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Institute for Transportation

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RESEARCH PROJECT TITLE
Robust Wireless Skin Sensor Networks for Long-Term Fatigue Crack Monitoring of Bridges – Phase I

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The mission of the Institute for Transportation (InTrans) at Iowa State University is to save lives and improve economic vitality through discovery, research innovation, outreach, and the implementation of bold ideas.

Robust Wireless Skin Sensor Networks for Long-Term Fatigue Crack Monitoring of Bridges (Phase I)

tech transfer summary

Wireless sensing skin technology was successfully used to monitor fatigue cracks on a steel bridge girder, demonstrating a cost-effective technology to detect, localize, and assess damage.

Objectives

- Develop sensing skin technology that can be deployed over strategic areas to detect, localize, and assess fatigue cracks
- Provide sensing skin with autonomous capabilities, including power harvesting, onboard processing, and wireless transmission
- Transform sensing skin signal into an index readily interpretable by infrastructure operators
- Demonstrate sensing skin technology in the field

Background

Fatigue is the weakening of steel materials or the accumulation of damage at a localized region caused by cyclic loading or repeatedly applied loads such as those caused by traffic. Fatigue-induced cracks are of great concern to departments of transportation (DOTs). A significant number of bridges in the country are fracture-critical bridges that are vulnerable to fatigue cracks due to the brittle nature of their failure modes.

In 2020, 37% of bridges totaling 231,000 in the United States needed repair work, and 7.5% of the nation's 617,000 bridges subjected to federal inspection requirements were rated in poor condition and classified as structurally deficient. The timely discovery and monitoring of fatigue cracks in steel structures is an important task to ensure their structural integrity.

Problem Statement

Automatic fatigue crack detection using commercial sensing technologies is difficult due to the highly localized nature of crack monitoring sensors and the randomness of crack initiation and propagation. Visual inspection is currently the most popular approach used in detecting fatigue cracks, but the process is time-consuming, labor-intensive, and reliant on the inspector's judgment.

Various nondestructive evaluation techniques for crack detection and quantification have been proposed to assist visual inspections. However, the mainstream nondestructive evaluation methods are typically temporary and conducted manually over limited components and sections of the structure, thus spatiotemporally limiting crack discovery.

Research Description

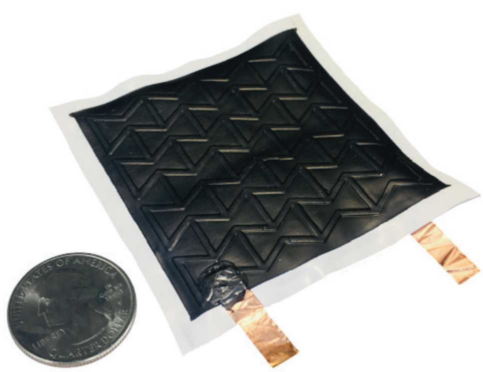
A large-scale deployable sensing skin system capable of robust long-term field deployment was developed based on a dense sensor network of capacitive-based strain gauges, termed soft elastomeric capacitors (SECs) or, in an updated version, corrugated SECs (cSECs).

The developed sensing skin technology can be seen as a low-cost alternative to the use of traditional strain gauges and is capable of measuring local strains over large surfaces. Data collected by the SECs can be directly correlated with fatigue crack activities by capturing surface deformations caused by cracking.

The general performance of the sensing skin, including its linearity, sensitivity, resolution, and accuracy, was characterized and evaluated through a series of fatigue crack tests conducted on small-scale specimens. A crack growth index (CGI) algorithm was formulated to directly quantify crack growth.

The investigation of the sensing skin extended to its application for measuring angular motion in steel components and for discovering and monitoring fatigue cracks on fillet welds through deployment of the sensors in a folded configuration.

The sensing skin was developed to be powered autonomously and capable of transmitting CGI data wirelessly to infrastructure operators. The wireless capacitance sensing capability was developed using a low-cost microcontroller-based sensor board interfacing with an Xnode solar-powered wireless sensor platform capable of bridge balancing, amplification, and shunt calibration. A series of laboratory tests were performed to validate the sensing system.

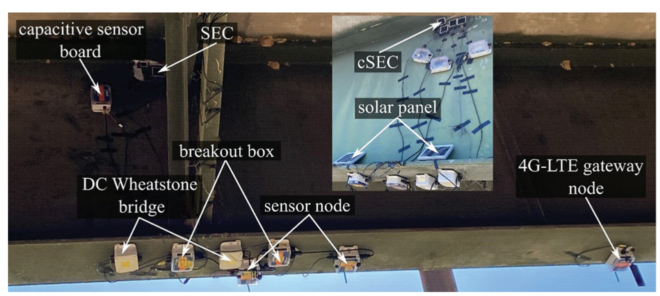


Soft elastomeric capacitor unit forming the sensing skin

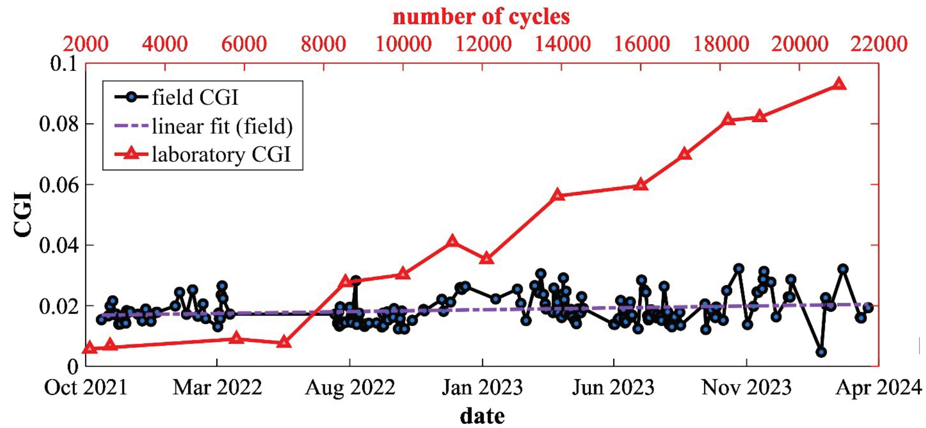
The sensing skin technology was deployed on a steel highway bridge on I-70 (eastbound) at the North 57th Street exit near Kansas City, Kansas. Sensors were placed on a steel girder, with one sensor deployed directly over an existing fatigue crack. Measurements were collected from October 2021 to April 2024. The demonstration site was visited regularly to update the sensing system, which was capable of collecting and transmitting data over the entire duration of the project.

Key Findings

- The laboratory investigations showed that sensing skin fabricated from a network of SECs can be used to monitor fatigue cracks in steel. This includes deployments in complex configurations, such as when a sensor is folded over a corner weld.
- The sensing skin can be used to detect cracks in concrete, but the concrete surface must be covered by a polymer before the SECs are installed to minimize noise caused by dielectric coupling.
- The sensing skin can measure large, localized strain on the order of 30% and can detect a fatigue crack of 0.28 mm in length over a flat surface and 0.48 mm in length in a folded configuration.
- The hardware developed in this research outperforms existing commercial systems and can be used to transmit low-amplitude capacitance data wirelessly.
- The field deployment further demonstrated that the sensing skin technology can be used to monitor fatigue cracks; an SEC deployed next to an existing fatigue crack measured a constant CGI throughout the study period.



Sensing skin technology deployed on a steel girder in the field



Field CGI values throughout the study period correlated to laboratory data, showing negligible growth for an existing crack

Recommendations

Given the successful field demonstration of the technology, it is recommended to develop large sensing sheets that can easily be deployed on-site rather than install and group individual SECs, as was done under this effort. Large sensing sheets can be developed by partnering with the flexible electronics industry to print sensing sheets equipped with embedded hardware capable of collecting measurements and transmitting them to a wireless platform.

It is also recommended to study the long-term performance of the sensing skin technology on a large number of bridges to provide infrastructure operators with convincing data sets and to enable a statistical study quantifying costs versus benefits.

Implementation Readiness and Benefits

The results of field testing on the I-70 steel bridge near Kansas City, Kansas, confirm the system's readiness for implementation, but commercial developments will be required to enable widespread deployment. For example, the sensing skin will need to be manufactured in the form of large sensing sheets than can easily be deployed on-site during maintenance operations.

The developed sensing skin is a scalable, low-cost solution for monitoring deformations over large surfaces. Its deployment at strategic locations on steel girders allows the detection of new fatigue cracks, which is not possible with existing sensing technology, and provides the means to monitor the evolution of cracks over time.

Given its capabilities, the system can be used to supplement inspections and provide timely information on bridge component health, thus enhancing bridge safety through the early detection of fatigue cracks and reducing the costs associated with bridge maintenance by enabling timely corrective measures.