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STATE OF THE ART REVIEW ON BRIDGES STRUCTURAL HEALTH MONITORING (TOOLS AND INSPECTION)

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Abstract

Traditionally, modern nondestructive evaluation techniques have been utilized to test bridges. Numerous nondestructive test procedures are available for use on bridge components. A single nondestructive testing technique could not give the inspector all the information he needs to obtain. In this chapter, the methods that are being successfully used in bridge inspection are presented. The physical principles of these techniques are briefly outlined. The latest research on their use is briefly stated. Their advantages and disadvantages are stated.

INTRODUCTION

Visual inspection of structural elements in bridges is the most basic approach to nondestructive evaluation. There are many advantages to visual inspection that include: (1) it requires minimal equipment, (2) it is one of the easiest to conduct, and (3) it is less time consuming and more economical than the more advanced nondestructive evaluation methods. Most bridge cracking problems have been discovered visually. Visual inspection detects obvious surface discontinuities only in the accessible areas of bridges. Among the limitations of the visual inspection is the subjectivity of the results as the method relies primarily on the inspector capabilities. The size of the detected defect depends on several variables: inspector visual acuity, lighting conditions, surface preparation, and viewing angle [1]. Consequently, relying only on visual inspection may lead to dangerous consequences.

In the United States, visual inspection is a primary component of both routine and in-depth inspections. A recent study conducted by FHWA [2] focused on examining visual inspection as a monitoring tool with four objectives. The first two objectives were to provide overall measures of the accuracy and reliability of routine and in-depth inspections. The third objective was to study the influence of several key factors to provide a qualitative measure of their influence on the reliability of routine and in-depth inspections. The fourth objective was to study the differences between state inspection procedures. Three primary activities were performed during the course of this study: (1) a literature review, (2) a survey of bridge inspection agencies, and (3) a series of performance trials utilizing State department of transportation bridge inspectors. The performance trials were conducted using 49 State bridge inspectors. These State bridge inspectors completed six routine Inspections, two in-depth Inspections, and two inspections following their respective state procedures (i.e., State-dependent procedures). Extensive information was collected about these inspectors and the environments in which they worked. This information was then used to study possible relationships of various factors with the inspection results.

From the survey of bridge inspection organizations, it was determined that professional engineers are typically not present on site for bridge inspections. Specifically, 60% of State respondents indicated that a professional engineer was on site for less than 40% of the inspections. In addition, vision testing of inspectors is almost nonexistent, with only two State respondents indicating that their inspectors had their vision tested. As was anticipated, visual inspection was the most frequently cited nondestructive evaluation technique used for concrete, steel, and timber bridges. From the survey, it was also found that many bridge inspection organizations have a need for additional research in the area of concrete deck and pre-stressed concrete inspection. Regardless of the type of inspection being completed, it was found that, when asked, many inspectors did not indicate the presence of important structural aspects of the bridge that they were inspecting. These would include such items as support conditions, bridge skew, fracture-critical members, and fatigue sensitive details. In addition, there is significant variability in how long inspectors anticipate they need to complete an inspection and how long the inspection actually takes.

From the routine inspection tasks, it was observed that routine inspections are completed with significant variability. This variability is most prominent in the assignment of condition ratings, but is also present in inspection documentation. As an example, on average, four or five different condition ratings were assigned to each element. Based on the application of statistical models, it is predicted that only 68% of the condition ratings will vary within one rating point of the average. Similarly, it is predicted that 95% of the condition ratings from bridge inspections will be distributed over five contiguous condition ratings, centered about the average. Also, it was observed that condition ratings are generally not assigned through a systematic approach. Based on the distribution of the condition ratings and observations made during the study, the National Bridge Inspection Standards condition-rating definitions may not be refined enough to allow for reliable routine inspection results. Nonlinear, multivariate regression analyses indicated that a number of factors appear to correlate with routine inspection results. In this study, they include factors related to reported fear of traffic, near visual acuity, color vision, formal bridge inspection training, light intensity, reported structure maintenance level, reported structure accessibility level, reported structure complexity level, inspector rushed level, and wind speed. From the in-depth inspection tasks, it was observed that in-depth inspections are unlikely to correctly identify many of the specific types of defects for which this type of inspection is frequently prescribed. As an example, only 3.9% of weld inspections correctly identified the presence of crack indications. Furthermore, it is concluded that a significant proportion of in-depth inspections will not reveal deficiencies beyond those that could be noted during a routine inspection. As with routine inspections, a number of factors appear to correlate with in-depth inspection results. In this study, they include factors related to inspector comfort with access equipment and heights, time to complete inspection, structure complexity and accessibility, inspector viewing of welds, flashlight usage, and number of annual bridge inspections. In addition, the overall thoroughness with which inspectors' complete inspections tended to have a large effect on the likelihood of defect detection. Not surprisingly, there also appears to be some correlation between the types of defects individual inspectors will note. Specifically, inspectors who find small, detailed defects are more likely to consistently note small, detailed defects regardless of the bridge. Also, inspectors who find gross dimensional defects are more likely to do so on other bridges as well.

Based on the State-dependent inspection tasks, it appears that most States follow similar inspection procedures and provide the same general information in their inspection reports.

With some notable exceptions, when element-level inspections were completed, they were generally consistent with the commonly recognized element guide for the major bridge elements. Inconsistencies were observed in the use of units, division of quantities, and the definitions of the condition states. From the State-dependent routine inspection, it appears that few inspection teams perform an in-depth level inspection of bridge decks as part of their routine inspection. When inspection teams were asked to perform an in-depth level inspection of a bridge deck, it was found that significant inaccuracies existed. As an example, only 6 of 22 teams were within 5 percentage points of the actual delamination percentage.

Based on these conclusions, several recommendations have been developed related to improving the state-of-the-practice, as well as additional research needed in the application of visual inspection to highway bridges. With respect to routine inspections, the accuracy and reliability may be greatly increased by revising the condition rating system. Additional work is needed to clearly define the source(s) of the inaccuracies. Similarly, the accuracy and reliability of in-depth inspections could be increased through increased training of inspectors in the types of defects that should be identified and the methods that would frequently allow this identification to be possible. Further examination and definition of the types and sizes of specific defects that are likely to be identified during an in-depth inspection are warranted. Specifically, this would include a study of the types of defects occurring in concrete superstructures, as well as different sizes of defects occurring in steel superstructures.

The accuracy and reliability of both routine and in-depth inspections could be further increased by considering the identified factors during the selection and training of inspectors, as well as during the design of bridges. Additional research is needed into each of these factors to establish useful guidelines. Additional research is also needed to determine whether ensuring minimum vision standards through vision testing programs (with corrective lenses, if necessary) would benefit bridge inspection. Since the primary focus of the routine inspection tasks in this study was on the assignment of condition ratings, more research should be performed to determine the accuracy with which the commonly recognized elements are used in the field. Further study of deck inspections is also required. This research should investigate team and individual detection abilities, as well as difficulties inherent in the reporting process. This research could also compare mechanical sounding deck inspection techniques to other nondestructive evaluation techniques.

REBOUND AND PENETRATION METHODS

Rebound and penetration tests measure the hardness of concrete and are used to predict the strength of concrete. The Schmidt hammer is probably the most commonly used device of this type. The extent of rebound gives an indication of the strength of the concrete at the surface position tested. Actual strength must be determined by other means. The relative compressive strength of concrete can also be determined by the "Windsor probe." It measures the penetration resistance of hardened concrete. This device drives a steel probe into the concrete using a constant amount of energy.

LIQUID PENETRANT TESTING

Certain liquids can penetrate into the space between two surfaces separated by a narrow gap as is the case with tight cracks. If these liquids are applied to the cracked surface, the crack becomes filled with the liquid. If the liquid is colored, or carries a brightly colored dye, once the surplus liquid has been moved, the crack opening should stand out more clearly than when the crack was in its original state [3]. An alternative approach with the same physical basis is to use a liquid fluoresces under ultraviolet light, so that the crack will become clearly visible when examined under ultraviolet radiation. This technique is used to detect cracks in welded component of steel bridges. It is simple, portable, well adapted for field use, and more reliable than visual inspection [4]. However, it can detect surface cracks only. Environmental hazards are major concerns while adopting this technique. A major concern is that cracks already filled with corrosion may not be detected.

MAGNETIC PARTICLE INSPECTION

If a tangential magnetic field is applied to the surface regions of a ferromagnetic specimen, it will normally lie totally within the specimen. However, if the specimen surface is cracked, a portion of the field is forced to leave the specimen locally, forming a stray field on the surface of the specimen. Magnetic particles will be preferentially attracted to these regions of stray field. The magnetic particle technique relies on the application of a stream of magnetic minute particles, which will tend to become attracted to any region of stray field located around cracks in the specimen. If these particles are clearly visible, the regions that are defective will be clearly delineated. This technique is a sensitive means of detecting surface or near surface cracks; however, it is limited to ferromagnetic materials.

RADIOGRAPHIC TESTING

Radiographic techniques for nondestructive testing were the earliest methods for inspecting items for internal defects. Today, radiography has expanded to encompass a variety of unique and useful methods. The mechanism of radiographic inspection is the propagation of energy from a radiation source through an object, and the evaluation of the energy pattern received on the opposite side. The radiation source emits energy that travels in straight lines and penetrates the investigated object. Once the radiation energy has passed through the item, an image received on a recording plane opposite to the source is used to evaluate the condition of the part being inspected. Then, the energy projects an image of strange structure inside the specimen onto the recording plane.

Two types of radiography are currently used in different fields of applications: X rays and Neutrons. The other two types, Gamma rays and Protons, have not been used for nondestructive evaluation of civil engineering structures. There is no essential difference between the X-ray and Gamma-ray techniques. X rays are produced artificially outside the nucleus of atoms as a result of the atoms either slowing down upon striking target atoms or knocking electrons out of orbit. However, Gamma radiation is a natural product from some radioactive materials. Its source is the process of radioactive decay in the nucleus of a radioactive atom. Both techniques involve some form of radiation hazard; therefore, their application is subject to safety checks.

In bridge applications, radiography is a very good tool to detect volumetric defects occurring during welding. The method is used extensively in workshops to evaluate the welding process since it can detect porosity, slag, and inclusions. In addition, it is utilized to detect fatigue cracking occurring in the vicinity of weld toes and predict presence of any inclusions in field welds [5, 6]. Lately, portable X-ray radiographic equipment was utilized to test pre-stressed concrete box-section bridges [7]. Mainly, the unit consisted of a power converter, a remote control panel, a remote dose-meter, and a safety alarm. The equipment was capable of detecting grout porosity and voids in concrete. A correlation was made to estimate the concrete compressive strength using the results of the radiographic testing. The method is well established; however, it is still one of the most expensive and hazardous nondestructive evaluation methods.

ACOUSTIC EMISSION

Weld discontinuities and high strain regions produce sound energy. Further, waves are generated by local stress redistribution associated with the motion of cracks. Acoustic emission uses these physical properties for defect detection and analysis. Acoustic emission testing system is composed of three elements: a sensor to detect the acoustic emission, an amplifier to boost the signal energy for transmission, and a processor to detect and quantify the signal (fig 1). Acoustic emission activity may occur at yielding; however, they may not emit enough sound when plastic deformation or cracking occurs, implying that acoustic emission cannot be used to detect plastic failures.

A recent use for acoustic emission was to monitor the welding process as the weld pool cools. The evaluation of this approach has shown that most of the important defects can be located in this way at an early stage. Several papers and reports were published recently to report the progress of using the acoustic emission methods in bridge nondestructive evaluation [8,9]. It has been utilized as complementary method for assessing concrete deck slabs in bridges [10] where it was able to detect voids and cracks. A more recent study [11] utilized acoustic emission sensors to assess the condition and monitor the health of five bridges in Vermont. Results show acoustic emission concept can be used in health monitoring of bridges.

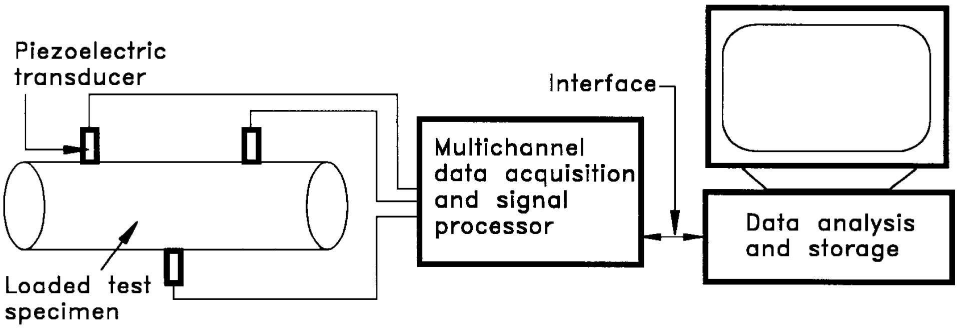

FIGURE 1 TYPICAL ACOUSTIC EMISSION TEST SETUP.

Lately, the method has been used to monitor the condition of pre-stressing strands and tensioned elements in structures [12]. Acoustic emission testing is a "passive" monitoring method in which the detection system waits for the occurrence and capture of stress wave emissions associated with cracking, corrosion, or wire breaks. In most cases, corrosion of high-strength steel wire in bridges is not visually evident. Grouted post-tensioned tendons are obviously not visible. The circumferential wire wrapping on suspension cables and the steel or polymeric protective sheathing on stay cables preclude non-intrusive visual inspection. Even for the suspender ropes (hangers) of suspension bridges, where corrosion is most likely to occur at the deck-level socket connections, the absence of visible wire breaks in the outer layer of wires cannot eliminate the possibility of internal breaks. In the laboratory, several tests were carried out on a freestanding bridge beam. The test protocol consisted of causing accelerated corrosion of grouted wires, as well as external wire breaks using a test rig designed to simulate fully grouted and partially grouted wire failures. Other events caused by impacts were also generated. In a combination of open and blind testing, the system correctly identified all 25 wire breaks generated [12]. The system was, further, tested under normal highway operating conditions. In October 1997, the monitoring system was tested on the Bronx Whitestone Bridge in New York City. This bridge, with a main span of 701 meters, was opened to traffic in 1939 and is owned and the Metropolitan

Transportation Authority of New York. The monitoring system was installed during a rehabilitation of the main cables (fig 2). This work involved removal of the circumferential wire wrapping, repair of broken wires and the application of corrosion-inhibiting oil to the wires. Consequently, it was possible to cut wires in the cable to test the system's recognition and location capabilities. Single sensors were attached to six cable bands, each 12.2 meter apart. An array of three additional sensors was placed around two of the cable bands to evaluate radial location capabilities. A portable acquisition system was set up at deck level and the testing was done while construction work was in progress. Six wires were cut within the monitored section in a blind test. The system correctly classified the events and located them longitudinally with errors ranging from 0.0 meter to 0.7 meter Radial location using all four sensors on a cable band was accurate to within 7.5°. Acoustic events caused by steel chisels being driven between the wires were easily identified and filtered. It should be noted that the commercial name of the system is “Sound Print”.

FIGURE 2. MOUNTING ACOUSTIC EMISSION SENSORS ON POST-TENSIONED TENDONS.

In the UK the Transport research laboratory (TRL) conducted an extensive evaluation on the use of acoustic emission to monitor the condition of post-tensioned cables. Following that evaluation phase, acoustic monitoring systems have been installed in the UK on 3 bridges: Huntington Viaduct, Soar River Bridge and Mossband Viaduct. In France the system is used for the monitoring of external tendons on 2 bridges: Saint Cloud Viaduct and Riviere d'Abord Bridge.

The monitoring system is particularly suitable for use on cable-stayed bridges. Because of the fact that, after construction is completed, visual inspection of cable components is not possible, the system can provide reassurance about the long-term integrity of the wires. In order to evaluate the performance of the system in this type of application, a temporary prototype system was installed on the Alex Fraser Bridge in Vancouver, Canada. The capability of the system to detect wire breaks from both ends of the stay (fig 3) was confirmed for all lengths of stay-cables on the bridge (the longest stays are 250 meter). No wire breaks were detected during the period of operation of the system.

FIGURE 3. ACOUSTIC SENSOR AT ANCHORAGE AND ALONG THE STAY.

A permanent installation has followed on Fred Hartman Bridge in Texas, USA. This is a twin-deck cable-stayed bridge with a main span of 380 meters. It has a total of 192 grouted monostrand stays. Wind-rain induced vibration of the stays has led to a concern about possible fatigue failure of the monostrand wires. Following extensive testing of the acoustic system at the University of Texas, The Texas Department of Transportation decided to install a system on all of the stays. A total of 576 sensors have been installed (3 per stay). A sophisticated multiplexing arrangement was developed to allow complete monitoring of all sensors with only 48 data acquisition channels. A custom-designed damping system is also being installed under a separate contract to address the vibration problem. The monitoring system can be adapted to integrate a vibration monitoring capability so that future vibration performance of the stays can be assessed.

ULTRASONIC TECHNIQUES

Sound is transmitted as stress waves through the vibration of particles in gases, liquids, and solids. Ultrasonic frequencies (not heard by the human ear) start at a frequency of 20,000 Hertz. Ultrasonic nondestructive inspection techniques use some particular characteristics of the propagating stress waves. Four types of these waves exist: (1) longitudinal waves with the particles oscillating in the same direction of wave propagation, (2) shear waves with the particles moving perpendicular to the wave direction, (3) surface waves which propagate on the free surface of any material, and (4) plate waves which propagate in thin plates. The ultrasonic velocity in a material depends on the wave type, the elastic modulus, and the density of the material. Plate thickness is also a parameter in case of plate waves. The velocities of longitudinal and transverse waves in a given material are given by

$$c_1 = \sqrt{\frac{\lambda + 2\mu}{\rho}} \text{ and } c_2 = \sqrt{\frac{\mu}{\rho}} \tag{1}$$

where c_1 = propagation speed of the longitudinal wave, c_2 = propagation speed of the transverse waves, λ, μ = Lame elastic constants, and ρ = density of the material.

An acoustic wave traveling through a material loses energy. Three basic processes account for the loss of energy: beam spreading, absorption, and scattering. Beam spreading is the result of the initial pulse energy being distributed over larger area as the wave front advances. Absorption accounts for the mechanical energy being transferred to heat energy. Scattering results from reflections at the grain boundaries, small cracks, and other material impurities.

Ultrasonic inspection is typically performed using either of the following procedures: (1) normal beam, pulse-echo, (2) normal beam, through transmission, (3) angle beam, pulse-echo, and (4) angle beam, through-transmission. In pulse-echo procedures, short pulses of sound are transmitted into the specimen through transducers and the returning echo is evaluated for the determination of reflector location and size. The depth of a reflector (mainly a defect) can be determined by knowing the velocity of the wave and the transit time. The strength of the returned signal is related to the reflector size. On the other hand, through-transmission (pitch-catch) inspection may be needed where a flaw does not provide a suitable reflection surface. In this technique, two probes are used, one as a sender and the other as a receiver. Through-transmission shortens the travel path by one-half, compared with the pulse-echo technique. Attenuation affects the depth of penetration of the ultrasound in the material.

In bridge structures, it is a standard test for steel bridges in case a crack is suspected and visual inspection was unsuccessful in locating it. Further, ultrasonic testing has been used to detect buried defects, inclusions, and slag lines, and determine thickness of covered components. Weld inspection is a frequent and effective application of ultrasonic testing. The most advantageous aspect of ultrasonic testing is the ability to examine the internal structure of a material, where accessibility is limited to one side. The method is adaptable to field-testing. Ultrasonic testing is most successful in locating discontinuities normal to the direction of wave propagation. Its use does not provide acceptable results in cases of rough surfaces and highly attentive materials. It is use to locate damage, if possible locations are not established, is seldom.

Mirmiran and Wei [13] employed Ultrasonic Pulse Velocity (UPV) to assess the extent and progression of damage in FRP-encased concrete. They found that the UPV damage index had a much better resolution for stress ratios and the volumetric strains after confinement was activated. A comparison of the UPV damage index with the normalized acoustic emission counts revealed that the two methods had different sensitivities at different stages of loading and could potentially complement each other as a hybrid damage assessment tool.

IMPACT ECHO METHOD

The impact-echo method is based on the use of transient stress (sound) waves for nondestructive evaluation of structures, particularly reinforced concrete structures. Small steel balls are used to impact the surface of the object. Consequently, low frequency stress waves propagate into the tested structure. These waves, like ultrasound waves, are only reflected at the structure boundaries and, if present, internal flows. A sensitive transducer at the proximity of the impact location is used to measure the surface displacement caused by the reflection of the stress waves.

The main difference between the pulse-echo and the impact-echo is in the wavelength of the transmitted signal. The impact-echo signals have higher wavelengths. As such, the impact-echo waves “recognize” concrete as a homogeneous material; whereas, the pulse-echo waves sense the aggregate composition of concrete as their wavelengths are much shorter than the concrete aggregate size. Therefore, pulse-echo waves scatter very quickly when transmitted in concrete objects contrary to the behavior of the impact-echo waves, which can reflect multiple times at the boundaries and internal flaws before attenuating.

Recognizing the condition of the tested object from the collected response in the time domain is very difficult. Often, the signal is transferred into the frequency domain where the resonance due to multiple reflections can be identified. Patterns in the spectral density of the measured signal contain information about the existence and locations of internal defects. The method has been successfully used to detect structural dimensions, defect presence, and locations in structural concrete. The impact-echo was first researched and developed at the National Institute of Standards and Technology and later at Cornell University [14]. The method is still in progress and is not commercially available.

EDDY CURRENT METHODS

The eddy current technique uses a coil to induce a current in the surface of a specimen immediately below. The apparent impedance of the coil is affected directly by the induced current. If the surface is broken by a crack, or if the conductivity or permeability of the material changes due to altered surface condition or composition, the eddy current distribution, or its density, is altered. This is the essential point in detecting cracks and discontinuity using this technique. Detection of surface or near surface defects is possible. However, detection will fail rapidly when the defect is further from the surface. In bridge applications, the use of eddy current technique is limited.

THERMOGRAPHY

Thermography is based on the principle that subsurface voids in a material affect heat flow through that material and, hence, cause localized differences in surface temperature. Thus, measuring surface temperature can determine the location of the hidden defects. Thermography has been used effectively for defect (primarily voids) detection in concrete deck slabs and pavements [15]. Advantages of this method are safety and performance of area testing [16]. An insignificant drawback of the method is that the defect depth cannot be determined. The first documented use was published in 1970s [17]. Since then, thermography proved to be the most accurate nondestructive evaluation method for deck slab evaluation. Yet, this method is not a standard method for evaluating bridge decks.

RADAR IMAGING

The theoretical basis of radar imaging is the electromagnetic analog of ultrasonic pulse-echo methods. That is, a portion of the energy of the incident beam of electromagnetic waves will be reflected upon arriving at the interface between two materials. The intensity of the reflected energy, *AR*, is related to the intensity of the incident energy, *AI*, (fig 4) by the following relationship

$$\rho_{1,2} = \frac{AR}{AI} = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1} \tag{2}$$

where $\rho_{1,2}$ = reflection coefficient at the interface, and η_1, η_2 = wave impedance of Materials 1 and 2, respectively.

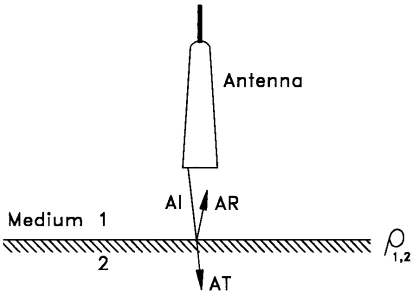

FIGURE 4. RADAR IMAGING TECHNIQUE.

The wave impedance of metals is negligible; this means that metals are perfect reflectors. Recently, radar-imaging techniques have been used to detect delamination and condition of reinforcing steel in concrete bridge decks [18]. A study was made to estimate the accuracy of radar in locating delamination in bridge decks [19]. In this study, 90% of the areas that were predicted by radar to be distressed in a deck were confirmed as such by core sampling, and 91% of the areas that were predicted to be sound were confirmed.

Based on the test results, a system of using the radar-imaging concept was developed. It was developed by FHWA and Lawrence Livermore National Laboratory, as part of the FHWA's Nondestructive Evaluation Program. The system is called HERMES Bridge Inspector. The HERMES Bridge Inspector incorporates a 64-module antenna array, which is capable of scanning bridge decks at highway speeds, and a computer workstation with software to reconstruct high-resolution images of the interior of a bridge deck. The system uses synthetic aperture radar techniques (SAR) to reproduce 2-m wide images at a time. Unlike other radar-based inspection systems, HERMES collects data at very small intervals (as small as 30 mm), locates steel reinforcement, and detects corrosion-related delamination, voids, and debonds at a penetration depth of up to 300 mm. The HERMES equipment is housed in a trailer and can be easily towed at highway speeds (fig 5).

FIGURE 5. RADAR IMAGING MOBILE SYSTEM (HERMES).

FIBER OPTICS AND APPLICATION IN SMART STRUCTURES

The field of fiber optics has undergone a tremendous growth and advancement over the last three decades. Initially, it was conceived as a medium to carry light and images for medical applications. Later, optical fibers were proposed as an adequate information-carrying medium for telecommunication applications. Ever since, optical fiber has been the subject of research and development.

Optical fiber is a thin cylindrical filament made of glass that is able to guide light through itself by confining it within regions having different optical indices of refraction (fig 6). The central portion where most of the light travels is called the core. Surrounding the core, there is a region having a lower index of refraction called the cladding. Light trapped inside the core travels along the fiber in the form of wave-guide modes. The principle of operation of a fiber sensor is that the sensing element (fig 7) modulates some parameter of the optical system, which gives rise to a change of an optical signal property received at the detector, such as intensity, wavelength, polarization, or phase.

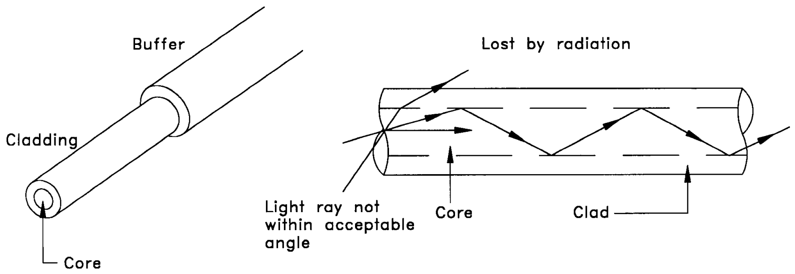

FIGURE 6. SCHEMATIC OF AN OPTICAL FIBER.

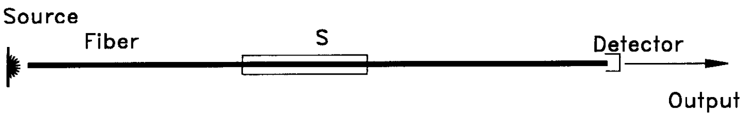

FIGURE 7. BASIC FIBER OPTIC SENSOR.

FIBER OPTIC SENSING SYSTEM

The fiber optic system is typically composed of a light source (Laser diode), a photo-detector, an isolator and couplers, etc. A Digital Storage Oscilloscope (DSO) is used to acquire the signal of strain and failure. In addition, the A/D converter card is utilized for data acquisition. The experimental data obtained from fiber optic sensor is transmitted to the DSO and A/D converter. The data obtained from the strain gage is transferred to the A/D converter. For post-processing, all the signals are stored in a personal computer. The arc-fusion splicer is used to connect the fiber optic sensor and the fiber optic system. The fiber optic sensor system is shown in fig 8.

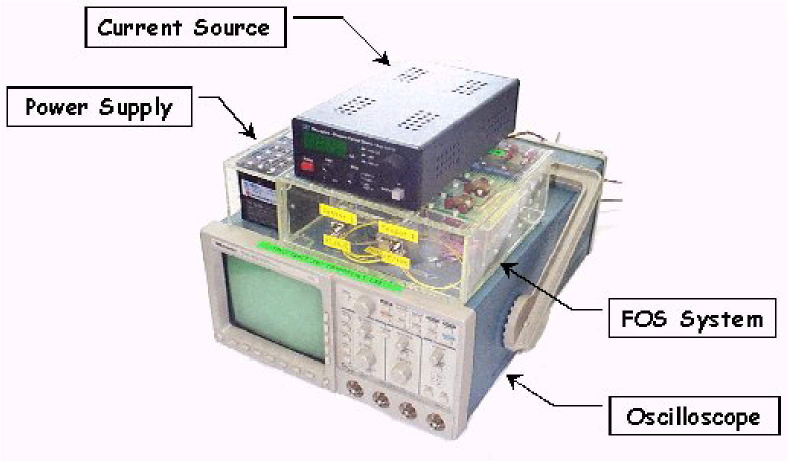

FIGURE 8. FIBER OPTIC SENSOR SYSTEM.

Optical fiber sensors have shown a potential to serve real time health monitoring of the structures. They can be used to estimate thermal stresses during concrete curing, detect cracks, measure strains, and find the deflection of an element. They can be easily embedded or attached to the structures and are not affected by the electro-magnetic field. Also, they have the flexibility of the sensor size (from few millimeters to thousand meters) and very highly sensitive. These advantages of optical fiber sensor make it to be the potential solution for sensor systems of smart structures.

For verification of the system's performance, the experiments of static and dynamic strain measurement were carried out [20]. Four optical fiber sensors were used to monitor strains of a scale-down bridge span. The span of scale-down Bridge was made by acrylic plate. The instrumentation allowed issuing a warning sound when the bridge shows the response of near certain level of strain. This early warning system could give time to undertake remedial works on bridges before a catastrophic disaster. Fig 9 shows the schematic of the experimental setup for the test. The span of bridge was clamped at its ends. Four sensors were bonded on the lower part of the span using epoxy. Experiment was performed by applying the concentrated load at chosen points of the bridge (as given in fig 10).

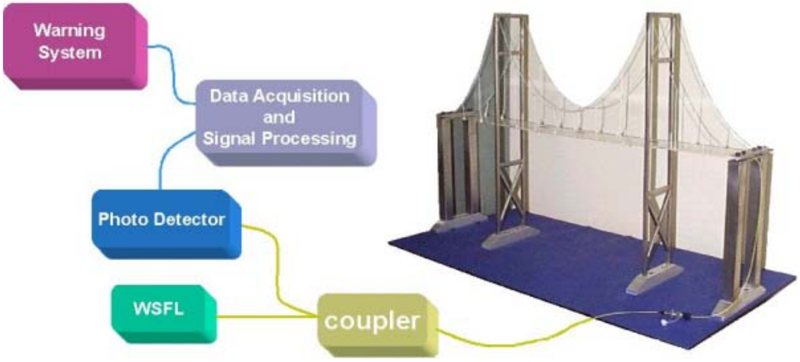

FIGURE 9 SCHEMATIC DIAGRAM OF SMART BRIDGE.

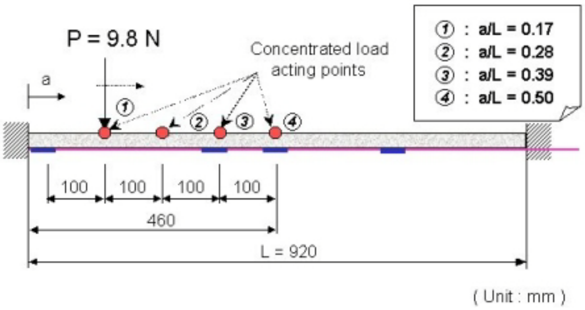

FIGURE 10. CONFIGURATION OF CONCENTRATED LOAD ACTING POINTS AT THE SPAN.

Fig 11 is a real-time strain measurement window by the signal-processing program. The window could monitor real-timely strain states of the sensors and inform user the dangerous state of the bridge by an alarming sound in the case that monitored strain exceeded a given threshold strain level. The real-time monitoring window has two charts showing strains and shape of the bridge span. First chart shows the strain history of four sensors when the vertical load moves discretely along the span of the bridge. Second chart shows a deflection shape of the bridge that is calculated using a clamped boundary condition and measured strains. The strains measured by the fiber optic sensors showed a good agreement with the strains calculated by a classical beam theory. When the bridge undergoes near threshold level of strain, the sensor system successfully gave early warning sound.

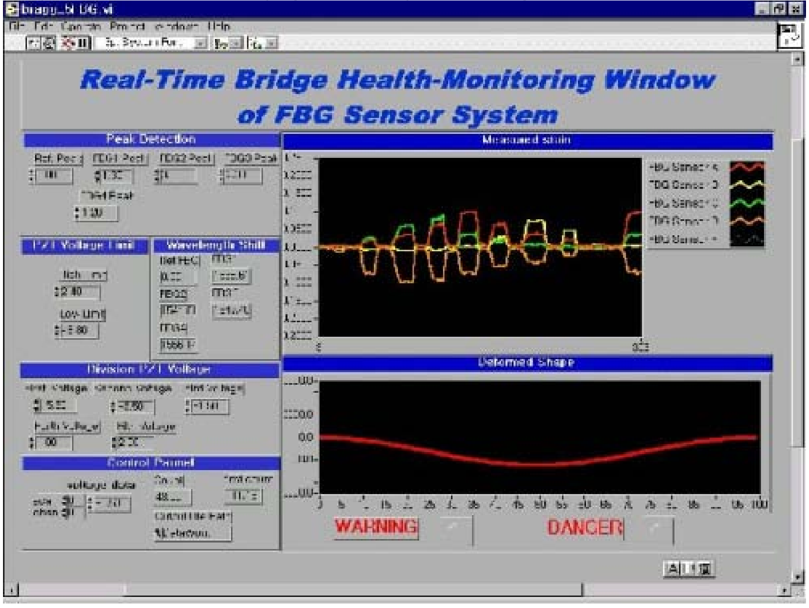

FIGURE 11 REAL-TIME STRAIN MONITORING WINDOW.

Idriss et al. [21] designed an optical fiber monitoring system and installed it into a 3 span high performance pre-stressed concrete (HPC) highway bridge in Albuquerque, NM. The data were collected during the beam fabrication, bridge construction, and service phases and analyzed to determine the prestress losses and get a better understanding of the properties and behavior of HPC. Results shows that implementing a fiber optic monitoring system in bridges is a powerful diagnostic tool as the monitoring system showed drastic change in the structure's response when a fracture was introduced to the bridge. A recent article reported on a monitoring system that uses of fiber optics to detect salt inside concrete bridge decks and rusting of the reinforcing steel bars [22]. The system can detect where and how much salt have penetrated in the deck overlay. The application of fiber optics to monitor bridge structures seems promising; however, it can be only applied to new constructions.

Fiber optic sensors were utilized in the Headingly (Taylor) Bridge [23, 24] located on Manitoba Provincial Road 334 over the Assiniboine River, west of Winnipeg to monitor the performance of FRP materials (fig 12). Two types of carbon FRP reinforcements were used. Carbon fiber composite cables were used to pretension two girders while the other two girders were pre-tensioned using indented lead line bars. Two of the four girders were reinforced for shear using carbon FRP stirrups and lead line bars in a rectangular cross section. The other two beams were reinforced for shear, using epoxy coated steel bars.

FIGURE 12. OVERVIEW OF TAYLOR'S BRIDGE [23].

The deck slab was reinforced by indented lead line bars similar to the reinforcement used for prestressing. Glass FRP reinforcement was used to reinforce a portion of the Jersey-type barrier wall. Double-headed stainless steel tension bars were used for the connection between the barrier wall and the deck slab. The bridge boasted a complex embedded fiber optic structural sensing system that allows engineers to compare the long-term behavior of the two materials. This remote monitoring was the key to acquiring data on FRP that would ultimately help it gain widespread acceptance. 64 single fiber optic sensors were used to monitor the bridge strains, loading and temperatures. The sensors were immune to electromagnetic interference and have long-term stability. The monitoring system provided a profile of the bridge with detailed information on its structural behavior as well as applied loads and environmental effects.

Seim et al. [25] reported that the Horsetail Falls Bridge (see Figure 19) was used as a pilot project to answer two key questions: (1) could a bridge be repaired and strengthened with FRP composites on critical elements, and (2) how the FRP would perform in the long term. In an attempt to answer these questions, fiber optic strain sensors were embedded into the structure (fig 14). Preliminary data were obtained and the bridge would be monitored for the next few years.

FIGURE 13. SENSORS EMBEDDED IN THE DECK OF TAYLOR'S BRIDGE [23].

FIGURE 14 HORSETAIL BRIDGE BEFORE STRENGTHENING.

Crail et al. [26] reported on utilizing fiber-optic sensors to monitor the condition of high speed track systems. Fiber-optic sensors were embedded in several levels and locations of the track system. The track system consists of pre-stressed precast panels of steel fiber concrete which are supported by a cast-in-situ concrete or asphalt base course. The sensors are to measure the bond behavior and the stress transfer in the track system. Measurements were taken on a full scale test sample (slab track panel of 6.45 meter length) as well as on a real high speed track. From the results obtained, a satisfying bond behavior of the supporting concrete layers could be concluded. Fiber-optic sensors guarantee the necessary resolution as well as the ability of calibration for separate measurements after long breaks. The small size of the embedded fiber sensors minimizes reactions to the material zone to be measured and it opens new possibilities to obtain information about the lower, inaccessible layers of complicated concrete structures.

FIGURE 15. INSTALLATION OF LONG GAUGE LENGTH SENSOR INTO THE BEAMS.

USE OF GROUND POSITIONING SYSTEMS

The aim of the Ground Positioning System (GPS) measurement system is to determine, by direct measurements, the absolute structural deflections arising from ambient effects (such as temperature differentials, and static and dynamic components of wind) as well other effects (including traffic loads). The system permits the analysis of data downloaded automatically and to occasionally adjust, by remote control, the system parameters. A typical GPS system is composed of three main sub-systems: (1) one base station comprising a dual-frequency, geodetic-grade GPS receiver installed at a nearby location, complete with mounting brackets, accessories and battery backup for operation for up to one day without power, (2) 'rover' stations, comprising of dual-frequency GPS receivers installed on existing masts attached the bridge to be monitored, and (3) control center PC running the real-time monitoring software. The communication link between the control center PC and the GPS stations was provided via a UHF radio link to the base station and connections to the 'rover' receivers. The UHF radio link transmits the base station GPS data to the rover receivers continuously, allowing for Real-Time Kinematic (RTK) solutions to be generated. Instantaneous time and position results for the rovers' antennas can then be output via the RS-serial ports. The system is designed to provide accurate position information of up to 10 samples/second in order to detect translational and torsional responses of the bridge to load. A robust data logging system to capture data from the GPS system, and to compute, for defined periods, statistics for each of the measuring components, is designed. New data overwrites old data over a specified age with the option of storing data on event trigger conditions (for example, occurrence of an earthquake, strong wind, etc.), and all data stored on the logging system are retrievable by modem without interrupting normal system operation.

A GPS-based system is currently used to monitor structural integrity of the Tsing Ma suspension bridge in Hong Kong [27]. The Tsing Ma Bridge, which spans 1,377 meters across the Ma Wan shipping channel, is the world’s longest span suspension bridge carrying both road and railway traffic (fig 16 and fig 17). The Tsing Ma Bridge was constructed at a cost of around $7 billion to provide high-speed car and rail connections to the Hong Kong International Airport.

FIGURE 16. TSING MA BRIDGE.

FIGURE 17. TOWER TOP RECEIVER ON TSING MA BRIDGE.

The GPS monitoring array, includes 29 high-precision GPS receivers, a Continuously Operating Reference Station (CORS), a central monitoring and control facility and a dedicated fiber-optic data communications network. The dual-frequency GPS receivers are being mounted on the Tsing Ma suspension bridge and the adjacent Kap Shui Mun and Ting Kau cable-stayed bridges. The GPS receivers are designed to measure their exact positions with millimeter-level accuracy, using signals from the orbiting GPS satellites and error correction data transmitted from the GPS reference station. The position data from each receiver will be transmitted at a rate of 10 times per second to the central monitoring facility via fiber-optic cables. The GPS-based monitoring system will operate automatically 24 hours a day, providing instantaneous 3D measurements of structural displacement due to environmental and applied loads, such as wind, temperature, seismic and traffic loads.

Conclusion

1. Fast algorithms for system identification are needed, if possible, on a real-time basis. First of all, the identification of the basic characteristics of existing bridges must be accurate and reliable.
2. There are still considerable uncertainties in the testing, analysis, and environment for the purpose of damage detection. Sometimes, it is very difficult to sort out the uncertainties and pinpoint whether the lack of reliable results was due to the damage or due to an error in the considerably complicated procedures of modal analysis.
3. Studies are needed to develop sensible hybrid damage detection methods that are easy to implement.

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