LONG-TERM STRUCTURAL PERFORMANCE MONITORING OF BRIDGES – Phase II
Development of Baseline Model and Methodology for Health Monitoring and Damage Assessment on Bridges in Los Angeles Highway Network

RESULTS: The Caltrans Division of Engineering Services instrumented three similar bridges located in Orange County. As a structure deteriorates due to aging or suffers from damage caused by extreme loads such as earthquakes, stiffness of the damaged structural elements would decrease, and as a result, the global vibration characteristics of the structure would change. Therefore, by monitoring the structural vibration, one can identify the change in structural vibration characteristics and then further identify the element stiffness. A number of system identification methods were reviewed and developed in this study for identifying the structural element stiffness based on measurement of bridge vibrations caused by traffic and seismic excitations. A unique traffic excitation model was proposed for more reliable stiffness identification based on traffic-induced vibrations. The effectiveness of these methods in evaluating seismic damage on a bridge structure was demonstrated through seismic shaking table tests of a multi-bent multi-column concrete bridge model. Long-term monitoring data from the instrumented bridges were analyzed and developed into a structural stiffness database using a software platform developed in this study.

Why We Pursued This Research

Structural condition assessment of highway bridges has long relied on visual inspection, which involves subjective judgment of inspectors and detects only local and visible flaws. The frequency of visual Inspection and the qualification of the inspectors are regulated by the National Bridge Inspection Standards. And the Federal Highway Administration (FHWA) Recoding and Coding Guide was also provided 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. Moreover, visual inspection cannot quantitatively evaluate the strength and/or deformation capacity reservation of a bridge. Local defects or flaws might or might not have a significant effect on the bridge global performance.

How it was done

Sensor-based Structural Health Monitoring (SHM) can revolutionize the traditional way we inspect structures, in a more timely, objective, and quantitative fashion. By installing appropriate sensors at critical locations on a bridge structure, transmitting the sensor data through a communications network, and analyzing the data through a software platform, the location and severity of bridge deterioration and damage can be automatically, remotely, and rapidly assessed, without sending inspection crews to the site. As the sensor, networking, and communication technologies advance, the sensor-based SHM has become an intensively investigated subject approaches and suggest future improvement. The monitoring results can also be used to improve the basic modeling assumption during design phase. Furthermore, the sensor-based continuous monitoring will potentially enable real-time and remote post-event damage assessment of highway bridges and early warning, significantly improving emergency response operations.

Methodology

In 1993, Rytter proposed a four-level hierarchy goals of SHM, namely, (I) detecting the existence of damage, (II) locating damaged portions, (III) evaluating the severity of damage and (IV) predicting its future consequences. Interpretation of vibration-based SHM following a statistical pattern recognition paradigm, consisting of a four-part process: (I) operational evaluation, (II) data acquisition, fusion, and cleansing, (III) feature extraction and information condensation, and (IV) statistical model development for feature discrimination. In this paradigm, features that are believed damage sensitive are extracted from vibration data, and a pattern recognition procedure is employed to classify the feature vectors to determine the existence, location and severity of structural damage. Since data from a damaged structure is seldom obtained and if exist, it is not adequate to cover all possible damage scenarios. Training patterns have to be generated by a mathematical model whose fidelity remains to be verified. A sufficient coverage on various scenarios by the training patterns, nonetheless, is essential in the supervised learning procedure. Research in vibration-based SHM has produced substantial literature, with many conferences and journals held for information exchange and demonstration of research. These methods can be grouped into either frequency or time domain. If it is in frequency domain, basically the changes in modal values; frequency, damping, shape, are used as an indication of damage. However, if one
wants to identify the changes more in detail like changes in elemental stiffness, time domain identification methods might be more appropriate. Time domain methods can be grouped into two depending on whether they are purely data driven or they are incorporating finite element (FE) model. If it is aimed to determine the changes in the stiffness values, FE model must always be used. Within time domain identification methods, the most common one is the least squares estimation (LSE). It is basically performing an optimization for the parameters such as stiffness and damping so that the error between the measured and the simulated responses is minimized.

Kalman filtering was a breakthrough in system engineering field when first proposed four decades ago. It not only uses the data in a probabilistic sense but also gets information from structural model (Kalman, 1960). Results obtained by the Extended Kalman Filter (EKF) approach from simulated data and well defined models with known damage scenarios were reported. However, applicability of the EKF approach to civil engineering structures involving high uncertainties in structures and loadings under realistic damaging events has not yet been studied.

Three similar bridges in the Orange County were instrumented with accelerometers, strain meters, displacement sensors and pressure gauges. Vibration and other data are collected periodically locally or remotely by wireless Internet. They were then using developed system identification software tools to extract structure primary vibration characteristic and to fit and update the FE models. All of those data were then stored in the developed database for future statistic analysis.

Research Results

The identified stiffness at the bridge superstructure and substructure (columns) of the three instrumented new bridges are down to 85% of their gross section properties. It is higher than the crack section used today. A stiffness baseline was updated for each of the bridges and it will be used for long-term monitoring purpose. Up to 6% fluctuations in the identified stiffness was observed for one of the bridges over a four-year period. This is considered due to change in environmental conditions such as temperature, humidity and aging.

Static and dynamic loading tests were conducted on one of the bridges using water trucks. From the strain observation during the static load test, Up to 5% variations were observed between bumping and breaking tests. This is considered due to the change in bridge vibration amplitudes.

The effectiveness of the seismic damage evaluation methods was verified by a large-scale shaking table tests of multi-bent, multi-span bridge models. Locations and extent of stiffness degradations in the bridge columns were successfully identified based only on the seismic (acceleration) responses of the bridge, as the bridge was progressively damaged to different extents by seismic excitations. The identified locations and extents of stiffness degradation were verified by the strain measurement and visual inspection. The shaking table tests conducted in this study represented the first effort in validating seismic damage evaluation methods using a realistic structural model subjected to realistic seismic damage.

Conclusion

This project has demonstrated the potential of using the sensor technology for long-term and real-time structural health monitoring and post-event damage detection. The baseline updating methods based on vibration measurement and stiffness identification developed in this study can also be applied to existing bridges (that represent the majority of the Caltrans inventory) in the following two ways; one is for establishing the current baseline of the bridge for its future damage detection and deterioration assessment, and the other is for assessing the ongoing “health” if a database of similar types of bridges exist for the comparison purposes.