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TOWARD FIELD IMPLEMENTATION OF CARBON NANOTUBE-BASED COMPOSITES FOR MONITORING AND REPAIRING FATIGUE DAMAGED STEEL STRUCTURES

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ABSTRACT

Fatigue damage of steel structures is one of the major reasons for deficient infrastructure. Adhesively-bonded fiber reinforced polymer (FRP) materials are an excellent candidate for repairing these fatigue-damaged structures. However, one of the major drawbacks of this repair scheme is that its visual inspection is difficult. Our research group developed and experimentally evaluated a novel configuration of FPR sheets by embedding a carbon nanotube (CNT)-based sensing layer in the adhesive joint, allowing condition monitoring capabilities. We have also found that the CNT sensor can be employed individually to detect and continuously monitor a fatigue crack. For the field implementation of this innovative fatigue crack sensor, we have developed and evaluated a protective layer for the sensor and a low-cost and reliable data acquisition system.

Keywords: steel structure, fatigue crack, structural health, monitoring, carbon nanotube sensor.

1. INTRODUCTION

ASCE's 2017 Infrastructure Report Card shows that one out of eleven bridges in the United States is structurally deficient. Corrosion and fatigue are two common reasons for the deterioration of bridges. It has been predicted that the majority of existing steel bridges have fatigue-prone details [1]. Given the significant budgetary constraints, maintaining these deteriorated bridges has been one of the major challenges. For repairing fatigue-damaged steel structures, adhesively bonded fiber reinforced polymer (FRP) composite materials have been proven to be an excellent candidate. However, the brittle debonding failure mechanism and the challenge to monitor debonding are major obstacles to deploy this repair technique in the field reliably. Also, the FRP repair scheme hides the damage, preventing visual inspection. Our research team has been developing and experimentally evaluating a repair and monitoring methodology for fatigue-damaged steel structures by integrating FRP sheets with carbon nanotube (CNT)-based sensing fabrics to mitigate these challenges. The advantage of our proposed methodology is that it can both significantly extend the fatigue life of a fatigue-damaged structure and simultaneously provide real-time feedback regarding fatigue crack activities underneath the FRP patch [2, 3]. Also, a CNT-based sensing layer in this scheme can effectively monitor debonding without diminishing the effectiveness of the repair [4, 5]. Finally, we have found that a CNT sensor can be employed individually to detect and continuously monitor a fatigue crack [3].

Currently, we are designing and evaluating a field-deployable system. The objective of this work is to find a suitable environmental protective coating for the CNT fatigue sensor and develop a low-cost and reliable data acquisition (DAQ) system.

2. SELECTION AND EVALUATION OF PROTECTIVE COATING

Our CNT-based fatigue sensor consists of a porous aramid veil coated with the CNT sizing agent [2, 6]. The sensor needs to adhere to the structure firmly to monitor the fatigue crack in it. A propagating fatigue crack in the substrate fragments the CNT sensor, thereby changing its electrical properties. Details of the sensing mechanism to monitor fatigue cracks can be found in Ahmed et al. 2018 [2]. Two-part epoxy paste adhesive (HYSOL 9309.3NA) has been used to bond the CNT fatigue sensor on the substrate using the vacuum bagging technique. A surface tomographic approach has been used to examine the porosity of the sensor surface. Figure 1 (a) shows a CNT sensor bonded to a steel substrate using vacuum bagging. Vacuum pressure infuses the CNT sensor and creates a thin layer on top of the sensor as shown in Figure 1 (b). The blue dash-dot line in Figure 1 (c) shows the top surface of the sensor, and the yellow curve shows the contour of the red line in Figure 1 (b). Thus, if the yellow curve falls below the green dash-dot line that indicates a percolating path exists in the thin layer adhesive. From these

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observations, we have found that the thin top adhesive layer is porous. Therefore, the sensor needs a protective coating.

The protective coating should have excellent water and chemical resistance and should be highly flexible so it remains waterproof as the fatigue crack propagates underneath it. Also, the coating should be transparent to allow visual inspection. Silicones are good candidates for the following reasons: transparent silicone pastes consist of only Si-O linkages and cure at room temperature, they are highly flexible and permit 25% permanent deformation, they remain flexible at low temperatures (as low as -40 ºC), they have excellent weather resistance and excellent resistance to chemicals, and they shrink a minimum amount during the curing process.

To evaluate the performance of the selected protective coating, a thick silicone layer was applied (see Figure 1 (d)) to prevent fluids from percolating through the paths on the thin adhesive surface. Figures 1 (e) and (f) show the surface contour of the coating that indicates the surface is impermeable.

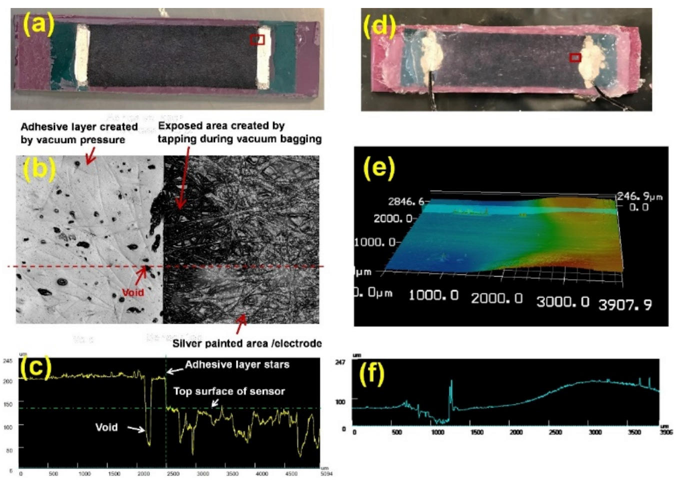


FIGURE 1: (a) PHOTOGRAPH OF A CNT FATIGUE SENSOR BONDED TO A STEEL SUBSTRATE; (b) MICROGRAPH OF SENSOR SURFACE INFUSED BY EPOXY BASED TWO PART ADHESIVE PASTE; (c) ELEVATION PLOT OF RED-DASH LINE IN (b); (d) PHOTOGRAPH OF THE SENSOR WITH PROTECTIVE COATING; (e) SURFACE ELEVATION MAP OF PROTECTIVE COATING (f) ELEVATION PLOT OF SURFACE OF PROTECTIVE COATING.

In a real-world scenario, the CNT fatigue sensor may be directly exposed to water. Therefore, the effects of water on the response of the sensor coated with epoxy and epoxy and the protective coating were investigated. The resistance of both specimens was continuously measured using a Keithley 3700A multimeter before, during, and after the spraying water onto the specimens. The insert in Figure 2 shows both wet specimens. After spraying water, both specimens were dried at room temperature. The curves of resistance change in Figure 2 show that the resistance of both specimens increased slightly during water spraying - probably due to the impact and weight of the water as well as temperature changes. As the water evaporated from the surface of the specimens, the response of both sensors almost revered to the original state. It is noteworthy to mention that the observed temperature drop after the water spraying, shown by the gray curve in Figure 2, occurred due to the fact that water was also sprayed on the thermocouple sensor.

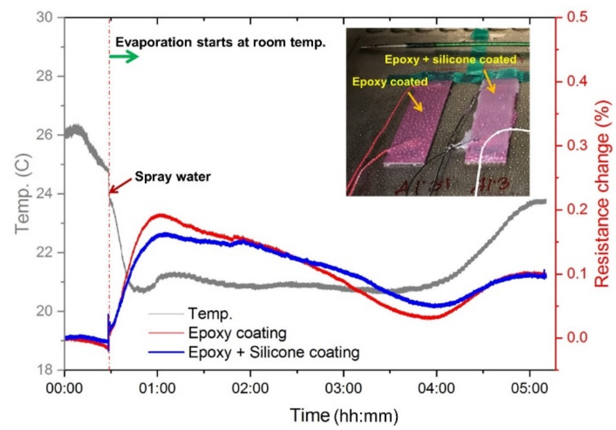


FIGURE 2: EFFECT OF SPRAYING WATER AND EVAPORATION AT ROOM TEMPERATURE ON THE RESPONSE OF SENSORS COATED WITH EPOXY AND EPOXY + PROTECTIVE COATING (SPECIMENS ARE SHOWN IN THE INSERT).

3. FIELD-DEPLOYABLE DAQ SYSTEM

A field-deployable Arduino-based DAQ system has been developed for measuring resistance change in the CNT sensor. The DAQ system consists of an Arduino Uno board, an analog-to-digital converter (ADC), an SD card reader, and a solar energy system (see Figure 3). A simple voltage divider circuit was used to measure the resistance change in the CNT-based sensor. Inserts in Figure 3 shows a voltage divider circuit where R_1 and V_{in} are known quantities, R_1 = 10 kΩ and V_{in} = 5 V. V_{out} was measured at the ADC pin. Now, R_2 was calculated using Eq. 1.

$$\text{Resistance of the sensor, } R_2 = R_1\left(\frac{V_{out}}{V_{in} - V_{out}}\right) \qquad (1)$$

A fatigue test was conducted with resistance data collected by the field deployable DAQ system and was compared with that of a laboratory precision system (Keithley 6430) to evaluate the capabilities of the field-deployable Arduino-based DAQ system. Two identical CNT fatigue sensors were bonded to either side of a compact tension specimen and a strain gage was bonded to the back of the specimen (BFS). Figure 4 (a) shows the experimental test setup.

Constant amplitude sinusoidal cyclic loading was applied to the fatigue test specimen to initiate and grow a fatigue crack and loading was continued until the specimen failed. The Arduino-based DAQ system used the principle of a voltage divider circuit to measure resistance. The two-wire technique was used in the Keithley 6430 system to measure the resistance of the other CNT sensor by sourcing a constant voltage of 20 V.

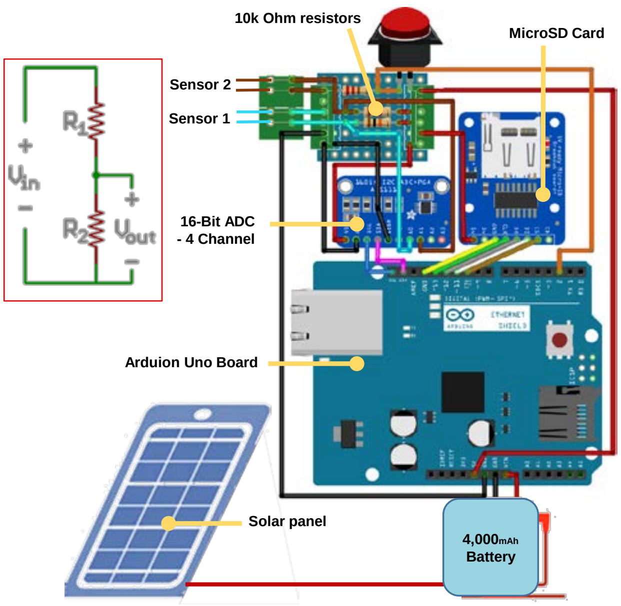
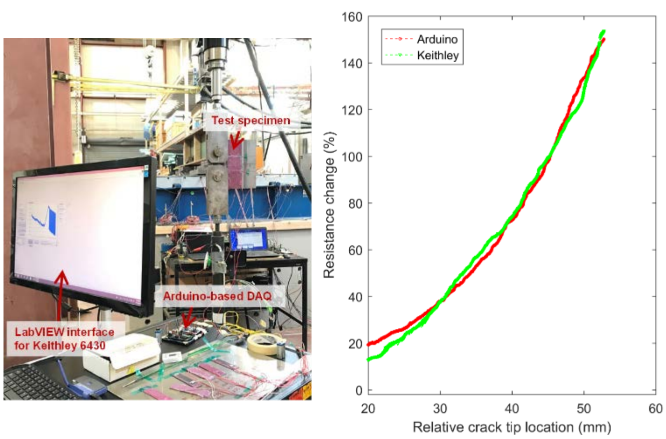


FIGURE 3: CIRCUIT SKETCH OF FIELD DEPLOYABLE DAQ SYSTEM CONSISTING OF ARDUINO UNO BOARD, 16-BIT (ADC), AND SD CARD READER. THE INSERT SHOWS THE VOLTAGE DIVIDER CIRCUIT.

Measurements of Arduino-based system were plotted against relative crack tip location (calculated using the BFS measurements) and compared with that of Keithley 6430 system (Figure 4 (b)). It is evident from this figure that measurements show a similar trend.



(a) (b)

FIGURE 4: (a) FATIGUE TEST SETUP (b) RESISTANCE CHANGES IN THE CNT FATIGUE SENSORS COLLECTED BY ARDUINO-BASED DAQ AND KEITHLEY 6430 SYSTEM VS. RELATIVE CRACK LOCATION.

4. SUMMARY AND CONCLUSIONS

Integrating health monitoring capabilities into a repair scheme is still an emerging field showing promise to mitigate the need for sustainable rehabilitation of deteriorating infrastructure. Also, the CNT sensor shows promise to overcome some of the shortcomings of commercial sensors for monitoring fatigue damage. Our solution should be low-cost and durable considering budgetary constraints and duration for infrastructure management. In this work, we have developed and evaluated a protective coating for the CNT fatigue sensor and a low-cost DAQ system. In the field, the protective coating on the sensor will ensure long term durability of the sensor. The Arduino-based system is low cost, and it can provide a reliable measurement of electric properties of the CNT sensor.

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