WIRELESS SENSOR NETWORKS TO MONITOR CRACK GROWTH ON BRIDGES

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INTRODUCTION

This paper describes the design and testing of a proof-of-concept instrumentation system that uses a wireless sensor network to monitor the growth of cracks in bridges. At present, crack growth is recorded qualitatively as part of bridge inspections that occur at least every two years. This wireless system can continuously and automatically measure the elongation of cracks, allowing quantitative measurements of crack growth of a bridge to be recorded over periods of months or years. This system is weather-resistant, battery-powered, and capable of solar recharging. It can be connected to the Internet to allow remote monitoring of real-time data, access to historical data, and timely e-mail alerts of significant crack growth. The next iteration of this system will provide a reliable stream of information to supplement standard bridge inspection practices and further ensure the safety of the travelling public on our nations bridges.

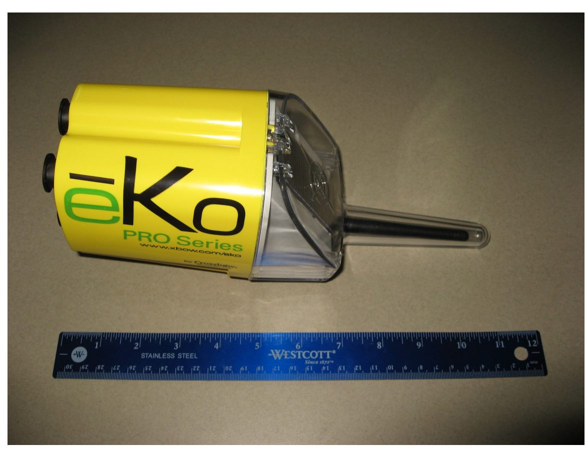
WIRELESS SENSOR NETWORKS

Wireless sensor networks (WSNs) are composed of several nodes, typically known as “motes.” Each mote is equipped with a radio, a power source (usually a battery), a microprocessor, specialized software, and usually one or more sensors. When deployed, a mote will record data from its sensors and transmit these data to a base station for processing or storage. The base station is typically not designed to be battery-powered and must be deployed in a location where reliable electrical service is available. In many cases, the communication range of the WSN can be extended by configuring the motes to form a mesh network over which data are transmitted through several “hops” before reaching the base station.

ēKo Motes

The ēKo Pro Series WSN, commercially produced by Crossbow Technology, Inc., is specifically designed for use in environmental and agricultural monitoring. Each ēKo mote is water and dust resistant, capable of operating in wide temperature and humidity ranges, and will operate for over five years with sufficient sunlight (*1*). The ēKo base station can send out e-mail alerts when sensor readings cross programmable thresholds. The ēKo WSN’s robust design makes it an attractive platform for deployment in the harsh operating environment of an in-service highway bridge. It is equally important that an ēKo mote end-user need not manually program the system to function properly, as this functionality is attractive to bridge engineers.

(a)



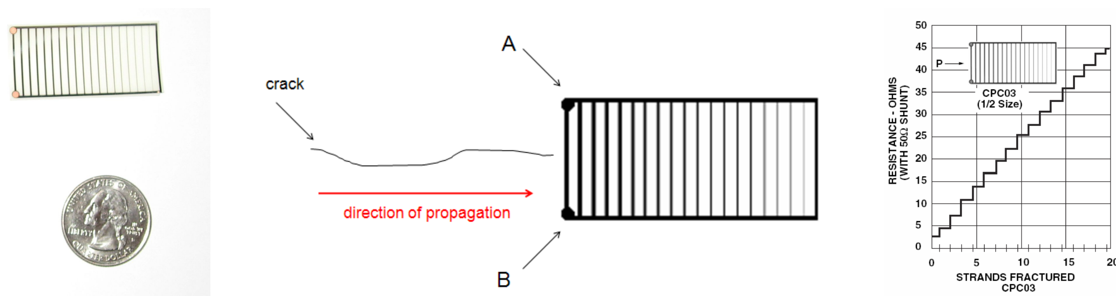
(b)

FIGURE 1 (a) ēKo Pro Series WSN including base station(*1*). (b) Individual ēKo mote with a 12-inch (30-cm) ruler for scale.

Crack Propagation Sensor

Several techniques exist to detect the growth of a crack electronically, including acoustic emission monitoring (*2*), or observing changes in the width of a crack (*3*). Direct measurement of elongation of a crack is possible using a *crack propagation pattern*: a brittle, paper-thin coupon containing a ladder-like pattern of electrically conductive material. When such a sensor is bonded to a section of material near the tip of a crack, as shown in Figure 2b, the individual rungs of the sensor will break as the crack passes through them. This will change the electrical resistance measured between the sensor's two terminals, as shown in Figure 2c.

Vishay Intertechnology, Inc. commercially manufactures a series of these crack propagation patterns. A Vishay TK-09-CPC03-003/DP crack propagation pattern, shown in Figure 2a, was chosen due to its linear resistance change in response to crack propagation. This gage is 0.0017 inches (0.043 millimeters) thick and can measure crack propagation in increments of 0.08 inches (2.03 millimeters) (*4*).



(a) **(b)** **(c)**

FIGURE 2 (a) Photograph of crack propagation pattern with quarter for scale. (b) Measure resistance between points A and B. (c) Resistance can be correlated to number of broken sensor rungs (*4*).

Interface between ēKo Mote and Crack Propagation Pattern

The ēKo Pro Series WSN is designed to be used with sensors that communicate over Crossbow's *Environmental Sensor Bus* (ESB). The ESB protocol (*5*) describes a specific connector type, power supply, and digital interface scheme that must be implemented by the sensor manufacturer if that sensor is to be used with an ēKo mote. The crack propagation patterns used in this experiment are not compliant with the ESB, so a customized interface cable was created.

The custom interface cable is composed of a Maxim DS2431 1024-Bit 1-Wire EEPROM, a Switchcraft EN3C6F water-resistant 6-conductor connector, a length of Category 5e sold-conductor cable, one 374Ω precision resistor and one 49.9Ω precision resistor. The EEPROM was soldered into the water-tight connector housing as shown in Figure 3a. The EEPROM allows the sensor to respond with a unique sensor identifier when queried by an ēKo mote such that the sensor will be properly identified and configured automatically by any mote on the WSN to which it is attached. After the EEPROM was mounted in the connector housing, the individual cable leads were attached and the water-tight cable assembly was completed as shown in Figure 3b. This cable can now be connected to any input port on any ēKo mote. Because the crack propagation pattern is a purely resistive sensor, two precision resistors must be used to create a circuit that can convert the resistance output into a voltage that the ēKo mote can read. The ēKo mote is able to supply a 3VDC regulated excitation voltage to the sensor which has a nominal resistance of 3Ω when fully intact, and behaves as an open-circuit when fully broken. Thus, the 49.9Ω resistor was placed in parallel with the two terminals of the crack propagation pattern while the 374Ω a resistor was placed in series with the mote itself. This circuit then causes each rung break to register an increase of approximately 10 millivolts on the ēKo mote. Figure 3c shows the circuit diagram. These resistors were placed within the cable itself so that two leads could be simply soldered to the two terminals of the crack propagation pattern.

PROOF-OF-CONCEPT TESTING

A laboratory test was performed to show that the ēKo mote can measure and record the propagation of a crack. A crack propagation pattern was bonded to a small test coupon composed of A36 steel. This coupon was fabricated with a wire-cut notch such that when the coupon was properly manipulated in a materials testing apparatus, a crack would grow and propagate through the portion of the coupon to which the sensor was attached. The testing apparatus applied force to the coupon by applying and releasing tension through two circular attachment points at the top and bottom of the test coupon. All displacements and forces are measured with respect to these two points.

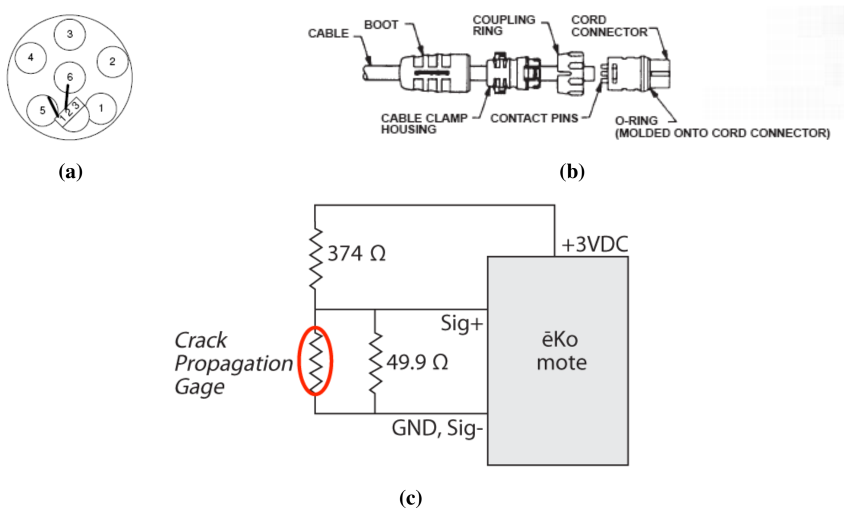


FIGURE 3 (a) Schematic of EN3C6F connector housing with EEPROM mounted (*5*). (b) Water-tight cable assembly (*7*). (c) Diagram of sensor readout circuit, adapted from (*4*).

Experimental Procedure

Before the sensor was bonded to the test coupon, the coupon was subjected to a pre-cracking procedure under the assumption that any crack to be instrumented in the field would have begun to grow before the sensor could be affixed. During the pre-cracking procedure, the relative displacement of the attachment points was cycled between 0.60 mm (0.24 in.) and 0.04 mm (0.0016 in.) at a frequency of 10 Hz until a crack was observed to be growing from the tip of the wire-cut notch. Approximately 10,000 cycles were required to initiate crack growth.

The selected crack propagation pattern was slightly too long for the test coupon. The total length was reduced by removing the three rungs farthest away from the initial crack tip. Due to the purely resistive nature of the crack propagation pattern, this modification did not affect its performance. After completion of the pre-cracking procedure, the crack propagation sensor was affixed using elevated-temperature-curing epoxy adhesive, per the manufacturer's instructions (*4*). Auxiliary terminals were affixed to the coupon for strain-relief. Figure 4 shows the completed coupon just before testing.

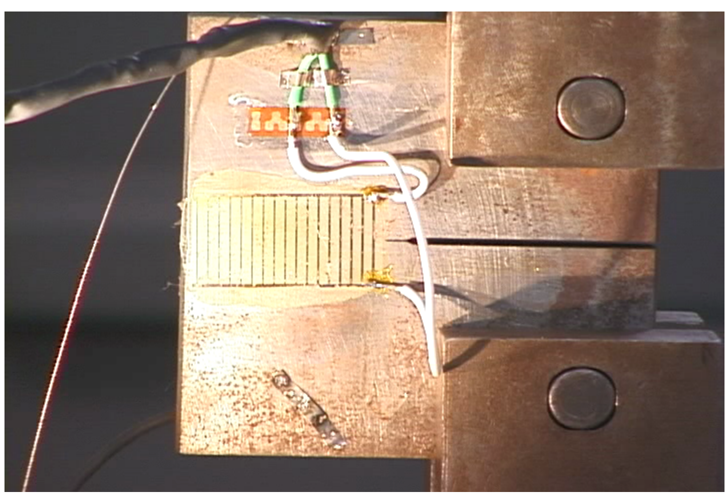


FIGURE 4 Completed test coupon mounted in test apparatus.

The test procedure consisted of cycling the load applied to the attachment points between 11 KN (2.5 kip) and 3 KN (0.07 kip) at 10 Hz. As the crack progressed, the frequency was reduced to maintain the peak load. The test was concluded when the test apparatus was no longer able to maintain the peak at a frequency of above 1 Hz.

RESULTS

During the approximately 80-minute test, cyclic loading of the coupon between between 11 KN (2.5 kip) and 3 KN (0.07 kip) at decreasing frequencies caused a crack to propagate through eight rungs of the crack propagation pattern. Figure 5 shows a plot of voltage versus time as measured at 15-second intervals by the ēKo mote. Figure 6 shows the progress of the crack through the test coupon.

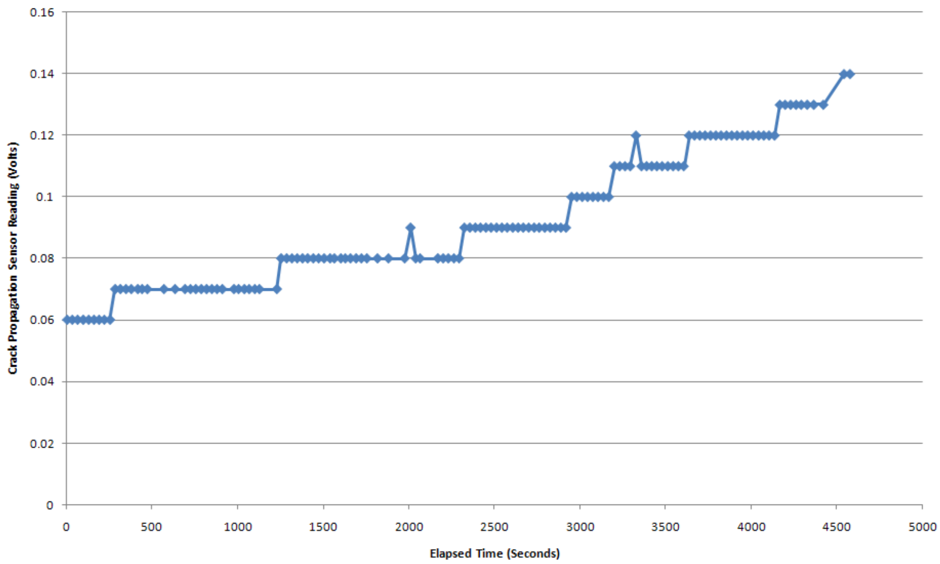
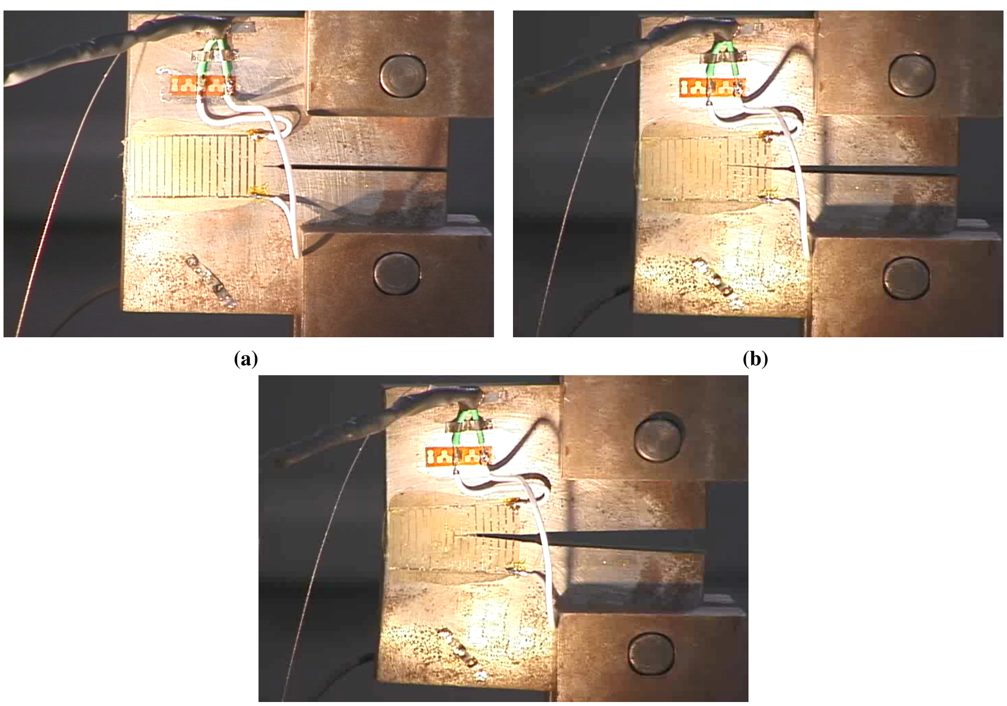


FIGURE 5 ēKo mote reading of voltage versus time.



(a) **(b)**

(c)

FIGURE 6 (a) Test coupon with no crack. (b) Test coupon with six broken rungs. (c) Test coupon with eight broken rungs.

DISCUSSION

During the test procedure, eight individual rungs of the crack propagation pattern where observed to have broken as a crack propagated through them. Figure 5 clearly shows eight individual 10-millivolt changes in the output of the sensor during the cyclic loading of the test coupon. Since the ēKo WSN is capable of sending out e-mail alerts when data readings cross a specific threshold, the system can clearly be used to alert proper personnel should a crack in a bridge begin to grow.

Though this proof-of-concept test showed that the ēKo WSN combined with crack propagation pattern is capable of detecting and recording crack growth in steel, deploying such a system in the field raises a new set of challenges, most notably sensor geometry and adhesion to the substrate.

The manufacturer indicates that elevated-temperature-curing adhesives are necessary to achieve proper functionality of the crack propagation pattern. On a small steel coupon, elevating the temperature is trivial and can be accomplished with a laboratory hot plate. In the field, however, raising the temperature of a member of a steel bridge may be difficult or impossible. This raises the need to explore other adhesive options for the crack propagation pattern.

The geometries of these crack propagation networks are predetermined and fixed by the sensor manufacturer. These shapes are only sufficient to measure crack propagation in one direction over a short distance. Different, more customizable sensors may be necessary to monitor cracks in certain deployment scenarios.

CONCLUSION

Based on the experience of this work, it can be concluded that a commercially-available wireless sensor network can be combined with commercially-available crack propagation sensors to create a system capable of alerting authorities to the growth of cracks in steel structures, but more development will be necessary to make the sensors suitable for practical use in the field.

ACKNOWLEDGMENTS

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