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

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Executive Summary

Fatigue-induced cracks are of great concern to State Departments of Transportation (DOTs). In particular, fracture critical bridges are vulnerable to fatigue cracks due to the brittle nature of their failure modes. Monitoring of fatigue cracks is critical for determining retrofitting and maintenance plans. In particular, measuring strains induced by cracking can be an effective way of monitoring fatigue cracks. However, traditional strain sensors such as metal foil strain gauges are not able to capture crack development due to their small size, limited measurement range, and high failure rate under harsh environment conditions. The goal of the proposed research is to develop a strain-based fatigue crack monitoring system using a large size, high ductility, and high precision elastomeric skin-type sensor, along with wireless sensing technology to enable long-term, low cost, autonomous, and continuous fatigue crack monitoring for fracture critical bridges.

Problem Statement and Objective

Fatigue cracks have been a major issue for steel bridges in the nation. State DOTs currently rely on a two-year inspection period to examine steel bridges for detecting fatigue crack activities. However, human inspection is time consuming, labor intensive, cost inefficient, and prone to error. Although Nondestructive Evaluation (NDE) techniques can improve inspection accuracy, the lack of autonomy and continuity in the inspection process still limits its ability to capture critical crack development in a timely fashion. After all, these cracks may occur between scheduled inspection periods and therefore can lead to catastrophic failure of steel bridges.

Measuring strain-induced crack development is an effective way of monitoring fatigue cracks. However, due to the randomness of crack paths, traditional strains sensors, such as metal foil strain gauges, are small and can only be deployed in a small and localized region, limiting their capability of detecting these cracks. Moreover, the limited ductility of these foil gauges leads to breakage under excessive strain, typical during crack formation. Meanwhile, a traditional wired monitoring approach imposes high cost to the overall system due to bulky data acquisition units and expensive cabling work, especially for long-span bridges. The centralized management scheme limits its flexibility and continuous monitoring capability due to potential data inundation.

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 in the following ways:

(1) The ability to collect objective information regarding fatigue crack activity under in-service loading of bridges in a continuous manner, improving the assessment, safety, and reliability of fractural-critical bridges, and providing early warning regarding evolving internal defects.

(2) The ability to improve prioritization of bridge repairs (condition-based maintenance) and retrofit for fatigue cracks so as to maximize the effectiveness of limited resources.

(3) The ability to better assess the effectiveness of various fatigue repair and retrofit techniques for steel bridges through long-term crack monitoring.

Background

To effectively capture crack development, strain sensors should cover large areas susceptible to fatigue cracking. In addition, these sensors should have enough sensitivity to measure small cracks and adequate ductility for large strain measurement to ensure mechanical robustness under large cracks. Traditional metal foil gauges are typically small in size (2-10 mm^2) and have limited range (≈ ±3%), thus are not suitable for crack detection and localization.

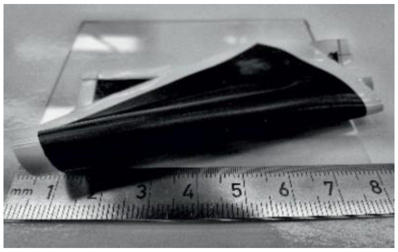


Figure 1. Elastomeric Sensing Skin

Figure 2. Wireless Smart Sensor (Imote2)

Recently, a newly developed soft elastomeric capacitor (SEC) skin-type sensor [1] showed great promise in crack monitoring through strain measurement. Inspired by biological skin, this new skin-type sensor (Fig. 1) consists of several individual capacitive sensors, transducing strain into changes in capacitance. Experimental tests showed that the sensing skin can measure large strains (20%) and has high resolution (25 με) necessary for crack detection; sensitivity could be further improved by developing a dedicated data acquisition system. The SEC sensor can be fabricated into large size patches and assembled in a matrix configuration to cover much larger area than metal foil gauges. The sensor is flexible, and can be installed in corners and joints. In addition, the strain sensor is made of low cost nanopolymer and is robust and easy to install. The sensor overcomes all limitations of traditional metal foil gauges and is able to provide essential strain measurement for long-term fatigue crack activity monitoring of steel bridges under harsh environment.

Wireless sensing technology (Fig. 2) has seen great advancement in recent years [2, 3]. The ability of wireless communication and data transmission removes the need for expensive cabling work and at the same time enables flexible and efficient sensor placement. The on-board computational units of wireless smart sensors enable on-line data processing and decision making, alleviating data inundation problem and facilitating continuous and autonomous operation of the monitoring system. Recent success of the long-term wireless structural health monitoring (SHM) system deployed on the Jindo Bridge in South Korea [2] demonstrated long-term stable performance of wireless SHM systems for monitoring large-scale civil infrastructure.

Integrating the SEC skin sensor with wireless sensing technology has the potential to provide a practical and cost-effective solution to continuous monitoring of fatigue cracks for steel bridges.

Low cost, high resolution Analog-to-Digital Converter (ADC) chips integrated into wireless sensors offer high quality signal conditioning to measured strain data by the SEC sensor with minimum noise. The SEC sensor can be made by using a number of patches positioned in certain patterns. With the on-board computation capability of the wireless sensors, processing these data on board enables more efficient crack development detection without transmitting all data back to the central base station. Data fusion among multiple measurements from different sensor patches has the potential to improve the effectiveness of fatigue crack detection. With a coordinated sensor network management scheme, smart triggering mechanisms can be implemented for capturing the most significant strain responses associated with crack activities.

Proposed Research

The proposed research consists of three phases of tasks from the development and validation of the basic crack sensor (Phase I), design, implementation, and small scale validation of the wireless data acquisition system and the autonomous sensor network operation strategies (Phase II), to the robustness, large scale, and long-term full scale validation tests of the integrated wireless crack sensor network system (Phase III).

Phase I tasks: Crack sensor

1. ***Crack sensor fabrication***: Fatigue crack sensors will be developed by fabricating the skin sensors tailored to fatigue crack detection. The thickness of these sensors will be 40 μm to enhance the mechanical robustness under harsh environment.

2. ***Small scale validation***: Tests will be designed and carried out to validate the crack detection capability of the crack sensor. The test setup will consist of a pre-notched steel member subjected to fatigue loading. The fatigue testing facility (Fig. 3) at the University of Kansas will also be used to perform tensile fatigue tests (a) and bending fatigue tests (b). An off-the-shelf data acquisition system will be adopted to measure the capacitance change of the sensors under crack development. Metal foil gauges will be used to provide reference measurement for validation.

(a) Tensile fatigue test setup

(b) Three-point bending fatigue test setup

Figure 3. Small scale fatigue testing facility at the University of Kansas

Phase II tasks: Wireless crack sensor network

3. ***Wireless data acquisition (DAQ) system***: A wireless data acquisition system will be developed for measuring capacitance change of the elastomeric skin sensor. The Imote2 smart sensor platform (Fig. 2) is selected because of its fully tested software package, which serves as the foundation of this integrated wireless skin sensor network system. The Imote2 sensor can measure voltage inputs between -5 V and +5 V using a stackable data acquisition (DAQ) board. An interface board between the elastomeric skin sensor and the Imote2 DAQ board will be developed to convert capacitance change into voltage signals.

4. ***Data quality assessment***: The quality of data collected by the integrated wireless sensing system will be evaluated. Focus will be placed on the noise level and resolution. The goal is to make sure the integrated system has adequate resolution and low noise level to capture the strain change associated with fatigue crack activity.

5. ***Crack detection algorithm***: Algorithms will be developed to process the measured strain data to reveal the crack activities underneath the skin sensor. Various sensor patterns will be investigated based on typical scenarios of fatigue cracks. Data fusion strategies combining on-board and in-network data processing will be implemented and tested for detecting active fatigue cracks as well as the propagation direction of these active cracks. The goal is to be able to make decisions using the smart sensors by locally combining and processing data measured at different locations without transmitting raw data back to the base station.

6. ***Autonomous sensor network***: Software will be designed to enable autonomous operation of the sensor network. Practical issues such as triggering of the sensor network, sleep-cycling to conserve energy, energy harvesting methods such as solar panels, and other energy efficient operation issues, etc. will be addressed in this task.

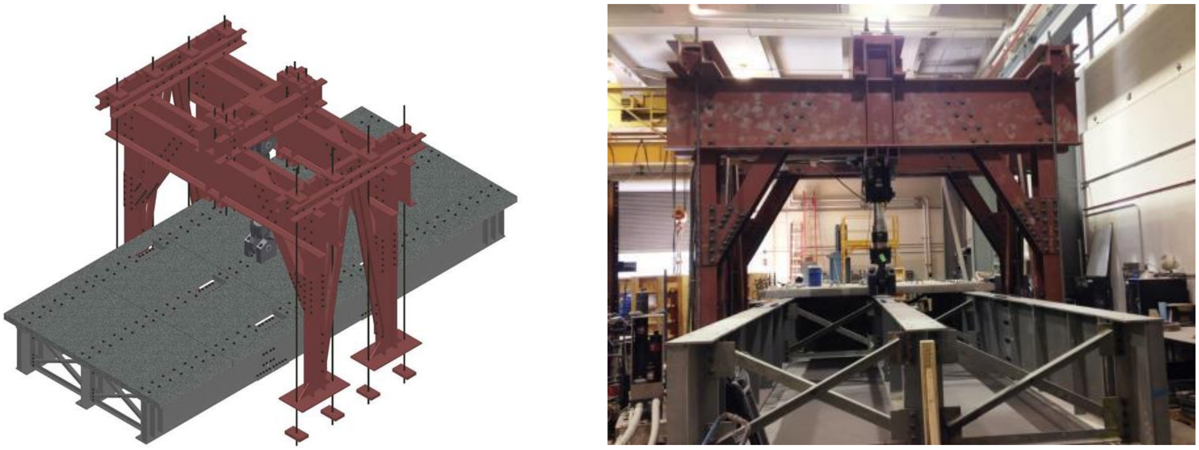
7. ***Small scale system validation***: The integrated system will be validated using the small scale pre-notched steel beam from Task 2 of Phase I.

Phase III tasks: Large/full scale validation

8. ***Robustness test***: The robustness of both hardware and software will be tested. Mechanical robustness against external impact on the elastomeric skin sensors, long term stability of the electrical signal generated by the crack sensor, and fault tolerance of the software for autonomous operation will be tested.

9. ***Large scale validation***: A network of crack sensors will be deployed on the existing large scale steel girder test bridge [4] at the University of Kansas (Fig. 4), which is a 30-ft long, three-girder bridge that includes realistic fatigue sensitive details. The steel bridge test setup was developed for Pooled Fund Study TPF-5(189) aimed at developing retrofitting methods for distortion-induced fatigue, and thus the test bridge includes such details as web gaps, transverse stiffeners, and bolted splices. Initial cracks will be developed in the test bridge under cyclic loading, and the integrated wireless skin sensor network will be applied in this realistic test set-up for verification. Application of the wireless skin sensor network in this test set-up will allow for verification using details that are geometrically complex and experience multi-directional stresses such as would be common in actual steel bridge infrastructure.

10. ***Full scale long-term validation***: A highway bridge with fatigue sensitive details or known fatigue cracks will be selected for full scale long-term deployment. Continuous and autonomous monitoring will be performed with a network of crack sensors deployed at various locations on the bridge. Deployment of sensor network and initial data collection will be completed within the time frame of this project. Selection of the bridge for long-term monitoring will be performed in conjunction with the Kansas DOT.



(c) 3D rendering of the KU three-girder test bridge

(d) Reaction frame and three-girder test bridge with deck partially removed

Figure 4. Large scale fatigue testing facility at the University of Kansas

Deliverables

The project team will offer a practical and cost-effective methodology for long-term, autonomous and continuous monitoring of fatigue crack activities for steel bridges based on the integrated and validated wireless skin sensor network system. The team will also provide technical advice on various issues including (but not limited to) sensor installation and placement, data interpretation, and network operation and management. Quarterly reports and a final report will be produced. The team plans to hold two pooled-fund project participant meetings during the project. The team also plans to disseminate the findings and results generated from this research through journal publications and conference proceedings.

Project Personnel

The proposed research will be carried out by a group of faculty from the University of Kansas and Iowa State University. Dr. Jian Li from KU is an expert on wireless smart sensor networks and structural health monitoring. He recently served as one of the main contributors to the deployment of the world's largest wireless sensor network for civil infrastructure monitoring in South Korea. Professor Simon Laflamme from ISU has done numerous research and testing on the elastomeric skin sensors for structural health monitoring, and his work has been featured in Scientific American and ASCE Civil Engineering Magazine. Dr. Stanley Rolfe from KU has vast experience in the field of fatigue and fracture. He has published over 70 technical articles in fatigue and fracture of steel structures, and is a recipient of the ASTM Fracture Mechanics Medal. Dr. Caroline Bennett and Dr. Adolfo Matamoros from KU have extensive experience in the area of fatigue and fracture in steel bridges. They have conducted a number of research projects aimed at improving the fatigue performance of structures, including Transportation Pooled Fund study TPF-5(189), "Enhancement of Welded Steel Bridge Girders Susceptible to Distortion-Induced Fatigue." Dr. Daji Qiao from ISU is an expert in energy harvesting and wireless networking and communications. He has designed and implemented many innovative protocols and algorithms that are related to energy conservation, harvesting, or replenishment. Dr. Brent Phares from ISU has been involved in both research and applications of nondestructive evaluation technologies to civil infrastructures since 1995.

Project Schedule

The anticipated project timeline is shown in Table 1, in which a set of durations in quarters is assigned to each task. Phase I and Phase II can start concurrently by the ISU and KU teams. The total duration of the project will be 36 months.

Table 1: Schedule of Project Tasks

Timeline	Year 1 ('14-'15)				Year 2 ('15-'16)				Year 3 ('16-'17)			
	Quarter											
Tasks	1	2	3	4	1	2	3	4	1	2	3	4
Phase I: Crack sensor	●→	→	▶									
Task 1: Crack sensor fabrication	▨											
Task 2: Small scale validation		▨	▨									
Phase II: Wireless crack sensor network	●→	→	→	→	→	→	→	▶				
Task 3: Wireless DAQ system	▨	▨										
Task 4: Data quality assessment			▨									
Task 5: Crack detection algorithm			▨	▨								
Task 6: Autonomous sensor network				▨	▨	▨						
Task 7: Small scale system validation						▨	▨	▨				
Phase III: Large/full scale validation							●→	→	→	→	→	▶
Task 8: Robustness test							▨	▨				
Task 9: Large scale validation								▨	▨	▨	▨	
Task 10: Full scale long-term validation											▨	▨
Task 11: Final report											▨	▨

Budget Considerations

The estimated total project cost is $497,407. Iowa DOT has committed $92,150 towards Phase I and part of Phase II tasks.

References

[1] Laflamme, S., Kollosche, M., Connor, J. J., and Kofod, G. (2013). "Robust Flexible Capacitive Surface Sensor for Structural Health Monitoring Applications." *ASCE Journal of Engineering Mechanics*, 139(7), 879-885.

[2] Jo, H., Sim, S., Mechitov, K. A., Kim, R., Li, J., Moinzadeh, P., Spencer Jr., B.F., Park, J.W., Cho, S., Jung, H., Yun, C.B., Rice, J., and Nagayama, T. (2011). "Hybrid wireless smart sensor network for full-scale structural health monitoring of a cable-stayed bridge." *Proc. SPIE Smart Structures/NDE 2011*, San Diego, CA.

[3] Li, J., Nagayama, T., Mechitov, K.A., and Spencer Jr., B.F. (2012). "Efficient Campaign-type Structural Health Monitoring Using Wireless Smart Sensors." *Proc. SPIE Smart Structures/NDE 2012*, San Diego, CA.

[4] Hartman, A., Bennett, C., Matamoros, A., and Rolfe, S. (2013). "Innovative retrofit technique for distortion-induced fatigue cracks in steel girder web gaps." *Bridge Structures*, 9:57-71.