CHALLENGES IN STRUCTURAL HEALTH MONITORING
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Abstract

Structural health monitoring through field instrumentation has been carried out successfully on many highway bridges to monitor the short-term and long-term performance of structures. Properly designed and strategically placed instruments can help collect valuable data regarding the condition, the stress and strain, deflection, temperature gradients, and the time-dependent properties, such as creep and shrinkage in a structure. The data may be used to verify the design assumptions, to make modifications, to improve on future designs, to assess the general health of bridges, and to provide valuable information for a bridge management system for making decisions regarding preservation decisions.

The challenges in structural health monitoring are in finding cost-effective and reliable sensors to remotely and continuously monitor the conditions of major bridges.

Introduction

Field instrumentation and structural health monitoring are becoming an important part of bridge design, construction, preservation, operation and structural safety. A well conceived instrumentation program can be invaluable in improving design, assuring quality in construction, assessing structural response and condition, verifying design assumptions, updating codes and making decisions on inspection, evaluation, rehabilitation, repair and replacement of bridges.

Many variations of instrumentation programs and structural health monitoring systems have been used on bridges. The basic program has the objectives of measuring the fundamental behavior of construction materials and the normal response of structures and/or their components. The more extensive program will attempt to monitor the condition and performance of a structure from construction through the entire useful life. During construction, measurements may be taken to verify material properties, fabrication quality, and construction compliance. Soon after completion of construction, the as-built condition of the structure can be measured to serve as a baseline for future condition assessment and performance evaluation. Measurements taken periodically or continuously during the service life of a bridge will identify changed conditions, which can be analyzed for structural safety by the owner as an essential part of a bridge

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management system.

Challenges and opportunities exist in developing structural health monitoring systems to remotely, continuously, reliably and cost-effectively monitor the physical and structural conditions of significant and large bridges. For example, many of the nation's long-span suspension bridges are over 50 years old, many of which have not received in-depth inspections and evaluations of the main cables. Owners are looking for reliable ways to inspect and evaluate the condition and capacity of the main cables, which are wrapped with an outer layer of wires and covered with a system of paints. Bridge owners are also interested in cost-effective and reliable bridge monitoring system that can be incorporated into new construction for measuring the long-term performance of bridges subjected to the normal service loads, environmental conditions, and extreme events.

An effective structural health monitoring system is expected to measure the short- and long-term performance of a bridge, and to evaluate the stress and strain distribution in the main load carrying members after subjected to unusually high loading, such as, overloads from vehicles, ship impacts, flood and scour, earthquake forces, high winds, large waves and surges, and other time-dependent and environmental effects. The system should be capable of manual operation or programmed to perform functions desired by the operator. The system should allow remote access through wireless or hard-wired modem communication.

Instrumentation and monitoring of structural performance of different types of bridges, from simple to more complex types, are briefly discussed in the following sections.

A Three-Span Prestressed Concrete Bridge

The SR18 Over SR516 Eastbound Bridge is a three-span continuous prestressed concrete structure built with high-performance concrete and located in King County, Washington State (See Figure 1). The center span has a length of 137 ft. and the end spans are 80 ft. each. The roadway deck is 38 ft. wide, carrying two 12-ft. lanes and 4-ft. and 10-ft. shoulders.

The instrumentation of this bridge was designed to measure strains, temperature, strand slipback, camber and strand stress. Five of the fifteen girders in the bridge were instrumented – three girders in the 137-ft. long Span 2 and two in the 80-ft. long end span.

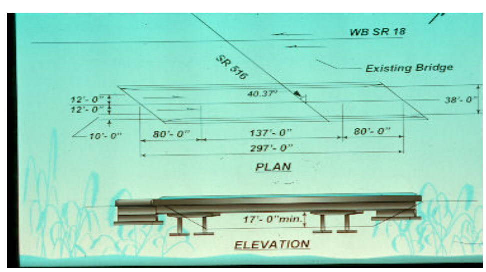

Figure 1 SR18/516 Bridge

Longitudinal strains and temperatures were measured by embedding vibrating wire strain gages in girders. These gages have a history of long-term reliability. The locations of the strain gages are shown in Figure 3. Each instrumentation site was instrumented in the same manner.

Girder camber was measured by using a wire stretched between two reference locations at the ends of the girders. One end of the wire was fixed in position. The other end of the wire was placed over a pulley and stressed by hanging a weight from the wire.

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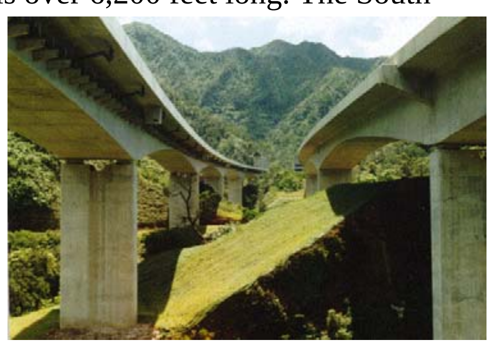
Here are some observations on the instrumentation and monitoring. The vibrating wire strain gages were robust and reliable. Their long-term stability and reliability made them very suitable for measuring long-term strains, such as, the strains due to creep and shrinkage. After three years, most of the strain gages were still operational. Only a few ceased to function. Other gages for strain and temperature measurements and the stretched-wire system for measuring camber performed well and provided reliable and reasonably consistent measurements. Overall, the instrumentation program was a success in meeting the specific objectives of the program. Camber growth and prestress losses were measured and compared to predictions by current design methods, such as the AASHTO and PCI methods. The average of the field measured final cambers was about 20% higher than the predicted camber for the girders in Span 2.

A Cast-In-Place Segmental Concrete Bridge

The North Halawa Valley Viaduct consists of two parallel bridges. The North Structure carries two lanes of traffic inbound to Honolulu and the South Structure carries two lanes of outbound traffic. The North Structure is over 6,200 feet long. The South Structure is over 5,400 feet long. Both are segmental cast-in-place concrete box-girder bridges built by the cantilever construction method on the island of Oahu, Hawaii.



The cantilever method of segmental construction requires careful geometric control to assure that the final bridge roadway profile will reasonably match the vertical alignment shown in the plans. The deflection and movement of the cantilevers during construction are affected by loads applied at various stages during erection, and the creep and shrinkage of the concrete after construction. The time dependent creep and shrinkage effects, which continue for 15 or more years, are the most difficult to predict accurately and compensate for in concrete bridge construction. Many creep and shrinkage predictive models have been developed and used by various codes.

The field instrumentation and monitoring program was designed to
(1) Evaluate the longitudinal strain history at critical locations of the bridge.
(2) Measure the deflections along the span and rotations at the piers.
(3) Collect concrete creep and shrinkage data.
(4) Compare the stress and deflection histories with those estimated by the predictive models used by the designers and established by other codes.

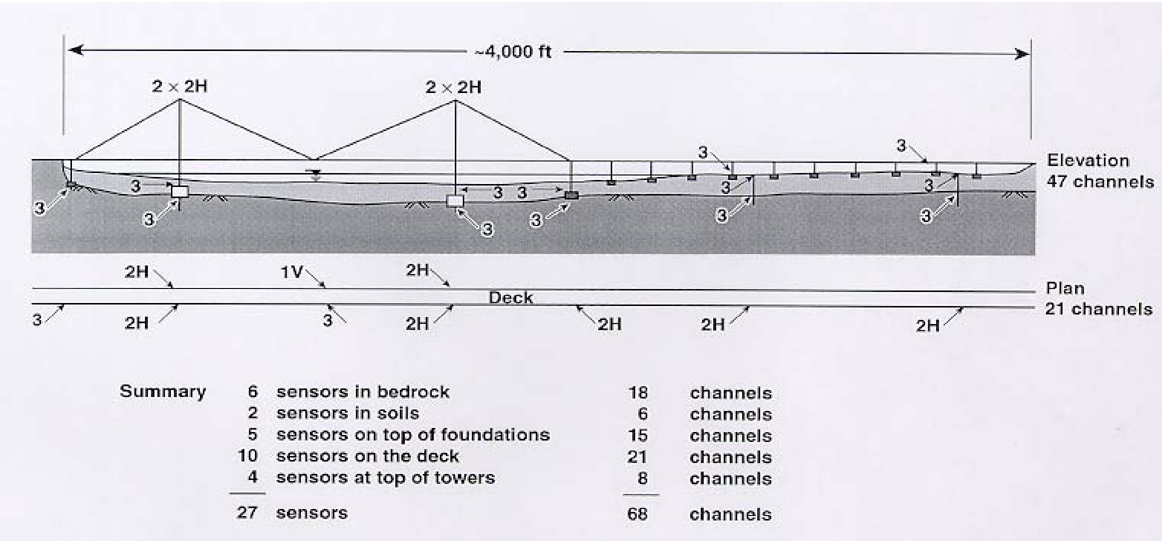
Seven sections of the northbound bridge were selected for instrumentation to measure concrete strain, span shortening, concrete creep and shrinkage strains, concrete and ambient temperatures, tendon forces, span deflections and support rotations. Vibrating wire gages, electrical resistance strain gages, mechanical strain gages, extensometers, thermocouples, tiltmeters, load cells, and a taut-wire baseline system were used in the instrumentation.

Here are some observations of the system. Overall, the instruments performed very well. Very few instruments were damaged during construction or malfunctioned after installation. Only a few gages were damaged during the concrete pour. The low rate of damage to instruments might be attributed to the care taken during installation to protect concrete from falling directly on the instruments and the careful monitoring of the concrete pouring operation to avoid concrete vibrators from coming in direct contact with the instruments. After three years of field exposure, less than ten gages failed to function.

The instruments were very reliable for both short-term and long-term monitoring. Field measurements have been collected and analyzed. The field measurements have been compared to mathematical models, analytical results and code recommendations. In general, the predictive models were not able to predict the effects of creep and shrinkage adequately. All the models used in the comparison underestimated both creep and shrinkage of the Hawaiian concrete. However, the test data could be used to improve the prediction of creep and shrinkage. The analytical deflections compared reasonable well with the measured deflections. 3-D computer model tended to produce better results as compared with field measured deflections. Physical and material properties used in the analytical computer models affected the accuracy of the results.

A New Cable-Stayed Bridge

The Bill Emerson Memorial Bridge (Cape Girardeau Bridge) is a new cable-stayed bridge, crossing the Mississippi River near Cape Girardeau, Missouri. It is located near to the epicentral region of the 1811-1812 New Madrid earthquakes. This seismically active region is an ideal place for instrumentation to monitor strong shaking of the bridge, and potential failure of the ground in the vicinity of the bridge. The seismic instrumentation includes accelerometers on the superstructure and substructure. In addition, anemometers are installed to record the response of the bridge and cables to wind-induced vibrations.



The objective of the seismic instrumentation and monitoring program is to gather data from the bridge during earthquakes. The data can be used to (1) assess the performance of the bridge, (2) check design parameters, including the comparison of dynamic response, and (3) improve seismic design of future bridges. With recent developments in digital and broadband technologies, the structural monitoring system can be configured to allow real-time streaming, viewing and recording of structural responses, and automatic recording of data after a certain threshold of earthquake or wind magnitude. The stay cables are instrumented to measure the vibration properties under wind-rain induced excitation.

This is the most extensively instrumented cable-stayed bridge in the U.S. The structural monitoring system is capable of providing extensive strong-motion data for studies and assessment of the bridge performance under strong seismic loads. The system is also capable of recording low-amplitude motions and wind-rain-induced vibrations.

Challenges and Opportunities

New and existing significant and large bridges of concrete and steel, such as suspension bridges, cable-stayed bridges, long-span truss bridges, movable bridges and floating bridges, are potential candidates for instrumentation and monitoring to assess condition, damage, degradation, and capacity of the bridge components and system. New bridges offer opportunities for developing complete structural health monitoring systems for bridge inspection and condition evaluation from "cradle to grave" of the bridges. Existing bridges provide challenges for applying state-of-the-art in structural health monitoring technologies to determine the current conditions of the structural elements, connections and systems, to formulate models for estimating the rate of degradation, and predicting the existing and future capacities of the structural components and systems.

The following sections will identify the needs for and potential applications of field instrumentation and structural health monitoring techniques for condition assessment of two types of bridges: truss and suspension bridges. These two types of bridges are used for illustration purpose only. Other types of bridges have similar needs and can benefit from structural health monitoring.

Steel Truss Bridges

Many long-span highway steel truss bridges have been constructed in the early and mid 1900's. They consist of through truss, half-through truss, deck truss, variable depth cantilever truss, arch truss and tied arch, etc. These bridges and their approaches are subject to much higher traffic loading than originally designed. These bridges also have fatigue prone and fracture critical details, some of which have already developed cracks. Manual inspection of these bridges is labor intensive and not always able to detect crack initiation and crack growth. Visual inspection on an annual, 2-year or 5-year basis is feasible, but may not be practical or even reliable. The difficulty in visual inspection is caused by the sheer size of the bridge, the large number of fatigue prone and fracture critical details, access problems, paint coating, poor lighting and other environmental effects.

There are needs to detect crack initiation and monitor crack growth on an on going basis to assure serviceability, safety and reliability. There is a challenge to develop a cost-effective and reliable instrumentation program to provide continuous remote data acquisition, monitoring and evaluation of the structural conditions of the bridge components and the system performance of the bridge.

Suspension Bridges

There are 57 major long-span suspension bridges in the United States. Most of them are over 50 years old, for example, San Francisco-Oakland Bay Bridge was completed in 1936. They represent significant investments and essential transportation links in the nation's infrastructure system. The needs to assess the conditions and to evaluate the safe capacities of these bridges are growing. Currently, there is no reliable and nationally recognized procedure, practical or theoretical, to inspect and evaluate the condition, strength, and safety of the suspension bridge cables. As a result, very few suspension bridges have received in-depth inspection of the main cables. Owners are reluctant to perform time consuming and costly in-depth inspection without any outside indications that potential problems exist within the cable wrapping. Current in-depth inspection of the interior of the main suspension bridge cables involves the following steps:

1. Remove the outer wrapping wire of the main cable.
2. Remove cable band(s) as necessary to provide adequate length for wedging without causing undue bending in the cable wires.
3. Wedge open the cable at several locations around the perimeter.
4. Inspect the condition of the wires.
5. Remove wires for laboratory testing.
6. Make decisions regarding the conditions of the bridge.

Typically, one to four locations of a cable are wedged open for visual inspection. Based on this inspection, evaluations are made on the degradation and remaining capacity of cables and decisions made regarding the safe operation of the bridge. Basically, major conclusions are drawn from observing less than 1% of the total length of wires in the cable. This practice results in different of opinions concerning the condition and capacity of the main cables. One group of inspection and evaluation team might conclude that the cable has a very low factor of safety and recommend cable replacement, while another team might conclude that the cable is quite safe and there is no need for replacement.

There is a need for more accurate and reliable nondestructive methods for determining cable conditions, extent of corrosion, rate of degradation and cable strength, with or without removing the outer wire wrapping. Here is the opportunity and challenge for developing a reliable, durable, serviceable and cost-effective structural health monitoring system for assessing the safe carrying capacity of the main cables of the nation's aging suspension bridges.

Further Challenges

Scour damage to bridges is a worldwide problem. There is a need for real-time monitoring of the depth of scour in a bridge before and after a flood. The scour monitoring system can help bridge owners prepare plan of actions against scour damage. The challenge is to develop a scour monitoring system with sensors that are cost-effective, reliable and overcome the environmental effects.

Partial or complete collapse of a bridge does occur in rare occasion. When that happens, there is a need of structural monitoring or sensing system that can trigger warnings to approaching traffic to stop from entering the bridge. There is a need for simple, low-maintenance and reliable sensing systems to sound an alarm, turn on flashing lights or activate barrier gates to keep vehicles from driving into a partially or completely collapsed bridge.

Concluding Remarks

Field instrumentation programs have consistently and reliably collected valuable data regarding the condition, stress and strain, temperature gradients, deflection, creep and shrinkage of bridges. The data have been used to verify design assumptions, improve design, construction and operation, assess short-term and long-term performance of structures, and support bridge management systems.

Many new and existing major bridges can benefit from a well-conceived instrumentation program and well-designed structural health monitoring system for remote and continuous condition assessment. Continuous structural health monitoring, remote data acquisition, and periodic inspection and testing can save labor cost in inspection, reduce maintenance cost, and improve safety and reliability of major bridges.

There are challenges and opportunities for integrating research, training and practice to successfully advance the state-of-the-knowledge in structural health monitoring and sensor technologies for improving safety and reliability of highway bridges.

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