Long Term Bridge Monitoring to Support Bridge Technology Innovations

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Abstract

The state of the practice of bridge inspection and bridge management in the United States is briefly discussed. This practice has many limitations. The most significant limitation is that the data collected is based solely upon visual inspection, augmented with limited mechanical methods such as hammer sounding or prying. Visual inspection is highly variable, subjective and inherently unable to detect invisible deterioration, damage or distress. There are many types of damage and deterioration that need to be detected and measured that are beyond the capabilities of visual inspection. Bridge performance also needs to be measured. The FHWA and many others have conducted research and development in technologies that can help meet these needs. Several examples illustrating the application of this technology for the long term monitoring of bridges are described. While the summary is not comprehensive it demonstrates that technology exists to meet the needs identified. Future directions and further application of bridge monitoring technology are also briefly discussed.

Introduction

In the United States as of 2002, XX% of the US bridges were structurally deficient or functionally obsolete, as reported by the Federal Highway Administration (FHWA). This assessment of the structural and functional condition of the nation's highway bridges is based upon data reported to the FHWA by bridge owners across the country and maintained by FHWA in the National Bridge Inventory (NBI) database. Bridge owners have been reporting this data to FHWA since 1972 when FHWA established the National Bridge Inspection Program. The National Bridge Inspection Program was established in response to the collapse of the "Silver" Bridge in 1967 and the program focuses on the safety of highway bridges. The bridge inspection program requires that qualified inspectors inspect highway bridges at least once every two years and that the results are reported to the FHWA. This data is used to report the condition of the nation's highway bridges to Congress every two years and to administer the Highway Bridge Replacement and Rehabilitation Program (HBRRP). Last year the HBRRP provided more than $3.5 billion to replace or rehabilitate deficient bridges.

Background and Need

The type of data collected and reported for the National Bridge Inspection Program is adequate for managing and administering a national program aimed at eliminating deficient bridges but it is inadequate for some other purposes. The data is not detailed enough to support bridge maintenance programs. The NBI does not record the condition of paint systems, joints or provide information on local damage or deterioration. The data

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is too general, subjective and qualitative to be used to develop plans and estimates for repair or rehabilitation work. For example, the NBI records condition data for the entire supersructure of the bridge with a subjective rating ranging from excellent to failed as a integer from 9 to 0. In response to these limitations, many states augment the NBI by collecting additional information or use a different, more refined, approach to collection and recording of bridge condition data. The more refined approach characterizes a bridge as a collection of elements, such as girders and piers, and records quantitative condition data on each element. Standardized elements have been defined for highway bridges and automated methods are used to translate the element level data into the NBI data required by the FHWA.

Although the element level inspections provide more detailed and useful information for network level bridge management, especially at the state and local level, the information collected is still very limited in several respects. The most significant limitation is that the data collected is based solely upon visual inspection, augmented with limited mechanical methods such as hammer sounding or prying. Visual inspection is highly variable. The FHWA's Nondestructive Evaluation Validation Center recently completed the first comprehensive and quantitative study of the reliability of visual inspection and the NBI condition rating system. The results of that study indicate that a range of condition ratings of 3 or 4 numerical values can be expected routinely with different inspectors reporting results for same bridge in the same condition. This variability is in addition to the inherent limitation of visual inspection to fail to detect invisible deterioration, damage or distress. There are many types of damage and deterioration that need to be detected and measured in order to determine if a bridge is safe or if repairs are required. Many of these are difficult or impossible to detect visually unless the damage or deterioration is severe. For example, it is not possible to look at a bridge and determine if it has been overloaded or if it has settled unless the damage is so severe as to cause the lines of the bridge to change. Frozen bearings, corrosion and fatigue damage can exist with no visible indications. Routine visits by bridge inspectors also do not collect information on the operational performance of bridges such as congestion, accident history or fatigue of structural members.

The implementations of customer driven quality improvement programs or asset management supported by true engineering economic analysis are immediately hindered by the lack of necessary information. We currently guess at average daily traffic values. We do not know the size, number and weight of the trucks our bridges carry. The actual stresses, strains, deflections and displacements the bridges experience are unknown. There is a need to more accurately quantify the operational performance of highway bridges. The performance measures, which are most immediate to the traveling public, are concerned with congestion, accidents, and service. These same performance measures can help to quantify the value of bridge as assets in terms of user costs and benefits. These need to be measured. It is a basic tenet of modern management theory and practice that if you can't measure it you can't manage it.

This same information is also needed to implement true life cycle cost analysis or performance based specifications. FHWA, like all federal agencies in the United States, is directed by executive order to consider life cycle cost for major projects. However, the life cycle of bridges has not been defined. The deterioration rates of different materials, structural systems in different environments of loading and climate have not been measured. There is a specific need to integrate quantitative performance measures into the management systems for the highway infrastructure. Some of the measurement and detection needs currently not met by our standard practice of visual inspections are tabulated below.

Damage	Detection	Operation	Service
Impact Overload Scour Seismic Fatigue Settlement Movement Lack of Movement	Corrosion Fatigue Water absorption Loss of prestress force Unintended structural behavior	Traffic counts Weight of trucks Maximum stress Stress cycles Deflection Displacement	Congestion Accidents Reduced traffic capacity Performance measures

These measurement and detection needs exist at many levels and can serve many purposes.

Summary of recent research to respond to this need

The FHWA and others have conducted research and development in technologies that can help meet these needs. Several examples illustrating the application of this technology to monitor and measure bridges are described in this article. This summary is not comprehensive. It is intended to demonstrate that technology exists to meet the needs identified and to stimulate interest in application and further development of innovative technologies to monitor the long term performance of bridges.

Global health monitoring has evolved to the point where a number of large systems have been implemented on large bridges in many parts of the world. One such system has been installed and is operating on the Commodore Barry Bridge over the Delaware River in Pennsylvania. Although promising, the full potential of this technology has not been realized or defined and significant issues remain to be researched. The information technology component is one such issue. In spite of these limitations, the information these types of systems already provide has proven to be very useful to the owners of the bridges where they have been installed. One example of the type of information these systems provide is the detection and quantification of unexpected bending of tension elements due to differential solar radiation exposure

Non-intrusive load capacity measurement is a pressing need. Substandard load capacity is the single most frequent reason for a bridge to be classified as structurally deficient in the United States. One technology, which the FHWA has adapted to meet this need, is a laser measurement system for bridge load testing. The system uses a computer-controlled mirror to aim an invisible, eye safe, infrared laser beam at a point on the bridge. The laser measures the range to the point on the bridge and reports the three-dimensional spherical coordinates of that point, relative to the local origin set by the laser system. The system can repeat this measurement at different points on the bridge hundreds of times in a few minutes. The system has a measurement range of about 30 meters and an accuracy, resolution and repeatability of a fraction of a millimeter. The system does not require special targets and works well on ordinary steel, concrete and timber surfaces. Using this system it is possible to rapidly measure the three dimensional deflection response of a bridge to a heavy truck. The system can also be used to rapidly and quantitatively measure if any part of the bridge has moved since the last time the bridge was scanned, with an accuracy, precision and repeatability of a fraction of a millimeter. This system is also capable of early detection of subsidence or loss of prestress. This example demonstrates that long-term monitoring does not always require a dedicated and permanently installed monitoring system for each bridge.

The detection and measurement of fatigue and vulnerability to fracture continue to be a pressing need for the hundreds of thousands of steel bridge in the nation. The National Bridge Inspection Program was initiated in 1971 in response to a bridge failure caused by a brittle fracture. The brittle fracture of a welded plate girder resulted in complete bridge failure in Milwaukee, Wisconsin in December 2001 demonstrates that this vulnerability still exists. This bridge had been visually inspected a few weeks prior to the failure and there was no visual indication of the impending failure. Subsequent forensic analysis has confirmed vulnerability to sudden brittle fracture due to welding practices and details that produced high residual stress and triaxial restraint. Visual inspection alone is not capable of detecting or quantifying these conditions.

Although fatigue was not a contributing factor to the brittle fracture in Milwaukee, it continues to be a major problem on aging steel bridges. The measurement and characterization of the random, variable amplitude cyclic stress that brides are subjected to is an essential measure need. Technology has been developed to help manage fatigue. Numerous examples of portable, battery powered, data acquisition systems now exist. These systems offer very high dynamic range, very low noise and adaptive digital spread spectrum radio network telemetry capabilities. Using this technology it is possible to rapidly instrument a bridge at fatigue prone or critical details and measure what happens under traffic and wind loading.

The wireless network technology can quantify the fatigue-loading regime at a fatigue prone detail but it cannot measure if a fatigue crack is growing under that load. These cracks do not grow continuously but advance in microscopic steps. The advance of the crack front is accompanied by release of potential energy that produce ultrasonic stress waves. This is similar in concept to the release of energy associated with an earthquake but on a microscopic scale. The stress waves can be detected using special sensors tuned for this purpose. The method is call acoustic emission (AE) and it has been used for many years in the energy and process industries. However, prior AE instruments were not practical for long term monitoring of fatigue cracks on highway bridges. The lack of electrical power on most bridges, the difficulty in accessing the details on the bridge, the very high background noise environment, and perhaps most importantly, the random loadings with rare high load events driving crack extension all worked against successful application of AE on bridges. A new battery powered, eight channel AE instrument specifically designed for the bridge monitoring need was developed in cooperation with the FHWA's NDE Validation Center. This system can also telemetry information via modem or radio link.

While the two prior systems are very useful, they are expensive (10's of $K), and they are still limited by battery power to relatively short term monitoring. A totally passive and inexpensive fatigue measurement sensor has also been developed to meet the need for very long duration fatigue measurement. This sensor is attached to the bridge and strains along with the bridge. The sensor is based upon a special passive strain amplification design and two, pre-cracked, coupons with integral analog crack length gages. The two coupons are fabricated with materials that have different crack growth properties. These manufactured fatigue cracks grow in response to the random variable amplitude strains on the bridge. By periodically measuring the crack lengths in the two coupons with a special reader, the effective number of cycles at a predetermined stress range can be quantified. This sensor can be likened to a fatigue odometer. Using this technology, it is possible to measure how the fatigue life of a highway bridge is being consumed.

Another example of new technology applied to help collect essential performance information is the development of a smart bridge bearing. Non-operating bearings, and the tremendous stresses that result, are a common factor in bridge failures. They are also a very common maintenance requirement. In addition, the distribution of live and dead loads to the bearings through the structural systems of the bridges is a possible diagnostic and damage detection capability that this technology will enable. If there is a significant change in stiffness of a structural member due to fracture, impact or other reason, it is likely that the distribution of the loads to the bearings will change. A smart bearing could "feel" the damage in the bridge. The enabling technologies are sophisticated but the concept is simple. The intelligence for the bearing is provided by multi-axis fiber optic strain sensors, capable of measuring both vertical and shear strains, that have been integrated into a composite panel. The panel can be integrated into the bearing. The panel could be laminated between the neoprene bearing pads commonly used on highway bridges and can measure the vertical and lateral forces transmitted from/to the bridge.

There are an almost unlimited number of possible applications for sensing and measurement technologies for highway bridges. The technology does not need to be expensive and sophisticated. Another example concerns a wing wall that was moving due to excessive hydrostatic pressure. Remedial measures were taken and the owner wanted to monitor the movement of the wall relative to the abutment. The environment is severe and an inexpensive but reliable sensor was needed. The NDE Validation Center conceived, designed, built and installed an inexpensive displacement sensor in a few weeks. The sensor has been monitoring the wall for three years and has proven that the remedial measures were effective. Over the years FHWA has developed a versatile modular instrumentation concept that facilitates rapid prototyping and deployment of specialized sensing applications. This lends itself to specialized and critical component monitoring where unique features or requirements can be readily accommodated.

An illustration of this versatility is another application on a fracture critical hanger on a pin and hanger detail. The hanger is being monitored using the same modular system that was used to monitor the wing wall. The sensors in use are welded resistive foil strain gages. The hanger is supposed to freely rotate about the pin as the bridge expands and contracts due to temperature changes. The hanger transfers vertical load and is designed as a tension element. If the pin and hanger interface corrodes, a very common occurrence, the friction between the pin and hanger can cause significant bending in the hanger. In addition, the sudden slippage of the pin hanger interface can result in tremendous dynamic stress. The fatigue and possible fracture consequences of this phenomenon were not considered in the design of these details. The response of the hanger was measured during a load test. In addition to bending in the expected direction, unexpectedly transverse bending of the hanger was also measured. Detection and measurement of unintended structural behavior is a major benefit of this type of monitoring.

Steel bridges are not the only bridges vulnerable to sudden failure and collapse. A number of prestressed concrete bridges have collapsed due to undetected corrosion of tendons. One recent example was the collapse of a pedestrian bridge in the summer of 2000 after only seven years of service. The failure was caused by corrosion and failure of the high strength steel tendons that helped support the bridge. The localized corrosion of the tendons was attributed to calcium chloride unexpectedly found its way into the grout used to fill in holes created during the fabrication of the precast girders. The source of the calcium chloride is still unknown but undetected corrosion of prestressing steel has led to the failure of a number of bridges.

When such a wire breaks there is a sudden and significant release of potential energy. Such wire breaks generate stress waves which propagate outward from the structure and which can be detected by sensors, such as accelerometers. By analyzing the arrival times of the signals, it is not only possible to detect the wire breaks but to also locate where the break occurred. The method is similar to a network of seismometers to locate and quantify earthquakes. Such systems are commercially available and are installed on a number of bridges.

Detecting wire breaks is certainly useful, but a potentially more useful technology is the detection and quantification of corrosion before failure occurs. The most common cause of corrosion in highway bridges is the salt placed on the bridges to keep the bridge open during winter storms. The corrosion of structural steel is usually visible. However, the corrosion of reinforcing and prestressing steel in concrete structures is not visible until significant damage has occurred. A new device, developed in cooperation with the FHWA, is an embeddable corrosion sensor. The sensor is designed to be placed inside of concrete structures and to measure corrosion rate, concrete conductivity and chloride ion concentration. The instrument is small and eventually will be powered and interrogated by wireless radio frequency methods. If the size and cost can be reduced, hundreds or thousands of these sensors could be economically embedded in a bridge to provide quantitative information about the state of corrosion well before severe damage has occurred.

Future direction

This paper has documented that much of the technology to monitor bridges is already available. This technology can provide the quantitative and objective information necessary to move beyond our current subjectively based bridge management systems. There is a need to evolve to a more quantitatively driven management approach. This need has been identified and emphasized by the United States National Academies of Science and Engineering.

The Academies have held several workshops where stakeholders from the public, private and academic communities have been bought together to identify the most pressing and highest priority research needs for dealing with an aging highway infrastructure. The result is a National Infrastructure Renewal Research Agenda. The need for reliable and timely data and information is recognized as critical to the efficient management of the nation's highways. The agenda also identifies the need for much improved decision support tools as well as to integrate probabilistic life-cycle analysis into infrastructure management. The need to value infrastructure assets and quantify the benefits of the system is also specifically mentioned. Quantitative, relevant and useful measures of performance are emphasized. Long term bridge monitoring addresses all of these needs.

The safety assurance of highway structures for extreme events would also be greatly enhanced by short and long term monitoring and measurement of the loading and structural response during extreme events. As already demonstrated, assessment and management of bridges and other structures demand the quantitative measurements provided by the monitoring of structures. It is not possible to develop enhanced specifications without long-term observation and quantitative measurement of structural behavior and deterioration. Finally, the basic information necessary to support the automation of design, construction and maintenance, identified as a national priority for infrastructure research and development must be provided by sensing and measurement technology.

For all of the reasons outlined, the Federal Highway Administration is proposing to begin a Long Term Bridge Performance Program. This program would be modeled after the Long Term Pavement Performance Program. The program will include detailed inspections and periodic evaluations conducted on a representative sample (in the thousands) of bridges to monitor and measure their performance over an extended period of time (at least 20 years). It is anticipated that the resulting database will provide high quality, quantitative, performance data for highway bridges to support improved designs, improved predictive models, and better bridge management systems. A second component of this long-term bridge performance program will be a subset of instrumented bridges (in the hundreds) that can provide continuous long-term structural bridge performance data. The third component of the program will include detailed forensic autopsies of several hundred bridges each year (out of the several thousand bridges that are decommissioned each year). These forensic autopsies could also be conducted for bridges that fail unexpectedly. The intent is to collect valuable performance data on corrosion, overloads, alkali-silicate reaction, and all other deterioration processes from these bridges.

The long-term bridge performance program will be designed to accommodate and develop both general trend information, and information specific to a variety of bridge types, locations, and environmental exposures.

Closure

To summarize, long term bridge monitoring can provide quantitative data for network and bridge level management. This could contribute to a much greater level of reliability and utility of data necessary for asset management. Bridge safety, especially during extreme events, is enhanced by measurement and monitoring of critical bridge components. Enhanced safety, reliability and efficient maintenance can result from improved incident detection and assessment. Global bridge health and performance assessment in support of asset management and enhanced specifications must be, and arguably can only be, accomplished using quantitative measurement methods. Subjective assessment simply is not adequate to meet these needs.