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Monitoring Suspension Bridges as an Asset Management Tool

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ABSTRACT: In recent years, much attention has been given to issues of aging, reliability and the remaining lifespan of the world's major infrastructure. Many of the suspension bridges in the greater New York area alone are approaching or have exceeded 100 years of service life: in-depth inspections of the cable systems of these bridges have revealed the presence of many broken wires, showing brittle fractures and extensive corrosion

The life expectancy of a suspension bridge is directly correlated to the condition of its cable system (formed with thousands of parallel high-strength steel wires) and, consequently, to the corrosion of the high-strength steel wires. Environmental factors such as temperature, moisture and pH levels are considered agents that might accelerate the chemical processes which lead to general corrosion, pitting and stress corrosion, corrosion-induced cracking and hydrogen embrittlement of high-strength steel wires

In a day, bridge cables may be exposed to a variety of weather patterns (e.g. rain and direct sun), temperature (e.g. day and night) and moisture levels (e.g. dry and wet). More significantly, moist air and water may enter the interior of a cable through any number of openings along the cable (i.e. imperfections of the coating system, poor compaction of the wires). Once inside, evaporation becomes nearly impossible and the wires may be directly exposed to wetness for extended periods of time.

In this paper, a sensor network, designed to monitor the environmental conditions (e.g. temperature and relative humidity) and corrosion activity within a suspension bridge's main cable, is proposed. The proposed sensing system combines temperature, relative humidity and corrosion rate sensors to provide both an "indirect" and "direct" method to obtain information regarding the corrosive nature of the internal environment of a main cable. A full-scale mock-up cable and environmental chamber were built in order to test the monitoring systems ability to accurately measure temperature, relative humidity and corrosion rate. Both graphical analyses and statistical methods were used to compare the experimental test findings to those available in the literature.

Furthermore, the proposed sensing system has been installed in one of the main cables of the Manhattan Bridge as part of FHWA sponsored research. The functionality and response of the in-service monitoring system will be evaluated and compared to that of the experimental system.

The paper will discuss the utilization of this system as an effective tool in bridge asset management.

1 INTRUDUCTION

Suspension bridges are essential links in the transportation networks especially of large metropolitan areas, such as New York City (see Fig. 1), and their serviceability is extremely important for the economic and societal growth. The safety of such structures is closely linked to the safety of the suspension system and, in particular, of their main suspension cables.

Current state of the art approach for cable evaluation, with visual inspection at a few locations was found to be deficient in identifying the worst and most critical condition along the main cable as discovered during cable rehabilitation projects where the entire cable length was unwrapped and in depth inspected.

Currently, all state and local agencies base their main cable maintenance plan mainly on previous experiences and on limited visual inspection of the exterior and (sometimes) of the interior of the cable.

In this 5 year research program, sponsored by the Federal Highway Administration (FHWA) and led by a research team consisting of Columbia University, Parsons Transportation Group and Mistras Group developed a corrosion detection and remote monitoring system for suspension bridge cables that is a

Figure .1. Suspension bridges in New York City

very effective tool in the bridge management system. An integrated methodology that uses the state-of-the-art indirect sensing capabilities and direct sensing NDE technologies to assess the cable conditions has been developed. A smart sensor system that would map the entire length of the cable was developed to provide an accurate and reliable condition assessment of suspension bridge cables. In addition to direct sensing technologies, an indirect sensing system was also developed, which consists of a

network of miniature sensors embedded deep within the cable monitor the internal environment of these cables and provide information that can be used to assess the potential for deterioration and its progression. This system was assembled and tested in both the laboratory as well as in the field.

2 SENSING TECHNOLOGIES

The objective of this research project was twofold: 1) to explore the most recent and promising NDE technologies for direct detection of the corrosion damage inside the main cables of suspension bridges and to select the most promising ones for further development and customizing for main-cable applications (Direct Sensing Method); and 2) to install a network of sensors that can monitor the external and by working few hundred feet above the roadway, with limited or no traffic disruption, in harsh environments, with limited power sources, and so on.

In the selection of the sensors to be used as Indirect internal environment of these cables and provide information that can be used to indirectly assess the cable's deterioration conditions and their progression over time (Indirect Sensing Method). (see Fig. 2).

The integration of indirect multimode sensing technologies and direct NDE technologies will allow us to make reasonable, cost-effective maintenance decisions. (see Fig. 4). To simulate conditions as close as possible to real operating conditions, a cable mock-up, 0.5m in diameter and 6m long subjected to dead load tension and fully instrumented, was built at Columbia University and was tested inside an accelerated corrosion chamber (see Fig. 3).

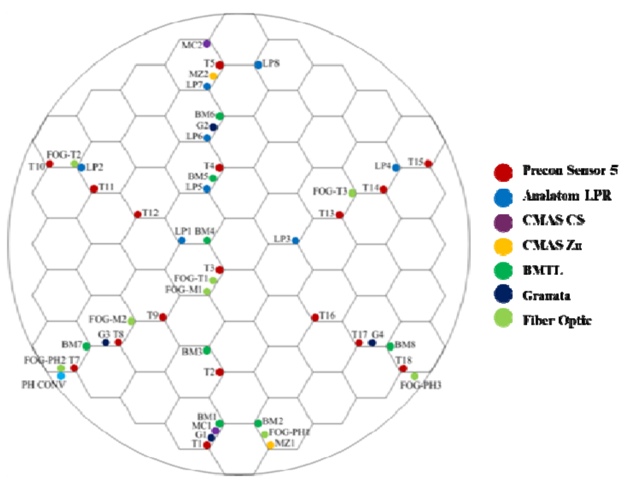

Figure. 2. A schematic drawing of cable cross section showing the embedded Precon temperature/humidity sensors and LPR/CMAS corrosion sensors and their distribution

Figure 3. Full scale cable mock-up, 6m long and 0.5m in diameter under tension is encased within a custom made corrosion chamber

The cable mock up was subjected to cyclic testing conditions consisting of high humidity (rain), heating and cooling representing the actual wet-dry cycle phases. A variety of sensors measuring temperature, relative humidity and corrosion rate was selected and integrated in one system that includes 76 sensors (see Fig. 2). Sensors were chosen after an extensive literature review that sought sensors that satisfied criteria related to: size, accuracy, resistance to compaction forces, environmental durability and sensitivity to environmental variables.

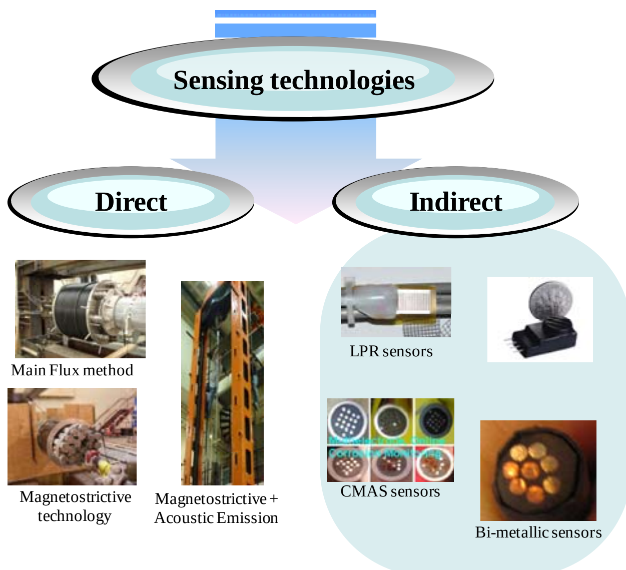

Figure. 4 Direct and indirect corrosion sensing technologies tested during the laboratory and the field phases

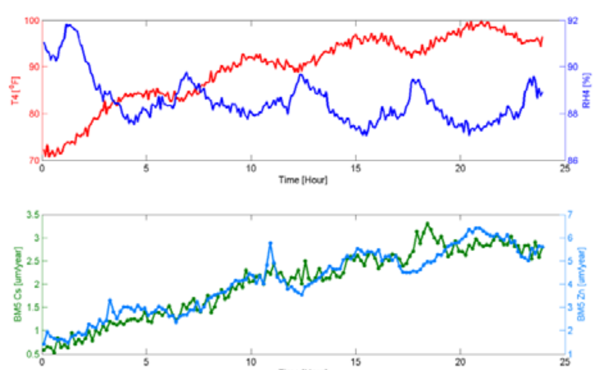

Fig 5. A direct data plot of temperature /humidity internal sensor (top) and corrosion bimetallic sensor (bottom) showing direct correlation between temperature, humidity and corrosion rate.

2.1 Indirect sensing technology

The HS2000V Precon sensor was chosen to measure temperature and relative humidity levels within the cable. The HS2000V provides both temperature and relative humidity readings accurate to ± 2%. The sensors may be used in an environmental operating temperature range of 0° to 70°C (32°F to 158°F) and an operational humidity range of 0-100%.

The second corrosion rate sensor considered in this study is CorrInstruments, Inc.'s Coupled Multiple Array sensor (referred to as CMAS). When covered by a corrosive aqueous solution, the CMAS sensors electrically connect anodic and cathodic sites of the same metal measuring the electron flows between the aforementioned sites and then converting them to non-uniform corrosion rates using Faraday's law. Upon completeion of the test all sensors survived as shown in Fig. 6.

Fig. 6. View of cable mockup during the after completing the test showing a temperature, humidity sensors which survived the harsh environmental test and compaction.

2.2 Cable Mockup

In order to test the effectiveness of the monitoring system, a full-size mock-up cable specimen was built and exposed to varying, controlled environmental conditions. The mock-up specimen was made with 73 hexagonally shaped strands, each consisting of 127-high strength steel wires, thus creating a cable with a 50.8 cm diameter and a cross-sectional area composed of 9,271 wires. Of the 73 strands, 66 measured 6.10 m in length, a length which is on the order of magnitude of the distance between two adjacent vertical suspenders. The additional 7 of the 73 strands were 10.67 m long; these strands were subjected to a tensile load that induced stresses in the wires up to 689.480 MPa (a stress level slightly higher than that experienced in service load conditions). This stress was used to highlight and eventually accelerate the phenomenon of stress-corrosion cracking.

Individual steel wires, with a 0.498 cm diameter, were galvanized by a Class A Zinc coating. The nominal ultimate tensile stress of the wires was 1,700 MPa, the yield stress approximately 1,400 MPa and the elastic modulus 200,000 MPa. The chemical composition of the galvanized wires was as follows: 0.80-081% carbon, 0.81-0.82% manganese, 0.23-0.27% silicon, 0.07-0.08% chromium, 0.06% nickel, 0.006% sulfur, 0.003% phosphorous and the remaining composite was iron. The compositions were within the typical ranges for high-strength bridge wires.

Following construction completion, the cable mock-up specimen was wrapped with an aluminum foil tape. The tape served as a wrapping for the high-strength steel wires, protecting them from direct contact with the environmental chamber's atmospheric conditions and simulating the protective action provided by wrapping wire or neoprene tape on actual suspension bridges.

2.3 Corrosion Chamber

An environmental chamber was built around the mock-up cable specimen (see Figure 3). The chamber was designed to expose the cable to controlled environmental conditions (simulated rain, heating and cooling) so to accelerate corrosion of the cable specimen, thereby assessing the functionality of the sensor network. Moisture was introduced into the system via water pumps and elevated punctured PVC piping so to simulate rainfall; midway through the test program, two openings in the wrapping were made on the underside of the cable to facilitate the influx of moisture to the inside of the cable mock-up. .Temperature increases were controlled with heat lamps located at the top of the chamber, with a cut-off temperature of 125°F, while an air-conditioning unit promoted temperature stabilization and decreases. A ventilation system allowed for increased control of the relative humidity levels within the chamber environment.
The cable mock-up specimen was exposed to a variety of cyclic environmental conditions, consisting of different combinations of acid rain, heat, air-conditioning, and ambient conditions.

2.4 Direct Sensing Technologies

2.4.1 Acoustic Emission

One direct sensing technologies tested was Acoustic Emission (AE) which is a powerful method for detecting wire breaks within the cable under stress. Acoustic Emission may be defined as a transient elastic wave generated by the rapid release of energy within a material, as shown in Figure 6. Materials produce AE when the local stresses around a discontinuity reach levels close to yielding. The high level of stresses can result in cracks growing, fibers breaking and many other modes of active damage in the stressed material.
Physical Acoustics Corporation has developed special instrumentation for the monitoring of suspension bridge cables these sensors were calibrated on the cable mock up.
A typical AE system consists of a piezoelectric sensor that detects the acoustic wave traveling through the material being tested and converts it into an electric signal, a preamplifier that adds gain to the electric signal and a A/D converter board where the signal is digitized and analyzed in both the time and frequency domains. By using several sensors distributed on the material under test, or along a suspension bridge cable, the sources of AE, such as wire breaks can be identified, detected and located even in the midst of background noise caused by bridge movement and traffic.

The AE SWII System was capable of detecting and accurately locating the wire breaks. The characteristics of the wire break signals were very different from background noise in their energy content. So they can be easily segregated. Although cylindrical and planar location provide excellent wire break position, within 1.5", they require a minimum of 4 sensors per cable band, which is not feasible in the field because of budgetary reasons. Linear location, on the other hand provides very good wire break position, within 1", along the length of the cable for R1.5I sensors and only requires 1 sensor per cable band

2.4.2 Magnetostrictive sensor (MsS)

The phenomena known as the magnetostrictive effect consist of a small change in the physical dimensions of ferromagnetic materials by the presence of a magnetic field produces and, conversely, a physical deformation or strain (or stress which causes strain) producing a change of magnetization in the material. Southwest Research Institute (SwRI) has developed technology based on Magnetostriction for inspection of pipelines and was adapted for use on steel cables in collaboration with Parsons on wire rope suspenders and strands used in traditional suspension bridges, for corrosion damage wires in the cable.

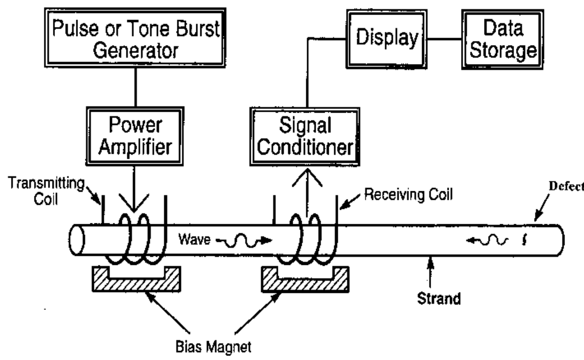

Fig 7. Magnetostrictive sensors system diagram

The sensor consists of two parts. One is a means for applying a time varying magnetic field or detecting a magnetization change in the material. This is most conveniently achieved by using an inductive coil that encircles a component under inspection. The other part is a means for providing DC bias magnetic fields to the component. This is achieved by using a permanent magnet. The DC bias magnetic fields are used to enhance the efficiency of the energy transduction between electric and mechanical energies and to make the frequency of the elastic wave follow that of the electrical signals and vice versa. When a pulse of electrical current is applied to the coil in the transmitting MsS, a time varying magnetic field is applied to the component under inspection. This field in turn generates a pulse of elastic waves in the component via the magnetostrictive. The generated elastic waves propagate in both directions along the length of the component. When the propagating elastic pulse reaches the coil in the receiving MsS, it causes a change in the magnetic induction of the material via the inverse-magnetostrictive. This change induces an electric voltage in the receiving coil that is subsequently amplified, conditioned, and processed.

3 FIELD PILOT TEST

3.1 Indirect Sensing

Upon the successful completion of the laboratory phase of testing the sensors, a refined setup of sensors distributed along 4 groove openings, namely the 12:00, 3:00,6:00 and 9:00 o’clock positions was selected for the field pilot program. Two 6 meter panels were selected on the cable. The cable was wedged at 4 groove position. (see Figures 8&9) both temperature/humidity and corrosion sensors were installed.

The sensors were wired to a data acquisition system located at roadway level with wireless modem which in turn transferred that data to secure server and then made available to all stakeholders via a secured web based portal.

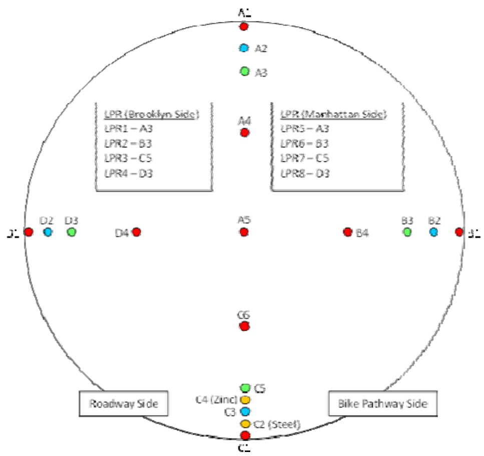

Fig. 8. Sensor distribution diagram within the cross section of the main cable.(grooves A,B,C &D) where A1, A4 and A5 are temperature/humidity sensors and A2 and A3 are corrosion sensors.

Fig. 9. View of indirect sensing sensors installed within the main cable at 4 groove positions and the direct sensing Main Flux scanner near the cable band.

4 CONCLUSIONS

The proposed sensor network system was successful in providing an understanding of the interior environment of a suspension bridge's main cable for the first time. The construction of an environmental testing chamber permitted the testing of various environments effecting the temperature, relative humidity and corrosion rate distributions within the mock-up cable. A corrosion rate analysis highlighted the distinct differences in the dependency of the corrosion process on the environmental variables of temperature and relative humidity. Increased levels of relative humidity resulted in increased levels of corrosion activity recorded by both types of

sensors. Furthermore, statistical analyses showed that the experimental dependence of corrosion rate values, as recorded by corrosion sensors, on temperature was strongly linear.
This system was installed on an in-service Manhattan bridge cable. Field testing was used to determine the real world functionality of the system and was proved successful.

The field pilot program was essential to validating the laboratory results and showed good correlation with the original assumptions.
Indirect sensing technologies can be useful in detecting the onset of corrosion as an early warning system and providing a corrosion rate for the first time on suspension bridge cable so that the remaining service life and factor of safety can be reliably calculated.
Also the internal sensors can be used for testing the reliability of a cable dehumidification system in case of pressure losses and leaks as well as dead zones along the cable. This information is valuable for providing the optimum life cycle cost of the dehumidification system in terms of operation and maintenance cost.
The direct sensing system can provide a qualitative assessment of the cable condition along its entire length so that a detailed inspection can be focused on the most critical segment of the cable. Also in some case where the cable is in poor condition it can provide a monitoring system until a repair is made.

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