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
$405,000	**$ 312,723**	**80 %**

Quarterly Project Statistics:

Total Project Expenses This Quarter	Total Amount of Funds Expended This Quarter	Percentage of Work Completed This Quarter
$ 36,353	**$ 36,353**	**8%**

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 team has been continuing the non-skewed bridge test, investigating the strategy for pre-balancing the sensor board in the lab before field deployment. KU team also performed a field test at the I-70 bridge.

UA Progress: UA team has been providing technical support to the KU team regarding the capacitance sensor board. Sensor boards have been fabricated and appropriate capacitor components will be installed to the boards.

Anticipated work next quarter:

ISU: Sensor production will continue in the next quarter. Technical support is being provided to KU on a continuous basis, as well as discussion and feedback.

KU: KU team will continue to complete the non-skewed bridge test, find solutions to the noise issue observed on the bridge, and deploy wireless sensors to the bridge.

UA: In the next quarter, Arizona team will complete the new sensor board assembly and testing, and ship the boards to KU. Arizona team will also continue to provide assistance to the KU team.

Significant Results:

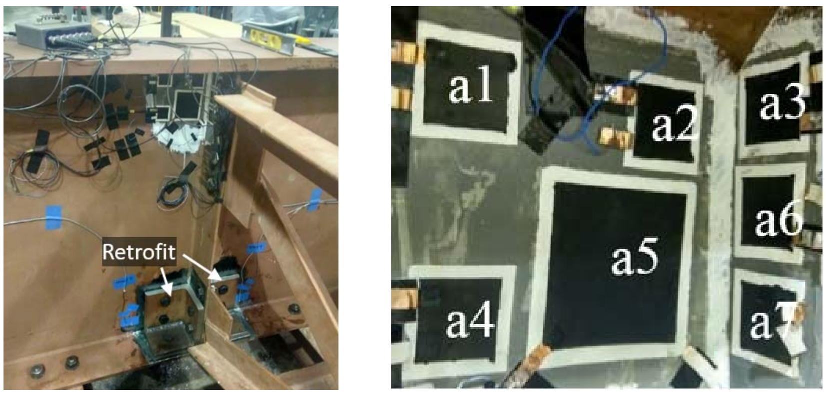
Results from the University of Kansas Team

The KU team focused on two tasks in this quarter including: continue the test on a non-skewed bridge girder to cross frame model; and new testing results from the field visit of the I-70 test bridge. Significant results are summarized as follows:

1. Experimental test on a non-skewed bridge girder

The last quarterly report reported preliminary test results on the non-skewed bridge girder to cross frame model. Results indicate that the SEC array can successfully detect and monitor a newly initiated fatigue crack at the bottom region of the connection.

In this quarter, the experimental program has moved into the second phase, as shown in Fig. 1. Briefly, the bottom SEC array has been removed after 21,000 fatigue load cycles. The results of the SEC array prior to 21,000 cycles were reported in the last quarter. Then, the model was fatigue loaded under 0.5 to 5.5 kip from 22,000 to 55,000 cycles while no SEC data was collected during this period. Next, two fatigue retrofit approaches were applied to the test model including: 1) carbon fiber reinforced polymer (CFRP) method; and 2) a pair of steel angles, as shown in Fig. 1a. These newly added retrofits would dramatically slow down the growth of the bottom fatigue crack.



(a) (b)

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

After applying the fatigue retrofits, the model was then fatigue loaded from 55,000 to 176,700 cycles (i.e. Phase II of the experimental program). The purpose of the second phase of the experiment is to monitor the top region of the connection through the SEC array. In total, 9 datasets of the top SEC array (denoted in Fig. 1b) were collected. Utilizing the previously established data processing algorithm, the crack growth index (CGI) were computed from each individual SEC in the SEC array and the results are shown in Fig. 2.

As shown in the figure, all SECs demonstrate a relative stable CGI response throughout the 9 datasets. Three SECs on the connection plate (i.e. SEC a3, a6, and a7 in Fig. 1b) have higher CGI responses than the rest of the SECs. This is because of the higher strain field in the connection plate. The stable CGI responses of the SEC arrays indicate that no crack initiated in the top region. This was also confirmed by the visual observations during the test.

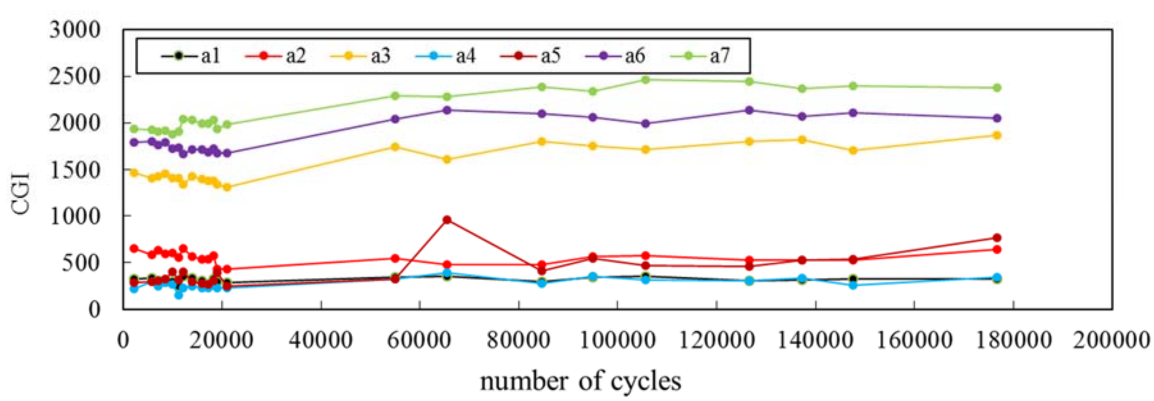


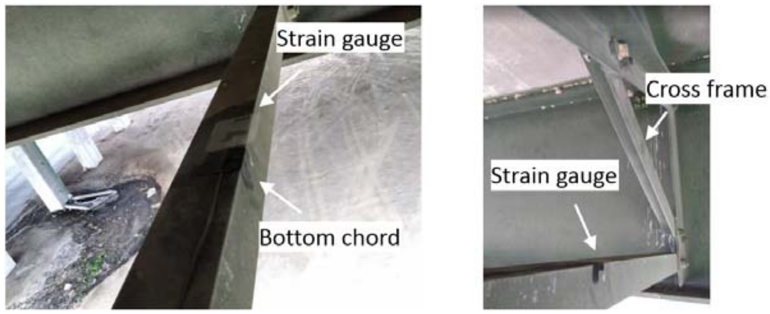
Figure 2. The CGI responses from the SEC array.

2. Second field visit

In the last quarterly report, we reported preliminary data obtained from the field deployment of a steel highway bridge on I-70 near Kansas City, Kansas. The bridge was named 70-105-41731-(127) and 70-105-417.32(128) according to the inspection report. The KU team paid a second visit to the bridge on 04/18/2018.

One of the purposes of this field visit is to check the strain gauge data that was installed on the cross frame during the previous field visit. In addition, additional measurements of the SECs were collected using both the off-the-shelf data acquisition (DAQ) system Pcap02 and the capacitance sensor board developed by the University of Arizona team.

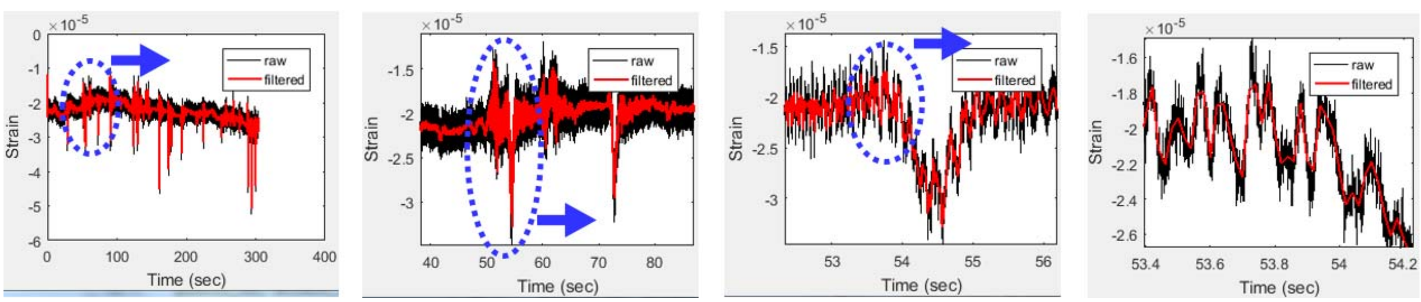
Fig. 3 shows the strain gauge installed in the steel bridge. Three datasets of the strain gauge were collected during this field visit. The durations of these datasets are about 5 mins, 5 min, and 1 min. Fig. 4 shows the strain measurements. The black lines represent the raw signals while the red lines represent the signals after applying a low-pass filter.



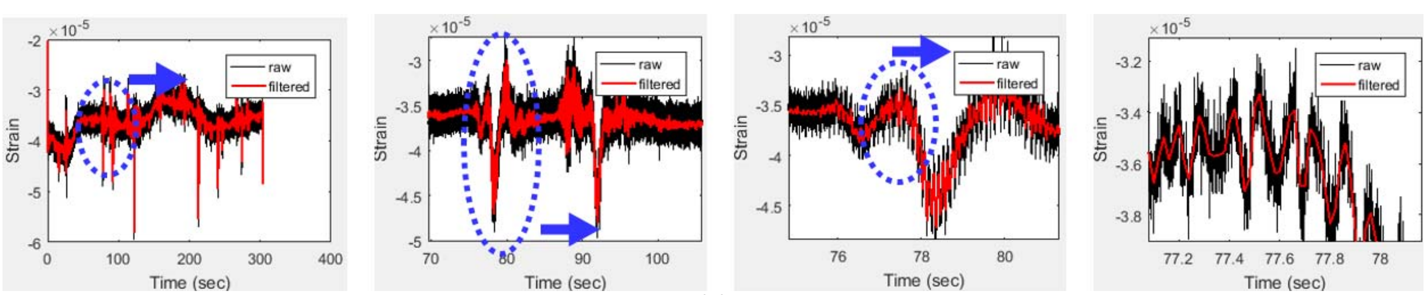
(a) (b)

Figure 3. Strain gauge installation.

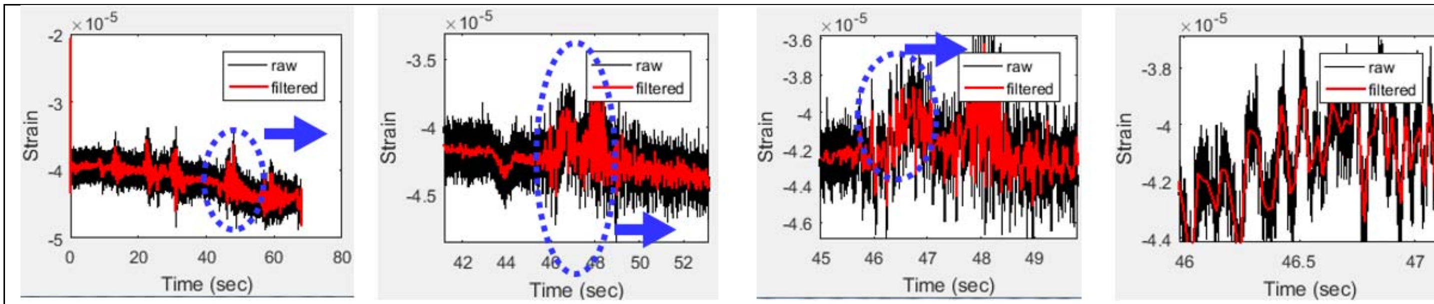
As shown in the first column of Fig. 4, the pulse-like responses are provoked by the passing vehicles. These pulse-like response can be clearly observed in the details such as the third column of Fig. 4. In addition, there are some high frequency oscillations in the measurements (shown in the last column). This may be induced by the free vibration of the bridge.



(a)



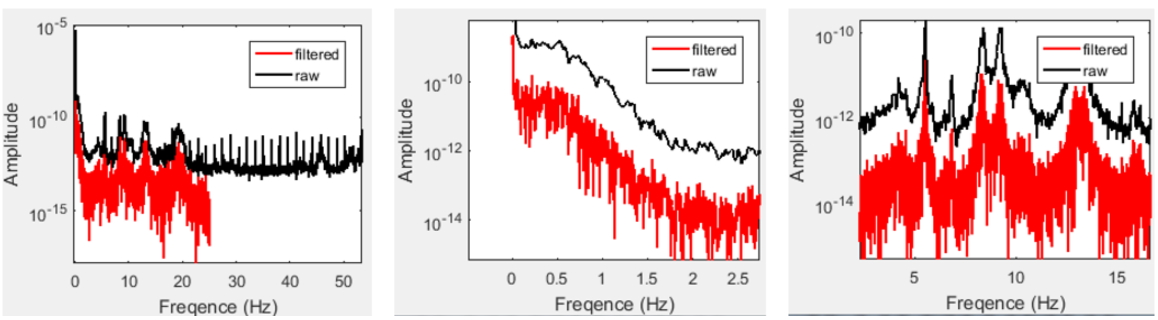
(b)



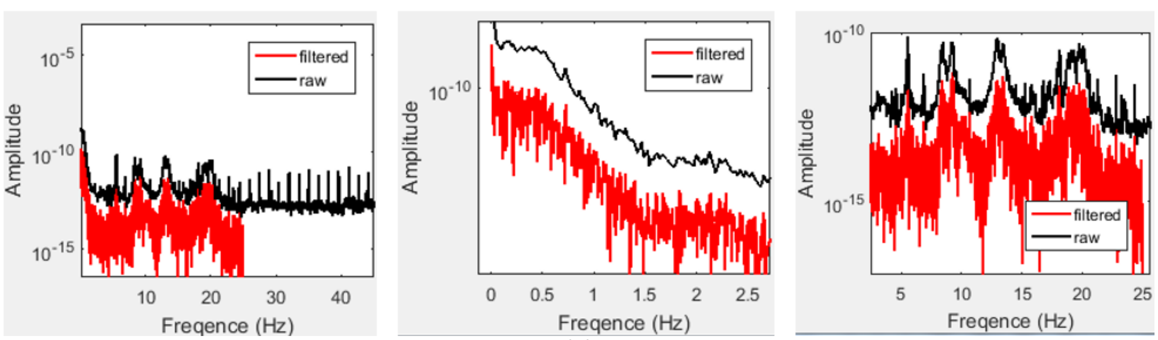
(c)

Figure 4. The first (a), second (b), and third (c) measurements from the strain gauge. The first column is the entire signal, other columns show the detailed signals. The black lines are raw measurements and the red lines are filtered signals.

The time-series signals are further converted into frequency domain to investigate the frequency content of the strain measurements. In particular, the power spectral density is computed for each measurement and the results are shown in Fig. 5. As can be seen in the first column of Fig. 5. Peaks can be found in both low frequency range (e.g. 1 Hz) and higher frequency range (e.g. 6, 10, 15, and 20 Hz). The low frequency response is provoked by the pulse-like response in the time-series signals caused by the passing vehicles. The high frequency responses in the PSD curves, on the other hand, are likely induced by the free vibration of the cross frame.



(a)



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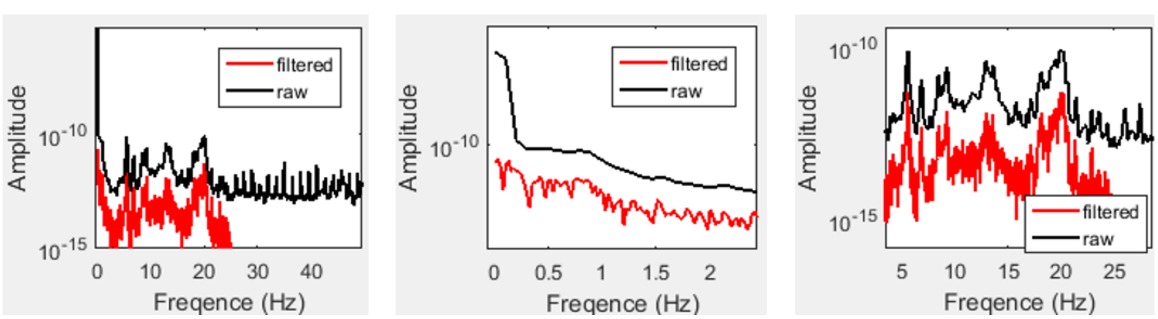
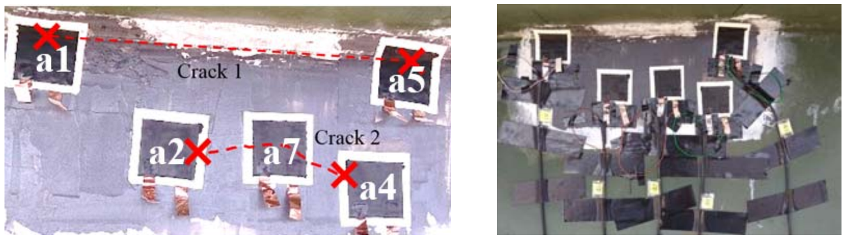


(c)

Figure 5. The first (a), second (b), and third (c) measurements from the strain gauge in terms of power spectral density (PSD). The first column is the PSD over entire frequency range, the columns hereafter represent the detailed lookup at low frequency and from 5 Hz to 20 Hz. The black lines are PSD from the raw measurements and the red lines are PSD from the filtered signals.

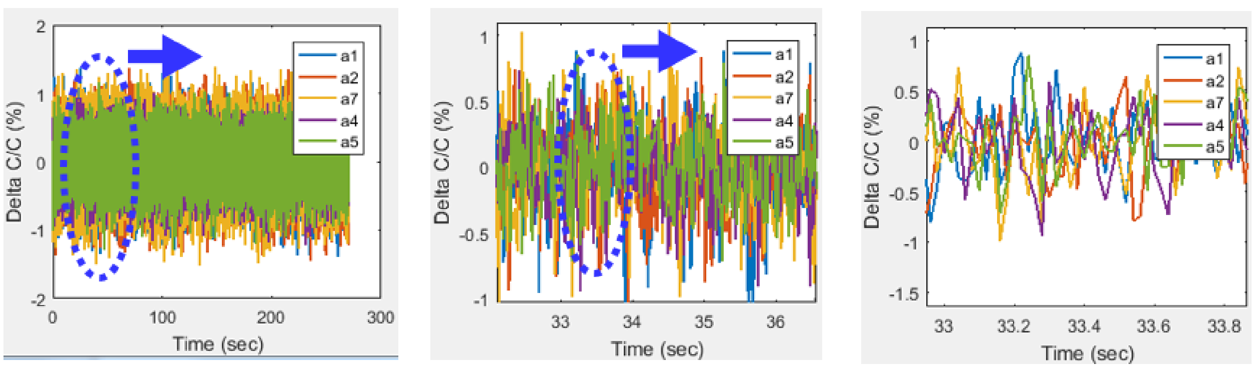
The second task of this field visit is to collect SEC measurements using pCap DAQ. Fig. 6 illustrates the five SECs on the exterior side of the girder that were installed during our previous field visits, where two SECs (a1 and a5) were installed to cover Crack 1 and three SECs were attached to Crack 2.



(a) (b)

Figure 6. (a) Arrangement of the SEC arrays; and (b) the SEC arrays after soldering the cables.

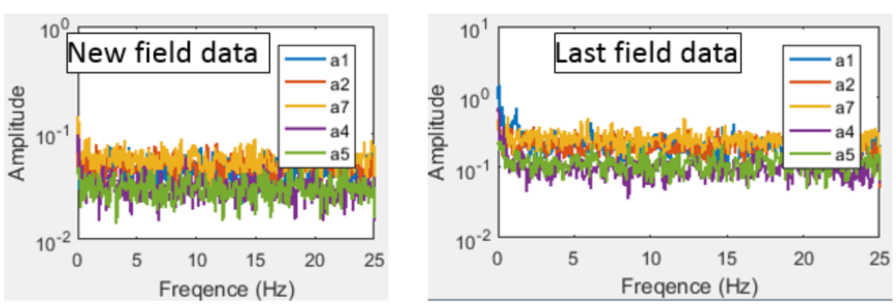
A sample measurement was collected in the field using the SEC arrays on the exterior side of the girder. The measurement was taken using the PCAP02 DAQ board. The measurement had about 5 mins duration and its time-series can be found in Fig.7a. Fig.7b and c show the detail of the signal. As can be seen in the figure, the noise level (peak-to-peak response) of the signal is about 1% (see Fig. 7b). Such a noise level gets improved compared with 2% that measured from our previous field visit, but is still much larger than the laboratory measurement, which is about 0.05% to 0.1%. The real SEC response under fatigue cracking would be contaminated by the noise floor in this case.



(a) (b) (c)

Figure 7. Time-series measurement of the SEC arrays where (a) full the time-series measurement; (b) from 32 to 37 sec; and (c) from 33 to 34 sec.

Fig. 8 further compares the PSD responses of the SECs from different field visits. As can be seen in the figure, the new data of the SECs has lower noise floor than is below 0.1 in terms of magnitude, while the previous SEC measurements is equal or beyond 0.1.



(a) (b)

Figure 8. PSD responses of the SECs from (a) new field visit; and (b) previous field visit.

3. C-strain sensor board setup

The sensor board designed by Arizona team is utilized to measure the capacitance of SEC sensor by converting the capacitance change to voltage change. At KU, we have been trying to balance the sensor board and perform shunt calibration based on the instructions provided by Arizona team by taking two steps. The first step is that the potentiometers on the sensor board need to be adjusted to match the signals of different jumpers monitored by oscilloscope. The second step is to perform shunt calibration to calculate the required coefficient to change the measured voltage to capacitance. For Shunt calibration, there are two switches on the board corresponding to two capacitors. By turning on and off the switches, two jumps can be observed in the measured voltage. The difference between those two jumps corresponds to a 4 pF change in capacitance. By having the change in voltage and knowing this 4 pF change in capacitance, the calibration coefficient can be calculated. It was reported in the last quarter that we have successfully performed the balancing step. In this quarter, our focus was on performing shunt calibration for the purpose of converting voltage to capacitance. To perform these steps, the Xnode is used as the power source for the board. Figure 9 presents the configuration of the connections between the sensor board, SEC sensor, and Xnode. Figure 10 presents an example of collected data for Shunt calibration together with the calculated calibration coefficient.

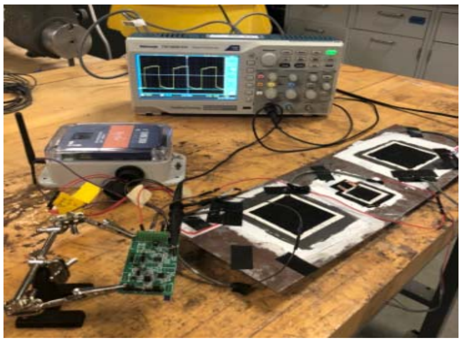
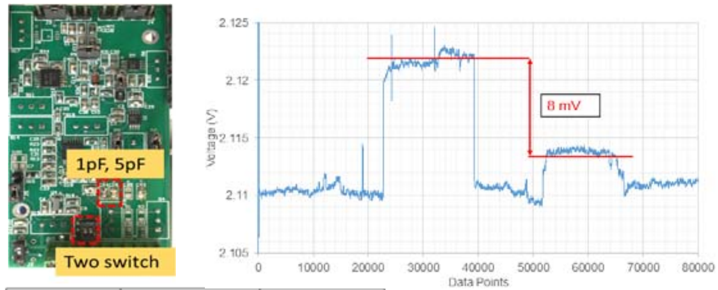


Figure 9. C-strain sensor board setup



ΔVoltage (mV)	Δcapacitance (pF)	Shunt calibration
8	4	2

Figure 10. Shunt calibration

This process including balancing and shunt calibration should be performed on each sensor board on the bridge, and it depends on the nominal capacitance of the SEC sensor. Implementing all the steps in the field for all SEC sensors is challenging due to space limitation, movement of the bucket, and noise. Therefore, by performing several lab tests in this quarter, we have confirmed it is possible to balance the board in the lab and only perform shunt calibration in the field. The way this strategy works is that if the nominal capacitance of each SEC sensor and its wire is measured for the installed SEC sensors on the bridge, we can built a SEC sensor with the same nominal capacitance in the lab, and balance the board using this SEC sensor in the lab. Later, when this board is connected to the SEC sensor in the field, Shunt calibration can be performed. To test this idea, two SEC sensors with the same nominal capacitance were prepared in the lab, the board was balanced using one of the sensors and then was tested on the other one. Figure 11 presents two critical stages of balancing for those two SEC sensors. Identical results between these two SECs indicate that the balanced board can be used of another SEC with same nominal capacitance.

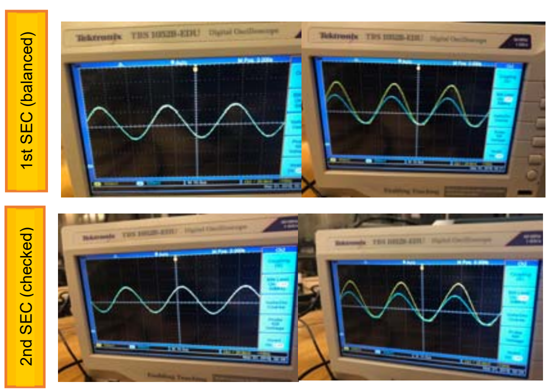


Figure 11. Balancing based on different SECs with same nominal capacitance

Finally, it was also observed in our last field visit on 4/18/2018 that it is challenging to perform the balancing steps on site. However, we will be able to balance all the boards in the lab before bringing them to the field.

4. Triggering mechanism to wake up Xnode

Our plan to perform long-term autonomous monitoring on the bridge is to wake up each leaf node when it is informed that a vehicle event is happening. This is achieved by monitoring the vibration level due to the truck and see if it is larger than a predefined vibration threshold. For this purpose, an additional accelerometer (ADXL362) will be connected to each Xnode to wake up the node. This accelerometer should be connected to the Xnode based on the circuit in Figure 12 (instructions from UIUC). At KU, We have been trying to figure out the connection between ADXL362 and the Xnode at KU during the past quarter and current quarter. It was reported in the last quarterly report that the ADXL is successfully connected to the Xnode, but there were some minor problems in terms of waking up the node with moving the ADXL362 that needed to be addressed. The work on this part is finished in this quarter, and the node can be successfully waken up using ADXL362 based on the triggering mechanism. Figure 13 presents the final stage of the connection.

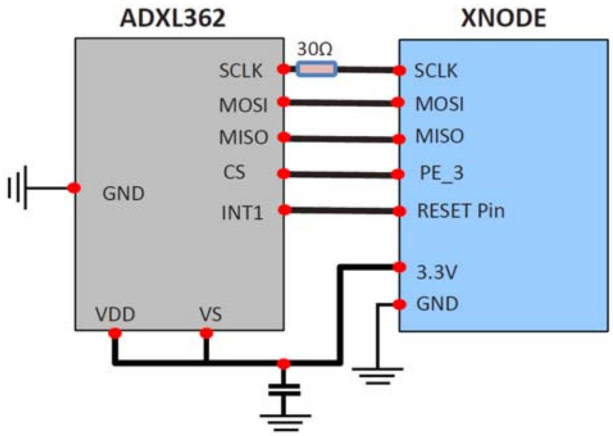


Figure 12. ADXL362 connection to Xnode

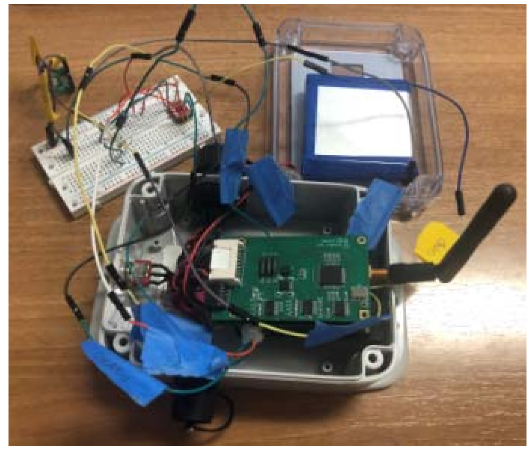


Figure 13. The circuit for ADXL362 connection at KU

Results from the University of Arizona Team

20 capacitance sensor boards have been made and are under hardware quality tests. The sensor board performance was evaluated by the incremental dynamic step-load test and shunt calibration test. 7 sensor boards (out of twenty) were configured for the large SEC with optimized bridge balancing and amplification setup.

1. Manufactured sensor boards

(a) (b) (c)

Figure 1. Manufactured sensor boards: (a) One of the sensor boards (detail), (b) 20 board array (front side), (c) 20 board array (bottom side)

20 sensor boards have been manufactured by 7pcb (a circuit board manufacture company) and shipped to the University of Arizona (Figure 1). Hardware assemblies for all sensor boards were in good shape.

2. Quality test

To evaluate the hardware quality, several performance tests were conducted including the incremental dynamic step-load test and shunt calibration test. Large SEC (3x3 in.) was used for the sensor board performance tests.

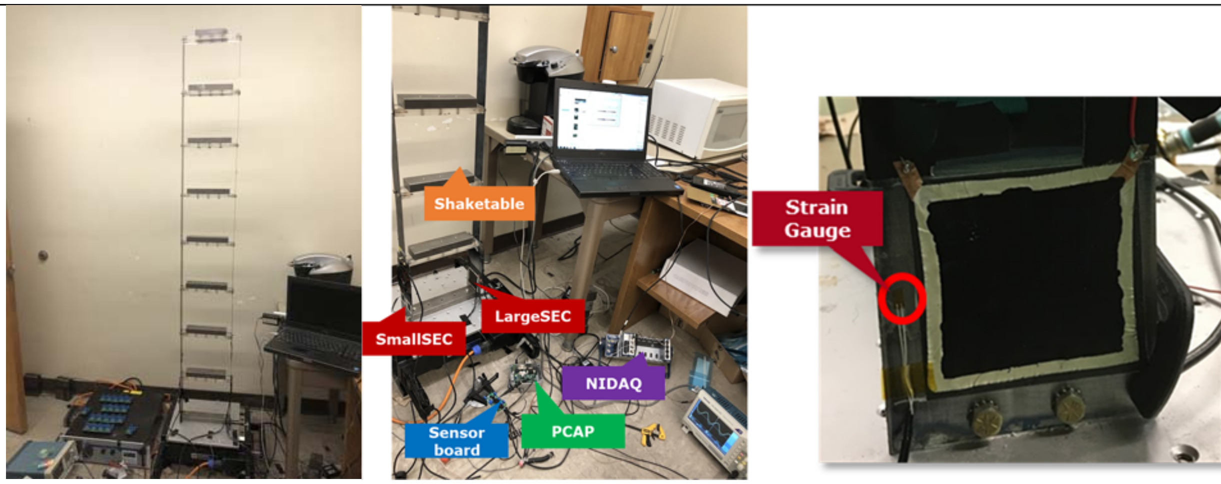


Figure 2. Test setup

2.1 Incremental dynamic step-load & shunt calibration test

1 Hz Sine wave with incremental step load was provided to the shear building via shake table APS400. Each step load sinewave was applied for 20 seconds and the amplitude was increased by 85 / 135 / 280 / 450 μ-strain. After the step load test, the shunt calibration test was conducted to convert measured voltage from sensor board into absolute capacitance value. Double-step shunt calibration process with 5pF and 1pF capacitors was employed. A resistive-type strain gauge was installed to provide reference measurements, and the measurements by the sensor board and the PCAP were compared with each other.

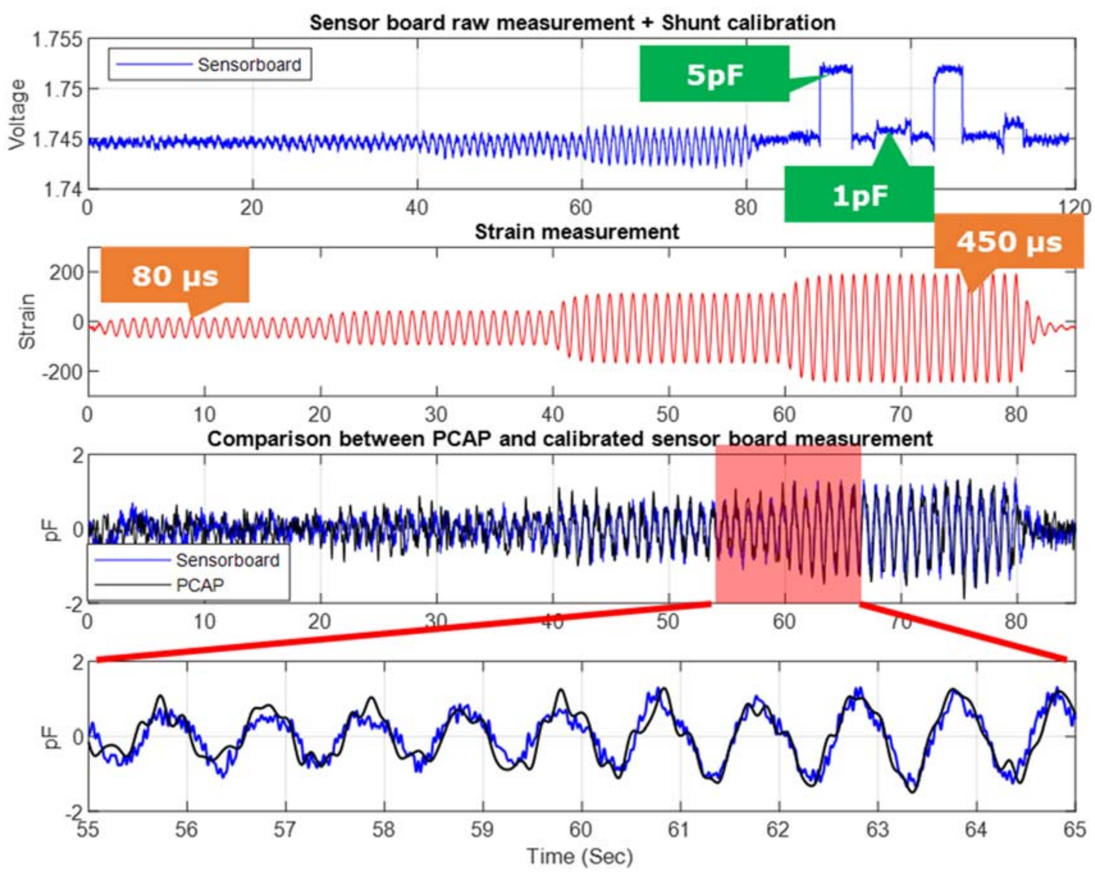
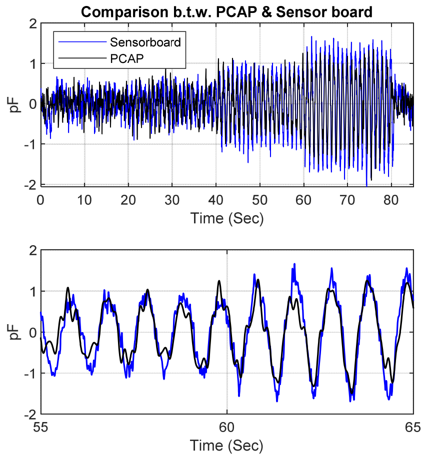
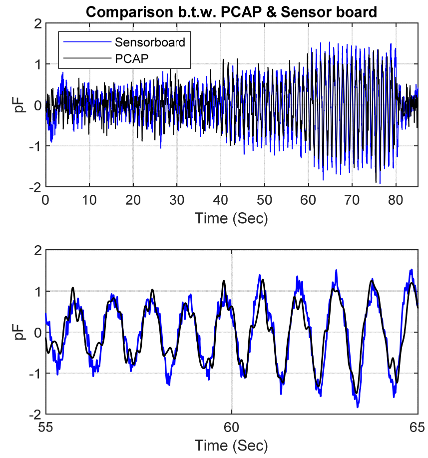


Figure 3. Example test results from the sensor board #1

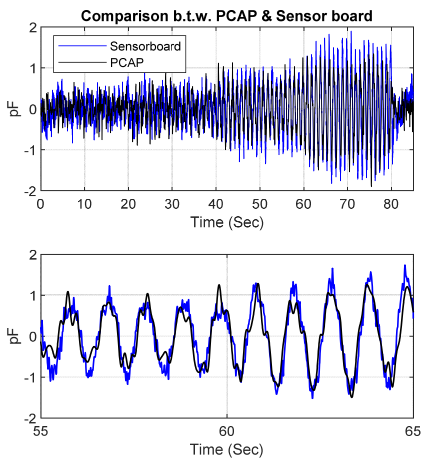
Figure 3 shows the example test result of the sensor board #1. Plot on first row shows raw measurements during the shunt calibration test. Second row shows strain measurement from the strain gauge as the reference. The trend of capacitance variation (3rd row) to the strain amplitude change (2nd row) matches well. The third row shows the comparison of PCAP (off-the-shelf wired) capacitance measurement with the sensor board measurement. Little more noise from the PCAP, but in general, both (PCAP and the sensor board) shows the similar performance for the step load tests. Figure 4 shows the example test results for the other 6 boards.



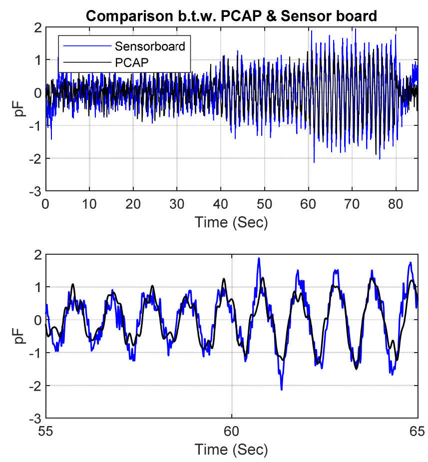
Board #2



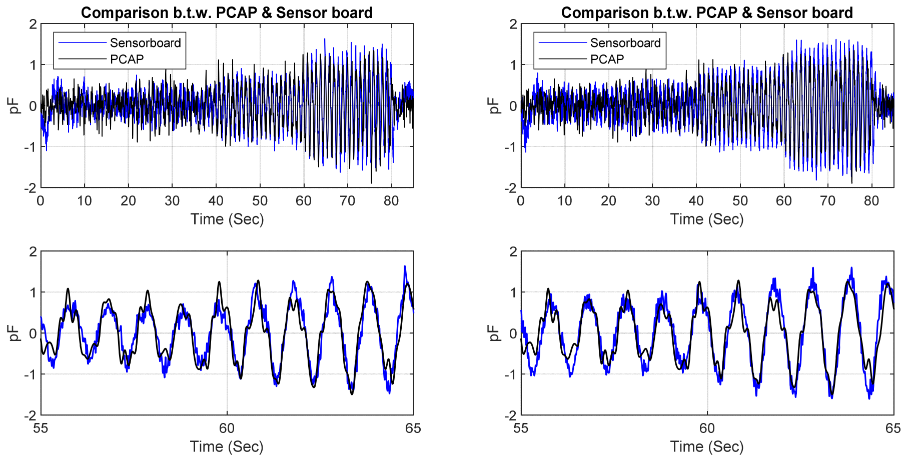
Board #3



Board #4



Board #5



Board #6 Board #7

Figure 4. Example test results of the sensor boards (#2 ~ #7): Comparison b/w the sensor board vs. PCAP

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.