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CIVIL INFRASTRUCTURE MONITORING, MAINTENANCE AND MANAGEMENT

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Abstract

In this paper, a simple framework is proposed to delineate how structural monitoring at component and network levels of bridges can positively contribute to the preservation of a rehabilitated component bridge and the asset management of networked bridges. Here, asset management means prioritizing the bridges for rehabilitation and replacement based on a life-cycle cost-benefit analysis. The proposed framework has an inner loop for monitoring and maintenance interaction, and an outer loop for the interaction among monitoring, maintenance, and management. The inner loop is illustrated with applications to 5 highway bridges in Missouri, USA. For practical applications of the proposed framework in large-scale civil infrastructures, attentions will then be directed to the laboratory investigation and field validation of two continuous sensors: coaxial cables and optic fibers. Both measure critical data that are directly related to bridge performances with little engineering interpretations.

INTRODUCTION

At their 2005 annual meeting, the AASHTO Highway Subcommittee on Bridges and Structures approved a Strategic Plan for Bridge Engineering (http://bridges.transportation.org/?siteid=34, visited April 2007). The Strategic Plan was developed based on the 2005 workshop report that was contributed by AASHTO State Bridge Engineers, the Federal Highway Administration (FHWA), consultants, and academics. The 7 prioritized grand challenges identified by workshop attendees include: extending service life, optimizing structure systems, accelerating bridge construction, advancing AASHTO specifications, monitoring bridge condition, contributing to national policy, and managing knowledge.

The foremost challenge in the 2005 Strategic Plan is to extend the service life of bridges. As of December, 2006, the U.S. National Bridge Inventory indicates that 25.7% of approximately 600,000 bridges are either functionally obsolete (13.4%) or structurally deficient (12.4%) (http://www.fhwa.dot.gov/bridge/yrblt06.xls). Approximately 75% of the deficient bridges have been in service for over 40 years, approaching or exceeding their design life. Rehabilitation and replacement of these deficient bridges will thus be the focus of bridge engineering in the years to come in the U. S.

To increase the life expectancy of future bridges, the deterioration process of existing bridges must be well understood and quantified. In other words, new limit states of bridge designs need to be identified, such as the effects of steel member corrosion on bridge performance and foundation scouring effects on the integrity of bridges. It is equally important to establish the relation between the de-icing service for safer and smoother mobility of people and the level of corrosion. Once identified, these new limit states or serviceability requirements can be designed to enhance the overall bridge performance with the use of new materials and structural systems that can be implemented in urban areas through accelerated construction techniques. Both high strength materials and accelerated construction are among the identified challenges in the Strategic Plan.

To understand the deterioration process of existing bridges, information and data related to the performance of bridge systems must be acquired effectively. The objectives of structural monitoring must be established, from which a part of the bridge is instrumented at various levels from member through component to system. Bridge condition monitoring is another prioritized grand challenge in the Strategic Plan.

In this paper, several structural monitoring technologies developed at the University of Missouri-Rolla and their applications on real-world bridges are briefly presented. An emphasis will then be placed on the development of a framework on how structural monitoring can be used as a cost-effective tool to assist in the maintenance and management of bridges in a transportation network. An example of 5 highway bridges is given to illustrate the use of a part of the proposed framework.

MONITORING, MAINTENANCE & MANAGEMENT FRAMEWORK

Bridge design and construction are traditionally separated from maintenance in their life span. This practice sometimes leads to structural failures over the years. As an example, Paseo Bridge in Kansas City, Missouri, is a self-anchored suspension structure. In January 2003, one of the 4 vertical linkages of the bridge fractured after nearly 50 years of service. This incidence resulted from a frozen pin condition at the lower end of the linkage due to lack of preventative maintenance of steel pins since the pin area was sealed and inaccessible (Chen et al 2005a). The bridge was closed for ten days for emergency repair, disrupting traffic in the urban area. Therefore, to have a safe, durable, and economic bridge, maintenance must be an integrated part of its design-build process.

As more bridges approach the end of their design life and as traffic volume and load continue being added to the nation’s highway, the demand for the rehabilitation and replacement of more bridge structures is ever increasing. The current budget available for bridge maintenance is insufficient to address all deficiencies in the nation’s aging transportation infrastructure. As such, it is critically important to invest the limited funds wisely to arrive at a safe, durable, and economic transportation system. For this purpose, a number of the state Department of Transportation (DOTs) in the U.S. have already used PONTIS software, a product developed and endorsed by AASHTO, for their asset management of bridges. PONTIS accepts inspection data for each structural member and rates a bridge system based on the worst condition of individual members. Users can provide their inputs on the development of life-cycle cost and structural deterioration models.

According to the FHWA study (Moore et al. 2001), routine visual inspections are often completed with significant variability. The condition ratings assigned by different inspectors could vary over a range of up to 5 different ratings due to their fear to traffic, visual acuity and color vision, light intensity, inspector rushed level, and perceptions of maintenance, complexity, and accessibility. Structural monitoring can be an effective means to supplement the visual inspection with quantitative data.

General Framework

The key elements of monitoring, maintenance, and management are described below. In this paper, a collection of monitoring, maintenance, and management is referred to as “3M” thereafter.

Monitoring. Several steps will be taken in this category. First, a suite of representative bridges are selected for instrumentation. The selection process must take into account the type, representation, importance, and geography of bridges. Second, for each selected bridge, an instrumentation system is designed, depending on potential failure modes, minimum data for the detection of a failure mode, and cost. For a reinforced concrete (RC) bridge, potential failure modes include concrete crack, rebar yielding, shear and flexural failure, concrete crushing, steel corrosion, and foundation scouring. Third and lastly, data related to the performance of the bridge are acquired, processed, and archived, as well as transmitted and stored elsewhere in the case of real time monitoring with autonomous processes. In many practical applications, however, monitoring can be done periodically.

It is noted that all the real-time monitoring systems currently installed on bridges use discrete sensors such as accelerometers and strain gauges. For a large-scale civil engineering structure, a large quantity of discrete transducers has been deployed to arrive at useful results. They will record an overwhelming set of measured data, from which damage identification algorithms must be developed to mathematically extract critical engineering information. However, the severity and location of damages to be identified will substantially affect the mechanical relation on which model-based identification algorithms are based. This dilemma has not yet been brought to the research forefront of structural health monitoring due to the fact that this emerging field is still at its early development stage; current focuses are limited to either numerical simulation of damages or interpretation of traffic-induced measured data, which involves no damage. As a result, the applicability of such identification algorithms is yet to be investigated. It is highly desirable to develop continuous sensors that only measure critical data for direct interpretation of structural behaviors. Such an effort will be discussed in the Continuous Sensors section.

Maintenance. For each instrumented bridge, the data acquired allows the understanding of deterioration process and the development of deterioration modeling. Based on the degree of deterioration in combination with visual inspection notes, engineers can make a sensible decision on the rehabilitation of its represented group of bridges.

Management. Asset management is considered for all bridges within an agency, e.g., Missouri Department of Transportation (MoDOT) in the state of Missouri. Both visual inspection data on all bridges and measured data on instrumented bridges are used. The ultimate goal of asset management is to develop a cost-effective rehabilitation and replacement program of the bridges within a specific budget constraint. The current available tool, PONTIS software, allows the input of cost and deterioration models, as well as the update of agency’s policies.

Further development in bridge asset management may be required in several areas. First, the cost and deterioration models must be updated over the years. Second, the currently used worst member strategy needs to be improved upon. Since serviceability and safety are two main concerns in practice, functionality and collapse requirements of a bridge system can be evaluated using a pushover analysis for lateral resistances. Third, and lastly, taking into account the economic development in a region and corresponding future expansions of the regional transportation network, the expected remaining service life (T_e) of some bridges can be determined *in prioror*. To prioritize bridges for a rehabilitation and replacement program using PONTIS software, a reliability-based cost-benefit analysis can be performed. Let T_r be the remaining service life of a bridge and C be a life-cycle cost to extend the service life of the bridge to the expected life, T_e, a priority index in year per million dollars can be evaluated by

$$Priority\ Index = I \bullet E((T_e - T_r)/C) \qquad (1)$$

in which I represents the importance of a bridge and E means the expectation of the random variable in parentheses. Here, both T_r and C are random. They depend on the deterioration and cost models with uncertain parameters, which statistical models can be developed from the measured data from a structural monitoring system.

Interaction among “3M”. The interaction among monitoring, maintenance, and management can be simply described by two loops as illustrated in Fig. 1. The inner loop indicates an immediate need for updating the relation between monitoring and maintenance. In the above context, as deterioration appears and rapidly grows in certain unexpected areas of a bridge, monitoring must be expanded to include these areas. The outer loop means a need for constant updating of the relation from monitoring through maintenance to management. For example, based on the cost-benefit analysis and the visual inspection data from all bridges, the monitoring program and then maintenance may need to be updated or expanded for more effective asset management of bridges.

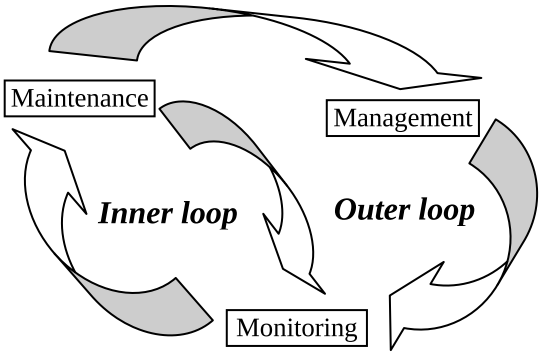


Fig. 1 “3M” interaction diagram

Fig. 2 Distribution of 802 bridges

The proposed framework can be realized with specialized initiatives. Two practical ways to do so are the Long-term Bridge Performance (LTBP) program at FHWA and any government-private partnering program that recently appeared interesting for a number of significant transportation projects. The LTBP program is anticipated to be successful over a period of 20 years as demonstrated by the FHWA long-term pavement performance program. A good example of government-private partnering programs is the recently announced MoDOT Safe & Sound 800 Bridges project (http://www.modot.org/safeandsound/, visited April 2007). Under this program, MoDOT has identified a design-build-maintain process to quickly replace or rehabilitate 802 of its lowest-rated bridges out of more than 10,200 state bridges. The 802 bridges are distributed throughout the state of Missouri as shown in Fig. 2. A winning team of design, construction, and financial firms must complete the upgrading of the 802 bridges in 5 years and maintain these bridges for a minimum rating of VI for 25 years or longer. Therefore, the Safe & Sound 800 bridge project is an excellent testbed for the development and calibration of the proposed framework.

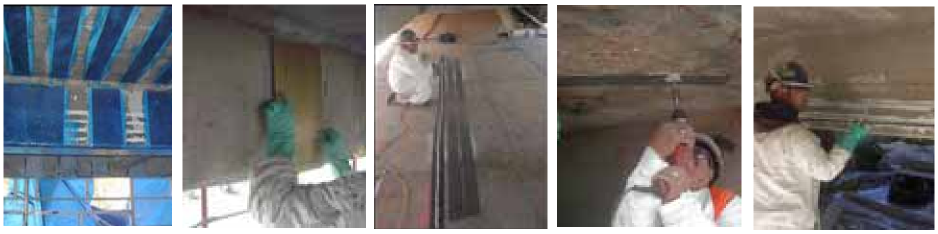
Potential Applications

The inner loop of the proposed framework is applied to 5 highway bridges that were strengthened with different techniques. Fiber Reinforced Polymer (FRP) sheets and rods can be externally added to an existing structural member to increase its load capacity. As such, they will carry significant loads when integrated into an existing structure. Therefore, monitoring on their load carrying characteristics becomes critically important for short-term validation and long-term durability.

Five existing RC bridges were strengthened using five different FRP technologies. These bridges are geographically spread over three MoDOT districts. The main objectives of this initiative were to validate the use of FRP materials for the strengthening of structurally deficient RC bridges and maintain these bridges by periodically monitoring the performance of various strengthening technologies. In the latter case, in-situ load tests prior to and after strengthening as well as non-destructive tests and sensor measurements were performed for all bridges over a period of 5 years. The Dallas County Bridge was also instrumented with fiber optic sensors and distributed crack sensors; it was periodically evaluated with non-destructive tests approximately every six months.

As external reinforcement, 5 strengthening systems were implemented on the bridges as illustrated in Fig. 3. These systems include:

- Manually laid up composite laminates. Dry composite fiber fabrics are impregnated and adhered to the surface of a structural member in-situ to form a fiber reinforced polymer (FRP) sheet for strengthening.
- Steel reinforced polymer (SRP) sheets. A dry brass fiber sheet is installed to a structural member in a similar way to the FRP sheet,
- Pre-cured composite plates. Pultruded laminate plates are installed similar to conventional steel plate bonding.
- Mechanically fastened composite laminates. The adhesives used to bond the composite laminate to a surface are replaced by mechanical steel fasteners.
- Near surface mounted (NSM) FRP reinforcement. FRP bars are installed in precut grooves and embedded in epoxy resin.



Manually laid up composite sheets

Manually laid up steel sheets

Pre-cured composite plates

Mechanically fastened sheets

Near surface mounted bars

Fig. 3 Technologies being field validated on 5 bridges

The Dallas County Bridge is used as one example of how periodical monitoring helps understand the condition of a highway structure as part of the maintenance program. As will be shown in Fig. 7(a), the bridge consists of three continuous spans with its solid RC deck reinforced by three longitudinal beams.

FRP and SRP strengthening systems can potentially degrade in several ways, including delamination, debonding, and loss of anchorage. To ensure the installation qualities of various strengthening systems and their integrity over the years, non-destructive tests and measurements from fiber optic and cable sensors were carried out. Specifically, near-field microwave tests and pull-out tests were conducted on representative parts of strengthening to detect potential delamination in field condition. Displacements were measured to ensure no stiffness degradation over the years. Fiber optic sensors were applied to measure strains of the bridge deck at various locations. Finally coaxial cable sensors were implemented to detect cracks in concrete. Due to limited space, only the measured data from coaxial cable Sensor 1, see Fig. 7(b), over a period of three years are shown in Fig. 4 under two load cases.

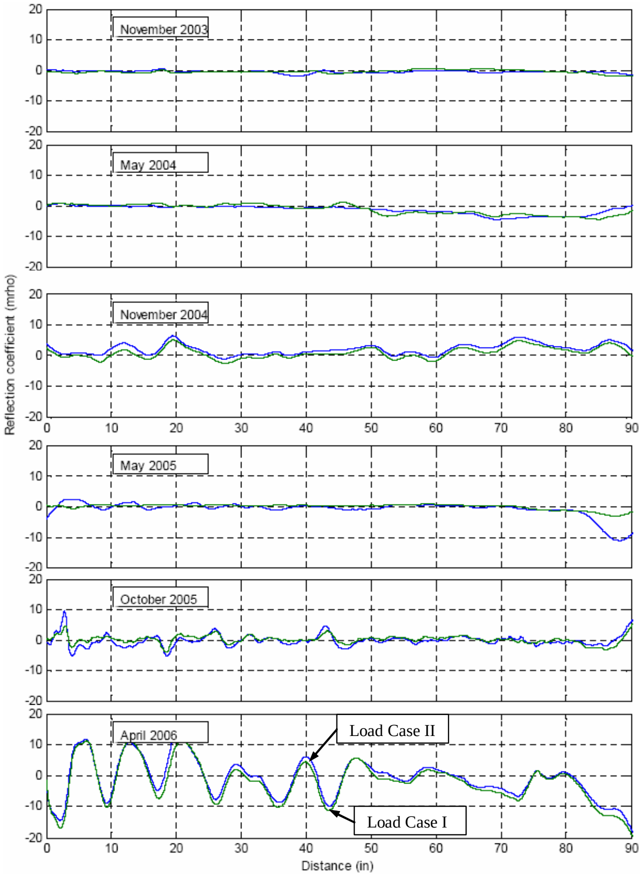


Fig. 4 Reflection coefficient waveforms

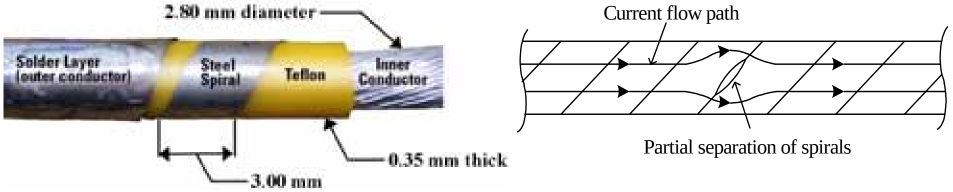
Fig. 4 shows that the sensor signals change little during the first five tests. However, Fig. 4 indicated some changes in sensor signals during the load tests in April 2006. Visual inspections during the test showed no visible cracks under the bridge deck (Brower 2007). It is possible that thermal effects may have caused the periodical change of the sensor as seen in Fig. 4. This issue will be subject to further investigation in the future. Overall, the sensor gave consistent readings over the past two and a half years.

CONTINUOUS SENSORS

Due to the large-scale nature of civil infrastructure, continuous sensors are advantageous over discrete sensors in that their measured data are inherently synchronized in time. They require less time to process the data received. More importantly, the following two types of continuous sensors can give engineers critical data that are directly related to bridge performance.

Electrical Time Domain Reflectometry Cables for Crack Detection

A fundamentally new, topology-based cable sensor design concept has recently been proposed (Chen et al. 2004). Cable sensors are basically communication coaxial cables with an innovative design of their outer conductor, spirally wrapped around dielectric or Teflon as illustrated in Fig. 5(a). The topology change in a cable sensor is realized after the spirals as outer conductor of the cable are separated due to local strain effects as illustrated in Fig. 5(b), resulting in a detour of current flow path along the outer conductor and thus a reflected signal when a series of low-amplitude and fast-rising step pulses are launched onto the cable. The arrival time of the reflected signal represents the distance from the point of monitoring to the discontinuity while the intensity of the signal represents the degree of the discontinuity.



(a) Cut-away coaxial cable sensor (b) Mechanism of topology-based sensors

Fig. 5 Coaxial cable sensor and working mechanism

The new design concept enhanced the sensitivity of traditional cables by over 10 times and the spatial resolution of less than 50 mm. It enabled the structural application of cable sensors as demonstrated by comparing the measured reflection coefficient waveforms under various crack widths with the crack pattern observed on the tested RC beam, Fig. 6 (Chen et al. 2004). Due to presence of the spiral outer conductor, when embedded near surface of a RC member, a specially-designed cable sensor can permanently record the most severe damage, both surface and hidden cracks, distributed along the RC member provided the cracks intercept the sensor (Chen et al. 2005b). This “memory feature” provides a high reliability of receiving damage data during a strong earthquake and a hurricane by allowing critical damage detected either in real time or after the catastrophic event.

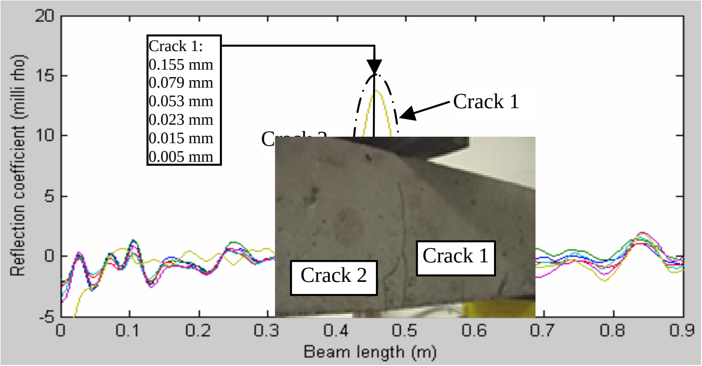
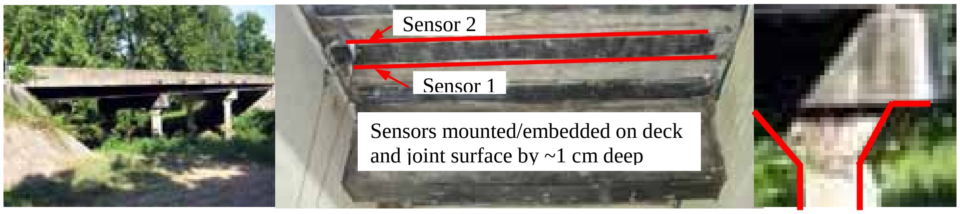


Fig. 6 Crack pattern and measured reflection coefficient at various loads

Two coaxial cable sensors were installed on a three-span continuous bridge of solid decks that are reinforced with three longitudinal RC girders, as shown in Fig. 7(a, b). Cable sensors can also be installed on the surface of columns as illustrated in Fig. 7(c). Some measurements taken from Sensor 1 were presented in Fig. 4 for two load cases. The test results showed that in field condition the level of noise and/or environmental effects is around 3 mrho in reflection coefficient within an effective range of the sensors between 10 and 220 cm in Fig. 4.



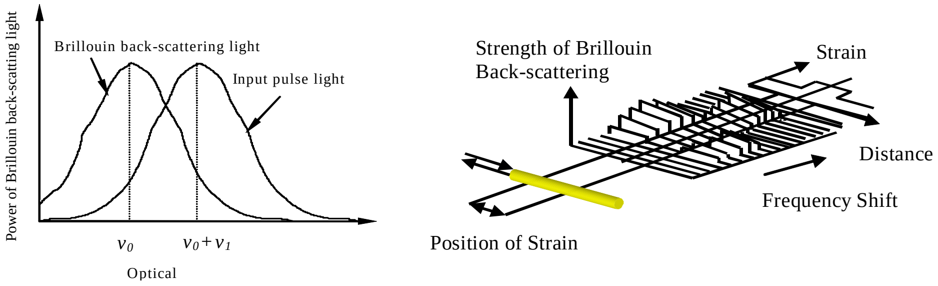
Sensors mounted/embedded on deck and joint surface by ~1 cm deep

(a) Bridge (b) Installation of cable sensors (c) Cable sensor in column

Fig. 7 Coaxial cable sensor application in Dallas County Bridge

Brillouin Optical Time Domain Reflectometry Fibers for Strain Measurement

In an optical fiber measurement with the Brillouin Optical Time Domain Reflectometry (BOTDR), the Rayleigh backscattering mechanism associated with a general distributed fiber sensing system is replaced by Brillouin backscattering. When a highly coherent incident light is transmitted through an optic fiber, Brillouin scattering occurs as a result of an interaction between the propagating optical signal and thermally excited acoustic waves in the GHz range present in the silica fiber. It can be viewed as the diffraction of light on a dynamic grating generated by an acoustic wave, which is actually a pressure wave that modulates the index of refraction through elasto-optic effects. The diffracted light experiences a Doppler shift since the grating propagates inside the fiber at the acoustic velocity. The dominant frequency of the scattered light is shifted from that of the incident light due to the propagation of the acoustic wave in a velocity that depends on the density of the medium and varies with temperature and strain applied on the medium. As a result the so-called Brillouin frequency shift, shown in Fig. 8(a), carries the information about the local temperature and strain of the fiber. The relationship between the strain and the frequency shift of Brillouin backscattering is illustrated in Fig. 8(b). The shift in the Brillouin frequency linearly increases with the tensile strain applied on the optic fiber.



(a) Shift of frequency (b) Frequency shift as a function of strain

Fig. 8 Brillouin scattering principle

Two or more optic fibers are embedded into a fiberglass sheet to form a “smart” fiberglass tape for simultaneous strain and temperature measurements (Bastianini et al. 2003). As shown in Fig. 9, for strain measurements, tight buffered optic sensors made of 9/125 mm silica single mode fibers with 900 mm tight PA buffer coating are used. For temperature measurements, loose buffered optic sensors made of 9/125 mm silica single mode fibers with 900 mm dry loosely-coupled PVA or wet loosely-coupled PE buffer coating. When applied for external strengthening of a beam, a fiberglass sheet and the tight optic fibers in it are subjected to the same level of strains that can be monitored with the BOTDR measurements. The effect of ambient temperature on the stain measurements can be compensated by the additional data from the loose optic fibers that are not subjected to strain since they are loosely connected with the sheet.

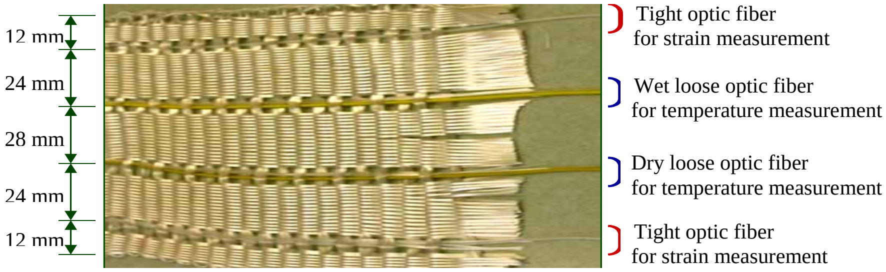


Fig. 9 “Smart” FRP tape with strain and temperature monitoring optic fibers

The “smart” fiberglass tape was applied to a five-span continuous, high performance steel girder bridge located at the Lake of the Ozarks in Miller County, Missouri, along US Route 54 over the Osage River (Matta et al. 2005). As shown in Fig. 10(a), it is symmetrical about the centerline of the River with two side spans of 44.8 m and 56.4 m long, respectively, and a center span of 61.0 m, resulting in a total span length of 263 m. The cross section of the bridge superstructure consists of five equally-spaced, built-up I-girders that are composite with a 216 mm thick RC deck. The end-to-end deck width is 12.4 m with a clear roadway width of 11.6 m. At each of the two ends, the bridge deck is supported on a seat-type abutment. Each of four intermediate bents is a two-column RC frame structure, which is supported by two RC circular drilled shafts, each having 1.83 m in diameter.

During construction, a facial girder fell off its supporting bents at two ends and experienced severe damage due to wind effects as shown in Fig. 10(b). It was straightened and repositioned for continuous uses. Because several cross sections along the girder have already experienced yielding, the owner of the bridge decided to evaluate the overall performance of the bridge through field monitoring and establish the actual behavior of the structure.

(a) Five-span continuous bridge (b) Damage of one steel girder

(c) Installation of a “smart” tape and two bare fibers

Fig. 10 Application of “smart” fiberglass tapes in a real-world bridge

A “smart” fiberglass tape and two bare optic fibers were epoxy-bonded onto web of Girder 1 along Span 1, and Girder 2, 4, and 5 along Span 1 and 2 as illustrated in Fig. 10(c). To facilitate the installation of sensors, a moveable platform was built and put in place underneath the bridge deck as shown in Fig. 10(c).

In addition to “smart” fiberglass tapes, a Leica TCA 2003 total station or Robotic Tacheometry System (RTS) was used to monitor deflections of the bridge girders during pouring of the concrete deck and after the completion of the bridge construction. Similar to any survey equipment, the total station can be programmed to automatically monitor the location of any reference point on the bridge by measuring three coordinates of the point in space. As indicated in Fig. 11, the test setup included a total of 22 reflecting prisms mounted onto the bottom flange of the girders and four reference targets placed outside the bridge superstructure (Bastianini et al. 2003).

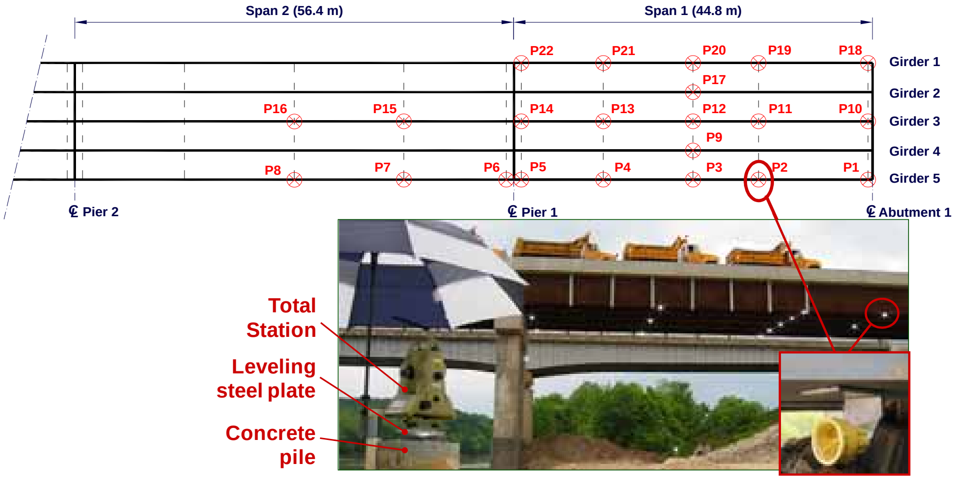
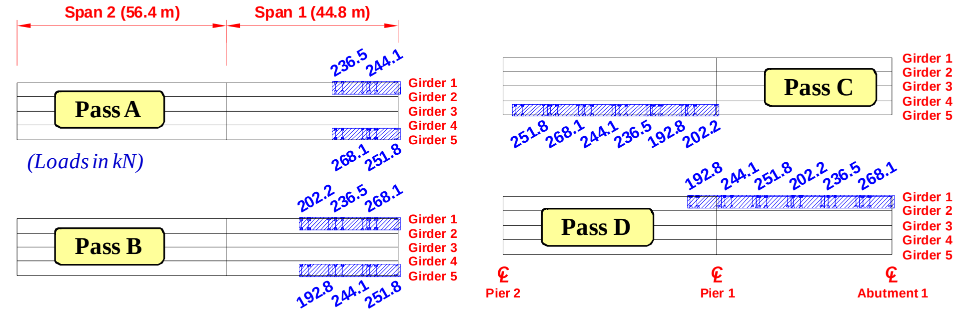


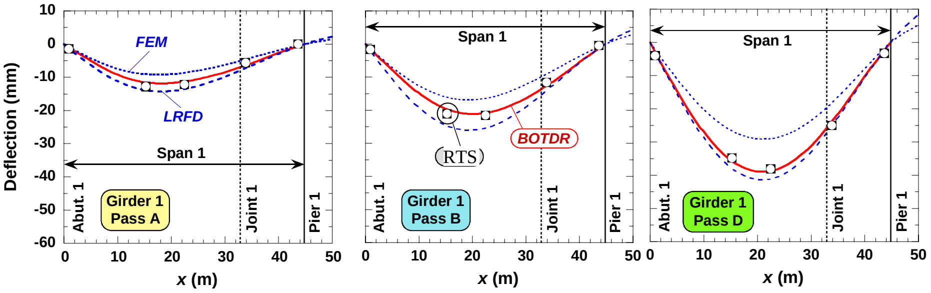
Fig. 11 Location of reflecting prisms for displacement measurement

The strain values measured from a "smart" fiberglass tape are converted into their corresponding deflections using a double integration method in structural analysis. The converted deflections and those from the total station are compared in Fig. 12, together with the theoretical predictions based on the AASHTO LRFD Bridge Design Specifications (AASHTO 1998). Six 10-wheel, 3-axle dump trucks were used to apply the required loads on the bridge. All load passes (A, B, C, and D) are illustrated in Fig. 12.

Fig. 12 indicates that the deflections of Girder 1 in Span 1, converted from the strain data measured using a "smart" tape (BOTDR) at the completion of the bridge construction, agree very well with those directly measured from the total station or RTS. It also indicates that AASHTO LRFD design provisions produce slightly conservative estimates, as opposed to a more refined analysis accounting for the contribution of secondary elements (e.g., cross frames and barriers). On the other hand, finite element method (FEM) was also used to analyze the bridge structure; its results generally underestimate the deflections for all cases since the effects of secondary members such as barriers, railings, and lateral bracings are often neglected.



(a) Load condition



(b) Experimental and theoretical results

Fig. 12 Validation of the performance of "smart" fiberglass tapes

CONCLUSION

A framework for structural monitoring, maintenance, and management has been proposed. It is composed of an inner and an outer loop. The inner loop related to monitoring and maintenance only is exemplified with its application to 5 highway bridges that were load tested over the past three years. Test results indicated no appreciable change in stiffness of the bridges, and no degradation in performance. In the presence of any engineering property changes, the original monitoring system may be updated or expanded, which results in interaction between monitoring and maintenance.

The concept of "critical data" collections for large-scale civil infrastructure was proposed. Two continuous sensors that measure critical data only were discussed. They included fiber optic and coaxial cable sensors. In comparison with Brillouin scattering fiber optic sensors, cable sensors are rugged for a wide range of crack widths, continuous in crack detection along each sensor, high in spatial resolution, inexpensive in measurement instrument, and fast in crack detection under dynamic loads. However, optic fibers virtually have no signal loss, allowing applications up to 10 km.

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