Structural Condition Assessment of Short-Span RC Highway Bridges by Ambient Vibration Monitoring

Maria Q. Feng and Yangbo Chen
Dept. of Civil and Env. Engng., UC Irvine, Irvine, CA

ABSTRACT
To assess the global structural condition of the bridges in an automatic, real-time and objective manner, two short-span box-girder reinforced concrete highway bridges in Orange County, CA have been instrumented with sensor systems to monitor their ambient vibration. Real-time vibration data are being wirelessly streamed to UC Irvine campus and shared on the Internet. Methodologies have been developed to assess their global structural conditions. For short- to mid-span highway bridges, ambient vibration is predominantly due to traffic excitation that mainly induces vertical vibration. Based on its physical nature, traffic excitation is modeled as moving loads from the passing vehicles and treated more properly in the system identification procedure to result in stiffness indices that represent the current health status of the superstructure. On the other hand, sub-structural integrity is better revealed by the transverse vibration of the bridge during earthquakes, which can also be captured by the same monitoring system. In this research, traffic-induced and ground-motion-induced ambient vibration data are treated separately for different assessment objectives, because of their different characteristics and measurability. By continuously monitoring the ambient vibration of an instrumented bridge, the global structural condition of both the super- and sub-structures can be evaluated with damage locations identified.

Key Words: Highway Bridge Health Monitoring, Ambient Vibration, Component Stiffness Identification

INTRODUCTION
Structural condition assessment of highway bridges has long been relying on visual inspection, which involves subjective judgment of inspectors and detects only local and visible flaws. A standard, the National Bridge Inspection Standards (NBIS 1996) and a guide, the Federal Highway Administration (FHWA) Recoding and Coding Guide (FHWA, 1995), were provided to regulate its frequency and the qualification of the inspectors, and to guide the procedure including the condition ratings and the documentation in current practice. Even with these provisions, a recent investigation initiated by FHWA to examine the reliability of visual inspections reveals significant variability in the structural condition assignments by inspectors (Phares et al., 2004). Moreover, visual inspection can neither quantitatively evaluate the strength and/or deformation capacity reservation of a bridge. In order to investigate the global structural condition of bridges in an automatic, real-time, objective and quantitative manner, structural
health monitoring has been promoted by researchers in the recent decade (e.g. Peeters et al, 2001; Aktan et al, 1997; Aktan et al, 2000; Catbas and Aktan, 2002; Doebling et al, 1998). Among many nondestructive evaluation methods (Chang and Liu, 2003), vibration monitoring is a promising one that can be implemented continuously on highway bridges without interrupting the traffic.

By instrumenting a bridge with accelerometers and other sensors, one is able to monitor ambient or forced vibration of the bridge. Ambient vibration, in this paper, refers to the vibration that bridges experience under their everyday service condition, where neither the excitation nor the bridge structures are purposely controlled or deliberately arranged as in an experimental setup. Ambient vibration measurement outwits controlled vibration measurement in that it requires no special test arrangement, such as traffic control or a heavy shaker, so that it can be continuously executed. However, methodologies have to be established for analyzing ambient vibration data that properly treat the different natures of ambient excitations due to different sources to avoid fallaciously identification of bridge conditions.

This paper presents monitoring systems developed by the authors for highway bridges. These systems feature a heterogeneous observation of the bridge structural behavior, including measurements from accelerometers, displacement meters, embedded dynamic strain gauges and soil pressure sensors. Also highlighted is the capacity of the systems to wirelessly stream back vibration data in real time to a center server on the UC Irvine campus and further distribute the data on the Internet. More importantly, this paper proposes a methodology for interpreting vibration data into structural health condition. This includes formulating a physics-based traffic excitation model, assessing the super-structural integrity by the traffic excited bridge vertical vibration, and complementally, assessing the sub-structural condition by low-amplitude bridge transverse vibration.

**MONITORING SYSTEMS OF HIGHWAY BRIDGES**

The authors have instrumented several highway bridges in California with sensor systems to monitor the vibration of the bridges (Feng et al, 2004). The Jamboree Road Overcrossing, as shown in Figure 1, is a typical three-span continuous cast-in-place prestressed post-tension box-girder bridge of the Eastern Transportation Corridor, located in Irvine, CA. The total length of the bridge is 110.9 m with each span length of 35.5, 46.1, and 30.3 m. The bridge is supported on two monolithic single columns and sliding bearings on both abutments. The sliding bearings allow creep, shrinkage, and thermal expansion or contraction.

The West Street On-Ramp, as shown in Figure 2, is a three-span continuous and curved cast-in-place prestressed post-tension box-girder bridge. The total length of the bridge is 151.3m with the span lengths of 45.8, 60.1, and 45.4m. The bridge is supported by two fixed columns and sliding bearings on both abutments similar to the Jamboree Road Overcrossing. This bridge is highly curved and inclined with a 12% super-elevation.

These two bridges represent two types of typical highway bridges in California, one is over- or under-crossing which is usually straight, and the other is on-ramp which is curved in plane. The instrumentation of a third highway bridge, the Fairview Road On-Ramp, will soon be completed.
This bridge falls in the on-ramp catalog, but has 4 spans (52.5, 59.5, 59.5 and 52.5 m) and is instrumented with a denser sensor system of 43 channels.

Figure 1. Sensor Layout and Channel Number at Jamboree Road Overcrossing

Figure 2. Sensor Layout and Channel Number at West Street On-Ramp
Monitoring systems involving accelerometers, strain gauges, displacement sensors and soil pressure sensors were installed at both super- and sub-structures. Uni-axial, bi-axial, and tri-axial force-balance servo-type accelerometers were installed on both of the bridges. The locations of the accelerometers at Jamboree Road Overcrossing are shown in Figure 1, and they are placed along the centerline of the bottom of the girder to minimize the torsional effect of the bridge box girder. Strain gauges, which are micro-displacement sensors, were permanently embedded in concrete on the West Street On-Ramp to measure dynamic strains. In order to measure the movement of the super-structure with respect to the abutment, a displacement sensor was installed at an abutment for each bridge. To measure the soil pressures at the abutment during earthquakes, a soil pressure sensor was installed on the back wall of the abutment at the West Street On-Ramp (Figure 2). Uninterruptible power supply systems were installed at the bridges to prevent power failure due to unexpected events such as earthquakes. In the Jamboree Road Overcrossing, a solar power supply system was also installed to power the monitoring system in the day time.

A wireless data transmission and remote data acquisition control system was installed at the Jamboree Road Overcrossing, to transmit real-time vibration data streams wirelessly to a server computer on the UC Irvine campus. The data logger is connected through its RS 232 series port to a LAN converter, a TIP/IP device that converts the data logger into an Ethernet node. A pair of Cisco Aironet 350 wireless bridges (IEEE 802.11b, 2.4 to 2.497 GHz) and a pair of Cisco AIRANT3338 Aironet Antennas (gain 21dBi) were installed both on the bridge site and on a high-rise building on the UC Irvine campus. Through these wireless devices, the data logger is linked to the backbone of the UC Irvine Ethernet, overcoming a distance of more than 6.5 miles. Ambient vibration data obtained by the sensor system on the bridge are wirelessly streamed to the server computer in real time, while control signals (triggering, calibration and configuration commands) to the data logger can be issued remotely from the server computer. Such a remote data acquisition system is essential for bridge health monitoring applications, because it enables one to check the working status of the monitoring system without traveling to the remote bridge site.

The server computer archives the vibration measurements and buffers them for a near-real-time waveform display on the Internet. A Java applet has been developed so that virtually any computer having internet connection can access the waveforms of the vibration signals almost in real-time, by visiting a web page. The waveforms are updated every 5 seconds. http://mfeng.eng.uci.edu/Maria_Feng/Research_activities/health_monitoring/waveform.html

VIBRATION RECORDS
A large amount of vibration data have been collected since these monitoring systems were established. Two types of vibration are observed. The first is traffic excited vibration, while the second is minor/moderate earthquake induced vibration. As one can see from the typical signals to be shown below, traffic mainly excite vertical vibration, while ground motion induces more transverse vibration, given that the bridge is essentially straight and its vertical and transverse modes are not highly coupled.

Typical traffic excited vibration
Typical traffic excited vibration records at selected channels in the Jamboree Road Overcrossing are shown in Figure 3. One can see that the vertical vibration (Ch-4) has much larger amplitude
(30 gal) than that (6 gal) in transverse direction (Ch-3). The sensors near the ground, such as Ch-10, barely capture the very low amplitude (1.5 gal) vibration. One interesting feature of the traffic excited vibration to note is its impulse-like patterns associated with each of the passing vehicles on the bridge.

**Typical earthquake record**

On June 16, 2005, a moderate earthquake occurred at 1:53 pm (PDT) in Yucaipa, CA. The local magnitude was between 4 to 5 MI, and the distance from the epicenter to Jamboree Road Overcrossing is about 105 km (65 miles). The monitoring system was triggered by this ground motion and recorded this event. The record shows a peak ground acceleration in North-South of 11.6 gal, in East-West of 13.0 gal and vertical of 3.55 gal.

The earthquake records of the same channels are plotted in Figure 4. One can observe that earthquake excited bridge vibration more in the transverse direction than the traffic does. Transverse vibration (Ch-3) has an amplitude of 25 gal, comparable to that of the vertical direction (Ch-4) in the same event, but much larger than the transverse vibration induced by traffic. The bridge vibration near the ground, such as Ch-10, is much stronger than that under traffic excitation. Also note that the vertical vibration remains in the same level for both traffic excited and earthquake vibrations. One can see the impulse-like pattern in the vertical vibration record during the event, indicating vehicles passing the bridge during the earthquake event.

![Figure 3. Typical Record of Traffic Excited Vibration](image1)

![Figure 4. Typical Earthquake Record](image2)

Observing the cumulated data from these instrumented bridges, one realizes that (I) ambient vibration of short- to mid-span highway bridges is mainly due to traffic excitations, and (II) traffic mainly induces vertical vibration. To assess the structural health by ambient vibration measurement, it is essential to model the traffic excitation properly. On the other hand, due to the fact that vertical vibration characteristics are not highly sensitive to the stiffness changes of the sub-structure (Feng et al., 2005), which is most vulnerable to earthquake damage, transverse (out-of-plane) vibration of the bridge, such as that in moderate earthquakes, rather than the traffic-induced vibrations, should be utilized to assess the sub-structural integrity.
SUPER-STRUCTURAL CONDITION ASSESSMENT BY TRAFFIC-INDUCED VIBRATION

Based on the above observation, we develop a complementary pair of methodologies to assess the global structural condition of a highway bridge. In this section, discussion will be on the methodology of super-structural condition assessment by vertical traffic-induced vibration, while in the next section, the methodology for sub-structural condition assessment by transverse vibration will be addressed.

Model the traffic excitation

During earthquakes, ground motion inputs to a bridge can be measured by accelerometers or displacement sensors on the ground. But this is not the case for traffic excitations. Measuring the tire forces of a moving vehicle has posed a great difficulty. The most convincing technology, weigh-in-motion (WIM), only accounts for the static but not the dynamic tire forces (FWHA, 1997). It is highly difficult, if not impossible, to measure traffic excitation inputs. In this research, the authors have developed a stochastic model of traffic excitation based on its physical nature. Traffic excitation is modeled as a stationary stream of vehicles (modeled as constant moving loads) arriving in accord with a Poisson process, traversing an elastic beam with constant speed. The randomness of vehicle arrivals, vehicle weights and speeds is taken into consideration. This model reveals that the traffic excitation is spatially correlated. When employing the dynamic nodal loading approach (Pan and Li, 2002), and given knowledge of the stochastic distributions of the vehicle arrivals and weights, the spectrum density matrix of the traffic excitation can be obtained in a close form. Detail derivation of this model, and the consequences of the usually neglected spatial correlation nature are referred to Chen et al. (2004 and 2005). It has been shown that incorrect modeling of traffic excitation can result in misleading bridge structural identification.

Identify bridge component stiffness by extended Kalman filter

With partial traffic information, namely, the arrival times and speeds of the passing vehicles, obtained from digital traffic video, the major characteristics of traffic excitation (for example, spatial correlation) can be reconstructed. In this study, traffic information is fed into an extended Kalman filter (EKF) to identify the structural condition of the super-structure continuously from the vertical ambient vibration measurement.

To verify this approach, vertical acceleration responses were first simulated for a bridge with assigned structural properties (i.e. $I_1^o$, $I_2^o$ and $I_3^o$ are the cross-section moments of inertia for the three spans, respectively), subjected to a vehicle weighing $P_1^o$ that arrives at 0.15 second and traverses the bridge with a speed of 13.75 m/s. Feeding this simulated response and the vehicle’s arrival time and speed into an EKF, the evolution of the identification results are depicted in Figure 5. Identification results are normalized by their benchmark values. In each of the plots in Figure 5, the solid line represents the estimated values (mean values) and the dotted lines are the means offset by a standard deviation (+/-σ). It is shown that the identification converges to the benchmark values as time goes and more data are collected. Meanwhile, the estimation is improved in a sense that the standard deviations decrease as well.

Because the component stiffness indicates the structural integrity of this component, once the component stiffness is properly identified, one can assess the structural condition of the entire bridge, evaluate its strength/deformation capacities, and identify damage to a component level.
SUB-STRUCTURAL CONDITION ASSESSMENT BY EARTHQUAKE-INDUCED VIBRATION

Complementally to the methodology described above for super-structures, the authors propose a methodology for assessing the sub-structural condition of highway bridges by transverse vibration records. One of the possible resources containing transverse vibration components is the records of the bridge responses during strong ground motions (Smyth et al, 2003). Unfortunately, this is not an ideal data set in that, the duration of the strong motion is too short, its amplitude is so high that it induces non-linearity in the bridge structure, demanding sophisticated data analysis method. On top of all these difficulties, because strong earthquakes are events with low occurring probability, such data are scarcely obtained for a monitored bridge.

Instead, low amplitude transverse vibrations, such as those due to minor/moderate earthquakes could be good alternatives to circumvent these difficulties. Their low amplitude allows the assumption of a piece-wise linear system, because they are similar to perturbations on the structure without engaging further damage or nonlinearity. They can, therefore, be treated by linear method, although evidently a structure in different damage stages should be modeled as a series of linear systems with different parameters. These parameters, when identified from vibration signals, represent the sub-structural damage and its location on a bridge. This proposed method was verified in a large scale full bridge shaking table test.

A series of large scale shaking table tests have been and more will be conducted in University of Nevada, Reno (UNR), in an NSF-NEES sponsored research to explore the seismic behaviors of reinforced concrete bridges and potential design philosophy/technology improvements. Taking advantage of this opportunity, the authors collaborated with researchers in UNR and installed additional accelerometers on the bridge specimen in order to verify the proposed method of structural condition assessment for bridge sub-structures.

In this test, a 2-span bridge specimen is supported on three shaking tables. Each of the three bents is driven by an individual shaking table in the transverse direction of the bridge. Damage stages were introduced by running strong ground motions with different amplitude levels. Between strong motions, the shaking tables were driven by low amplitude white noise signals, and structural vibration was measured by accelerometers (see Figure 6 for sensor layout). The test procedure is listed in Table 1. Only the vibration records during low-amplitude transverse vibration (tests WN-X-1 to 5) are processed and results are correlated with the damage stages.
Actual sectional stiffness is represented by a set of correction coefficients, $\beta_i$’s, being a fraction of the sectional stiffness calculated from drawings. To be specific, $\beta_i = (EI)_A^i / (EI)_D^i$, where $(EI)_A^i$ is the actual (subscript $A$) sectional bending stiffness of the columns in Bent $i$ (superscript $i$), and $(EI)_D^i$ is the sectional bending stiffness of the columns in Bent $i$ calculated from drawings (subscript $D$). $\beta_i$’s corresponding to different damage stages are identified from the acceleration observations in the five tests WN-X-1 to 5 by a weighted-nonlinear-least-square procedure (Polak, 1997). Results are listed and graphed in Table 2. Because the shaking table excitation time histories were also recorded, bridge responses can be simulated given a set of candidate parameters $\beta_i$’s. Therefore, the identification procedure is essentially searching for $\beta_i$’s that minimize the difference between the simulated and the measured responses.

Note that the identified sectional stiffness coefficients clearly indicate the same damage sequence as observed in the experiment. Bent 1 yields $\rightarrow$ Bent 3 yields $\rightarrow$ Bent 2 yields $\rightarrow$ Bent 3 steel buckles. Between WN-X-1 and WN-X-2, $\beta_1$ and $\beta_3$ drop from 0.78 to 0.52 and from 0.84 to 0.61 respectively, while $\beta_2$ remains same level, indicating in a quantitative manner the yielding of Bent 1 and Bent 3 between these two tests. Then between WN-X-2 and WN-X-3, the decrements in all $\beta_1$, $\beta_2$ and $\beta_3$ signal that not only Bent 2 yielded, but also the damage in Bent 1 and Bent 3 further developed. In WN-X-4, $\beta_3$ touches down to a very low value, 0.11, associating with the severe damage in Bent 3 (steel buckling). And the results of WN-X-5 are comparable to those in WN-X-4, which is consistent with the observation that the after shot earthquake actually has not further destroyed the bridge specimen significantly.

This large-scale shaking table test verified the methodology proposed for assessing sub-structural integrity by analyzing low-amplitude transverse vibration of the bridge under a piece-wise linear assumption.

**CONCLUSION**

Identification of changes in structural component stiffness based on ambient vibration measurement can be a powerful tool for assessing bridge structural condition in an automatic, continuous, real-time, objective and quantitative manner, provided proper instrumentation and data analysis methodology are established.

This paper reports on the instrumentation of several Caltrans highway bridges for exploring real-time structural condition assessment. Successful solutions to issues such as system design, wireless remote data acquisition and transmission, Internet data publication are demonstrated.
Methodologies are proposed for data interpretation and structural condition assessment for short- to mid-span RC bridges. The super-structural integrity is evaluated by integrating the vertical vibration measurement and traffic video, based on a traffic excitation model proposed by the authors. The seismic damage on the sub-structure is revealed by earthquake-induced transverse vibration. Large scale shaking table tests demonstrated that seismic damage can be successfully located and quantified using the proposed methodology.

<table>
<thead>
<tr>
<th>Tests</th>
<th>Ground Motion Description</th>
<th>PGA (g)</th>
<th>Damage</th>
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</thead>
<tbody>
<tr>
<td>S-1</td>
<td>Snap (Arouse Free Vibration)</td>
<td></td>
<td></td>
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<tr>
<td>WN-X-1</td>
<td>White Noise in Transverse</td>
<td></td>
<td></td>
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<tr>
<td>WN-Y-1</td>
<td>White Noise in Longitudinal</td>
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<tr>
<td>T-12</td>
<td>Low Earthquake in Transverse</td>
<td>0.0851</td>
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<tr>
<td>T-13</td>
<td>Low Earthquake in Transverse</td>
<td>0.1729</td>
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<td>T-14</td>
<td>Moderate Earthquake in Transverse</td>
<td>0.3193</td>
<td>Bent 3 yields.</td>
</tr>
<tr>
<td>S-2</td>
<td>Snap (Arouse Free Vibration)</td>
<td></td>
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<tr>
<td>WN-X-2</td>
<td>White Noise in Transverse</td>
<td></td>
<td></td>
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<tr>
<td>WN-Y-2</td>
<td>White Noise in Longitudinal</td>
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<tr>
<td>T-15</td>
<td>High Earthquake in Transverse</td>
<td>0.6272</td>
<td>Bent 2 yields.</td>
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<td>Severe Earthquake in Transverse</td>
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<td>T-17</td>
<td>Extreme Earthquake in Transverse</td>
<td>1.135</td>
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<td>S-3</td>
<td>Snap (Arouse Free Vibration)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WN-X-3</td>
<td>White Noise in Transverse</td>
<td></td>
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<tr>
<td>WN-Y-3</td>
<td>White Noise in Longitudinal</td>
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<td></td>
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<tr>
<td>T-18</td>
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<td>T-19</td>
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<td>1.7033</td>
<td>Bent 3 buckles.</td>
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<tr>
<td>S-4</td>
<td>Snap (Arouse Free Vibration)</td>
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<tr>
<td>WN-X-4</td>
<td>White Noise in Transverse</td>
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<td>WN-Y-4</td>
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<tr>
<td>T-20</td>
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**ACKNOWLEDGEMENT**

This study is sponsored by Caltrans under the contact 59A0311. Mr. Li-hong Sheng provides insightful suggestions and helped to make the shaking table tests possible. The shaking table tests were conducted at University of Nevada, Reno. Deep appreciation is owed to Prof. Saiidi Saiidi, Prof. David Sendars, Dr. Patrick Laplace and Mr. Paul Lucas for their kindly help during the experiment and for providing us with their design drawings, push-over analysis results and some experimental data.

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