TRANSPORTATION POOLED FUND PROGRAM
QUARTERLY PROGRESS REPORT

Lead Agency (FHWA or State DOT): ____Kansas DOT______________________________

INSTRUCTIONS:
Project Managers and/or research project investigators should complete a quarterly progress report for each calendar quarter during which the projects are active. Please provide a project schedule status of the research activities tied to each task that is defined in the proposal; a percentage completion of each task; a concise discussion (2 or 3 sentences) of the current status, including accomplishments and problems encountered, if any. List all tasks, even if no work was done during this period.

Transportation Pooled Fund Program Project # **TPF-5(328)**	**Transportation Pooled Fund Program - Report Period:** ☐Quarter 1 (January 1 – March 31) ☒Quarter 2 (April 1 – June 30) ☐Quarter 3 (July 1 – September 30) ☐Quarter 4 (October 1 – December 31)

Project Title:
Strain-based Fatigue Crack Monitoring of Steel Bridges using Wireless Elastomeric Skin Sensors

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Lead Agency Project ID: **RE-0699-01**	**Other Project ID (i.e., contract #):**	**Project Start Date:** **9/2015**
Original Project End Date: **Multi-year project**	**Current Project End Date:** **8/31/2018**	**Number of Extensions:** **N.A.**

Project schedule status:

☒ On schedule ☐ On revised schedule ☐ Ahead of schedule ☐ Behind schedule

Overall Project Statistics:

Total Project Budget	Total Cost to Date for Project	Total Percentage of Work Completed
$405,000	**$ 358,267**	**91%**

Quarterly Project Statistics:

Total Project Expenses This Quarter	Total Amount of Funds Expended This Quarter	Percentage of Work Completed This Quarter
$ 45,544	**$ 45,544**	**11%**

Project Description:
The main objective of this proposed research is to *provide state DOTs a practical and cost-effective long-term fatigue crack monitoring methodology using* ***a wireless elastomeric skin sensor network****.* This research is intended to demonstrate the value-added of fatigue crack monitoring of steel bridges using wireless skin sensors over the traditional bridge inspection.

Progress this Quarter (includes meetings, work plan status, contract status, significant progress, etc.):

ISU Progress: Under this task, fatigue crack sensors are to be produced with an approximate thickness of 100-200 μm to enhance the mechanical robustness under harsh environment. Acceptable range of capacitance is 800-1000 pF. The anticipated number of sensors is 150 to 200 for the duration of the project.
Technical support (Task 3) is being provided to KU on a continuous basis, as well as discussion and feedback (Task 4).

KU Progress: KU has been continuing the non-skewed bridge component test, integrating and testing and wireless sensor system, and carrying out field tests.

UA Progress: UA has been providing technical support on the capacitance sensor board.

Anticipated work next quarter:

ISU: Technical support is being provided to KU on a continuous basis, as well as discussion and feedback.

KU: KU will continue to complete the wireless sensor deployment on the I-70 testbed bridge analyze the field data and draft the final project report.

UA: UA will continue to provide technical support to KU on the senor board and assist with drafting the final report.

Significant Results:

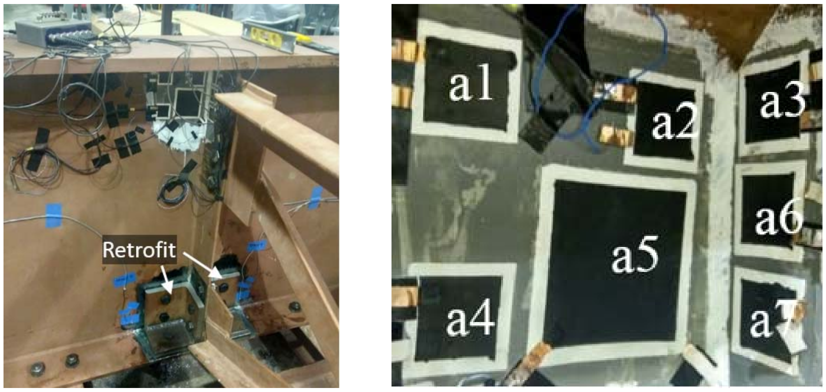
The KU team focused on four main tasks in this quarter including: continuing testing on a non-skewed bridge girder to cross frame model; and new testing results from the field deployment of a steel bridge, integrating the SEC sensor board with the wireless sensor node, Xnode, and testing the trigger mechanism for autonomous monitoring. Major results are summarized as follows:

1. Experimental test on the non-skewed bridge girder

In the last two quarterly reports, we reported some preliminary test results on the non-skewed bridge girder to cross frame model. Results indicated that the soft elastomeric capacitor (SEC) array can detect a fatigue crack at the bottom region of the connection. Then, the experimental program was shifted into the second phase, where the bottom SEC array has been removed after 21,000 fatigue cycles. Next, the tested model was loaded to 1,050,000 cycles.

The results of the SEC array prior to 21,000 cycles have been reported in the 4th Quarter of 2017; results of the SEC array prior to 176,700 cycles have been reported in the 1st Quarter of 2018 (i.e. last quarter report). Here we report the latest results obtained in this quarter.

The fatigue load range was from 0.5 to 5.5 kip. Fig. 1a shows the retrofit applied at the bottom of the connection after the SEC array was removed. Fig. 1b shows the top SEC arrays aiming to detect the newly developed fatigue crack.



(a) (b)

Figure 1. (a) Retrofits applied at the bottom region of the model; (b) the SEC layout at the top region of the connection.

Utilizing the previously established data processing method, the crack growth index (CGI) was computed from each individual SECs in the SEC array and the results are shown in Fig. 2. As shown in the figure, all SECs demonstrate relatively stable CGI responses, except for the slight drop around 0.3 million cycles. The drop was due to the fact that a fatigue crack was generated at a cross frame member (see Fig. 3), leading to decrease of the CGIs at SEC a3, a6, and a7.

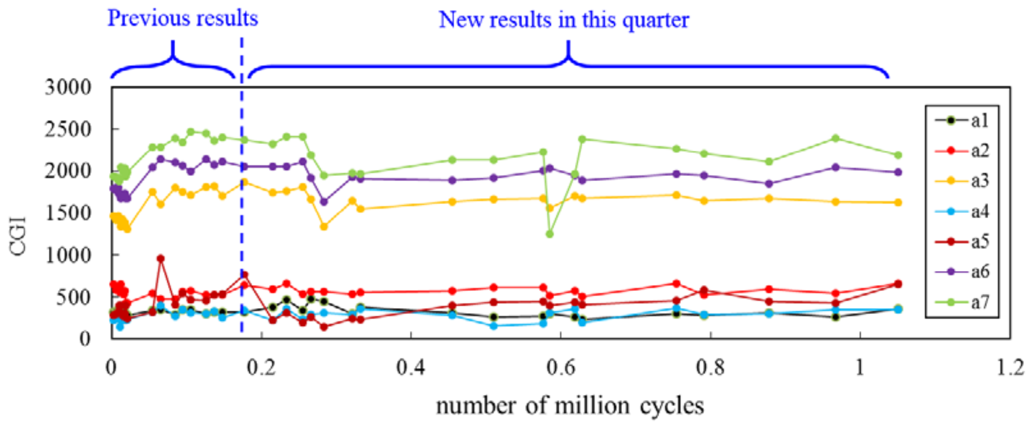


Figure 2. The CGI responses from the SEC array.

Figure 3. A fatigue crack was found at the diagonal member of the cross frame. The crack in the photo was later retrofitted by welding.

2. New results from the field deployment

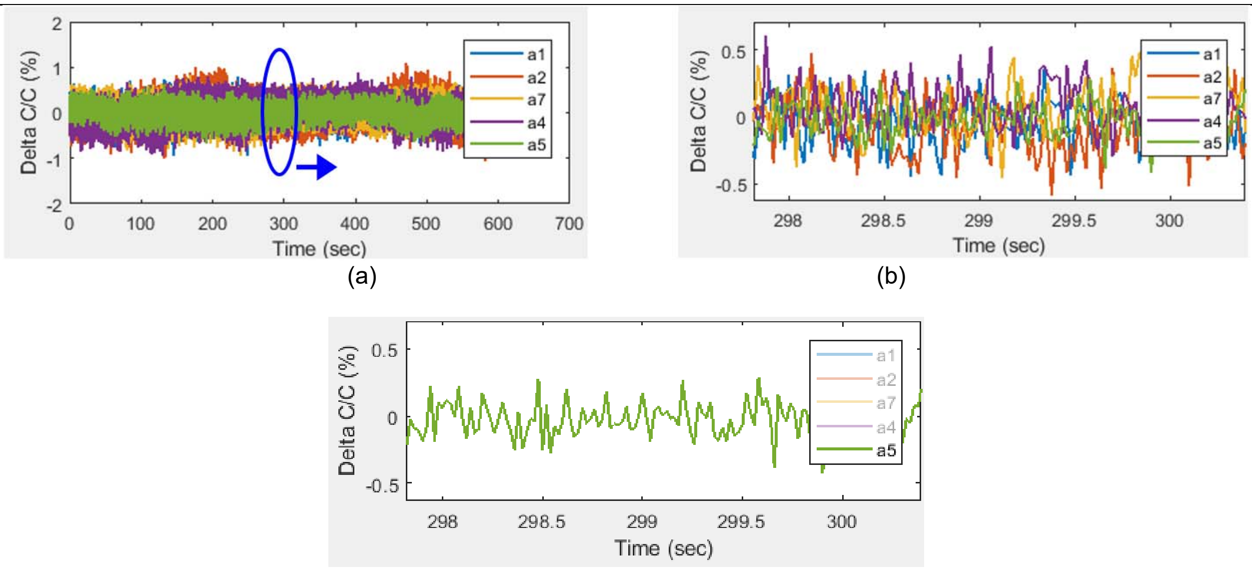
In this quarter, the KU team performed three field tests to continue the investigation of the signal noise issue. Several SEC sensors were installed on a side span next to the east abutment. Measurements from the wired DAQ indicated that the noise level was comparable to the lab environment. The team then suspect the noise observed at the mid-span was caused by the bucket truck engine. Therefore, the team visited the truck shop and tested the noise level next to the truck with the engine first turned on then turned off. Test results showed that the truck engine did not have observable impact on the signal noise level.

The third field test was performed on the mid-span. Fig. 4 shows the setup of the field deployment where measurements of 5 SECs were collected through PCAP02 data acquisition system. The data acquisition system is shown in Fig. 4b, while the SECs are shown in Fig. 4a. The 5 SECs are named a1, a2, a7, a4, and a5 starting from left.

(a) (b)

Figure 4. (a) The SECs deployed on the bridge; and (b) the wired data acquisition system.

Fig. 5a shows measurements of the SECs in the field. The duration of the measurements is about 10 mins. A detailed look of the measurements can be found in Fig. 5b and a typical measurement of one SEC is shown in Fig. 5c. As can be found in Fig.5c, the peak-to-peak noise level is about 0.3%, which is much less than our previous measurements performed in January 25 and April 18.



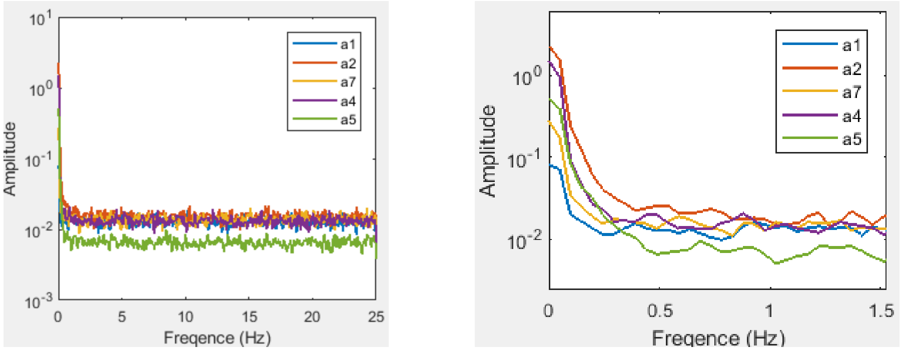
(a)

(b)

(c)

Figure 5. (a) Measurements of the SECs; (b) detailed view around 300 sec; and (c) signal from SEC a5

Fig. 6a shows the power spectral density (PSD) results of the SEC measurements. Fig. 6b shows the low frequency part of the PSD. As can be found in the figure, all measurements demonstrate higher energy from 0 to 0.5 Hz. Two main factors contribute to this energy content including: 1) the mean capacitance drifts occurring at the time history measurements; and 2) meaningful response of the SEC under traffic load.



(a)

(b)

Figure 6. (a) PSDs of the measurements; and (b) detailed view at low frequency

3. SEC sensor board setup and integration with Xnodes

The integration of the wireless sensor system has been completed. This includes connecting the SEC sensor board for power supply and data acquisition, and testing the triggering accelerometer for autonomous data acquisition.

The manufactured sensor boards were shipped to KU in this quarter. The boards were tested for quality assurance at KU as well. As mentioned in our previous report, balancing and shunt calibration should be performed on each sensor board, and both depend on the nominal capacitance of the SEC sensor including its cable. Implementing all the required steps in the field for all SEC sensors would be challenging due to space limitation, movement of the bucket, and noise. It was reported in last quarter that we have confirmed pre-balancing the board in the lab can be done for the SEC sensors before field deployment.

To further validate this idea, we also tested the pre-balanced sensor boards on the I-70 bridge. During our field visit to the bridge abutment span on 05/04/2018, we checked the balancing of a pre-balanced sensor board with a SEC sensor with the same nominal capacitance which was attached on the bridge near the abutment. Several data sets were collected using the pre-balanced SEC sensor, and the noise level was also investigated. It was observed that the noise level was about twice as in the lab. However, this noise level allows collection of meaningful measurements from the bridge. Figure 7 presents a picture of our test setup, while Figure 8 shows one sample measurement in the field on 05/04/2018.

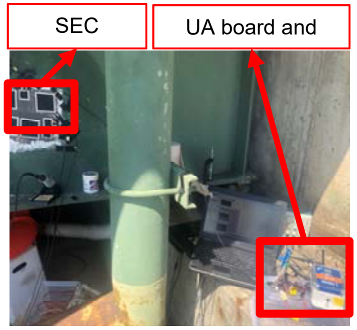


Figure 7. Test setup near the east bridge abutment

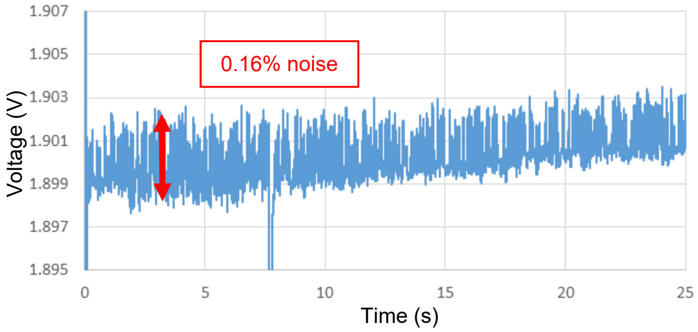


Figure 8. A sample measurement from abutment span

We confirmed both in the lab and in the field that we are able to successfully balance all the boards in the lab and install them on the bridge. Therefore, during a field visit, we measured the nominal capacitances of all SECs installed on the bridge mid-span. We have used the measured nominal capacitances in this quarter to pre-balance all the boards and calculate their Shunt calibration coefficients. Thus, in the next deployment, we only need to connect the SEC sensors on the bridge to the sensor boards.

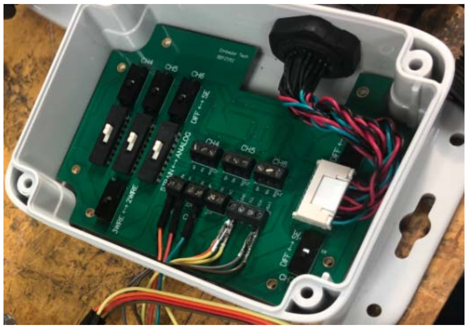


Figure 9. The breakout box between the sensor board and the Xnode

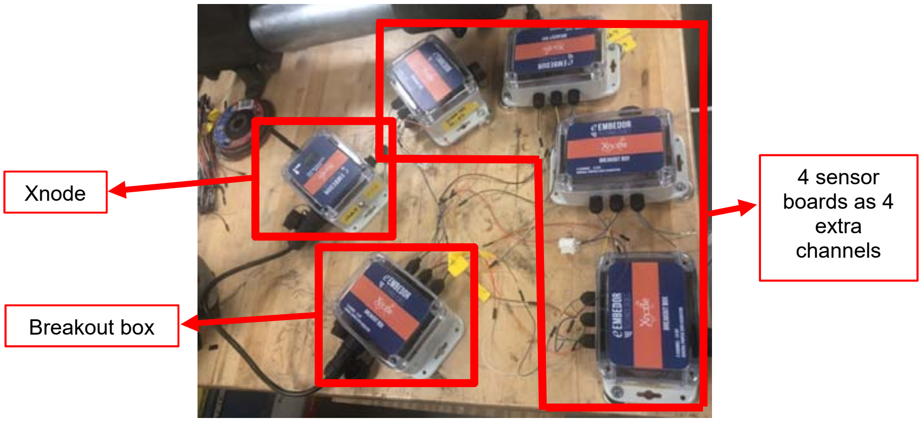
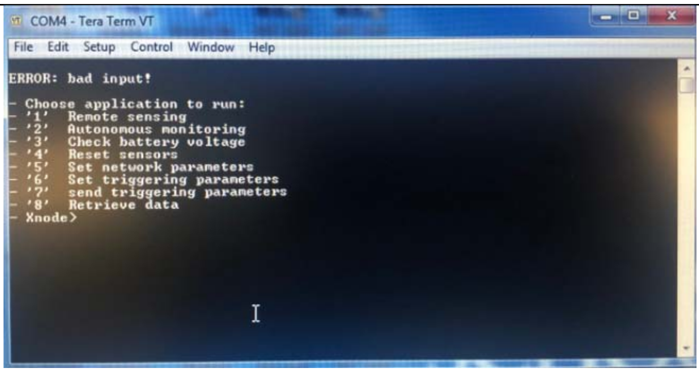


Figure 10. Connection of sensor boards to Xnode through breakout box

Our final task was to incorporate the breakout box which is an interface between the Xnode and the SEC boards for power supply and data collection. Figure 9 present the board inside the breakout box. This board allows us to integrate the connections of all 5 extra channels to the sensor boards and SEC sensors. Figure 10 shows how we used the breakout box to make all the connection required between the Xnode, the sensor boards, and the SEC sensors.

4. Triggering mechanism to for autonomous sensing

The triggering mechanism of the Xnode was introduced in previous reports. The triggering mechanism helps to wake up each sensor node when it is informed that a vehicle event is happening and makes it possible to perform long-term autonomous monitoring of the bridge. Each node wakes up when the vibration level due to the truck is larger than a predefined vibration threshold associated with each leaf node. For this purpose, an additional accelerometer (ADXL362) should be connected to each Xnode to wake up the node. In the most recent updated version of the Xnodes, ADXL362 was integrated into the radio board, and the required changes were made to the software. In this quarter, we have tested the triggering functionality of the new Xnodes together with the updated software. Figure 11 presents the options that we have to perform long-term monitoring. The updated software makes it possible to modify all the sensing parameters and retrieve the measured data from the leaf nodes through wireless communication.



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ERROR: bad input!

- Choose application to run:
- '1'  Remote sensing
- '2'  Autonomous monitoring
- '3'  Check battery voltage
- '4'  Reset sensors
- '5'  Set network parameters
- '6'  Set triggering parameters
- '7'  send triggering parameters
- '8'  Retrieve data
- Xnode>
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Figure 11. Available functions for the Xnode

In our last field visit on 07/02/2018, we investigated the vibration level of the bridge due to the passing vehicles by collecting acceleration measurements. Based on the measured acceleration time histories, we tried several different vibration thresholds for the sensors to perform triggered sensing. The goal was to select an appropriate trigger threshold to reach a balance between the level of vibration and the number of sensing events. The first trial threshold was 50 mg, which turned out too low because the nodes were almost constantly taking measurements under this threshold. After several trial-and-errors, 100 mg was finally decided as the vibration threshold for trigger sensing. The sample time for each measurement is seta as 60 seconds. Figure 12 shows a picture of our wireless sensor deployment on the bridge on 07/02/2018.

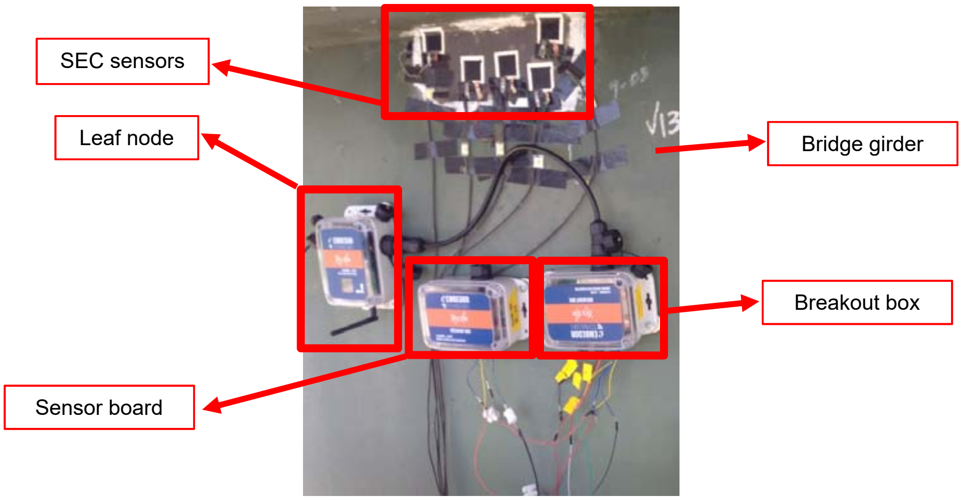

Figure 12. Wireless sensor deployment

Circumstance affecting project or budget. (Please describe any challenges encountered or anticipated that might the completion of the project within the time, scope and fiscal constraints set forth in the agreement, along with recommended solutions to those problems).

None.