The 3rd International Conference on Structural Health Monitoring of Intelligent Infrastructure
Vancouver, British Columbia, Canada
November 13-16, 2007

VIBRATION-BASED DAMAGE DETECTION OF SUPPORT SOFTENING UNDER A TIMBER BRIDGE STRINGER

Yang Sun
University of Saskatchewan, Canada

Leon D. Wegner
University of Saskatchewan, Canada

Bruce F. Sparling
University of Saskatchewan, Canada

Abstract

This paper describes the results of a study to explore the ability of vibration-based damage detection techniques to identify a reduction in support stiffness that could be caused by the deterioration of the timber substructure of a bridge. The dynamic properties of a timber stringer, salvaged from a decommissioned bridge, were measured as the stiffness of the support under one of the pile caps, and was varied in order to simulate the deterioration of the supporting piles. Results show that it is possible to identify and locate support softening by simple observation of the fundamental mode shape, without taking into consideration baseline measurements prior to damage. Four different vibration-based damage detection techniques were also applied, each relying primarily upon changes to measured mode shapes. The change in mode shape and change in flexibility methods are capable of identifying a decrease in support stiffness using only the first mode of vibration.

INTRODUCTION

The process of implementing a damage detection strategy for civil engineering infrastructure is referred to as Structural Health Monitoring (SHM) [1]. The primary goal of SHM is to ascertain the condition, or ‘‘health,’’ of a structure so that decisions can be made with regards to appropriate maintenance or remediation strategies. A number of SHM methods have been developed for and implemented on timber bridges, including visual inspection, resistance drilling, stress wave or ultrasound techniques, radiography, and proof load testing/vibration analysis [2-6]. Many of these methods are performed on a localized scale, meaning that the evaluation of an entire structure using these methods can be very time consuming and inefficient [7-9].

Global SHM methods, on the other hand, utilize changes in the overall response of a structure as indicators of damage. One set of global SHM techniques attracting increasing attention in recent years are vibration-based damage detection (VBDD) methods. The basic idea behind this approach is that modal parameters (notably frequencies, mode shapes, and modal damping) are functions of the physical properties of the structure (e.g., material properties, geometrical configuration, distribution of mass, and support boundary conditions), and therefore any changes to these physical properties caused by damage will be reflected in changes to the modal characteristics. VBDD methods, therefore, rely on accurate measurements of vibration mode parameters, as well as on damage detection algorithms to detect, locate, and quantify damage.

The potential effectiveness of VBDD methods has been demonstrated in terms of their capability to identify and/or locate damage both in steel bridges [10-12] and in concrete bridges [13]. The application of VBDD methods to timber structures has been investigated in the laboratory [7,8,14-18] and in the field [5,9,14,19-21]. These investigations have focused on the capabilities and limitations of VBDD methods to identify and/or locate damage within timber superstructures and/or timber stringers.

The province of Saskatchewan, Canada, currently maintains a large inventory of short and medium span timber bridges. In recent years, routine inspections and premature failures have revealed that the substructure (i.e. timber abutments and piers) in many of these bridges have experienced significant deterioration. Given the large number of timber bridges, the effort required to perform detailed assessments on the entire inventory is prohibitive. However, it is critical that these deficiencies be identified so that appropriate repairs may be undertaken.

A research program was recently initiated at the University of Saskatchewan to investigate the application of VBDD methods to detect and locate small-scale damage within short and medium span timber bridges and bridges with timber components (e.g. timber piles). A primary initial focus of this program has been on determining whether the VBDD techniques are capable of providing a relatively quick assessment of the state of deterioration of the timber substructure, such that bridges requiring immediate attention may be identified. This paper reports the results of an initial investigation in which an experimental study was performed using a timber bridge stringer salvaged from a decommissioned timber bridge.

EXPERIMENTAL PROGRAM

The experimental system used in this study was a 5.46 m long timber stringer, 200 mm x 400 mm in cross section, salvaged from a decommissioned bridge. It is shown in its experimental setup in Fig. 1. To simulate realistic boundary conditions, the stringer was supported on timber pile caps, also in a salvaged condition, which were, in turn, supported as described below. In addition, one end of the stringer was connected to an adjacent span stringer by their mutual connection to the pile cap below and wood flooring above. The support under this end of the stringer is referred to as the middle support. Connection details were identical to those used in the field, such that the setup represented a typical stringer line along a two-span timber bridge.

In addition to a rigid support case in which pile caps were supported by a steel plate resting on steel blocks, three simulated foundation softening damage cases (as shown in Fig. 2) were introduced at the middle support. These were implemented by varying the stiffness of the support under the pile cap using different sets of springs, resulting in support stiffnesses of 1852 kN/m, 1660 kN/m, and 1497 kN/m for damage cases 1, 2, and 3, respectively. These cases were intended to simulate progressive deterioration of the supporting piles.

he experimental procedure consisted of measuring the initial dynamic properties of the system, and subsequently measuring the properties under each of the damage cases just described. Where required by VBDD techniques, the baseline properties for the three foundation softening damage cases were taken to be those of the initial system.
Dynamic excitation was generated by means of a hydraulic ram equipped with a proportional valve and attached to the horizontal cross piece of a steel loading frame. A 5 kN load cell was connected directly to the bottom of the ram

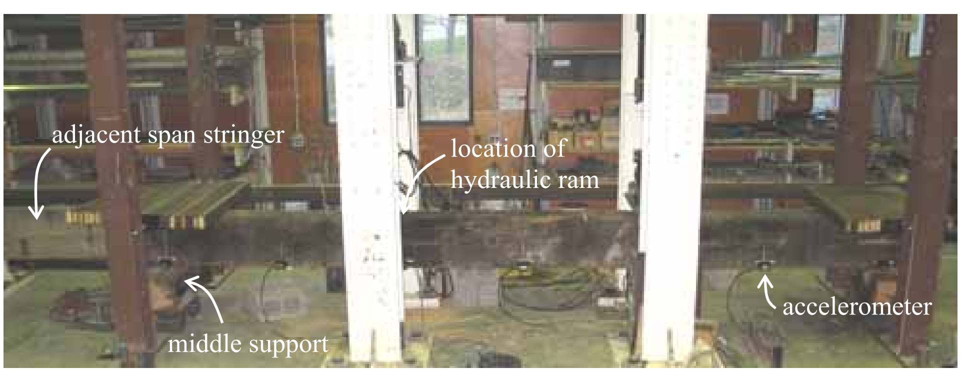

Figure 1. Laboratory timber stringer model.

Initial rigid support   Damage Case 1   Damage Case 2   Damage Case 3

Figure 2. The four support conditions investigated.

to accurately measure the excitation force history. The ram was located above the stringer at approximately one-third of the span from the middle support. The signal for the shaker was generated using LabView™ software [22] implemented on a laptop computer.

Seven accelerometers (EpiSensor, model ES-U), evenly spaced longitudinally at 0.91 m intervals, were used to measure the dynamic response of the stringer. Each accelerometer was configured for a maximum range of ±0.5g and a precision of 0.00025g. After the accelerometers had been calibrated, they were attached to a side face of the stringer near its bottom face by wood screws, oriented to measure vertical acceleration.

Data from the load cell and accelerometers were acquired at a sampling rate of 500 Hz using a 12-bit data acquisition system (National Instruments SCXI 1001, LabView™) connected to a desktop computer. MACEC [23], a data processing software package developed at the Department of Civil Engineering, Katholieke Universiteit Leuven, was used to extract the natural frequencies and the associated mode shapes. Three system identification methods were used to extract the dynamic parameters of interest, namely, peak-picking using the output-only response, stochastic subspace identification, and peak-picking based on the frequency response function (FRF). Before the application of the system identification method, a Hanning Window was applied to each two second data segment to reduce spectral leakage [24].

System identification was performed in two steps. First, four Gaussian white noise load signals with different rms levels were applied, while load and response data were acquired at 500 samples per second for a period of 60 seconds. Possible natural frequencies were identified from the corresponding response spectra by a peak-picking method based on the FRF results. A sinusoidal excitation was then applied at each of the possible natural frequencies, with frequencies resulting in a maximum response selected as the resonant frequencies. Responses at the resonant frequencies were recorded in order to accurately measure the corresponding mode shapes. During this procedure, each set of data was acquired at 500 samples per second, with 20 seconds of data broken into 10 two-second segments. Mode shapes acquired from each of these segments were unit-mass normalized before being used to calculate an average unit-mass normalized mode shape, which was used for further interpolation, as described below. Only the fundamental mode was used for damage detection.

For mode shape identification, the excitation force was applied at the fundamental natural frequency with a constant amplitude of approximately 225 N for the rigid support case and approximately 450 N for the damaged support cases about a mean preload value of 1.0 kN. Preliminary tests were conducted on the system with the rigid middle support case with mean preload values ranging from 0.5 to 2.5 kN to investigate the influence of preload on the dynamic response.

For the application of VBDD techniques, modal displacements for the fundamental mode at measurement locations were obtained by numerically integrating the acceleration signal twice to obtain first velocity and then displacement. Since some of the VBDD techniques investigated required mode shape curvatures, it was necessary to estimate the modal displacements between measurement points. These were obtained using a cubic spline interpolation procedure (defined by enforcing zero curvature at supports and continuity of curvature at measurement points) in which cubic polynomials were used to define the mode shapes between measurement points. In this way, mode shapes were defined at 101 evenly spaced points along the beam. Mode shape vectors were unit-mass normalized before applying the VBDD techniques. When required, a central difference approximation for the second derivative was applied to the mode shape vectors to obtain modal curvature vectors.

Prior to conducting the damage detection investigation just described, a series of static and dynamic tests were performed to determine the degree of continuity that existed across the middle support, as provided by the adjacent

Table 1. Natural frequencies (Hz) measured at different levels of preload

Preload (kN)	Mode 1	Mode 2	Mode 3
0.5	28.81	39.55	55.66
1.0	30.27	39.06	56.15
1.5	31.25	40.04	56.64
2.0	31.73	40.04	56.64
2.5	32.23	40.53	57.13

stringers' mutual connection to the pile cap and wood flooring. Results of these tests are not reported in detail here; however, the static tests showed that very little flexural continuity was provided across the middle support, thus confirming the reasonableness of the assumption of zero curvature at this location for interpolation. On the other hand, the connection was sufficient for forced harmonic excitation applied on one span to excite a significant dynamic response in the adjacent span.

DAMAGE DETECTION TECHNIQUES

Four VBDD methods available in the literature were applied. These included the change in mode shape method [25], the change in mode shape curvature method [26], the damage index method [27], and the change in flexibility method [28]. The first three methods require only consistently normalized mode shape vectors in the undamaged and damaged conditions, while the last method requires the resonant frequencies in addition to the mode shape vectors in the undamaged and damaged conditions.

Among these VBDD methods, only the damage index method has a threshold for determining whether damage has occurred at a particular location [12]. The other three methods are based solely on the largest change in a particular parameter. Further details related to these techniques may be found in the cited references [12,25].

Due to the assumption of zero curvature at the supports, it should be noted that the two curvature-based methods (the mode shape curvature and damage index methods) are unable to produce non-zero values at the location of damage (i.e. the support). However, support softening is expected to change the distributions of curvature and flexural strain energy in other regions, so that these methods may provide an indication of the presence of support damage. In addition, these techniques could be applied to detect other forms of damage occurring away from supports, and it is important to understand how support softening affects their distributions.

In addition to the VBDD methods just mentioned, the damaged mode shapes alone were examined to determine whether it was possible to identify the presence of support softening without reference to a baseline, undamaged mode shape.

RESULTS AND DISCUSSION

The influence of the level of preload on the dynamic properties of the stringer is illustrated in Table 1 and Fig. 3. As seen in Table 1, the natural frequencies increased with increasing level of preload, which can be attributed to the closure of cracks within the stringer and pile caps, as well as of gaps between the two components, with increasing load to produce stiffer support conditions. The increased support stiffness is also reflected in the absolute displacements measured for the fundamental mode shapes shown in Fig. 3, which shows a general trend of decreasing movement at the supports, with increasing preload level. This phenomenon will undoubtedly introduce complications to the field application of vibration-based monitoring to identify support softening, since the condition of pile caps and connections are expected to vary greatly from bridge to bridge, and since precise control of load is difficult to achieve during field testing. Also apparent in Fig. 3 is an increased overall system stiffness with increasing preload, manifested by lower amplitude displacements along the entire beam. This unexpected phenomenon may suggest that the closure of cracks within the stringer itself leads to increased capacity for shear flow, resulting in the stringer acting more as a monolithic section.

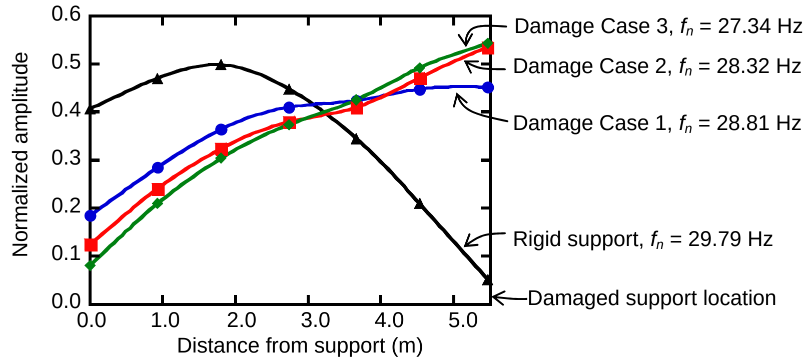

Figure 4. Unit-mass normalized fundamental mode shapes for all damage cases.

Figure 4 shows the unit-mass normalized fundamental mode shapes of the stringer for the four support conditions investigated, along with the corresponding natural frequencies. A reduction in natural frequency with decreasing support stiffness is clearly evident. In addition, there is a significant change in the character of the mode shape as the support stiffness decreases, from one that resembles a sinusoid for the rigid support case, to one that is increasingly linear, representing a response that is dominated by rigid body motion of the stringer as it rotates about the left support and vibrates on the flexible support. The ratio of the amplitude at the damaged (right) support to that at the rigid (left) support also increases with decreasing support stiffness, as expected. These results demonstrate that the reduced stiffness of a support is evident in the mode shape itself, without reference to a baseline, undamaged case. This should make it possible to identify damage to the substructure without requiring prior baseline measurements, although further investigations are required to see how this could be applied to field structures.

The distributions of the VBDD parameters, calculated using the unit-mass normalized mode shapes of Fig. 4, are shown in Fig. 5. Several observations may be made. First, both the change in mode shape and change in flexibility methods (Figs. 5a and b) show unequivocal maximum values at the support with reduced stiffness for all damage cases; the maximum values increase with larger reductions in support stiffness. Both methods are therefore effective in detecting and localizing this form of damage. On the other hand, the change in curvature and damage index methods (Figs. 5c and d) are unable to provide a non-zero value at supports, as mentioned previously, and therefore cannot directly identify and localize the damage. The parameter distributions for these two methods do show significant values at other locations, though, which could be used as an indicator of the presence of damage. However, they do not exhibit obvious patterns that might point to support softening. In fact, both distributions feature significant peaks at other locations which may be erroneously interpreted as identifying a damage site. The damage index peaks exceed the threshold value of 2.0, making an erroneous interpretation an even greater possibility. The analyst must be aware of this possibility, particularly since the VBDD methods will typically be applied to detect the presence of other forms of damage, in addition to support softening. An erroneous conclusion may be averted by considering all four VBDD methods simultaneously rather than any single method in isolation.

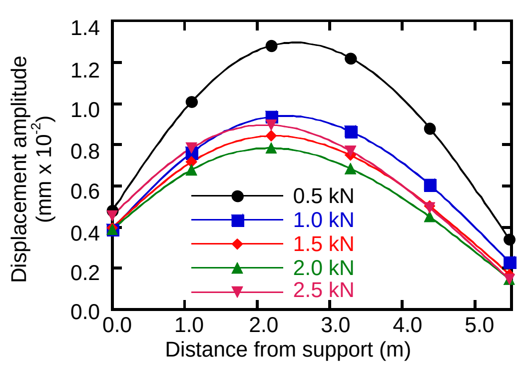

Figure 3. Fundamental mode shapes for the rigid support case with different levels of preload.

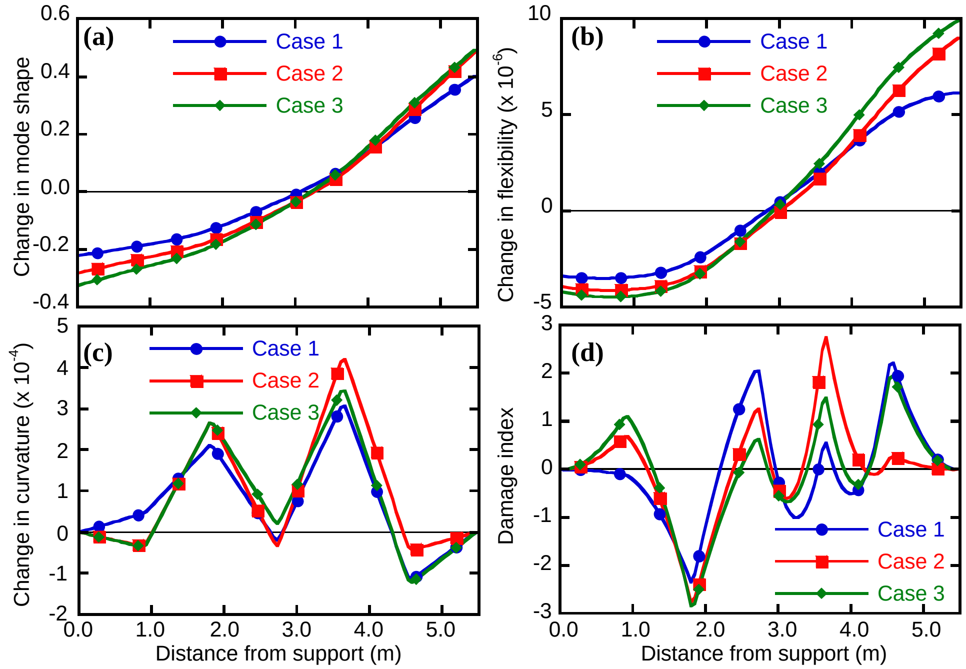

Figure 5. Distributions of (a) change in mode shape, (b) change in flexibility, (c) change in mode shape curvature, and (d) damage index parameters for damage cases 1 to 3.

CONCLUSIONS

In summary, based on work performed on the timber stringer, it can be concluded that reduced support stiffness can be identified and localized by simple observation of the fundamental mode shape without reference to baseline measurements. Among the other VBDD methods investigated, the change in mode shape and change in flexibility methods were capable of detecting and localizing the simulated foundation softening, but the change in mode shape curvature and damage index methods were unable to localize the damage, and could lead to an erroneous conclusion that damage exists at another location if they are used in isolation.

While the presence and location of foundation softening within a salvaged single timber stringer with realistic boundary conditions could be identified in the laboratory, further laboratory tests are required to explore the capabilities and limitations of applying VBDD methods to identify and/or localize damage within more complex structures [18].

ACKNOWLEDGEMENTS

The financial support of the ISIS Canada Network of Centres of Excellence and the Saskatchewan Department of Highways and Transportation is gratefully acknowledged. The contributions of Mr. D. Pavier, Mr. B. Pokoyoway and Mr. D. Bitner to the experimental aspects of this work are also gratefully acknowledged.

REFERENCES

1. Sohn, H., Farrar, C. R., Mehez, F.M., Shunk, D.D., Stinemates, D.W. and Nadler, B.R., 'A Review of Structural Health Monitoring Literature: 1996-2001' (Los Alamos National Laboratory Report, LA-13976-MS, 2003).
2. Ross, R.J., Brashaw, B.K. and Wang, X., 'Structural condition assessment of in-service wood', Forest Products Journal 56(6)(2006) 4-8.
3. Rens, K.L., Nogueira, C.L. and Transue, D.M., 'Bridge management and nondestructive evaluation', J. Performance of Constructed Facilities 19(1)(2005) 3-16.

4. Brashaw, B.K., ‘Advanced Timber Bridge Inspection Techniques: MN/DOT Implementation Final Report’, (Minnesota Department of Transportation Research Services Section, St. Paul, Minnesota, 2004).
5. Peterson, M.L. and Gutkowski, R.W., ‘Evaluation of the structural integrity of timber bridges’, NDT&E International 32 (1999) 43-48.
6. Emerson, R.N., Pollock, D.G., Kainz, J.A., Fridley, K.J., McLean, D.I. and Ross, R.J., ‘Nondestructive evaluation techniques for timber bridges’, Proc. of the 5th World Conference on Timber Engineering, Montreaux, Switzerland, August 1998 (Presses Polytechniques et Universitaires Romandes, Lausanne, 1998) 670-677.
7. Morison, A.M., Van Karsen, C.D., Evensen, H.A. and Ligon, J.B. ‘Dynamic response of timber bridges as a tool to measure structural integrity’, Experimental Techniques 27(3)(2003) 25-28.
8. Peterson, S.T., McLean, D.I. and Pollock, D.G., ‘Application of dynamic system identification to timber bridges’, J. Struct. Eng. 129(1)(2003) 116-124.
9. Crews, K., Samali, B., Li, J., Bakoss, S. and Champion, C., ‘Testing and assessment procedures to facilitate the management of timber bridge assets’, Proc. of the 3rd Civil Engineering Conference in the Asian Region (CECAR), Seoul, August 2004 (Asian Civil Engineering Coordinating Council, Seoul, 2004).
10. Mazurek, D.F. and DeWolf, J.T., ‘Experimental study of bridge monitoring technique’, J. Struct. Eng. 116(9)(1990) 2532-2549.
11. Stubbs, N. and Kim, J.T., ‘Damage localization in structures without baseline modal parameters’, AIAA J. 34(8)(1996) 1644-1649.
12. Farrar, C.R. and Jauregui, D.A., ‘Comparative study of damage identification algorithms applied to a bridge: I. Experiment’, Smart Mater. Struct. 7(5)(1998) 704-719.
13. Park, S., Stubbs, N., Bolton, R. and Choi, S., ‘Field verification of the damage index method in a concrete box-girder bridge via visual inspection’, Computer-Aided Civil and Infrastructure Engineering 16(1)(2001) 58-70.
14. Wang, X., Wacker, J.P., Ross, R.J. and Brashaw, B.K. (2005), ‘Nondestructive assessment of timber bridges using a vibration-based method’, Proc. of the 2005 ASCE Structures Congress and Exposition, New York, April 2005 (American Society of Civil Engineers, Reston, VA, 2005) 381-392.
15. Chen, S.E., Delatte, N., Sehdev, A., Ong, C.K., Siswobusono, P., Zinger, N., Thomas, M., Nishihama, Y., Taylor, R., Tolbert, R., Thornburg, D. and Hawkins, R., ‘Modal testing of ASCE competition timber bridges’, Proc. of the 21st International Modal Analysis Conference, Kissimmee, February 2003 (Society for Experimental Mechanics, Bethel, CT, 2003) Paper No. 226.
16. Morison, A., VanKarsen, C.D., Evensen, H.A., Ligon, J.B., Ross, R.J. and Forsman, J.W., ‘Dynamic characteristics of timber bridges as a measure of structural integrity’, Proc. of the 21st International Modal Analysis Conference, Kissimmee, February 2003 (Society for Experimental Mechanics, Bethel, CT, 2003) Paper No. 204.
17. Peterson, S.T., McLean, D.I., Symans, M.D., Pollock, D.G., Cofer, W.F., Emerson, R.N. and Fridley, K.J., ‘Application of dynamic system identification to timber beams: I’, J. Struct. Eng. 127(4)(2001) 418-425.
18. Peterson, S.T., McLean, D.I., Symans, M.D., Pollock, D.G., Cofer, W.F., Emerson, R.N. and Fridley, K.J., ‘Application of dynamic system identification to timber beams: II’, J. Struct. Eng. 127(4)(2001) 426-432.
19. Horyna, T., Foschi, R.O. and Ventura, C.E., ‘Response of timber bridge to traffic loading’, J. Bridge Eng. 6(1)(2001) 69-77.
20. Horyna, T., Ventura, C. and Foschi, R.O., ‘Modal characteristics of timber bridges under traffic loading’, Proc. of the 14th International Modal Analysis Conference, Dearborn, MI, February 1996 (Society for Experimental Mechanics, Bethel, CT, 1996) 226-232.
21. Morison, A., Van Karsen, C.D., Evensen, H.A., Ligon, J.B., Erickson, J.R., Ross, R.J. and Forsman, J.W., ‘Timber bridge evaluation: a global nondestructive approach using impact generated FRFs’, Proc. of the 20th International Modal Analysis Conference, Los Angeles, CA, February 2002 (Society for Experimental Mechanics, Bethel, CT, 2002) 1567-1573.
22. LabView™, (National Instruments Corporation, Austin, TX, 2002).
23. Branden, B.V.D., Peeters, B. and Roeck, G.D., ‘Introduction to MACEC V2.0: Modal Analysis on Civil Engineering Constructions’ (Katholieke Universiteit Leuven, Dept. of Civil Engineering, 1999).
24. De Silva, C.W., ‘Vibration: Fundamentals and Practice’ (CRC Press LLC, Boca Raton, FL, 2000).
25. Zhou, Z., Wegner, L.D. and Sparling, B.F., ‘Vibration-based damage detection on a prestressed concrete girder’, Proc. of the 5th CSCE Structural Specialty Conference, Saskatoon, June 2004 (CSCE , Montreal, 2004) Paper ST-085.
26. Pandey, A.K., Biswas, M. and Samman, M.M., ‘Damage detection from changes in curvature mode shapes’, J. Sound Vibration 145(2)(1991) 321-332.

27. Stubbs, N., Kim, J.T. and Farrar, C.R., 'Field verification of a nondestructive damage localization and severity estimation algorithm', Proc. of the 13th International Modal Analysis Conference, Nashville, TN, February 1995 (Society for Experimental Mechanics, Bethel, CT, 1995) 210-218.
28. Pandey, A.K., and Biswas, M., 'Damage detection in structures using changes in flexibility', J. Sound Vibration 169(1)(1994) 3-17.