TRANSPORTATION POOLED FUND PROGRAM
QUARTERLY PROGRESS REPORT

Lead Agency (FHWA or State DOT): IOWA 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(449)*	**Transportation Pooled Fund Program - Report Perio** Quarter 1 (January 1 – March 31, 2023) **x** Quarter 2 (April 1 – June 30, 2023) Quarter 3 (July 1 – September 30, 2022) Quarter 4 (October 1 – December 31, 2022)	
Project Title: Robust wireless skin sensor networks for long-term fatigue crack monitoring of bridges		
Project Manager: Khyle Clute	**Phone:** 239-1471	**E-mail:** khyle.Clute@iowadot.us
Project Investigator: Simon Laflamme	**Phone:** 294-3162	**E-mail:** laflamme@iastate.edu
Lead Agency Project ID:	**Other Project ID (i.e., contract #** Addendum 736	**Project Start Date:** May 15, 2020
Original Project End Date: May 14, 2023	**Contract End Date:** May 31, 2024	**Number of Extensions:** 1 extension granted to May 2024

Project schedule status:
x On schedule □ On revised schedule □ Ahead of schedule □ Behind schedule

Overall Project Statistics:

Total Project Budget	Total Cost to Date for Projec	Total Percentage of Work Completed
$ 540,000 (Phase I)	$348,765	92% of Phase I

Quarterly Project Statistics:

Total Project Expenses This Quarter	Total Amount of Funds Expended This Quarter	Percentage of Work Completed This Quarter
$88,077		

Project Description:

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

- TAC meeting on Dec 13th 2022.
- ISU refined the design of the paintable version of the SEC. Results are now archived in journal paper [11]. Below is a key result showing a 70 micro-strain resolution for the paintable sensor. The resultion compares well with that of the original SEC (25 micro-strain).

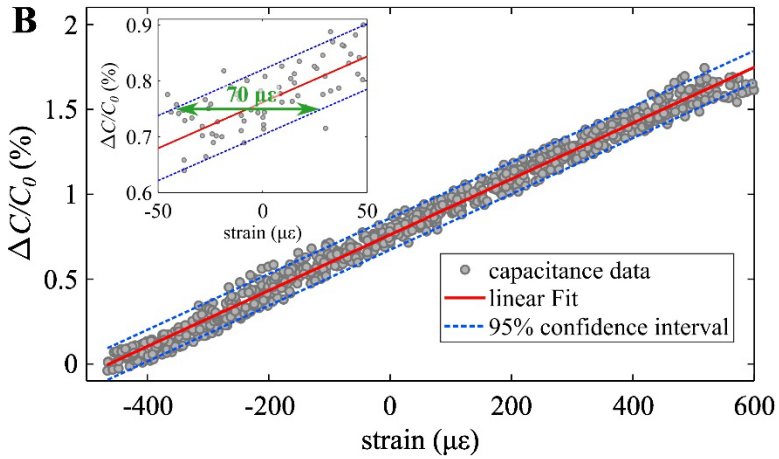

Figure: elecrical signal versus true strain for the paintable sensor.

- KU established a linear relationship between CGI and temperature through regression analysis (Figure below).

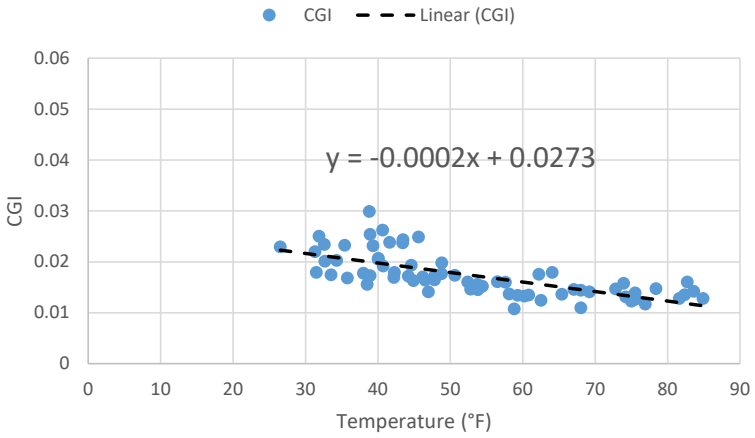

Figure: Linear relationship between CGI and temperature

Using the linear relationship, the CGI was updated to exclude the temperature effect (Figure below).

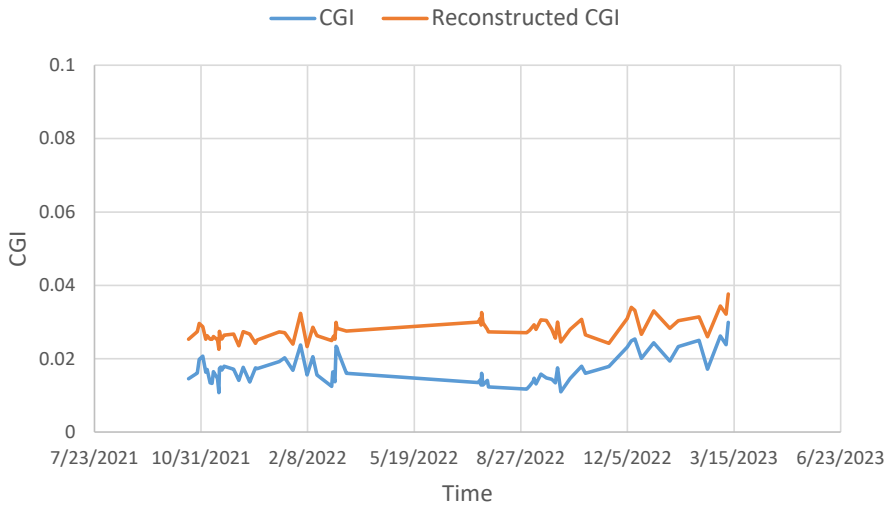

Figure: CGI before and after temperature compensation

- KU has been testing the new sensor board developed by the University of Arizona Team. The goal is to obtain satisfactory result in the laboratory before field deployment.
- UA continued testing and refining the new sensor board.
- USC conducted crack sensing on concrete using the extended SEC. The concrete specimen underwent three-point bending on a dynamic testing machine (MTS) shown in the Figure below. The SEC readings matched that of the MTS's. It should also be noted that the sensor survived failure of the beam, afterwhich the capabitance dropped and remained constant.

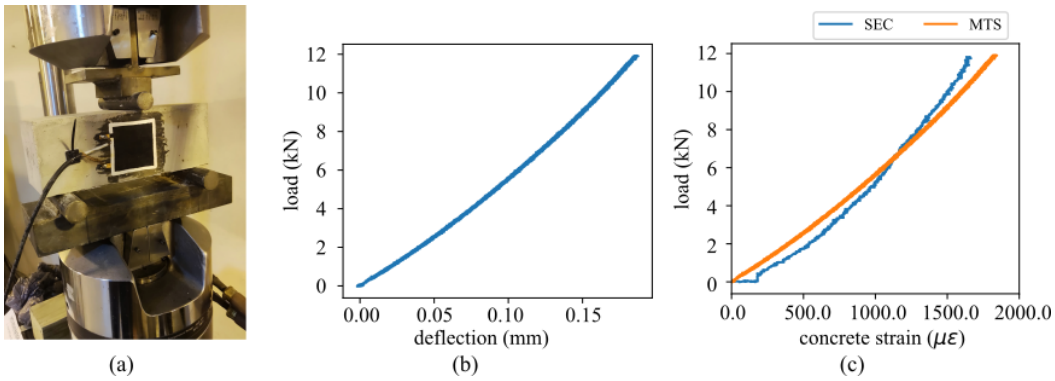

Figure: (a) three-point bending test set-up for loading the concrete specimen; (b) the load against the deflection, and; (c) the strain recorded by the SEC and MTS during the static loading.

Anticipated work next quarter:

- ISU will start working on a promotional video for the pooled fund project.
- KU will continue to collect and analyze data from the wireless sensors.
- KU will continue to test the new sensor board before field deployment.
- UA will continue testing the sensor boards.
- USC will continue investigations on concretes using the cSEC.

Significant Results:

- Paintable SEC mix finalized.
- CGI results are now temperature-compensated.

Products (pooled fund sponsoring acknowledged):

Journal Publications

[11] Liu, H., Laflamme, S., and Kollosche, M., *Paintable Silicone-Based Corrugated Soft Elastomeric Capacitor for Area Strain Sensing*, Sensors. (2023)

[10] Liu, H., Laflamme, S., Li, H., Downey, A., Bennett, C., Collins, W., Ziehl, P., Jo, H., and Todsen, M., *Sensing Skin Technology for Fatigue Crack Monitoring of Steel Bridges: Laboratory Development, Field Validation, and Future Directions*, International Journal of Bridge Engineering and Management, invited inaugural contribution.

[9] Liu, H., Kollosche, M., Laflamme, S., Clarke, D. *Multifunctional Soft Stretchable Strain Sensor for Complementary Optical and Electrical Sensing of Fatigue Cracks*, Smart Materials and Structures (2023).

[8] Ogunniyi, E., Vereen, A., Downey, A., Laflamme, S., Li, J., Bennett, C., Collins, W., Jo, H., Henderson, A., and Ziehl, P. *Investigation of Electrically Isolated Capacitive Sensing Skins on Concrete to reduce Structure/Sensor Capacitive Coupling*, Measurement Science and Technology, 34(5), (2023).

[7] Liu, H., Laflamme, S., Taher, S., Jeong, J.-H., Li, J., Bennet, C., Collins, W., Eisenmann, D., Downey, A., Ziehl, P., Jo, H., *Investigation of Soft Elastomeric Capacitor for the Monitoring of Large Angular Motions*, Materials Evaluation (in press).

[6] Taher, S. A., Li, J., Jeong, J. H., Laflamme, S., Jo, H., Bennett, C., Collins, W. & Downey, A. R. (2022). Structural Health Monitoring of Fatigue Cracks for Steel Bridges with Wireless Large-Area Strain Sensors. *Sensors*, *22*(14), 5076.

[5] Jeong, J. H., Jo, H., Laflamme, S., Li, J., Downey, A., Bennett, C., Collins, W., Taherand, S., Liu, H. & Jung, H. J. (2022). Automatic control of AC bridge-based capacitive strain sensor interface for wireless structural health monitoring. *Measurement*, *202*, 111789.

[4] Liu, H., Laflamme, S., Li, J., Bennett, C., Collins, W. N., Eisenmann, D. J., Downey, A., Ziehl, P. & Jo, H. (2022). Investigation of textured sensing skin for monitoring fatigue cracks on fillet welds. *Measurement Science and Technology*, *33*(8), 084001.

[3] Liu, H., Laflamme, S., Li, J., Bennett, C., Collins, W. N., Downey, A., Ziehl, P, & Jo, H. (2021). Soft elastomeric capacitor for angular rotation sensing in steel components. *Sensors*, *21*(21), 7017.

[2] Liu, H., Laflamme, S., Zellner, E. M., Aertsens, A., Bentil, S. A., Rivero, I. V., & Secord, T. W. (2021). Soft Elastomeric Capacitor for Strain and Stress Monitoring on Sutured Skin Tissues. *ACS sensors*, *6*(10), 3706-3714.

[1] Liu, H., Laflamme, S., Li, J., Bennett, C., Collins, W., Downey, A., ... & Jo, H. (2021). Investigation of surface textured sensing skin for fatigue crack localization and quantification. *Smart Materials and Structures*, *30*(10), 105030.

Conference Proceedings

[6] Vereen, A. B., Downey, A., Sockalingam, S., & Laflamme, S. (2022, April). Large area capacitive sensors for impact damage measurement. In *Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2022* (Vol. 12046, pp. 115-120). SPIE.
[5] Smith, C., & Downey, A. R. (2023). Additively Manufactured Flexible Hybrid Electronic Sensor for Discrete Fatigue Crack Detection. In *AIAA SCITECH 2023 Forum* (p. 2417).
[4] Ogunniyi, E. A., Liu, H., Downey, A. R., Laflamme, S., Li, J., Bennett, C., Collins, W., Jo, H. & Ziehl, P. (2023, April). Soft elastomeric capacitors with an extended polymer matrix for strain sensing on concrete. In *Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2023* (Vol. 12486, pp. 262-270). SPIE.
[3] Liu, H., Laflamme, S., Zellner, E. M., Bentil, S. A., Rivero, I. V., Secord, T. W., & Tamayol, A. (2021, May). Corrugated Compliant Capacitor towards Smart Bandage Application. In *2021 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)* (pp. 1-6). IEEE.
[2] Vereen, A. B., Downey, A., Sockalingham, S., Ziehl, P., LaFlamme, S., Li, J., & Jo, H. (2021, March). Monitoring impact damage in composites with large area sensing skins. In *Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2021* (Vol. 11591, pp. 336-344). SPIE.
[1] Liu, H., Laflamme, S., Li, J., Bennett, C., Collins, W., Downey, A., & Jo, H. (2021, March). Experimental validation of textured sensing skin for fatigue crack monitoring. In *Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2021* (Vol. 11591, pp. 345-351). SPIE.

Invited Presentations

[8] Soft Sensing Technology for Fatigue Crack Discovery and Monitoring, University of Perugia, Seminar of the Intl Doctoral Program in Civil and Env. Eng., Nov. 11th 2022.
[7] *Tianjin University*, Tianjin, China, "Advanced sensing and computer vision for civil infrastructure monitoring and inspections. " November 10, 2022.
[6] Liu, H., Laflamme, S., Li, J., Bennett, C., Collins, W., Downey, A., Ziehl, P., & Jo, H., Robust Wireless Skin Sensor Networks for Long-Term Fatigue Crack Monitoring of Bridges, Mid-Continent Transportation Research Symposium, Ames, IA, Sept. 15 2022.
[5] *Harbin Institute of Technology*, Harbin, China, "Advanced sensors and computer vision for civil infrastructure monitoring and inspections. " August 1, 2022.
[4] *Shenzhen University*, Shenzhen, China, "Advanced sensors and computer vision for civil infrastructure monitoring and inspections. " January 4, 2022.
[3] *The SIR Frontiers Seminar Series, South China University of Technology,* Guangzhou, China, "Advanced sensors and computer vision for civil infrastructure monitoring and inspections. " August 12, 2021.
[2] Field Deployable Textured Sensing Skin for Monitoring of Surface Strain, webinar (Department of Civil & Environmental Engineering), U. Mass. Lowell, April 19th 2021.
[1] Field Deployable Sensing Skin for Monitoring of Surface Strain, webinar, Electric Power Research Institute, Nov 5th 2020.

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