 (1.22)	17.85 (0.55)	22.19 (1.59)
	D8	7.78 (1.60)	12.00 (0.46)	15.59 (0.23)	17.92 (0.14)	22.51 (0.17)

Note: Natural frequencies decrease in all damage cases.

5. Results and discussion

5.1 Frequency change

The first five natural frequencies and mode shapes are extracted from the eigenvalue analysis of the bridge model. No structural damping is used in the free vibration analysis. The natural frequencies of the first five modes of truss bridge before and after damage in eight damage cases are shown in Table 4. It is found that frequency decreases in all damage cases D1-D8 including deck damage, truss damage and combined damages. It is also found that damage in a truss member (stiffness reduction of 0.5A) in general causes a comparatively larger change in the fundamental frequency than deck damage (stiffness reduction of 0.5E), where ‘A’ and ‘E’ are the cross section area and elastic modulus of truss member. This is evident by comparing the frequency changes in damage cases D3 with D1 (single damage) and D4 with D2 (triple damage). It is also interesting to note that the change in frequency in damage case D8 is the sum of frequency changes in damage cases D1 and D3, across all five modes, which match with the damage scenarios. By observing frequency changes for D1 and D2 for deck damage and D3, D4 and D5 for truss damage, it is noteworthy that higher levels of damage severity lead to greater changes in frequency in all vibration modes (mode 1 - mode 5). The first five vibration mode shapes for the undamaged bridge are illustrated in Fig. 7. It appears that the dynamic behaviour of the bridge model, characterised by

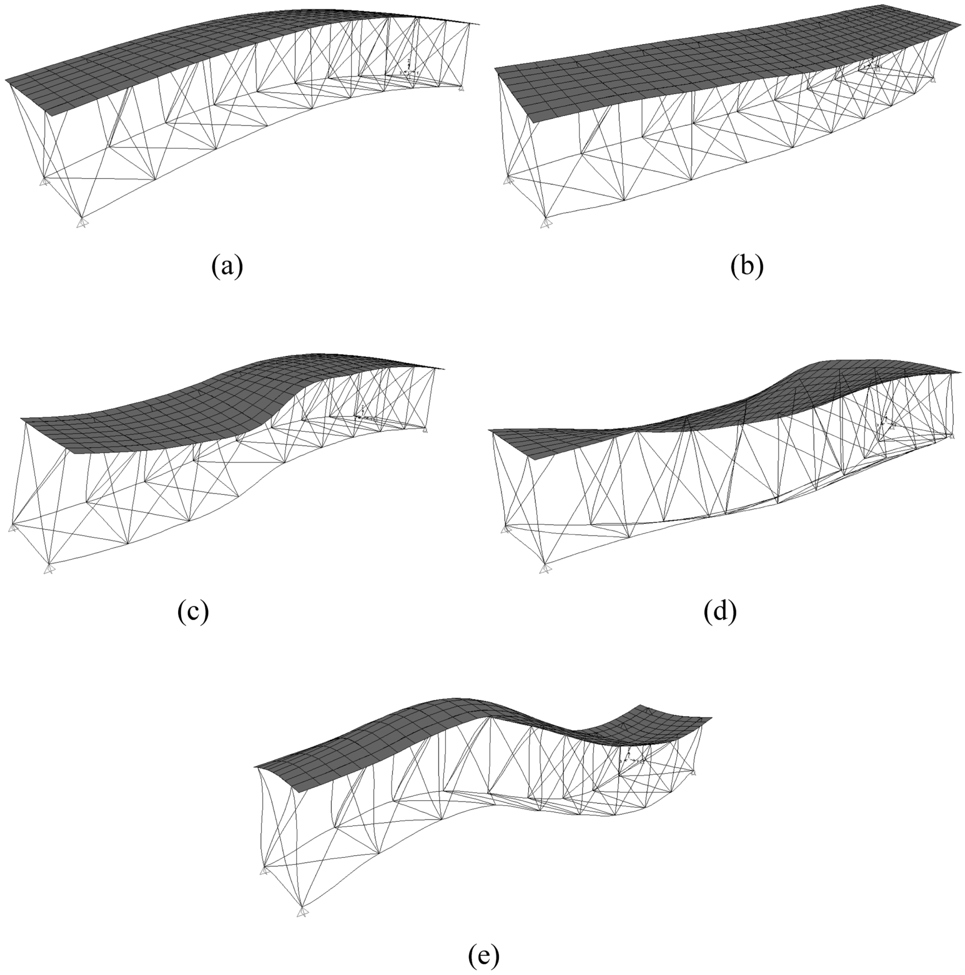


Fig. 7 First five vibration modes of FE model (a) Mode 1: f_1 = 7.9 Hz, (b) Mode 2: f_2 = 12.05 Hz, (c) Mode 3: f_3 = 15.63 Hz, (d) Mode 4: f_4 = 17.95 Hz, (e) Mode 5: f_5 = 22.55 Hz

the first 5 modes, is governed by predominantly vertical bending modes (modes, 1, 3 and 5) along with coupled vertical, lateral and torsional vibration modes (modes 2 and 4) in the frequency range of 7.9-23 Hz. Some local vibration of truss members was also observed in all the modes. The fundamental mode is predominantly the vertical bending mode coupled with some local modes of the truss members, having a natural frequency of 7.9 Hz.

5.2 Modal flexibility change (MFC)

The first five natural frequencies and associated mode shapes obtained from the Eigen-value analysis are used to calculate the MFC. Plots of MFC in deck for damage cases D1, D2, D3 and D8 are shown in Figs. 8(a)-(d). The maximum or peak values of the plots indicate the damage locations on deck. In Fig. 8(a), there is a distinct peak at the mid-span of deck, which conforms well with the damage cases D1. In Fig. 8(b) there are three peaks which correspond to the three damaged

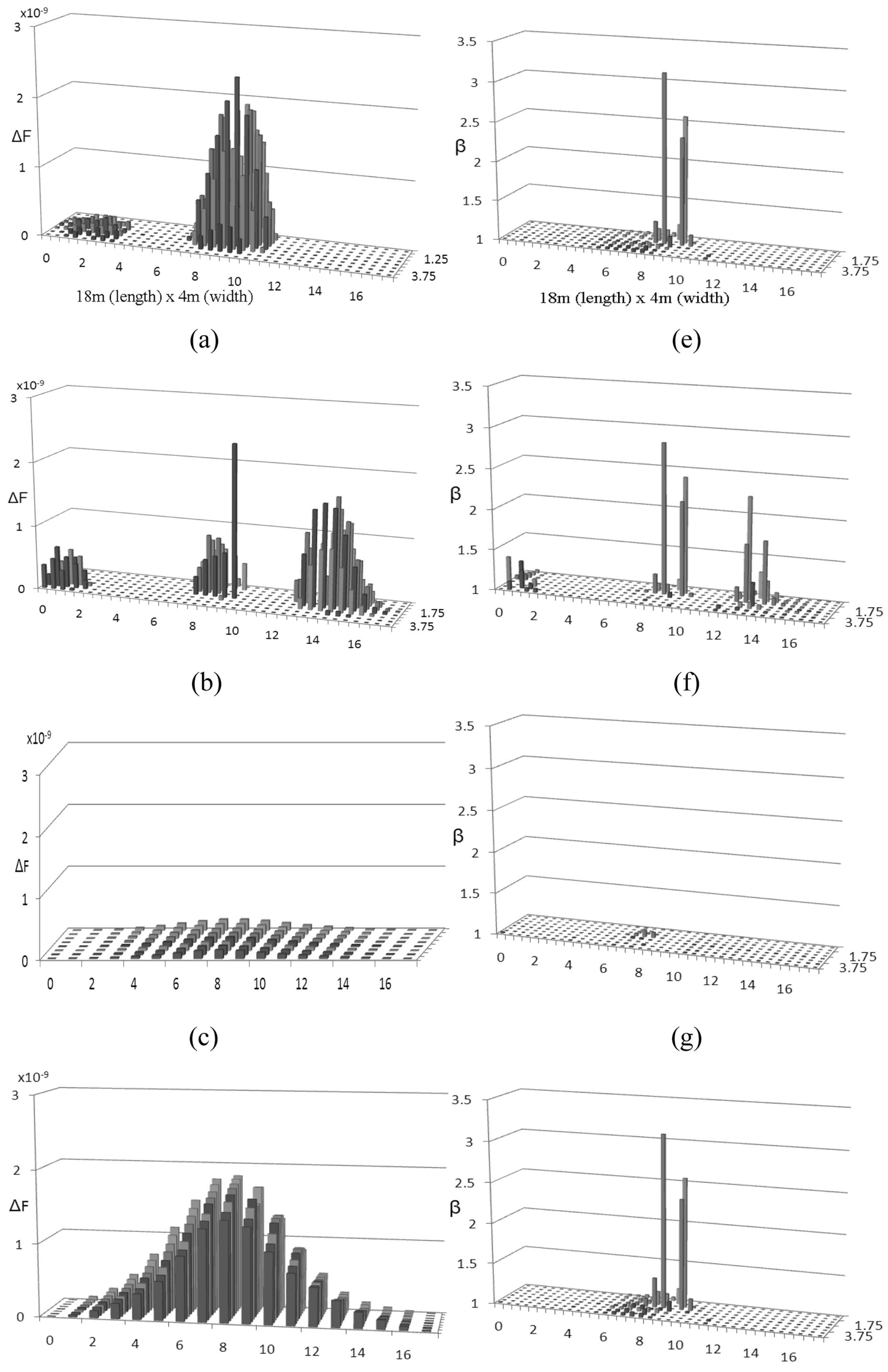


Fig. 8 Modal flexibility change: (a) D1, (b) D2, (c) D3, (d) D8; Modal strain energy based damage index (e) D1, (f) D2, (g) D3, (h) D8

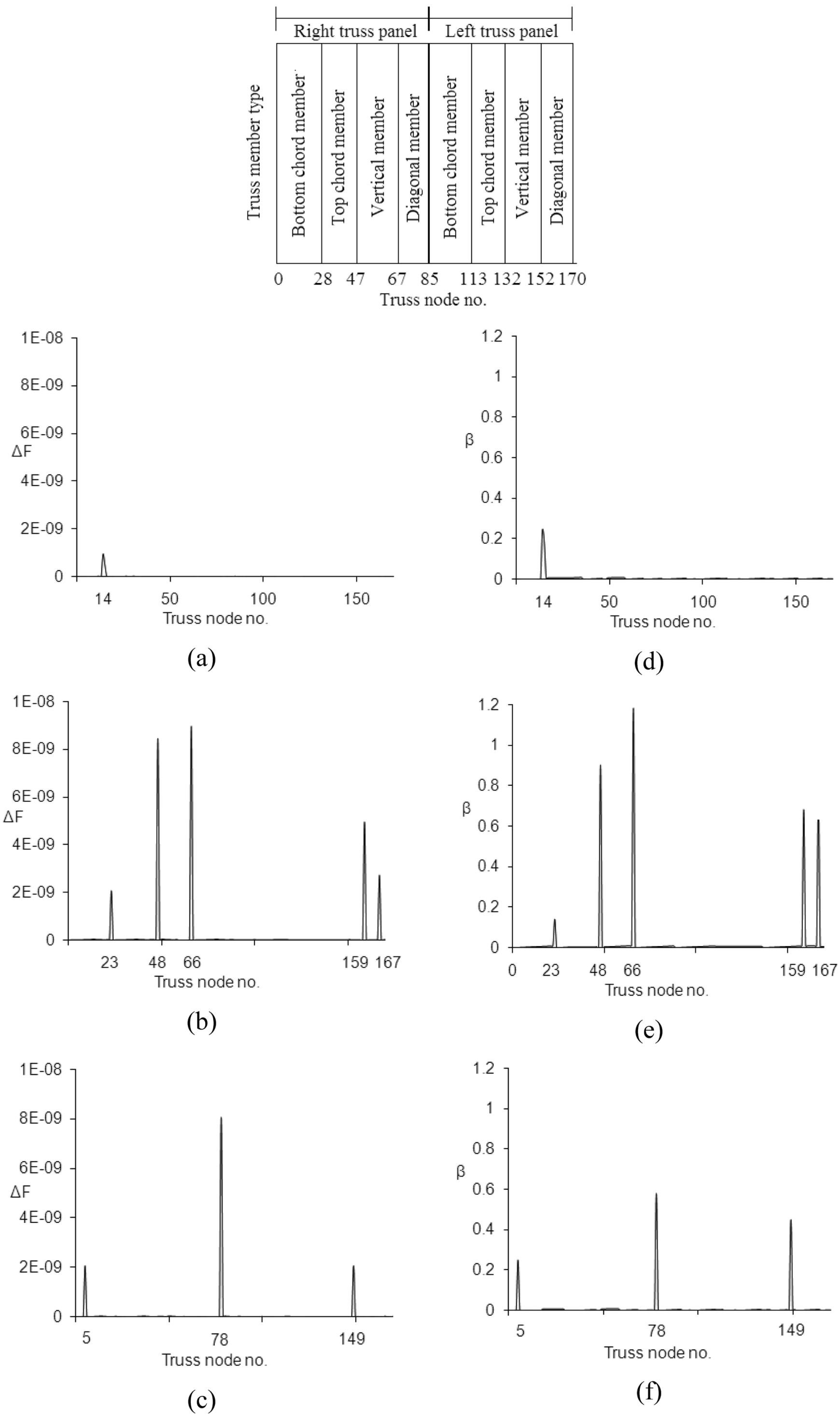


Fig. 9 Modal flexibility change: (a) D3, (b) D6, (c) D7; Modal strain energy based damage index: (d) D3, (e) D6, (f) D7

elements on the deck in damage case D2. Plots of MFC on deck for damage case D3, which pertain to girder damage (only) are shown in Fig. 8(c). As expected there are no distinguishing peak(s) in the plots of MFC, as these are small in magnitude and randomly distributed across the intact deck. Plots of MFC on deck for damage case D8, which pertain to both deck and girder damage are shown in Fig. 8(d). Though there is no distinct peak, there is a clear maximum value at mid-deck indicating the damage. A gradually increasing MFC with a maximum value at the deck centre, instead of a distinct peak, may be due to the existence of simultaneous truss damage. MFC in the deck for the other girder damage cases (D4, D5 and D6) and combined damage case (D7) are not shown as results are analogous to those for damage cases D3 and D8.

The plots of MFC along the truss for damage cases D3, D6 and D7 are shown in Fig. 9. In Fig. 9(a), the distinct peak of the plot indicates correctly the damage locations on truss elements of bottom chord member. For damage cases D6 and D7 as shown in Figs. 9(b) and (c), MFC shows great ability on localizing all damaged elements accurately. Overall, it is concluded that MFC provides feasible, reliable and effective results on localization of truss damage.

5.3 Modal strain energy change (MSEC) – β

The first five mode shapes obtained from the eigenvalue FE analysis are used to calculate the MSEC parameter β. Plots of MSEC on deck for damage cases D1, D2, D3 and D8 are shown in Figs. 8(e)-(h). The peak values of the plots indicate the location of damage on the deck. Similar to the MFC parameter, it is found that the MSEC parameter is able to detect and localize damage zones on deck precisely in all cases of deck damage. In Fig. 8(g), random distribution of all damage indicators ($\beta < 1.0$) of the plot implies that no damage occurs on the deck. For damage case D8 (deck and girder combined damage) as shown in Fig. 8(h), MSEC is able to detect the damaged element precisely. MSEC in deck for the other girder damage cases D4, D5 and D6 and combined damage case D7 are not shown as they draw the same conclusions as with D1-D3 and D8.

The plots of MSEC (β) along the truss for damage cases D3, D6 and D7 are shown in Figs. 9(d)-(f). Similar to the MFC parameter, the MSEC parameter is able to detect and locate multiple damages on truss panel(s) precisely in all truss damage cases. Damage cases D4, D5 and D8, are not shown here, as they have analogous results with D3, D6 and D7.

From the extensive numerical analyses, it is found that MSEC and MFC are both performing reasonably well in detecting deck and girder damage in all damage cases.

6. Conclusions

A number of vibration-based methodologies have been found in the recent literature to identify, locate and estimate the severity of damage in structures using numerical simulations. The most common vibration-based damage detection techniques include changes to mode shapes, modal curvatures, flexibility curvatures, strain energy curvatures, modal strain energy, flexibility and stiffness matrices. The other vibration-based techniques include numerical model updating and neural network based methods. The amount of literature in non-destructive vibration methods is quite large for treating single damage scenarios, however is limited for multiple damage scenarios. Most existing methods are based on a single criterion and most authors demonstrate these methods mainly in beam-like or plate-like elements. Also existing methods, which depend only on changes in frequencies and mode shapes, are limited in scope and may not be useful in several realistic situations.

The main contribution of this paper is that the proposed multi-criteria approach is shown feasible for damage detection in the truss bridges based on the results from the extensive dynamic computer simulations. It shows that the developed multi-criteria based non-destructive damage detection methodology can be successfully applied to truss bridges. The proposed procedure incorporates two damage detection parameters based on changes in (1) modal flexibility matrix and (2) modal strain energy, in addition to changes in natural frequencies, all of which are evaluated from the results of free vibration analysis of the damaged and healthy structural models. In the illustrative example of truss bridge, two types of damage severity including flexural stiffness reduction of 50% on deck and axial stiffness reduction of 50% on truss member are investigated at selected damage locations. A total of eight damage cases are investigated in the study: two combined damage cases, in which deck and truss girder are damaged simultaneously along with two deck damage cases and four truss girder damage cases. Traditional vibration tests will be used to obtain the dynamic characteristics for the proposed damage detection techniques, e.g., (Farrar and Cone 1994). With a careful planning of the deployment of accelerometers, the modal parameters of a structure in its damaged and healthy states can be determined using standard experimental modal analysis procedures. A rational fraction polynomial, global, curve-fitting algorithm in some commercial modal analysis software packages can also be used to fit the analytical models to the measured data and to extract resonant frequencies, mode shapes etc. From the illustrated numerical examples, it is noted that the two damage localization methods (Modal flexibility change and modal strain energy change) are effective in locating areas with stiffness reductions ranging from 20%-50% by using the first five mode shapes of the finite element models before and after damaged. The general observation resulting from this study is that higher damage severity pertaining to multiple damages causes higher frequency change ratios across all the modes. It is also evident that both damage assessment parameters MFC and MSEC are able to detect and accurately locate multiple damages in the trusses for all damage cases. In deck damage cases there could be some ambiguities in either parameter. MSEC has distinct peaks at the damage locations, but there could also be a (slightly smaller) spike in the vicinity (D1, D2 and D8). When there is truss damage in addition to deck damage (D8), MFC gradually increases to a maximum value at the deck damage location (instead of a distinct peak). As there could be some discrepancies in both damage assessment parameters (MFC and MSEC), especially for deck damage cases, the combination of MFC & MSEC together with the changes in natural frequencies provides the optimum chances of accurate damage assessment under all damage scenarios as demonstrated through the examples. Due to the major advances in the fields of structural dynamics, finite element techniques and experimental modal analysis, the multiple criteria approach shows promise in being used for detecting and locating damage in structures. It can be concluded that the proposed multi-criteria vibration based approach provides reasonably reliable and accurate tools for identification and detection of multiple damages in truss bridges.

Acknowledgements

This research forms part of a continuing study of structural health monitoring of structures conducted in Queensland University of Technology. H.W. Shih is supported by a Queensland University of Technology Postgraduate Research Award.

References

Adewuyi, A.P. and Wu, Z.S. (2010), "Modal macro-strain flexibility methods for damage localization in flexural structures using long-gage FBG sensors Journal of structural control and health monitoring", *Struct. Control Hlth. Monit*., **18**(3), 341-360.

Araújo dos Santos, J.V., Maia, N.M.M., Mota Soares, C.M. and Mota Soares, C.A. (2008), "Structural damage identification: a survey", (Eds. Topping, B.H.V. and Papadrakakis, M.), *Trends in Computational Structures Technology*, Saxe-Coburg Publications, Stirlingshire, UK.

Baghiee, N., Esfahani, M.R. and Moslem, K. (2009), "Studies on damage and FRP strengthening of reinforced concrete beams by vibration monitoring", *Eng. Struct.,* **31**(4), 875-893.

Cornwell, P., Doebling, S.W. and Farrar, C.R. (1999), "Application of the strain energy damage detection method to plate-like structures", *J. Sound Vib.*, **224**(2), 359-374.

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

Doebling, S.W., Hemez, F.M., Peterson, L.D. and Farhat, C. (1997), "Improved damage location accuracy using strain energy-based mode selection criteria", *AIAA J*., **35**(4), 693-699.

Doebling, S.W., Farrar, C.R., Prime, M.B. and Shevitz, D.W. (1996), "Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: a literature review", Report no. LA-13070-MS, Los Alamos National Laboratory, Los Alamos, USA.

El-Ouafi Bahlous, S., Smaoui, H. and El-Borgi, S. (2009), "Experimental validation of an ambient vibration-based multiple damage identification method using statistical modal filtering", *J. Sound Vib.,* **325**(1-2), 49-68.

Fang, S.E. and Perera, R. (2009), "Power mode shapes for early damage detection in linear structures", *J. Sound Vib.,* **324**(1-2), 40-56.

Farrar, C.R. and Cone, K.M. (1994), "Vibration testing of the I-40 Bridge before and after the introduction of damage", *Proceedings of 13th International Modal Analysis Conference*, Nashville, TN, February.

Fernandes, K.M., Stutz, L.T., Tenenbaum, R.A. and Silva Neto, A.J. (2008), "Vibration and wave propagation approaches applied to assess damage influence on the behavior of Euler-Bernoulli beams: Part I direct problem", (Eds. Topping, B.H.V. and Papadrakakis, M.), *Proceedings of the Ninth International Conference on Computational Structures Technology*, Civil-Comp Press, Stirlingshire, UK.

Ge, M. and Lui, M. (2005), "Structural damage identification using system dynamic properties", *Comput. Struct.,* **83**(27), 2185-2196.

Goldfeld, Y. (2009), "A direct identification procedure for assessment of stiffness distribution", *Eng. Struct.,* **31**(5), 1068-1076.

Guan, H. and Karbhari, V.M. (2008), "Improved damage detection method based on Element Modal Strain Damage Index using sparse measurement", *J. Sound Vib.,* **309**(3-5), 465-494.

Housner, G.W., Bergman, L.A., Caughey, T.K., Chassiakos, A.G., Claus, R.O., Masri, S.F., Skelton, R.E., Soong, T.T., Spencer, B.F. and Yao, J.T.P. (1997), "Structural control: past, present, and future", *J. Eng. Mech.,* **123**(9), 897-971.

Huth, O., Maeck, J., Kilic, N. and Motavalli, M. (2005), "Damage identification using modal data: Experiences on a prestressed concrete bridge", *J. Struct. Eng.-ASCE,* **131**(12), 1898-1910.

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

Lee, L.S., Karbhari, V.M. and Sikorsky, C. (2004), "Investigation of integrity and effectiveness of RC bridge deck rehabilitation with CFRP composites", Report no. SSRP-2004/08, Department of Structural Engineering, University of California, San Diego.

Paz, M. and Leigh, W. (2004), "Structural dynamics: theory and computation", Springer Science + Business Media Inc., United States of America.

Peng, Z.K., Lang, Z.Q. and Chu, F.L. (2008), "Numerical analysis of cracked beams using nonlinear output frequency response functions", *Comput. Struct.,* **86**(17-18), 1809-1818.

Petryna, Y.S., Ahrens, A. and Stangenberg, F. (2006), "Damage simulation and health assessment of a road bridge", (Eds. Topping, B.H.V., Montero, G. and Montenegro, R.), *Proceedings of the Eighth International Conference on Computational Structures Technology*, Civil-Comp Press, Stirlingshire, UK.

Perera, R., Ruiz, A. and Manzano, C. (2007), "An evolutionary multiobjective framework for structural damage localization and quantification", *Eng. Struct.,* **29**(10), 2540-2550.

Petryna, Y.S., Krätzig, W.B. and Stangenberg, F. (2002), "Structural damage: simulation and assessment", (Eds. Topping, B.H.V. and Bittnar, Z.), *Computational Structures Technology*, Saxe-Coburg Publications, Stirlingshire, UK.

Ren, W.X. and Sun, Z.S. (2008), "Structural damage identification by using wavelet entropy", *Eng. Struct.,* **30**(10), 2840-2849.

Rytter, A. (1993), "Vibration based inspection of civil engineering structural", Doctoral Dissertation, Department of Building Technology and Structural Engineering, University of Aalborg, Aalborg, Denmark.

Sazonov, E.S., Klinkhachorn, P., Halabe, U.B. and GangaRao, H.V.S. (2003), "Non-baseline detection of small damages from changes in strain energy mode shapes", *Non-Des. Test. Eval.*, **18**(3-4), 91-107.

Shi, Z.Y., Law, S.S. and Zhang, L.M. (2000), "Structural damage detection from modal strain energy change", *J. Eng. Mech.*, **126**(12), 1216-1223.

Shih, H.W., Thambiratnam, D.P. and Chan, T.H.T. (2009), "Vibration based structural damage detection in flexural members using multi-criteria approach", *J. Sound Vib.,* **323**(3-5), 645-661.

Stubbs, N., Kim, J.T. and Farrar, C.R. (1995), "Field verification of a non-destructive damage localization and severity algorithm", *Proceedings of 13th International Modal Analysis Conference*, Nashville, USA.

Wang, S., Zhang, J., Liu, J. and Liu, F. (2010), "Comparative study of modal strain energy based damage localization methods for three-dimensional structure", *Proceedings of the Twentieth International Offshore and Polar Engineering Conference*s, Beijing, China, June.

Xia, Y., Hao, H. and Deeks, A.J. (2007), "Dynamic assessment of shear connectors in slab-girder bridges", *Eng. Struct.,* **29**(7), 1475-1486.

Yan, Y.J., Cheng, L., Wu, Z.Y. and Yam, L.H. (2007), "Development in vibration-based structural damage detection technique", *Mech. Syst. Signal Pr.*, **21**, 2198-2211.

Zacharias, K., Douka, E., Hadjileontiadis, L.J. and Trochidis, A. (2008), "Non-linear vibration technique for crack detection in beam structures using frequency mixing", (Eds. Topping, B.H.V. and Papadrakakis, M.), *Proceedings of the Ninth International Conference on Computational Structures Technology*, Civil-Comp Press, Stirlingshire, UK.

Zapico, J.L. and Gonzalez, M.P. (2006), "Vibration numerical simulation of a method for seismic damage identification in buildings", *Eng. Struct.,* **28**(2), 255-263.

Zhao, J. and DeWolf, J.T. (2002), "Dynamic monitoring of steel girder highway bridge", *J. Bridge Eng.,* **7**(6), 350-356.

Zhao, J. and Dewolf, J.T. (2006), "Sensitivity study for vibrational parameters used in damage detection", *J. Struct. Eng.*, **25**(4), 410-416.