NON-DESTRUCTIVE MONITORING AND ACTIVE PREVENTION OF CORROSION IN SUSPENSION BRIDGE MAIN CABLES

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Abstract

In this paper, the results of a multi-year project that led to the development of a corrosion monitoring system to be embedded inside a main cable are presented. A variety of state-of-the-art sensing and non-destructive evaluation technologies have been considered and tested, using a full-scale specimen of a suspension bridge main cable. The selected sensors were then installed on a main cable of the Manhattan Bridge in NYC and temperature, relative humidity and corrosion rate measurements were recorded for almost one year, collecting very interesting information on the internal environment of the cable. Such a monitoring system is currently being used in testing the effectiveness of the practice of cable dehumidification: while this technology has already been installed on real bridges, there is no experimental validation of its effectiveness.

Introduction

In the maintenance and rehabilitation of cable suspension bridges that have been in service for many years, the issue of the assessment of the remaining strength of the main cables is still unresolved.

Currently, all state and local agencies responsible for the maintenance of suspension bridge cables base their maintenance plan mainly on previous experiences and on limited information from limited inspections. Usually, exterior covering of the cable are visually inspected biannually. If such inspections reveal some deterioration problems, main cables undergo "in-depth" inspections if the maintenance budget allows for such undertaking. The cable is then unwrapped at a few locations along the cable length and is wedged into its center. After this, a visual inspection of the wires' conditions is performed and, in some cases, a few wires are cut and removed for laboratory testing. As a result of the NCHRP Project 10-57, guidelines for inspections have been developed so as to standardize such cable inspections.

In-depth inspections of cable systems in aging suspension bridges in the New York metropolitan area and in the North-East of the United States have shown that 1) there is often water trapped inside the cable, with a pH as low as 4, and 2) there are broken wires (in some cases up to 300 broken wires in between two cable bands) inside the cables and at the anchorages (Betti and Yanev, 1999), indicating brittle fractures and extensive corrosion (see Figure 1). These alarming findings are inexplicable and the reason of the presence of such broken wires must be found in the complex deterioration process within a main cable. In fact, while the effects of corrosion on ordinary structural steel can be mainly characterized by the loss of material and by the ensuing reduction of the cross sectional areas of members, the

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failure of high-strength bridge wires manifests itself, in addition to the loss of material, in a number of related phenomena referred to as stress corrosion, corrosion cracking, corrosion fatigue, and hydrogen embrittlement. These phenomena appear to have a much more detrimental effect on the strength of wires than just the reduction of the wire's cross section area and play a fundamental role in the difficult task of determining the "actual" strength of bridge cables.

Figure 1: Broken wires in a suspension bridge main cable

Unfortunately, current visual inspections can provide neither an adequate amount nor sufficiently reliable data that can be used for an accurate estimation of the remaining strength of a deteriorated main cable. A natural progression towards the use of Non-Destructive Testing (NDT) methods and enhanced sensing technologies to assess a cable's remaining strength results from the downfalls of present inspection techniques. Sensing technologies measuring environmental variables directly related to high-strength steel corrosion, such as temperature and relative humidity, may provide engineers with an evolving portrayal of the cable's conditions and help them formulate a more "informed" assessment of the cable's condition and its maintenance needs.

In this paper, the results of a multi-year research project on the development of a corrosion monitoring system for main cables of suspension bridges and its application to assess the effectiveness of the cable dehumidification practice are briefly presented. This monitoring system has been tested on a full scale cable mock-up in the Carleton Laboratory at Columbia University as well as in service conditions on one of the main cables of the Manhattan Bridge in NYC.

Corrosion Monitoring System

To select the most appropriate technologies to be used in such a study, a complete survey of the available corrosion monitoring techniques and sensors was conducted. The goal was to find out about the state-of-the-art of the currently available sensor technologies, especially corrosion monitoring techniques, and to see whether these sensors/technologies could be applied to the monitoring of main cables in suspension bridges. Technologies were classified into two categories: 1) Indirect Sensing Technologies and 2) Direct Sensing Technologies. With the term "Indirect Sensing technologies", we indicate all sensors and technologies that measure quantities that can be either directly (e.g. corrosion rate) or indirectly (e.g. temperature) related to corrosion of the wires. Direct Sensing technologies, instead, represent those technologies that can directly measure the effect of corrosion on the cross-section of the cable (e.g. magnetic flux measurements can be directly correlated to the cross-section of the specimen).

Various types of sensors that satisfied criteria related to size, accuracy, resistance to compaction forces, environmental durability and sensitivity to environmental variables, etc. were selected and tested. First, such sensors were tested in an accelerated corrosion chamber and then placed inside the cable specimen. Among the sensors selected, there were HS2000V Precon sensors (to measure temperature and relative humidity levels), Analatom Linear Polarization Resistance sensors and the CorrInstruments Coupled Multiple Array and Bimetallic sensors (to measure corrosion rate). A total of 72 sensors was placed inside the cable specimen in an arrangement shown in Figure 2:

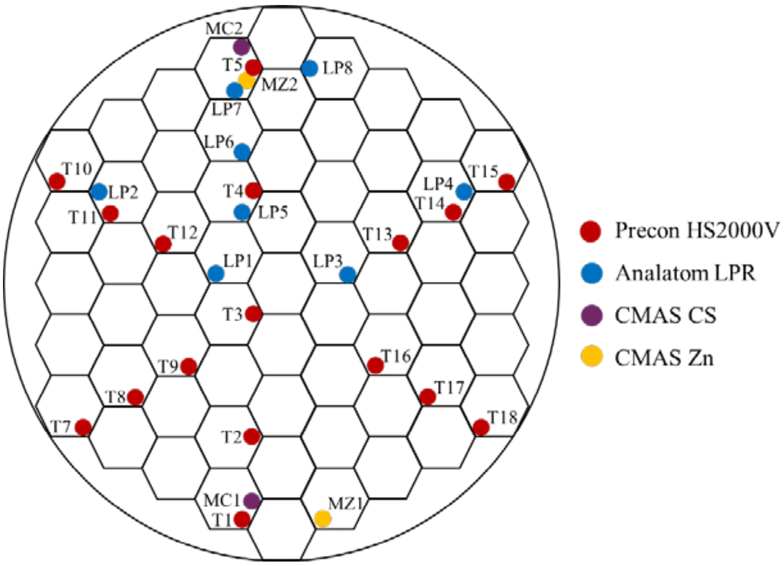


Figure 2: Schematic representation of sensor distribution inside the cable specimen

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 while the remaining 7 were 10.67 m long; these long strands were subjected to a tensile load that induced stresses in the wires up to 700 MPa so to highlight and eventually accelerate the phenomenon of stress-corrosion cracking. An environmental chamber was built around the mock-up cable specimen so to expose the cable to controlled environmental conditions (simulated rain, heating and cooling) in order to assess the functionality of the sensor network. Figure 3 shows the full-scale cable specimen with the environmental chamber.

Figure 3: Cable mock up and environmental chamber

Results from Laboratory Testing Program

After the cable mock-up was built, a long series of cyclic corrosion tests was planned with the purpose of testing the sensors that were part of the proposed corrosion monitoring system. These tests consisted in subjecting the cable specimen to cycle of rain, heat and cooling of different duration: each experiment lasted for many days and, at the end of each test, measurement data were analyzed and, if necessary, changes of the test conditions were made. The total duration of this experimental phase lasted about a year.

During each test, the temperature, relative humidity and corrosion rate were recorded at various locations in the cable cross-section so to have an experimental image of the distributions of temperature, relative humidity and corrosion activity within the cable. Figure 4 shows the recorded measurements of the temperature inside the cable specimen along a vertical radius during a test consisting of a series of 4-hour rain-heat-air conditioning cycles (Sloane et al. 2013). From these measurements, it was concluded that, with greater distance from the heat source, the temperature variations within the cable's cross-section diminish with respect to the outside temperature. Maximum temperatures within the cable did not reach levels as high as those recorded in the chamber and temperature fluctuations decreased with increased distance from the heat source. The upper outer region showed substantial temperature fluctuations whereas near monotonic increases in temperature occurred in the center of the cable. Average temperature gradients found during the heating phase of each cycle prove that the cable heated evenly with maximum heating rates being obtained at central vertical locations. Lastly, the time to which the cable interior was affected by temperature fluctuations increased with greater cable depth.

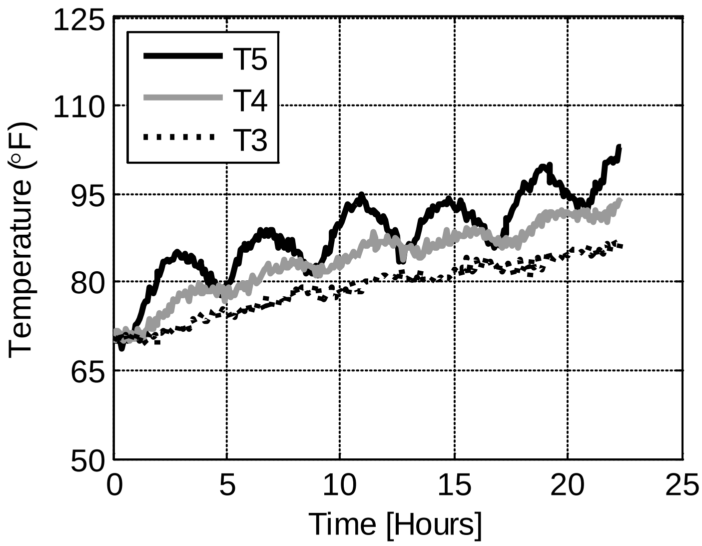


Figure 4: Temperature vs. time plot along the vertical radius

Much more complex is the interpretation of the relative humidity data because, while the temperature data lends itself to a collective analysis, general trends are not as identifiable in the relative humidity data. This is because water can penetrate inside the cable from many different locations and can find many different paths to spread in between the many wires and reach the sensors at different times. However, some "very general" trends can still be found and provide useful information on the good functioning of certain sensors.

Looking at the data recorded by all the various sensors, it can be concluded that increased levels of relative humidity results in increased levels of corrosion activity, as recorded by different types of corrosion sensors. Statistical analyses showed that the experimental dependence of corrosion rate values, as recorded by LPR sensors, on temperature was strongly linear.

With regard to the Direct Sensing technologies tested (Main Flux and Magnetostrictive technologies), none of them showed to be ready for field applications, even though some have great potential for future applications. In the specific problem in question, the size of the main cable is the main road block for their immediate applicability, tied to logistical (large magnetic fields) and sensitivity (detection of small wire breaks) constrains.

System Installation in one of the Main Cables of the Manhattan Bridge

Once the laboratory testing phase was completed, the entire system was installed inside two cable panels of the Manhattan Bridge in New York City. Built in 1912, this suspension bridge is one of the main traffic arteries between Manhattan and Brooklyn. Spanning over a length of 2089 m. with a central span of 448.1 m., this bridge carries a daily traffic flow of over 72,000 vehicles per day. There are 4 main cables, each made of 37 strands of 256 wires each, for a total of 9,472 wires bundled in a cable of a 21-in. diameter. The number of wires and the corresponding cable diameter of one of the Manhattan Bridge cables are quite close to the number of wires and cable diameter of the cable mock up tested in this study.

In each of the two panels, the main cable was wedged at 4 groove positions along the circumference and 19 sensors per panel were installed inside the cable. These sensors consist of temperature/relative humidity sensors and of three types of corrosion rate sensors. The data collection lasted about 11 months, at the end of which, the monitoring system was removed.

The data collected by the 38 sensor network provided a quite unique, real time picture of the internal environment of the cable, which is an important key to understanding corrosion in suspension bridge cables and can help develop a cost effective mitigation strategies. For example, it was extremely interested to see the variation of the temperature and relative humidity inside the cross-section of the cable in service conditions. Figure 5 shows the distribution of the maximum and minimum temperature and relative humidity over the entire cable cross section recorded on different days during the year. These maps show clearly that the distribution of temperature and humidity is not uniform across the cable cross section and that the bottom and shaded side portions of cable are likely to retain higher levels of humidity than the upper portion. Moreover, there are higher temperature and lower humidity during the day. In addition, when comparing the humidity levels between summer (August) and winter (January), it confirms that the internal relative humidity level is higher in the winter months than during summer months. An interesting observation is that, during the spring months when the temperature range is between 49^{o}F and 60^{o}F and the relative humidity between 40% - 95%, the internal cable environment is the most conducive to corrosion, with high level of humidity and with daily temperature cycles between day and night.

With regard to the corrosion rate sensors (Analatom LPR, CorrInstruments CMAS and Bi-metallic), all the sensors provided some useful and consistent measurement of corrosion activity. For example, all sensors showed that no corrosion activity was detectable when the relative humidity was below 45%.

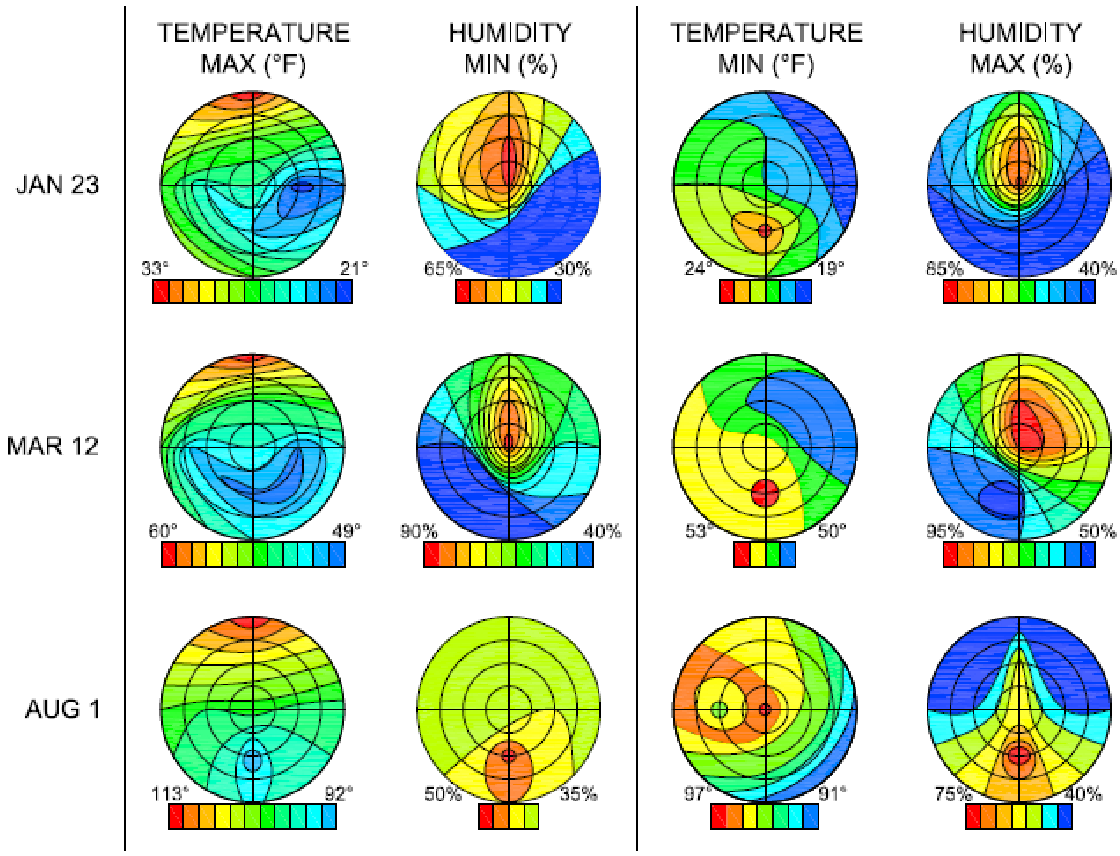


Figure 5: Distribution of Temperature and Relative Humidity inside a Main Cable

<u>Testing the Effectiveness of the Dehumidification "Practice"</u>

Having a monitoring system that can measure the distribution of temperature and relative humidity inside a cable allows us to test how effective the current practice of cable dehumidification is. Today, there is a trend of installing dehumidification systems that, when needed, inject dry air inside the cable, with the goal in mind to keep the humidity level inside the cable below 40%. The need for the system's activation is regulated by measuring the humidity of the outflow air at some specific locations along the length of the cable: such a measurement, based on the results obtained from the field investigation presented before, could be misleading. In fact, this measurement could not be representative of the complex humidity pattern inside the cable (see Figure 5).

To study how effective the dehumidification system is, the full-scale cable mock-up has been redesigned (Figure 6) so to accommodate a cable dehumidification system and a new series of tests have been planned.

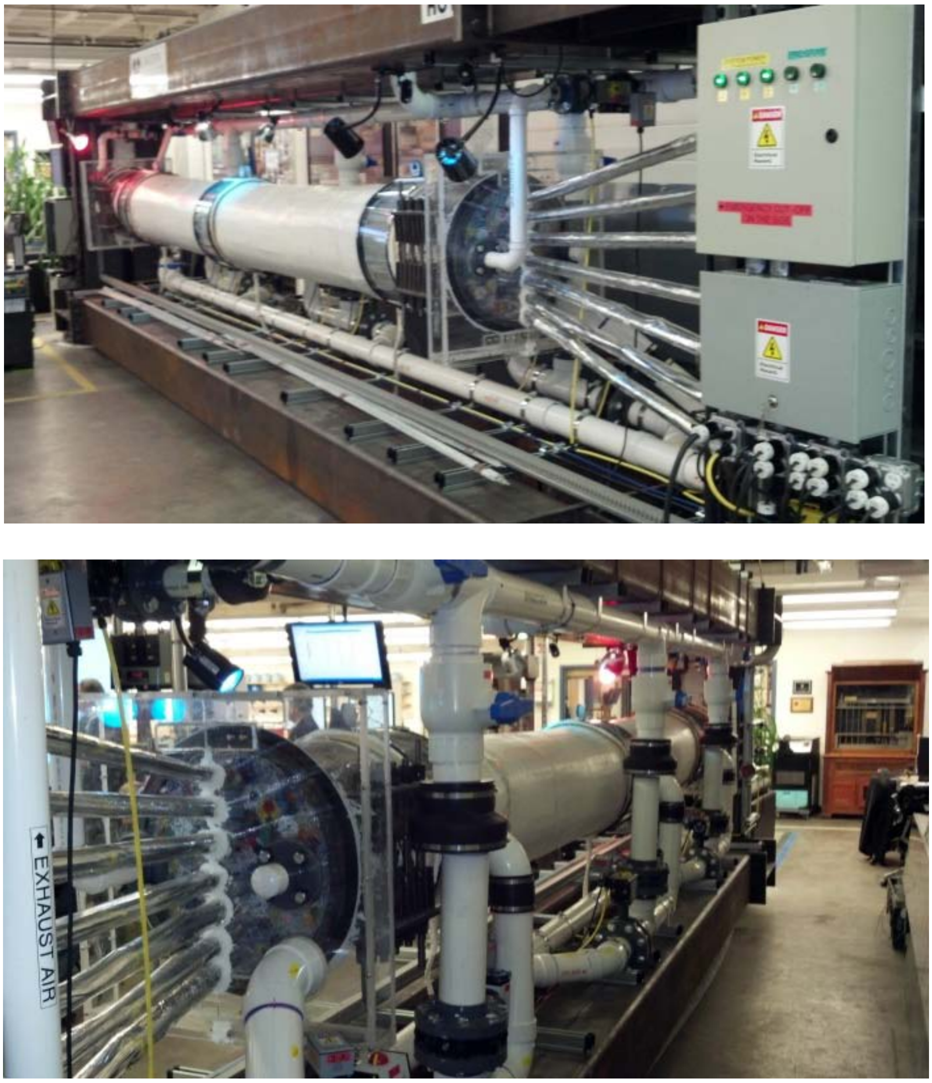


Figure 6: Front and Back View of the Cable Mock-up with Dehumidification System

In each test, first, the level of the relative humidity is elevated to a high value (above 90%) practically constant over the entire length of the cable specimen, and then dry air is injected inside the cable through a set of injection ports.

The cable specimen has been enclosed through a combination of D.S. Brown's Cableguard® Elastomeric Cable Wrap System and custom made PLEXIGLAS ports and end boxes manufactured in the Carleton Laboratory at Columbia University. Inlet/outlet ports have been placed at the center as well as at each end of the cable specimen so to allow for different injection-exhaustion configurations. The cable system has been humidified by two Nortec RH2 Space humidifiers, blowing humid air through Direct-Drive Corrosion-Resistant 10" duct fans with airflow 620 cfm @ 1/8" static pressure and 565 cfm @ 3/8" static pressure, and dehumidified by pumping dry air from a Honeywell DH150 Dehumidifier (with the flow also boosted by the Direct-Drive Corrosion Resistant 10" duct fans). Figure 7 shows a schematic representation of the humidification/dehumidification system set up.

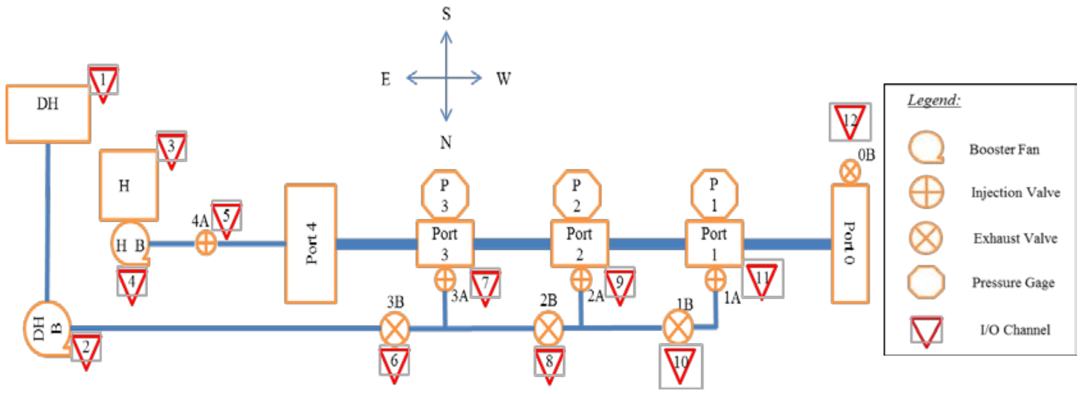


Figure 7: Schematic representation of Humidification/Dehumidification System

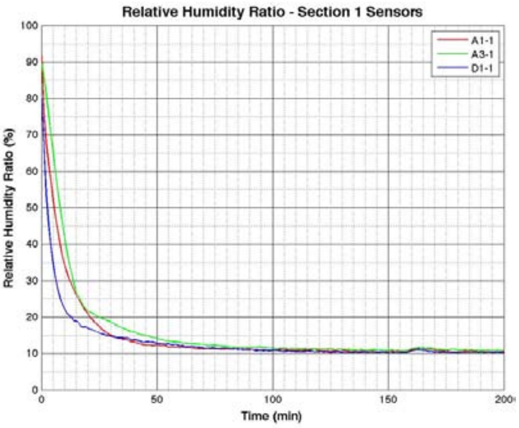
The monitoring system consists of 39 temperature and relative humidity sensors placed at three locations along the length of the cable specimen (center and both ends). At each location, the 13 sensors have been placed along three diameters, spaced at about 180^{o} from each other, so to have a overall picture of the distribution of temperature and relative humidity over the entire cable cross-section.

Preliminary Results from Dehumidification Tests

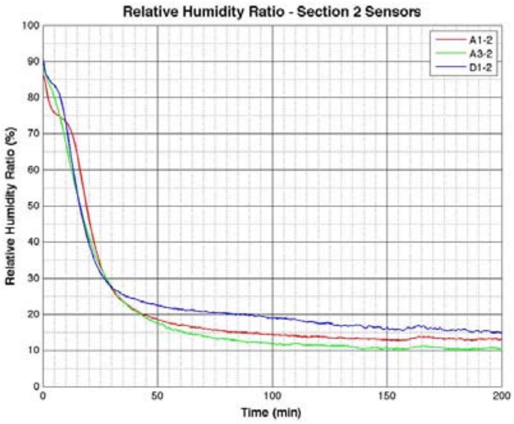
At the time of the writing of this paper, the series of the dehumidification tests is still ongoing and the data are still being analyzed. However, there are some preliminary data worthy of our attention that could lead to interesting results.

Figure 8 shows the time variations of the relative humidity recorded at different depth along the vertical diameter (just below the cable surface (A1), at the center of the cross-section (A3) and at the bottom of the cross-section (D1)) for the three different cross-sections where the sensors are (Figure 8a at the injection port, Figure 8b at the center of the cable's length and Figure 8c at the exhaust port).

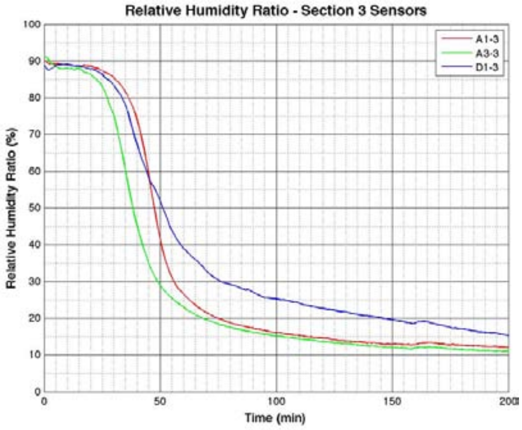
These results seem to confirm some of the expectations the dehumidification system is supposed to provide. First of all, as expected, there is a time lag, among the three cross-sections, for the time at which the relative humidity is dropped below 40%: from almost constant level of 90% relative humidity over the length of the cable, the system very rapidly reduces the humidity level at the injection port (less than 15 minutes) but it takes almost an hour to reach the same level at the farthest cross-section. It is also interesting to see the pattern in which dehumidification occurs within cable cross-sections: in the injection port, the outer areas of the cable are dehumidified faster than the core of the cable. This is expected because, at the injection port, the dehumidified air can freely move around the cable, affecting first the outer areas and then the center. However, once the dry air is in the cable, it is pushed by the ventilation system along "preferential" routes that depend on factors like cable compaction, wire misalignment, presence of corrosion products, etc.. These effects change the pattern with which the cross section is dehumidified: in fact, for the other cross sections (at mid length and at the other end), it appears that the core is dehumidified first and then the surroundings (in Figure 8(c), sensors A3 shows a faster drop of relative humidity with respect to the outer sensors (A1 and D1)).



(a)



(b)



(c)

Figure 8: Plots of Relative Humidity vs. Time: Input in Port 1 and Exhaust in Port 3

These different patterns are a clear indication that the assumption of uniform dehumidification of the cross-section should be taken quite loosely, since the pattern is affected by factors that are quite different to quantify a priori. Even within a cross-section, as shown in Figure 8(c), different locations in a cross-section could reach the same level of humidity at different times: for example, the center and the lower portion of the cross-section reach the same 40% relative humidity threshold with a time lag of 20 minutes over a 1 hour test.

Another interesting aspect that needs further attention is concerning about the effectiveness of the dehumidification practice at low temperatures. When the system operates at much lower temperatures, the effectiveness seems to be drastically reduced. Figure 9 shows the same relative humidity-time diagram for same test conditions as in Figure 8(a) but conducted at a lower temperature (around 0^{o}C).

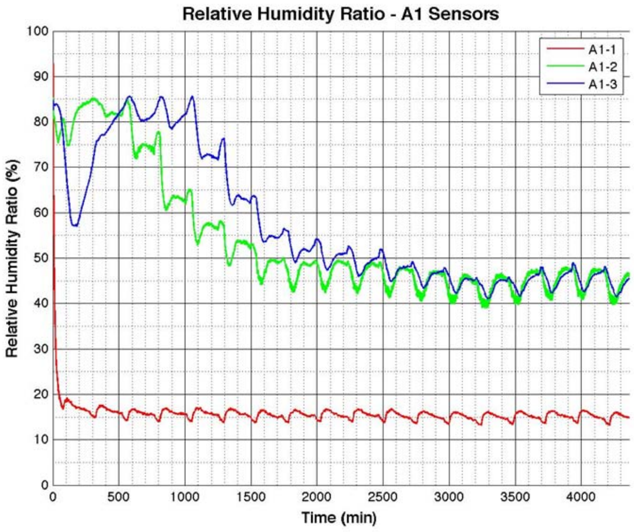


Figure 9: Relative humidity vs time at the injection port during a low temperature test.

Here, the plots of the relative humidity vs time recorded at the top sensors along the length of the cable specimen are presented and a puzzling result appears. From a preliminary analysis, it seems that the dehumidification system is not capable of bringing the relative humidity level down below 40% for cross-sections different from the injection one. While the system is very effective, as expected, in decreasing the level of relative humidity at the injection location, the dry air cools off when moving along the length of the cable and is not as effective as before in reducing the level of humidity away from the injection point. This could have implication on how to run a dehumidification system during the winter season. However, these are just preliminary results of a test program that is currently ongoing and general recommendations will be provided at a later time.

Conclusions

In conclusion, this study demonstrates that it is possible to measure corrosion activity inside the main cables of suspension bridges. The selected sensor network system was successful in providing information on the interior environment of a suspension bridge's main cable, helping understanding the conditions in which main cables of suspension bridges operate. The information provided by such a system can be used to make more reliable estimation of the safety factor and remaining service life of such important structural elements as well as to help bridge engineer in conducting more efficient and cost-effective inspections. The sensor system developed in this study represents a unique tool for testing the effectiveness of the cable dehumidification practice, practice that, although implemented already, has no experimental validation.

Acknowledgements

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