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STATE OF THE ART REVIEW ON BRIDGES STRUCTURAL HEALTH MONITORING (CONCEPTS)

Ayman H. Khalil [1], Khaled M. Heiza[2], Omar A. El Nawawy[3]

[1,3] Professor of RC structures, Faculty of engineering, Ain Shams University, Egypt.
[2]Professor of RC Structures, Vice Dean, Faculty of Engineering, Menofia University, Egypt.

Abstract

Due to a wide variety of unforeseen conditions and circumstances, it will never be possible or practical to design or build a bridge that has a zero percent probability of failure. Structural aging, environmental conditions, and reuse are examples of circumstances that could affect the reliability and the life of a bridge. There are needs of periodic inspections to detect deterioration resulting from normal operation and environmental attack or inspections following extreme events, such as strong-motion earthquakes or hurricanes. To quantify these system performance measures requires some means to monitor and evaluate the integrity of bridges while in service. Due to several bridge failures, considerable advances have been achieved in research on structural health monitoring and nondestructive damage detection in the recent years.

Introduction

In general, a structural health monitoring system has the potential to provide both damage detection and condition assessment of a bridge. Assessing the structural condition without removing the individual structural components is known as nondestructive evaluation (nondestructive evaluation) or nondestructive inspection. Most nondestructive evaluation techniques have been used successfully to detect location of certain elements, cracks or weld defects, corrosion/erosion, and so on. The Federal Highway Administration (FHWA) sponsored a large program of research and development in new technologies for the nondestructive evaluation of highway bridges. One of the two main objectives of the program is to develop new tools and techniques to solve specific problems. The other is to develop technologies for the quantitative assessment of the condition of bridges in support of bridge management and to investigate how best to incorporate quantitative condition information into bridge management systems. They hoped to develop technologies to quickly, efficiently, and quantitatively measure global bridge parameters, such as flexibility and load-carrying capacity. Obviously, a combination of several nondestructive evaluation techniques may be used to help assess the condition of the system. They are very important to obtain the database for the bridge evaluation.

Structural health monitoring is also an active area of research in aerospace engineering, but there are significant differences among the aerospace engineering, mechanical engineering, and civil engineering in practice. For example, because bridges, as well as most civil engineering structures, are large in size, and have quite low natural frequencies and vibration levels, at low amplitudes, the dynamic responses of bridge structures are substantially affected by the non-structural components, and changes in these components can easily to be confused with structural damage. Moreover, the level of modeling uncertainties in reinforced concrete bridges can be much greater than in a single beam or a space truss. All these give the damage assessment of bridges a still challenging task for bridge engineers. In the following sections, the historical development of health monitoring and bridge inspection techniques is outlined. In addition, functional requirements of health monitoring systems are presented. Finally, challenges facing bridge engineers in applying health monitoring tools are detailed.

Historical development

The need to carefully monitor the condition of bridges became apparent after the collapse of the Silver Bridge between Point Pleasant, West Virginia, and Gallipolis Ohio in 1967 [1]. The loss of 47 lives due to the instantaneous fracture of an eye-bar caused great concern about the safety of bridges. At the time, there was no systematic maintenance program in place to monitor the condition of the bridge population. In fact, the exact number of bridges that were standing in the United States was not even known at that time.

To address this problem, the Federal Highway Act of 1968 created the National Bridge Inspection Program (NBIP), which ordered state agencies to catalogue and track the condition of bridges on principal highways. Specifically, the program set standards for state highway departments to conduct safety inspections, establish the maximum time lapses between inspections and determine the qualifications of those responsible for carrying out the inspections. The data collected as part of the NBIP is submitted after every inspection period and maintained by the FHWA in the National Bridge Inventory (NBI) database.

The Federal Highway Act of 1970 used the information contained in the NBI as the basis for funding for the Special Bridge Replacement Program (SBRP). This program provided federal funding to states in order to replace bridges that were in the most danger of failure. Under this program, bridges were classified under two different schemes. First, the condition of the bridge is rated according to one of three categories: nondeficient, structurally deficient, or obsolete. A bridge that is classified as nondeficient if it is in satisfactory condition and adequately serves the specifications for which it was designed. A structurally deficient bridge has either been closed because of structural inadequacy or in immediate need of rehabilitation in order to remain open. A functionally obsolete bridge is inadequate due to its geometry or the traffic on the road it serves, although the bridge may be structurally sound. Second, a sufficiency rating is calculated based upon the NBI data items related to its structural condition, functional obsolescence and essentiality for public use. If the sufficiency rating for a bridge was less than 50, then the bridge was eligible for SBRP funds.

To provide further guidance with the NBIP, the FHWA published the Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges. Specifically, the Coding Guide outlined the specific elements that are required to be inspected on each bridge and guidelines regarding the inspection procedures. The Coding Guide has been revised in 1972, 1979 and most recently in 1988.

Later, the Surface Transportation Assistance Act of 1978 (STAA) changed the basis for eligibility of bridges for federal funding. Under this act, the NBIP was expanded to include bridges on all public roads, not just principal highways. The SBRP was replaced by the Highway Bridge Replacement and Rehabilitation Program (HBRRP), which provided funding for bridge rehabilitation in addition to replacement projects. The intent of this change was to begin repairing bridges before they deteriorated into a critical state. If the sufficiency rating for a bridge was less than 80, but more than 50, then the bridge is eligible for rehabilitation funding. The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) further recognized the need for the preventative maintenance of infrastructure to minimize problems before they occur. This legislation mandated that every state department of transportation and metropolitan planning organization implement six different management systems that maximize resource allocation for maintenance planning. Specifically, the objective of the BMS is to establish the most cost effective maintenance schedule for a network of bridges.

ISTEA originally established a deadline in 1995 that all states must implement a BMS. However, due to delays in the rulemaking process, the notice of proposed rulemaking (NPRM) was not issued until March 1993 and the interim final rule until December 1993. Under the interim final rule, states had a work plan to implement a BMS in place as of 1994, with the system fully operational as of 1998. The FHWA is responsible for monitoring the compliance of the schedule.

Functional requirements of health monitoring

Structural health monitoring research can be categorized into the following four levels: (I) detecting the existence of damage, (II) finding the location of damage, (III) estimating the extent of damage, and (IV) predicting the remaining fatigue life. The performance of tasks of Level (III) requires refined structural models and analyses, local physical examination, and/or traditional nondestructive evaluation techniques. To perform tasks of Level (IV) requires material constitutive information on a local level, materials aging studies, damage mechanics, and high-performance computing.

With the above in mind, monitoring may be seen as the periodic or continuous observation and recording of information on the conditions or performance of bridges. Its main purpose is to detect and follow the initiation and progress of deterioration, should it occur. Periodic observations are carried out at discrete intervals. Within this category fall both experimental measurements and visual inspections. Visual inspections give a qualitative estimation of the conditions of bridges, by identifying the level and extent of deterioration. Their frequency varies in function of the level of damage ascertained (from a few months to a few years). Experimental measurements (both periodic and continuous), as part of an on-site investigation, are a necessary input for the subsequent assessment of bridge conditions. Their results are also used to calibrate and validate the predictive models of deterioration. In particular they are used to: (1) determine the extent of damage; (2) determine the strength of concrete, steel, etc (for instance from laboratory testing); (3) determine the condition of concrete, depth of carbonation, chloride penetration, (4) determine corrosion of steel components, (5) determine loss/rupture of pre-stressing, and (6) determine the load-carrying capacity (on-site load testing).

Measuring techniques are only one aspect of a monitoring program, as this one must be tailored to the different monitoring objectives, to the bridge type and to the bridge life cycle situation. For instance, in the service life of concrete bridges, a monitoring objective may be detection of corrosion. A number of different techniques are available, from portable equipment to sensors permanently installed on the structure. For this last category of continuous monitoring, in particular with remote systems, their convenience depends on the type of construction, level of damage observed and foreseeable consequences in terms of costs of maintenance and costs for the collectivity. Applications of remote systems may be foreseen for: (1) prototype structures or structures of strategic importance; (2) large structures; (3) structures in particularly aggressive environment; (4) parts of the structures difficult to access; (5) individual structures representative of a population of similar bridges; (6) structures where damage has been detected and monitoring is used to gather further information before repairs are carried out; (7) testing the efficiency of repairs when this type of repair is typical for a large number of structures (i.e. waterproofing).

Assessment may be loosely defined as the estimation of the bridge conditions. It may be the result of visual observations with all the limits of this practice; in this case, no complex computations are required. Or else, it may be the result of periodic (on site local testing) or continuous monitoring. In this case, testing results are linked to the definition of alarm thresholds or limit values for the monitored parameters, which might required a deeper knowledge of the structural behavior (displacements smaller than an acceptable value) or of the characteristics of the bridge (acceptable chloride content).

Finally bridge assessment may consist of determining the load carrying capacity in relation to specific loadings. It may be necessary or advisable when: (1) loads are modified from the original design loads; (2) the geometry is changed (number of lanes or the deck is widened); (3) a structure has been damaged; (4) repairs or alterations have been carried out which modify the structural performance; and (5) exceptional loadings are present.

According to AASHTO, nondestructive testing shall determine properties of bridge elements or materials. Further, it indicates specific aspects of durability, deterioration or damage. Test can be collected in four categories: tests for protection of elements, tests for vulnerability, tests for attack, and tests for damage. Protected elements resist aggressive agents. Protection is provided by features such as paint, sealers or membranes, and may be provided by superior durability of materials or design details. If elements are not protected, then they are exposed. Elements are vulnerable when damage mechanisms such as corrosion or cracking can begin. Vulnerability is a lack of protection combined with environmental conditions that make the occurrence of a damage mechanism likely. Elements are attacked when a damage mechanism is active. Elements are damaged when there are detectable losses or cracks. Tests detect transitions among condition states. These condition states are generic. Condition states are given explicit meaning for specific elements and types of deterioration [2].

Challenges to bridge inspection and health monitoring

Before health monitoring can be implemented in a systematic manner to provide a more quantitative assessment of the condition of critical elements of bridges, major barriers must be overcome. In the following sections, some of the problems that have to be dealt with if health monitoring is to be effectively applied to bridges. Challenges are divided into two groups: (1) bridge related problems, and (2) technology related problems. Problems specific to bridges include: accessibility, environment and operator skills. Those related to technology are related to advances in the monitoring technology. Both types are explained in the following sections [3].

ACCESSIBILITY

Bridges are large civil structures and usually traverse both difficult terrain and water. Their height can range from 5.00 meters to hundred meters or more. Common practice, particularly in older structures was to provide little if any access to critical elements of the bridge that need to be examined. The inspector in these cases is forced to scale high steel or use devices such as a man-lift to gain access. Access difficulties can place the inspector in life threatening situations. These conditions both contribute to very low productivity, and tend to reduce the reliability of the tests being performed. It is difficult for a trained inspector to apply careful judgment and sophisticated expertise to performance of the test, when he thinks that he may be about to make an unplanned attempt at a new high diving record [4].

Bridges that have no provisions for access (i.e. ladders and catwalks) are typically inspected using various forms of the man-lift Fig. 1. This approach is quite effective for providing access to accomplish close visual inspection and some ultrasonic testing or surface nondestructive evaluation but space is quite limited in the "bucket" so that large pieces of equipment would be impractical. This type of access equipment typically provides power for equipment that needs it. The use of this approach requires closing of one traffic lane on the bridge and necessary associated traffic control. Furthermore, the presence of heavy truck traffic causes the bridge to move and the movement is amplified by the lever arm of the reach-all. The motion is easily sufficient to induce motion sickness in most people, which further reduces productivity. Even in structures that have ladders and catwalks, accessibility to the test site can be a challenge. Fig. 2. shows an overall view of a typical deck truss bridge with an overall length of approximately 2000 meters. It was built in 1960 and the main truss members are fabricated from high strength steel. Cover plates were fillet welded to the bottom H section at the point of connection with the vertical truss member. Cracks developed in these welds, which were subsequently ground out, and bolted doubler plates were added for redundancy. This structure requires periodic monitoring because of the fracture critical nature of the connections in question. Access to the truss is gained by means of a ladder from a road passing beneath the bridge. This ladder connects with a 320-meter foot catwalk to the end of the first truss span at which point a descent of a 16-meter ladder leads to the truss catwalk.

Figure 1. Mobile man-lift device.

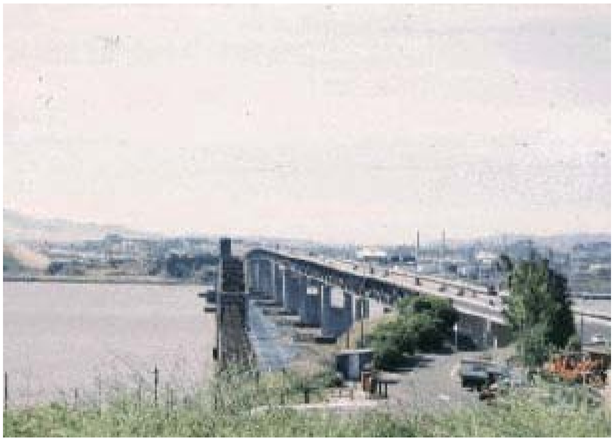

Figure 2. View of a 2000-meter truss bridge.

A view of this catwalk is shown in Fig. 3. This catwalk extends the length of the truss portion of the structure and is the path over which any inspection equipment must be carried to reach the critical truss members. This bridge is an excellent example of what can be done to provide access to the critical portions of a structure. This approach is unfortunately, very rare. Even with an approach like that, one can clearly see the advantages to be gained by developing small or remote sensor. A box weighing 10 pounds or more will become a serious problem if it has to be carried and lifted over the range of distances that are encountered on this type of structure.

Figure 3. A view of the central catwalk.

ENVIRONMENT

The bridge environment provides its own set of challenges to the application of nondestructive evaluation and health monitoring technologies. Besides the typical hazards provided by the local weather of temperature extremes, precipitation, and winds, the bridge itself adds the challenge of vibration and noise. Any test procedure that requires either partial or total closure of the bridge to traffic causes major problems that include: (1) added cost for traffic control, (2) restricted working hours (i.e. late at night), and (3) scheduling problems and delays. The bridge surfaces that must be inspected will typically be covered with rust and dirt. Fig. 4 shows example of the typical surface conditions encountered on a bridge. The figure shows a close-up of a typical pin and hanger detail. The pin and hanger is located in an expansion joint area and is subject to run-off of water from the deck that has dissolved deicing salts. This detail is a major inspection problem in parts of the country where heavy use of deicing salts are encountered. Paint thickness on older bridges may become excessive and severely hamper the application of many nondestructive evaluation methods. Lead based paint, which is common on older structures, must be dealt with carefully. If paint must be removed, proper safety procedures must be followed to prevent damage to the environment and potential health problems for the inspector. The latter becomes a serious consideration when the inspection must be accomplished in confined spaces such as inside box girders.

Figure 4. Close-up of pin and hanger detail.

OPERATOR SKILLS

Common practice has been to reduce the work force to comply with budget cutting measures. In the United States, many experienced bridge inspection personnel have been given early retirement and either have not been replaced, or have been replaced by entry level personnel with minimal experience and training. This steadily worsening situation places a great deal of emphasis on the need for easy to use equipment that produces clear unambiguous results. This situation also points out the growing need for application of automated systems to the bridge-monitoring problem. This latter need will become increasingly acute as expertise is continued to be lost from this field.

Sensing, data acquisition, transmission and processing

Research in this particular field has been partitioned, often focusing on just one sensing technology such as fiber optics, acoustics, etc. In large-scale applications, many different sensor and data acquisition systems have to be integrated and data flow has to be synchronized. Sensing systems comprised of mixed sensor and data acquisition suites need to be calibrated.

In long-term field measurements it is essential to fuse the output from a mix of sensors with different operating principles and attributes. For example, strain measurements by resistive and vibrating wire gages, streaming video, wind-speed, temperatures, displacements and accelerations all need to be measured, synchronized and integrated. Each type of data mode and the corresponding sensor system with its signal conditioning and data acquisition elements will offer different strengths and weaknesses, complementing each other. More importantly, reliable structural identification requires measuring the incident inputs and a mix of global and local responses, hence the need for diversity and redundancy in measurement.

Field observation, measurement and experimental technologies

These are classified into: (a) monitoring of geometry by surveying, close-range photogrammetry, and satellite-based images and sensing; (b) controlled static or dynamic testing with known inputs; (c) localized testing for material characterization by sampling as well as in-situ, nondestructive testing; and, (d) continuous monitoring. Here it is important to note that meaningful structural identification and health monitoring application scenarios require the integration of many of these technologies. During the design and execution of any experiment, it is critical to design the sensors, data acquisition, data processing and archiving or warehousing in conjunction with the design of information fusion, presentation/display, and interpretation. Measurement and data repeatability or variability will depend on many parameters. Some of these parameters include the design and execution quality of the experiment, the quality of the data measurement, the physical and stochastic characteristics of the phenomena being measured, the physical principles employed by the sensors and their installation characteristics, level of uncertainties inherit in observation and measurement recognized.

Analytical and computational techniques for simulation

Systems identification and characterization is an essential foundation for health monitoring, requiring an optimum integration of experiment, observations, conceptualization, and analytical modeling and parameter identification for reliable simulations. These issues are: (a) parameter identification, updating and validation to yield models that are computationally tractable, and appropriately validated as credible design and decision tools; (b) material modeling to represent a broad range of conditions and to address multi-constituent, multi-scale and multi-physics issues, and the capability to model interfaces between components; (c) integration of heterogeneous models to assure simulation of civil and mechanical systems; (d) representation and propagation of uncertainty in a complete and consistent manner from model parameters to a probabilistic estimate of performance; and (e) model updating and validation using techniques (e.g., sensitivity and optimization) to adjust parameters and sizes so that the model matches observed performance.

Information technology

Within the spectrum of critical technologies that need to be integrated for health monitoring, one that is nearly untouched is information. Since information technology itself is an emerging field, integrating its potential applications health monitoring and management are yet pending. Some of the challenges include: (a) integrative information systems that will take advantage of the existing data. Such material, if it exists at all, is typically in disconnected and non-relational databases in many different forms. There may be significant variation in the confidence interval and objectivity of legacy data representing the condition and performance of various asset classes. Information systems should also permit the management of large amounts of new objective data and information retrieved from relevant components throughout the critical locations of an infrastructure system.

APPLICATION SCENARIOS OF HEALTH MONITORING

The application scenarios may be classified as: (a) implementations to major bridges, (b) implementations to large number of existing common short and medium span bridges, and (c) integrated structural and operational health and security monitoring [5].

APPLICATIONS TO NEW VERSUS EXISTING BRIDGES

The distinction between implementation to new as opposed to existing bridges is that the former provides an opportunity for measuring: (a) The precise geometry of the as -constructed system before commissioning; (b) Material properties (chemical and physical properties of aggregate, cement and any additives, mix properties, curing conditions, strains and temperatures, in-situ properties such as porosity following curing, initial micro-cracking and any cracking, etc); (c) The flexibility coefficients, frequencies, mode shapes, damping coefficients; (d) The transient and any trapped intrinsic forces at the critical regions of a bridge system during its fabrication, erection and construction.

Monitoring of the material and structural properties in the course of construction by objective and effective measurement technologies and their thorough documentation, together with the environmental conditions affecting the construction, would serve as an excellent “baseline” for making future assessments and management decisions along the lifecycle of a bridge.

In the case of health monitoring of existing bridges, instrumentation and measurement opportunities are somewhat more limited and certain information about the initial forces and the previous loading history cannot be reliably measured. However, in spite of these limitations it is still possible to collect a wealth of data and information that offers a great payoff potential for enhancing any aspect of the performance and effective management of the bridge.

APPLICATIONS TO POPULATIONS OF COMMON BRIDGES

Applications of advanced technology to common bridges are currently driven by concerns over their structural condition and performance, and often when a performance problem is identified during a visual inspection. For example, there is an increasing interest in the use of load testing for load capacity rating of posted bridges. However, there is also remaining concerns that applications of load testing as per the new AASHTO Manual may fall short of a complete understanding of a bridge's load resisting mechanisms and cannot assure that the load capacity estimated by the test will be maintained over several years following a test.

Further, before increasing the rating of a bridge, sufficient redundancy for system reliability should be verified and undesirable failure modes should be ruled out. These require reliable analytical modeling and simulations. All of these concerns point to the need to conduct load testing as a component of a comprehensive health-monitoring program and not just as an isolated application. In addition to concerns over insufficient load rating typically leading to posting, there are other incentives for health monitoring applications to existing common bridges as a management strategy discussed in the following.

FLEET HEALTH MONITORING OF LARGE BRIDGE POPULATIONS

Experienced bridge engineers inspect and make decisions about condition and maintenance of a bridge by taking advantage of the heuristics they accumulate from past efforts on similar bridges. The science of statistical sampling, applied in conjunction with structural identification and health monitoring, would permit to group bridges into populations whose critical loading and behaviors, i.e. the mechanisms that control their serviceability, load capacity and failure modes, may be expressed in terms of only a small number of statistically independent parameters. In this manner, a large population of several thousands of reinforced concrete deck on steel-girders bridges, with similar geometry, materials, design and construction history and behavior similarities, would be categorized into groups represented by statistical samples for their in-depth evaluation and analyses. For example, the reinforced concrete deck-on-steel girder bridges may be classified into a number of groups that have comparable system-reliability and load capacity rating, governed by only a very limited number of design, construction, location and maintenance-related parameters. Such an approach may permit an authority with an inventory of ten-thousand steel stringer bridges to classify these into a limited number of fleets and represent each fleet by a statistical sample depending on the statistically independent parameters that govern the load capacity rating and other concerns that are taken into consideration for bridge management. The sample bridges would be rigorously inspected and tested by expert bridge engineers in a few years, creating a sufficient amount of data and insight for their management in the decades to come. In this manner, it is possible to take maximum advantage of the bridge-type specific heuristics that has been accumulated in the few, experienced engineer-experts that are available in the country, and integrate this with the advanced technological tools that offer reliable and measurement-based determination of serviceability and load capacity. Once a "bridge fleet" is re-qualified by objective data based on an in-depth study of its representative statistical population, and an objectively measurable indicator of health that may be measured by a practical experiment is developed and calibrated to "take the pulse of any bridge within the fleet," it would then be possible to formulate a rational and effective approach for the condition assessment and optimum management of the fleet.

CONCLUSIONS:

The conclusions that can be drawn from this paper can be summarized in the following points:

1. There is a great advance in the recent years in the field of developing and applying health monitoring tools applied to bridges.
2. For a health monitoring scheme to be applied to bridges, the accurate definition of damage and new sensitive damage indices should be developed. These indices could distinguish not only the place and the extent of damage, but also the types of damage in a structure.

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