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Application of structural health monitoring in civil infrastructure

M. Q. Feng*

Center for Advanced Monitoring and Damage Inspection, Department of Civil and Environmental Engineering, University of California, Irvine, CA 92697, U.S.A.

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Abstract. The emerging sensor-based structural health monitoring (SHM) technology has a potential for cost-effective maintenance of aging civil infrastructure systems. The author proposes to integrate continuous and global monitoring using on-structure sensors with targeted local non-destructive evaluation (NDE). Significant technical challenges arise, however, from the lack of cost-effective sensors for monitoring spatially large structures, as well as reliable methods for interpreting sensor data into structural health conditions. This paper reviews recent efforts and advances made in addressing these challenges, with example sensor hardware and health monitoring software developed in the author's research center. The hardware includes a novel fiber optic accelerometer, a vision-based displacement sensor, a distributed strain sensor, and a microwave imaging NDE device. The health monitoring software includes a number of system identification methods such as the neural networks, extended Kalman filter, and nonlinear damping identificaiton based on structural dynamic response measurement. These methods have been experimentally validated through seismic shaking table tests of a realistic bridge model and tested in a number of instrumented bridges and buildings.

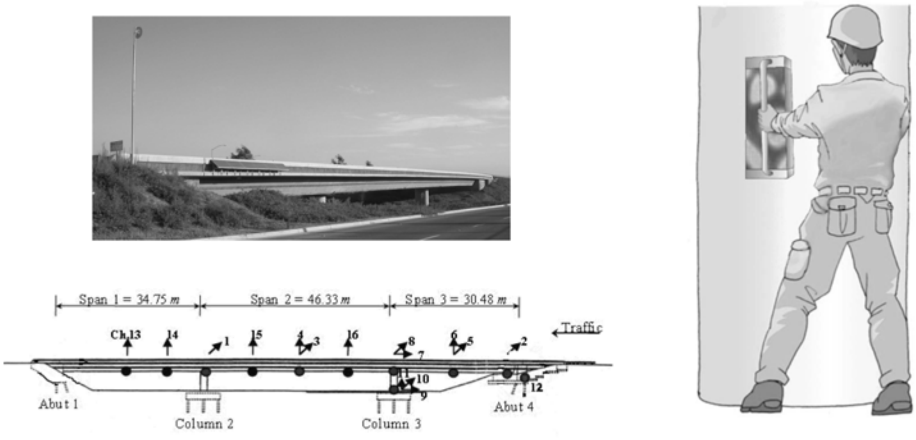
Keywords: structural health monitoring; seismic damage assessment; advanced sensors; health diagnostics.

Introduction

Due to aging and structural deterioration, civil infrastructure around the world is becoming increasingly vulnerable to natural and man-made disasters. The recent tragic collapse of the Minneapolis bridge has highlighted the urgent needs for improving the current structural inspection and maintenance practice. The emerging sensor-based SHM technology has a significant potential to monitor structural integrity in real time, establish scientific and timely prioritization for structural repair and rehabilitation, and provide early warning before catastrophic structural failure. However, field implementation of SHM faces significant technical challenges due to the lack of suitable sensors as well as reliable methods for interpreting sensor data. Particularly the large scale of civil infrastructure such as bridges, dams, and pipelines demands a cost-effective strategy for implementation of SHM.

The author has proposed a strategy to integrate continuous monitoring of global structural integrity using on-structure sensors with targeted local inspection based on visual and non-destructive evaluation (NDE). The concept is illustrated in Fig. 1 through a highway bridge, one of the author's field SHM research laboratories. Accelerometers are installed at strategic locations to continuously monitoring

*Professor, Corresponding Author, E-mail: mfeng@uci.edu



(1) Global monitoring using on-structure sensors (2) Targeted local NDE inspection

Fig. 1 Integration of global monitoring with targeted local inspection

change in vibration characteristics of the bridge due to aging and structural deterioration, or damage caused by, for example, earthquakes. Based on analysis of measured vibration data, the existence, location, and extent of damage can be identified in real time and in an automated fashion at a remote location. Then inspection crews can be sent to the bridge site for more detailed visual inspection and NDE at the identified "hot" spots - problematic locations. Such condition-based inspection represents significant advantages over the current time-based periodic inspection, as the realtime identification of structural problems enables timely remedial actions. The use of on-structure sensors and NDE devices can result in more quantitative evaluation even for invisible damage, compared with vision inspection.

Significant efforts have been made in recent years to study the key technical components of the integrated global monitoring and local inspection strategy. Focusing on the activities in the author's research center, this paper presents a number of sensors for global structural monitoring and local NDE inspection, together with several methods for assessing structural integrity and furthermore estimating remaining structural capacity based on analysis of sensor data. These methods have been validated through large-scale seismic shaking table tests of a realistic bridge model, and are being implemented and tested in a few instrumented bridges and buildings.

2. Sensor and sensor networks

One of the major obstacles preventing the implementation of sensor-based monitoring is the unavailability of reliable, easy-to-install, and cost-effective sensors that are suited for and can be densely deployed on civil engineering structures. Civil infrastructure systems such as bridges, dams, and pipelines place unique demands on sensors. Besides the accuracy, sensors and their cables are expected to be low cost, lightweight, small size, and have strong resistance to EM interference, high reliability, and long service life. They are required to withstand harsh environments, be moisture proof, corrosion resistant, lightning proof, and explosion proof.

The author's center has developed a number of novel advanced sensors for monitoring civil infrastructure. The fiber optic accelerometer can be used for continuous monitoring of global structural performance; the distributed Brillioun fiber optic strain sensor and the microwave imaging system are

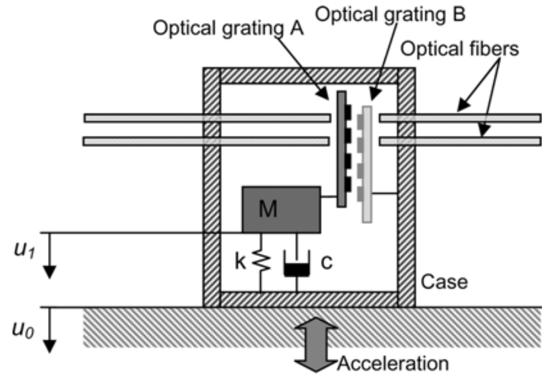


Fig. 2 Fiber optic accelerometer

suited for targeted local monitoring and inspection, while the vision-based displacement sensor can be applied for either global or local structural health monitoring.

2.1. Fiber optic accelerometer

The fiber optic accelerometer is based on a novel integration of the moiré fringe phenomenon with fiber optics (Feng and Kim, 2006). The sensor head, shown in Fig. 2, contains a pendulum and a pair of parallel optical gratings panels; one fixed to the pendulum and the other to the sensor case. The relative displacement between the mass and the sensor case can be measured by "viewing" and counting the number of moiré fringes formed on the optical gratings using optical fibers. By properly designing the dynamic parameters of the pendulum, the relative displacement becomes proportional to the acceleration of the sensor case.

Compared with its conventional counterparts (electric sensors), this optical fiber accelerometer has (1) total immunity to electromagnetic interference and lightning strikes due to the non-existence of electric signals or electric cables, (2) unique safety in dangerous environments where electric sparks causes explosion concerns, (3) extremely high sensitivity, resolution, along with a large measuring range, particularly high performance in low frequencies, (4) a small sensor head with a lightweight optical fiber cable, making it much easier to install on an existing structure, (5) robustness against to environmental (temperature, moisture, etc.) changes due to the use of the well-understood and reliable measuring mechanism of the moiré phenomena, (6) much lower cost than most of the optical fiber sensors due to its simple signal processing, (7) a versatility to measure different dynamic quantities upon simple modification.

An acceleration measurement system has been successfully developed, that consists of multiple accelerometer heads driven by a multi-channel control unit and a PC for signal processing. A measured frequency response plotted in Fig. 3 shows the dynamic bandwidth of the sensor, which is suited for monitoring civil engineering structures whose natural frequencies are often low. Furthermore, multiple sensor heads can be multiplexed by the time or wavelength division method to achieve a distributed sensor network using one common optical fiber cable.

The fiber optic accelerometer system has been applied to measure ambient and earthquake response of the Calit2 Building on UCI campus, the Vincent Thomas Bridge in Long Beach, CA, and the Painter St. Overcrossing in Eureka, CA. Fig. 4 is ambient vibration of the building measured by the sensor, in comparison with those by a high-performance reference sensor. Excellent agreement was observed in

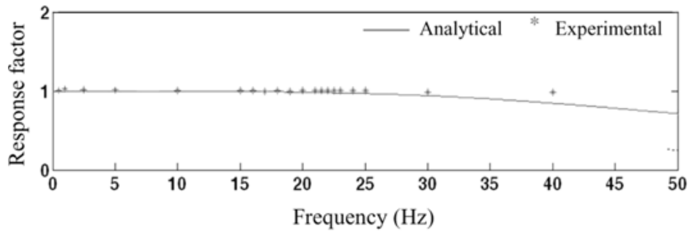


Fig. 3 Dynamic performance of fiber optic accelerometer

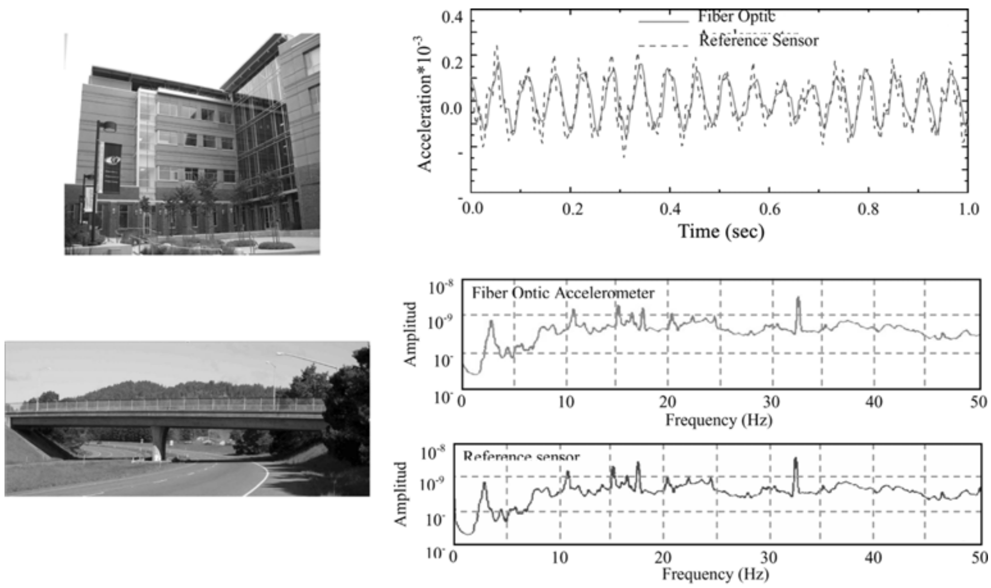


Fig. 4 Field implementation of the fiber optic accelerometer

both time and frequency domains. The high resolution of the sensor for measuring micro ambient vibration was demonstrated, and yet the same resolution can be maintained when measuring strong motion response up to 3 g, another significant advantage of the sensor.

2.2. Vision-based displacement sensors

In many situations when monitoring a civil engineering structure such as a bridge, non-contact sensors are desired due to the difficulty to access. The author developed a low-cost, non-contact, real-time displacement measurement system. As shown in Fig. 5, the system is composed of a digital camcorder (Panasonic PV-GS35) with 30x optical zooming capability and maximum resolution of 740 by 480, a telescopic lens with 8x optical zooming capability, a target panel marked with a geometric pattern, and a notebook computer with image processing software. To measure the displacement of a structure, the target panel is attached on the structure and the camcorder captures the movement of the target panel from a remote location, which is regarded as a fixed reference point. It is noted that the pattern can be directly marked on the structure without using the panel. The captured images are streamed into the computer through an IEEE1394 connection, and special image-processing software on the computer computes the displacement of the target panel using an efficient image-processing

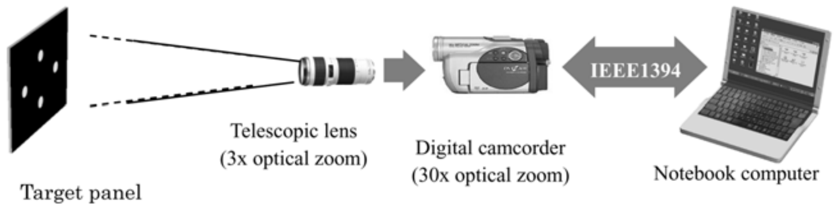
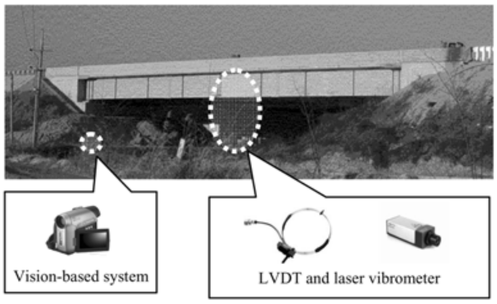
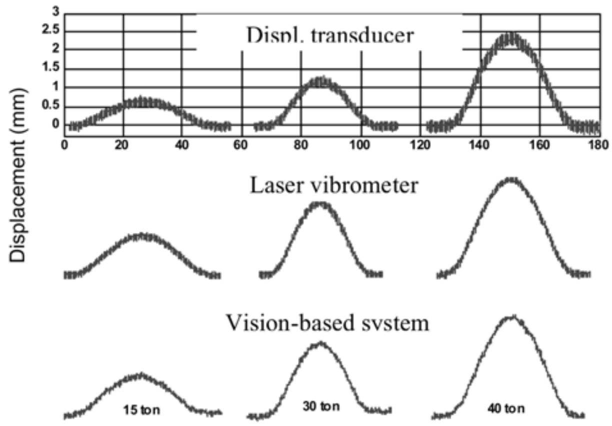


Fig. 5 Vision-based displacement sensor system



(a) Bridge and three types of displacement sensors



(b) Comparison of measured bridge displacements

Fig. 6 Field test of the vision-based displacement sensor

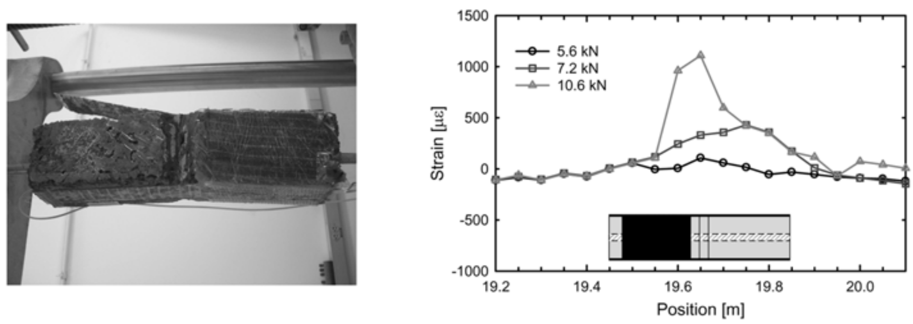
technique with pre-measured calibration parameters.

A field experiment was performed to measure displacement of the Samseung Bridge, a single-span highway bridge consisting of five steel plate girders, as shown in Fig. 6. Response displacement of the bridge to a vehicle running at different speeds were measured at the center of the span in the vertical direction by three different sensors: a conventional contact-type OVDT, a non-contact type laser vibrometer with the sampling rate of 100 Hz, and the vision-based system with 30 frames per second. Excellent agreement was observed among the displacements measured by the three types, as shown in an example measurement in Fig. 6. This field test confirmed that the vision-based displacement sensor system can measure dynamic response up to 10 Hz with a high accuracy. Considering that most of the large-size civil engineering structures have natural frequencies lower than 4-5 Hz, the non-contact vision-based system developed in this study is appropriate for monitoring dynamic response of large-size civil engineering structures. To measure motion of higher frequencies, a camcorder with a higher frame rate can be employed.

2.3. Distributed fiber optic strain sensor

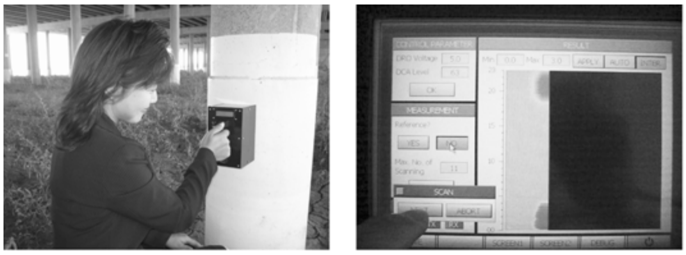
Brillouin-scattering-based distributed sensors can measure strain and temperature along the entire length of a fiber, rather than at discrete points, by using fiber itself as the sensing medium. One class of the Brillouin sensors is based on the Brillouin loss technique, whereby two counter-propagating laser beams, a pulsed Stokes beam and a continuous wave pump beam, exchange energy through an induced acoustic field. The interaction magnifies the pulsed Stokes beam at the expense of depleting the pump beam, which is then detected as a loss signal. The maximum depletion of the pump beam at a point along the fiber happens when the frequency of the acoustic wave at that point matches the beat frequency of two laser beams. The frequency of the acoustic wave, referred to as the Brillouin frequency shift, is related to the fiber properties (the local acoustic velocity and refractive index in glass) which have a linear temperature and strain dependence (Kurashina, *et al.* 1990, Zou, *et al.* 2004). Therefore, by scanning the beat frequency of the two lasers and measuring the intensity of corresponding signal, a Brillouin loss spectrum is obtained, which enables the measurement of continuous temperature and strain distribution along the sensing fiber. Spatial information along the fiber length is obtained through Brillouin optical time domain analysis by measuring the propagation times when the light pulses travel in the fiber, in which the spatial resolution is inversely proportional to the width of the Stockes pulse (Zou, *et al.* 2005). Therefore, the spatial resolution can be adjusted for different applications simply by altering the pulse duration, even after the fiber is installed. This is a unique advantage of the Brillouin loss technology.

This distributed fiber optic sensor system was applied to detect delaminations between a concrete specimen and carbon fiber reinforced polymer (CFRP) sheets, as shown in Fig. 7. The notched specimen was subjected to double shear loading, generating cracks and demalinations on FRP near the notch. The sensing fiber bonded on the surface of the CFRP sheet successfully detected the strain increase on the FRP surface near the notch as the load increased and the demalinations became more severe. The same sensor system is being implemented for monitoring strains in large-scale civil infrastructure such as pipelines, as well as for detecting cracks in steel and concrete structural members.



(a) Concrete specimen bonded with CFRP (b) Strain distribution along sensing fiber on GFRP

Fig. 7 Test of distributed fiber optic strain sensor for delamination detection



Handheld scanner Real-Time Imaging

Fig. 8 Microwave imaging system

2.4. Microwave imaging system

For damage inspection, current practice relies heavily on visual inspection, due to lack of reliable and easy to operate NDE devices. Feng, *et al*. (2006) developed a handheld real-time microwave imaging system developed in the author's center challenges the NDE limitations. As shown in Fig. 8, the system consists of a handheld scanner and a specially designed compact computer equipped with real-time imaging software and an LCD monitor. The array antenna inside the scanner sends focused microwave to illuminate a point of inspection and at the same time receives reflected signals. By analyzing the signals, invisible defects and damage including, but not limited to, air voids and delaminations inside fiber reinforced polymer (FRP) composites, concrete, and other materials can be identified (Feng, *et al*. 2001, Kim, *et al.* 2004, Feng, *et al.* 2006).

The handheld imaging system has been tested on a number of concrete bridges. Fig. 9 shows NDE inspection of an FRP-wrapped concrete girder of the Dang-Jeong Overcrossing located in Gun-Po, Korea. The bridge girder was retrofitted with two layers of E-Glass FRP sheets and external post-tensioning. Although majority of the area showed no sign of debonds, two debonding areas were identified as shown in the images in Fig. 9. The field evaluations proved the ease of use and the effectiveness of the microwave NDE technology.

3. Health diagnosis methods and applications

Detecting damage, identifying its location, assessing its extent and evaluating its consequences have been identified as a four-tiered goal of SHM (Doebling, *et al*. 1996). Reliable methods for interpreting sensor data are crucial for successful field implementation of SHM by achieving this goal. Significant research efforts have been made in recent years, most of which are based on structural vibration

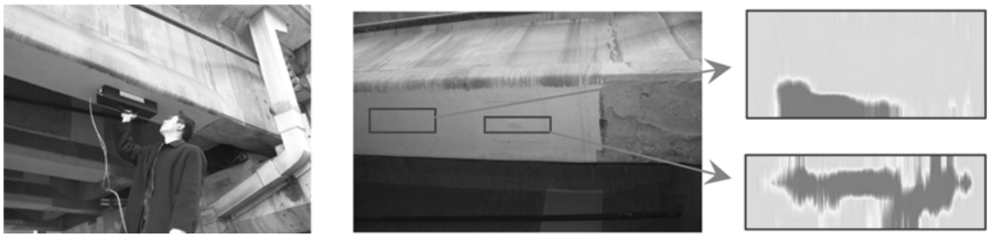


Fig. 9 Field evaluation of the microwave imaging system

measurement and analysis, partially due to the fact that accelerometers can be easily installed on a structure compared with other types of sensors that requires embedment or a reference point (e.g. Sohn, *et al.* 2004, Montalvao, *et al*. 2006).

The author proposed the use of structural stiffness and/or nonlinear damping as a health index. As a structure suffers from damage by natural or man-mad disasters, the stiffness of the structure will degrade and nonlinear damping will increase, that will result in a change of vibration characteristic of the structures. Therefore, it is possible to identify change in structural stiffness and damping from measured structural vibration. The use of structural stiffness as a health index will enable not only the detection of damage occurrence, but also identification of damage locations, and quantification of damage extent. The following will present a number of frequency domain and time domain methods for identifying change in structural stiffness and damping. These methods were experimentally verified for seismic damage assessment of concrete structures through large-scale of seismic shaking table tests.

3.1. Neural networks for long-term monitoring

Frequency domain methods typically identify change in natural frequencies, damping ratios, or modal shapes based on measurement of structural vibration. Structural element stiffness values can then be further identified by minimizing the errors between the modal parameters identified from the vibration measurement and from finite element analysis using the identified stiffness. The neural network technique can be employed to identify structural elemental stiffness from the measured modal frequencies and shapes (Feng and Kim 1998, Feng and Bhang 1999, Feng, *et al.* 2003, Levin and Lieven 1992, Masri, *et al.* 2000). This technique is capable of obtaining elemental stiffness values even if the measured modal information is incomplete due to a limited number of sensors.

The authors has applied the neural networks for identifying change in structural stiffness of an instrumented testbed bridge, the Jamboree Road Overcrossing, over a five-year period based on monitoring of its traffic-induced vibration (Soyoz and Feng 2008). As shown in Fig. 1, the three-span 111-m long continuous concrete bridge is permanently instrumented with 13 accelerometers at both the superstructure and the columns. Sensor data are acquired by an on-site data recorder and transmitted to a server computer and published on Internet in real time.

Over the five-year period, 1707 traffic-induced vibration data sets were collected. These data were processed in the frequency domain to identify modal parameters of the bridge using the frequency domain decomposition approach. Based on statistical analysis of the identified modal parameters for each year, a 5% decrease in the modal frequencies was observed over the five-year period.

Based on the measured modal parameters, structural parameters including stiffness and mass of the bridge were further identified using the neural networks, in which the input layer consists of measured natural frequencies and modal shapes, while the output layer consists of correction coefficients of structural parameters including mass and stiffness of the bridge structure and the abutment soil. The correction coefficient is the ratio between the values identified based on the measurement and the design values. The relationship between input and output of a neural network are determined by the weights assigned to the connections between the neurons in two adjacent layers. A systematic way of determining the weights of the network to achieve a desired input/output relationship is referred to as training or learning. In the present study, input–output data sets for the training purpose were obtained by extensive finite element analysis using 10000 sets of correction coefficients. Once the neural network is trained and tested, the frequencies and modal shapes identified from the vibration measurement are then input to the network to produce the output, the correction coefficients of the structural parameters.

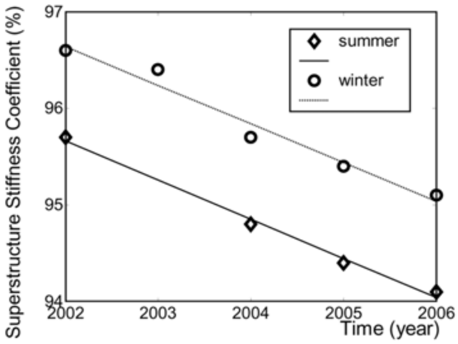


Fig. 10 Change of bridge superstructure stiffness

Based on statistical analysis of the collected data for each year, 2% decrease in the superstructure stiffness was observed over the five-year period as shown in Fig. 10. Considering the fact that the monitoring of the bridge started four years after the bridge was built, it is likely that the change in structural stiffness due to the prestress loss had stabilized in the first four years. Therefore the identified decrease in the stiffness value is not due to prestress loss. The degradation of the stiffness is considered due to material deterioration over the monitoring period, but more monitoring data during a longer term are needed to make meaningful observations. Such information regarding long-term change in structural parameters is invaluable for studying aging of similar bridges and for determining damage criteria for damage assessment purposes.

3.2. Extended kalman filter for seismic damage assessment

Different from frequency domain methods, time domain methods are capable of identifying non-linear systems. Along this line, the extended Kalman filter (EKF) studied for seismic damage assessment of concrete structures. The Kalman filtering technique uses not only the measurement data in a probabilistic sense but also information from structural models so that identification becomes possible even under noise contaminated measurements and for uncertain models (Kalman 1960). Results obtained by an extended Kalman filter approach from simulated data with known damage scenarios were reported (e.g. Yun and Shinozuka 1980, Hoshiya and Saito 1984, Loh and Tou 1995, Yang, *et al*. 2005).

In this study, the extended Kalman filtering (EKF) method was applied for seismic damage assessment by

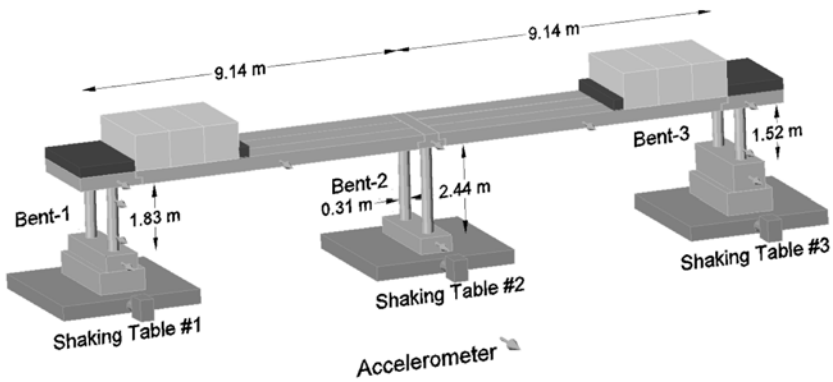


Fig. 11 Seismic shaking table test of concrete bridge

instantaneously identifying change in elemental stiffness values of a structure based on seismic response measurement (Soyoz and Feng 2008b). A large-scale shaking table test was performed on a three-bent concrete bridge model was performed to verify this method. Fig. 11 shows the bridge and the locations of accelerometers installed on the bridge. The model was placed on three individual shaking tables and shaken in the transverse direction to different levels of damage by a sequence of earthquake ground motions with increasing intensities. Table 1 lists the sequence of the tests and the peak ground acceleration (PGA) of some representative inputs.

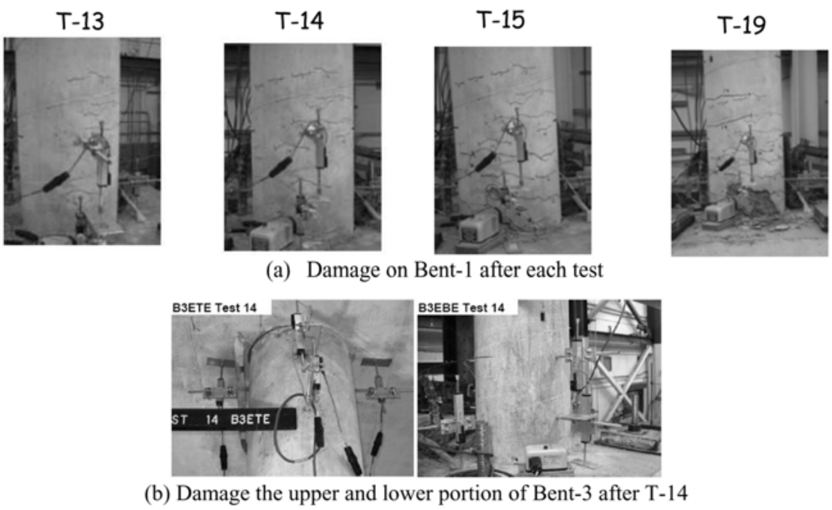
Damage of the bridge columns after each earthquake shaking is shown in Fig. 12. Due to different stiffness of the bents, dynamic behavior was highly dominated by the torsion demanding high transverse movement for the first and the third bent, causing severe damage on columns in Bent 1 and Bent 3.

Using the response acceleration measurement during each earthquake, elemental stiffness values at the upper and lower locations of the bridge columns were instantaneously identified by the extended Kalman filter method, in which the unknown stiffness consitute the extended states of the Kalman filter. Fig. 13 shows the time histories of the identified stiffness correction coefficients at the top and bottom of each column in each bent. The identified stiffness degradation based on vibration measurement is consistent with the results from visual observation and strain measurement using embedded strain sensors at the rebars.

It is noted that although after the T-13 and T-14 earthquakes, no apparent damage is visible (see Fig. 12),

Table 1 Shaking table test procedure

Test	Ground motion description	PGA (g)	Damage description
WN-1	White noise in transverse		
T-13	Low earthquake in transverse	0.17	Bent-1 yields
T-14	Moderate earthquake in transverse	0.32	Bent-3 yields
WN-2	White noise in transverse		
T-15	High earthquake in transverse	0.63	Bent-2 yields
WN-3	White noise transverse		
T-19	Extreme earthquake in transverse	1.70	Bent-3 steel buckles
WN-4	White noise in transverse		



(a) Damage on Bent-1 after each test

(b) Damage the upper and lower portion of Bent-3 after T-14

Fig. 12 Observed seismic damage

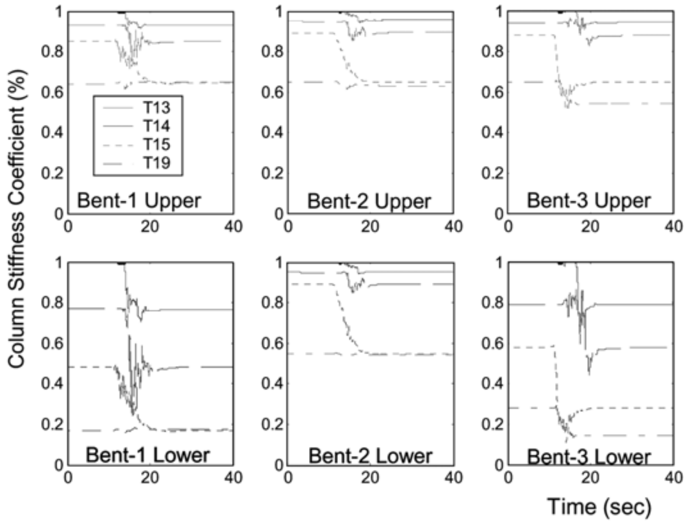


Fig. 13 Identified stiffness degradation during seismic event

stiffness degradation was identified on Bent-1 and Bent-3. This demonstrates the capability of the sensor-based method for identifying invisible damage. In addition, identification of the structural elemental stiffness enables location as well as quantification of structural damage. Finally the extended Kalman filter method is capable of dealing with damaged nonlinear structures and identifying damage in real time. This shaking table test represents, for the first time, an experimental validation of a structural damage assessment method using a ***realistic*** bridge model subjected to ***realistic*** seismic damage.

Other stiffness-based damage assessment methods were developed including the recursive Bayesian filtering and the hysteresis method, which were validated by the same seismic shaking table test (Chen and Feng 2008, Chen, *et al*. 2008). Excellent agreement is observed among these stiffness-based methods is observed; As seismic damage becomes more severe, the stiffness of the bridge columns decreases.

3.3. Nonlinear damping for seismic damage assessment

Another time-domain method using nonlinear damping as a structural damage index was developed and validated by the same shaking table tests (Feng, *et al.* 2008). Different from the extended Kalman filter method, the nonlinear damping method is based on the ambient vibration measurement taken after a damaging earthquake. Different from other frequency domain method, the nonlinear damping method uses only one measurement without the need for measuring a baseline of the "undamaged" structure.

If a concrete element is damaged, within the cracks the most significant energy dissipation mechanism can be represented with Coulomb friction. A cracked bending element can be modeled as a combined system of friction damping and viscous damping (in the compression zone). Each system has different free vibration characteristics - an exponential decay by viscous damping vs. a linear decay by friction damping. Therefore, by performing free vibration tests and analyzing damping, one can identify the existence of friction damping, i.e. structural damage (Franchetti 2004). However, it is not convenient to perform a free vibration test on a heavy civil engineering structure. This study used ambient vibration (such as the traffic excitation on a bridge), and applied the random decrement technique to obtain a free vibration signal from the measured ambient vibration. During the shaking table test of the bridge model

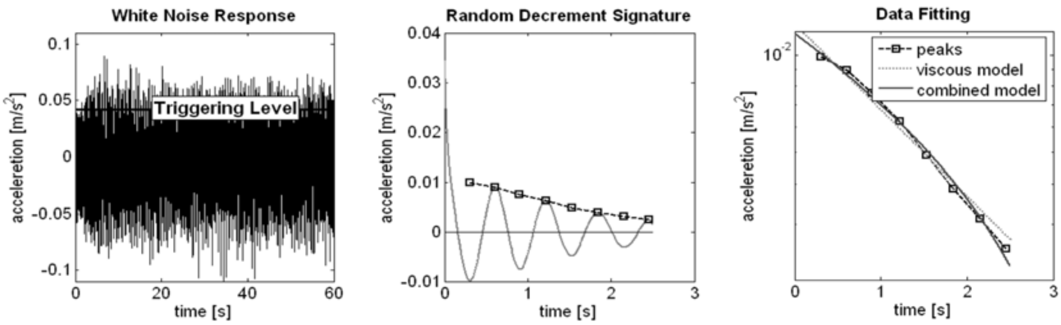


Fig. 14 Damping analysis based on ambient vibration

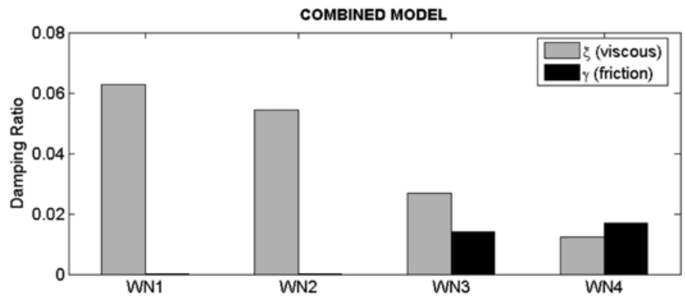


Fig. 15 Viscous and friction damping elements

(as presented in the proceeding chapter), white noise excitations were performed after each major seismic shaking.

Fig. 14 illustrates the procedure of damping analysis based on the acceleration response of Bent-1 to white noise WN-3. From the white noise response in Fig. 14(a), a random decrement signature - the solid line in Fig. 14(b) - is obtained and an envelope - the dotted line in Fig. 14(b) - is identified by picking both the positive and negative peaks. Then the identified envelope is compared with the envelopes computed based on the assumption of the viscous model and the combined viscous-friction model. Fig. 15 indicates the contribution of each of the two damping elements when using the combined model. As the bridge damage becomes more severe, the friction damping increases while the viscous damping decreases.

4. Conclusions

The emerging sensor-based SHM technology has a significant potential for revolutionizing the current practice in inspection and maintenance of civil infrastructure. With sensors installed at strategic locations to continuously “watch” the global structural behavior and identify hot spots in real time, inspection can be performed efficiently by focusing on the targeted spots and remedial actions taken timely and cost-effectively. The advanced sensor systems together with methods for interpreting sensor data discussed in this paper represent recent progress made toward the field implementation of SHM. The sensors are well suited for monitoring large-scale civil infrastructure systems and the health diagnostic methods have been validated in large-scale seismic shaking table tests of a concrete bridge model. Long-term field monitoring database are being established in order to develop reliable diagnostic and prognostic tools and to incorporate the SHM results into structural maintenance practice.

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