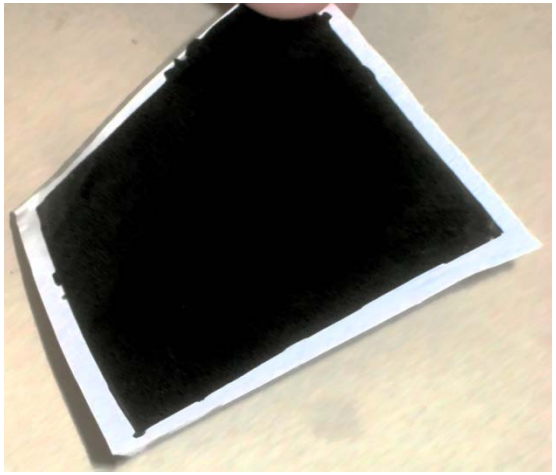
Smart Skin for Fatigue Crack Detection



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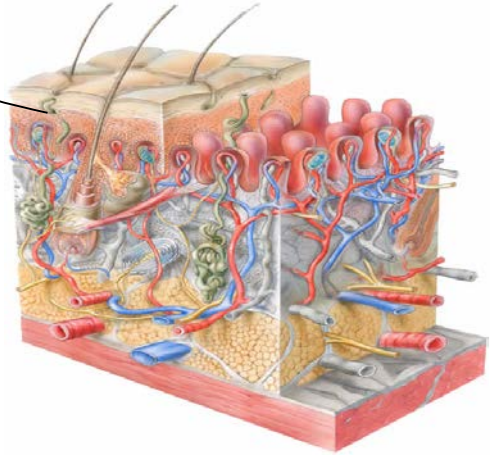


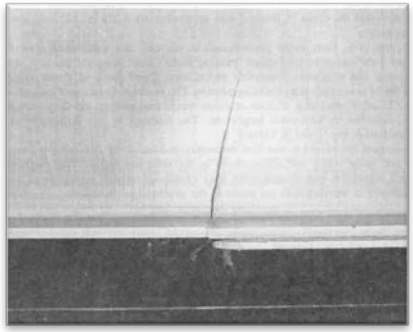
Introduction

Fatigue cracks in steel bridges

- Fatigue-induced cracks are one of the major concerns for steel bridges
- Monitoring fatigue cracks is critical

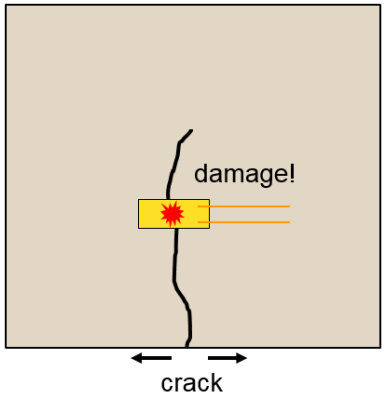
Crack monitoring methods

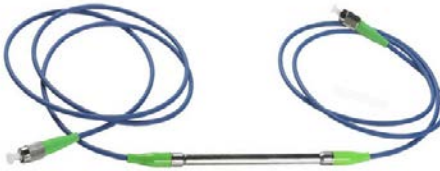
- Visual inspections



- Nondestructive testing
- Computer vision methods

- Strain sensing methods
  - Foil strain gauge
  - Fiber optic sensor
- Limitations
  - Small sensing area
  - Low ductility of sensing material



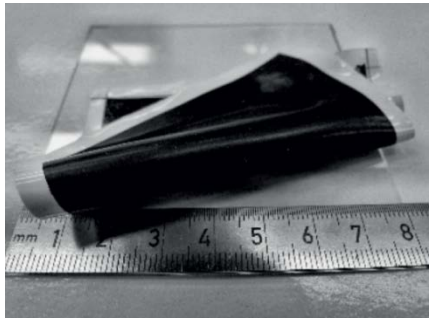


Fiber optical sensor
http://cindtechs.ca/

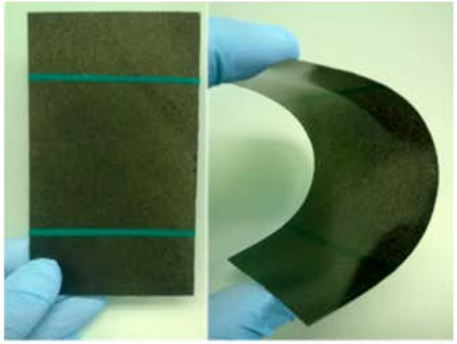
Sensing Skins

Large-area strain sensors

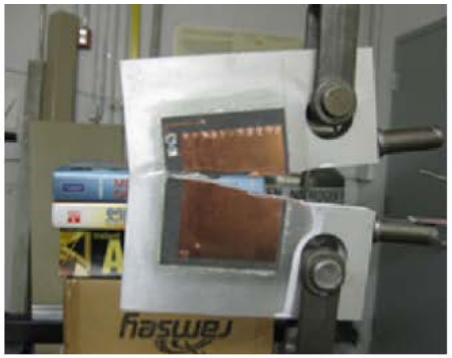
- Printable conductive polymer (Loh, 2007)
- Carbon nanotube thin film sensor (Loh, 2008; Thostenson, 2015)
- Resistive sensing sheet (Yao and Glisic, 2015)
- Patch antenna sensor (Huang, 2010; Wang, 2013)
- Soft Elastomeric Capacitor (SEC) (Laflamme, 2012)



Laflamme, 2012



Thostenson, 2015



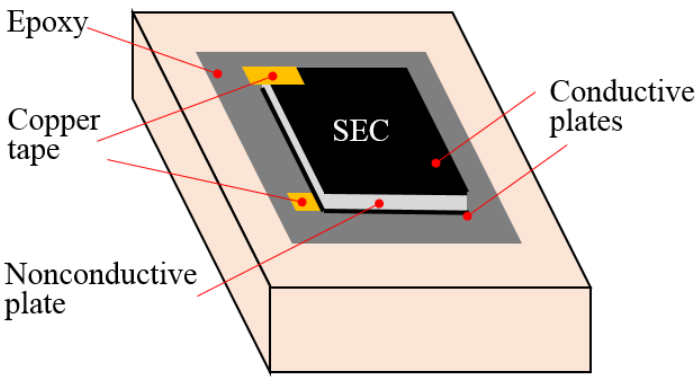
Wang, 2013

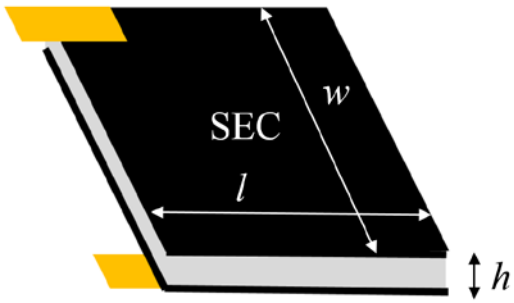
Yao and Glisic, 2015

Smart Sensing Skin

Soft elastomeric capacitor (SEC)

- Wider range of strain measurement (20%)
- Large sensing area (76 mm × 76 mm)
- Low cost and mechanically robust





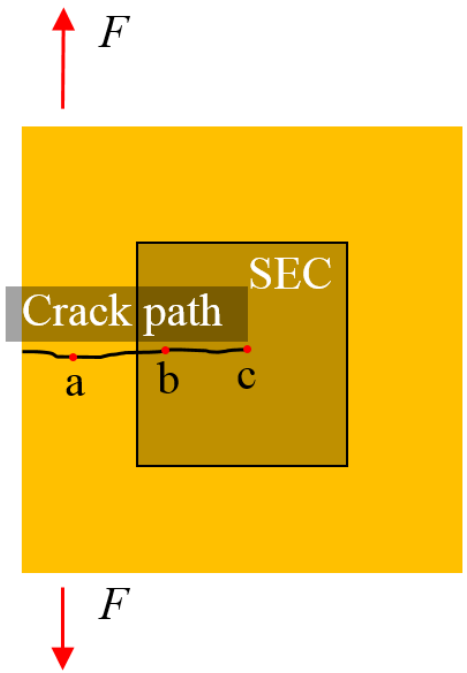
$$C = \frac{e_0 e_r A}{h}$$

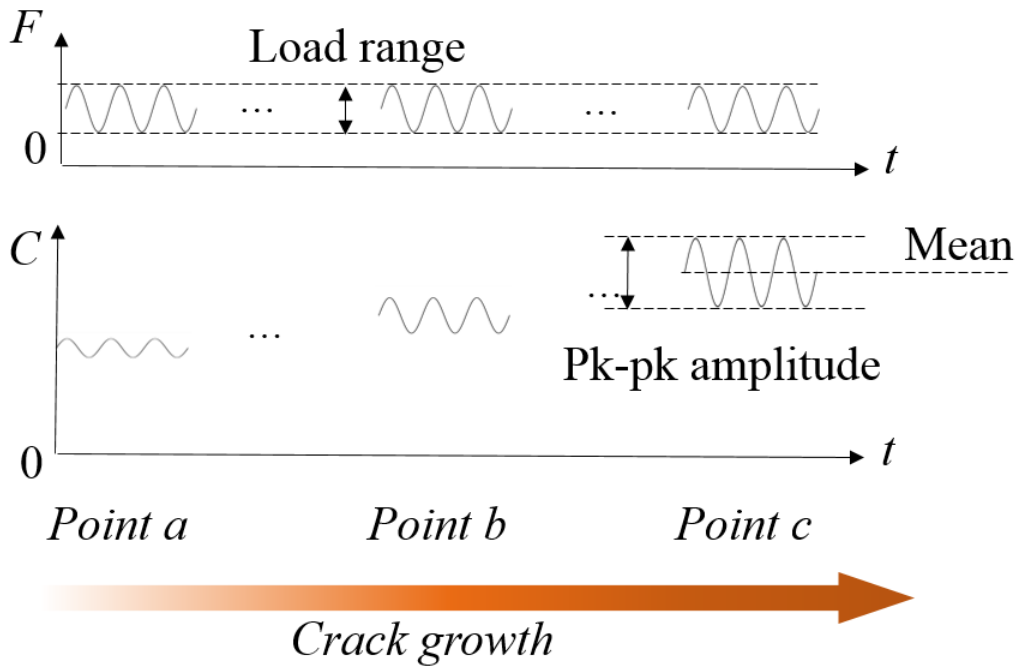
e_0, vacuum permittivity
e_r, relative permittivity of the polymer
$A = wl$, area of sensor
h, thickness of sensor

Smart Sensing Skin

SEC for crack monitoring

- Increasing mean capacitance
- Increasing peak-to-peak capacitance (pk-pk amplitude)

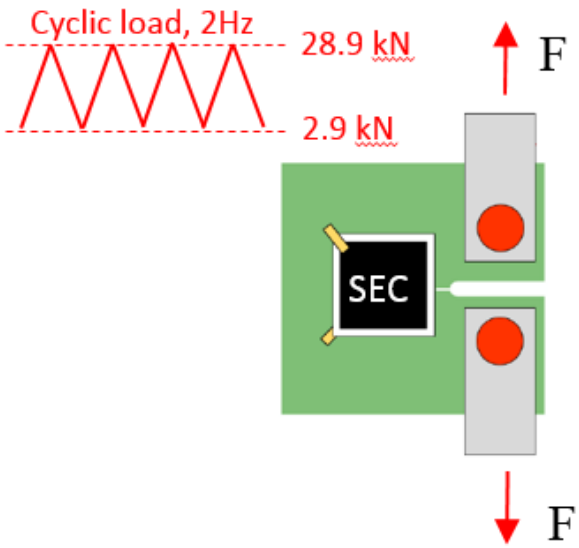


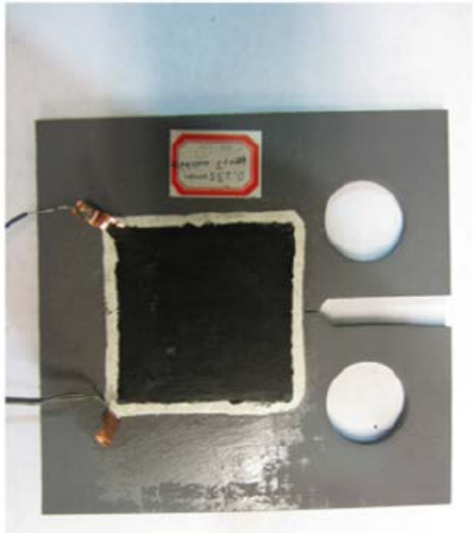


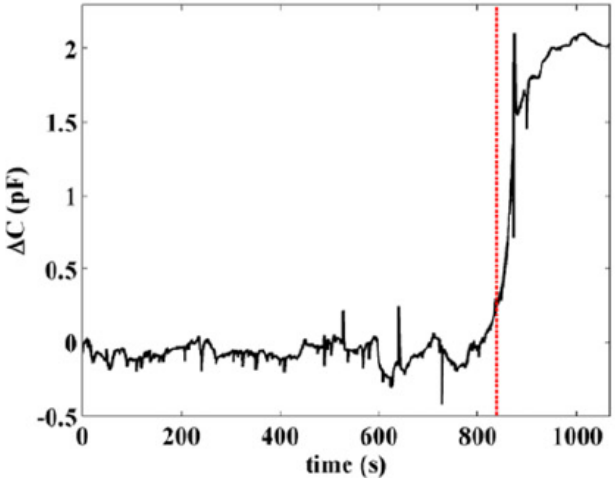
Smart Sensing Skin

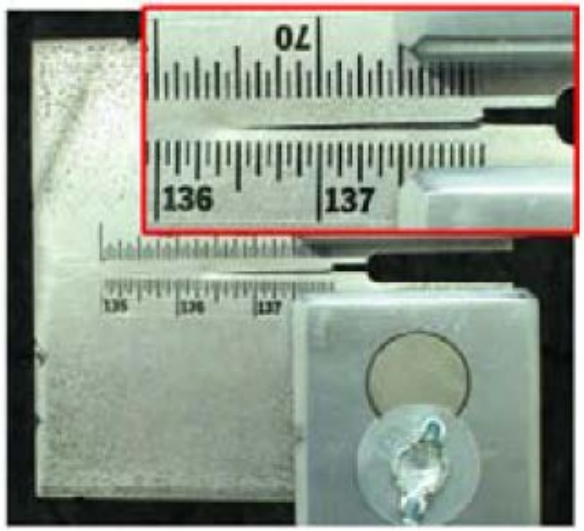
Previous tests

- Verified the capability of the SEC for crack detection and localization
- Low-cycle fatigue crack









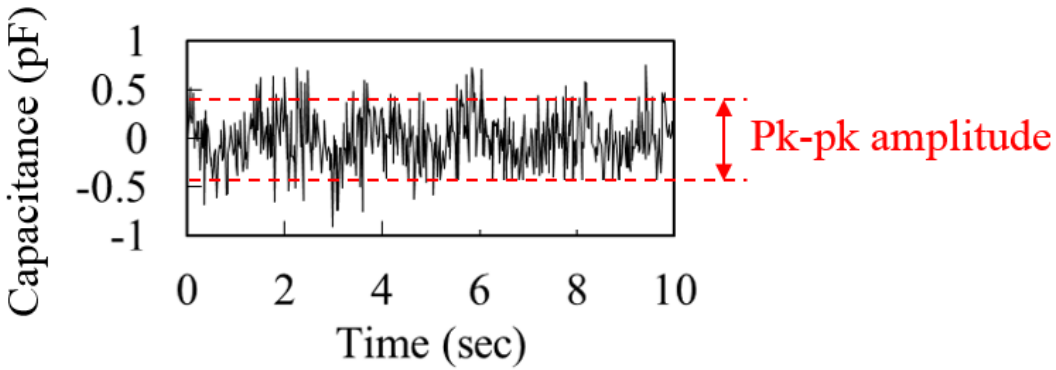
Smart Sensing Skin

High-cycle fatigue cracks in steel bridges

	Fatigue life	Stress level	Crack opening
Low-cycle fatigue	Short	High	Large
High-cycle fatigue	Long	Low	Small

Challenges for monitoring high-cycle fatigue

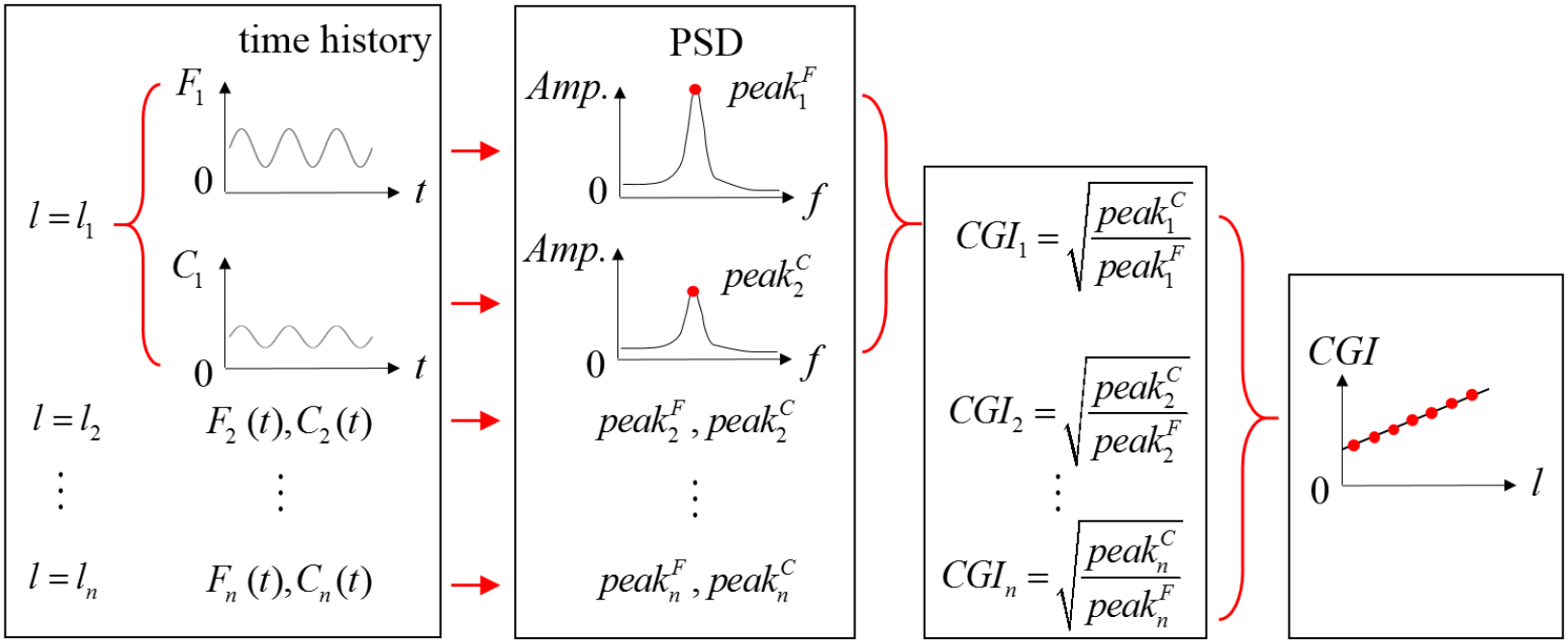
- 1) Mean capacitance drift over long term
- 2) Lower sensor response under lower stress level



Smart Sensing Skin

Proposed algorithm

- Four-step procedure: 1) data collection; 2) frequency analysis; 3) computing Crack Growth Index (CGI); and 4) crack growth monitoring

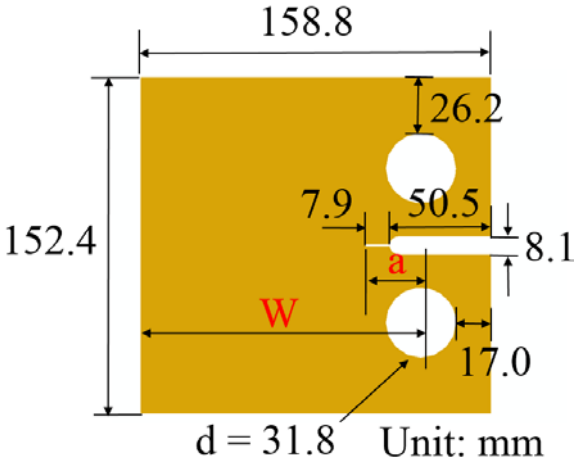


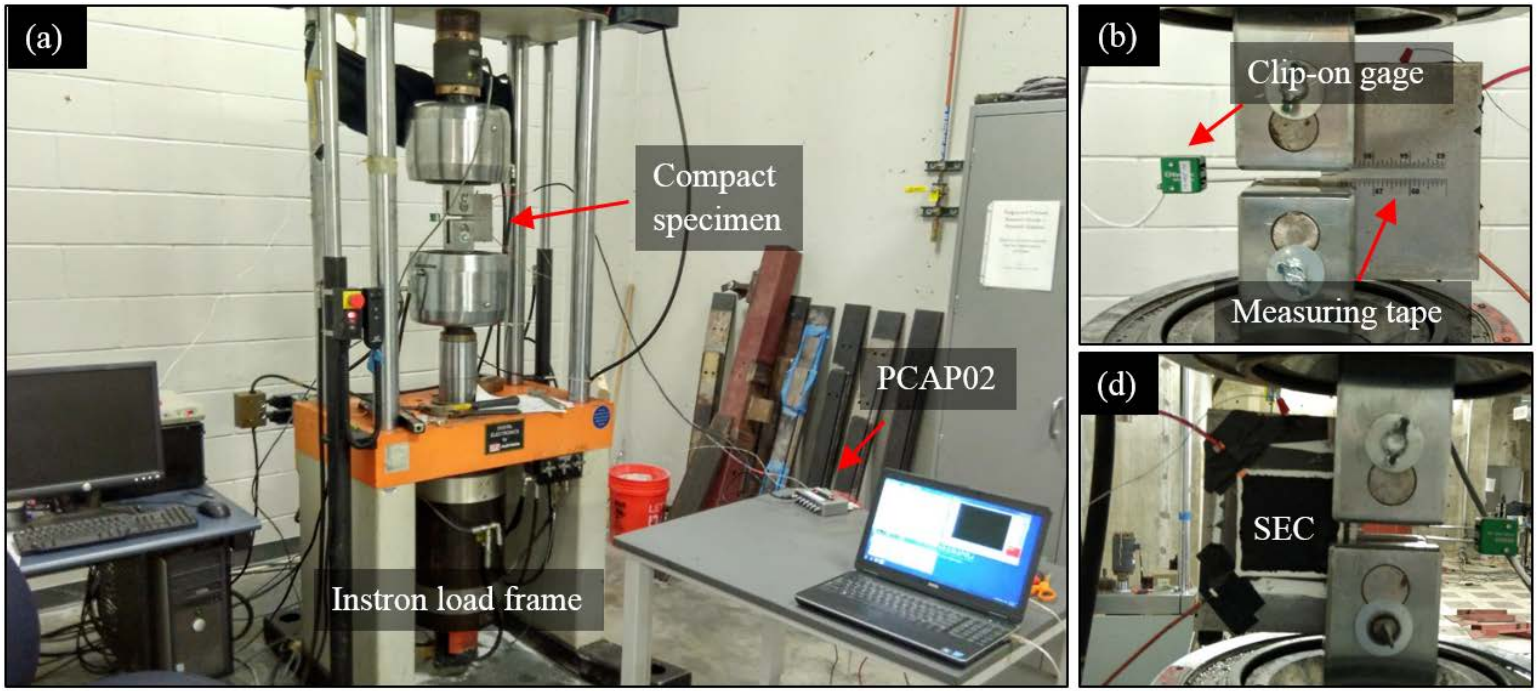
(a) (b) (c) (d)

Small-scale Testing

Test setup

- Compact steel specimen
- Instron load frame
- Off-the-shelf DAQ: ACAM PCAP-02
- Load cycle: harmonic





Small-scale Testing

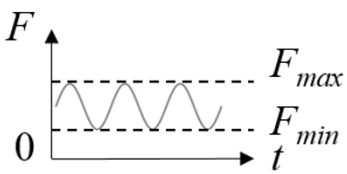
Loading protocols design

- Motivation: limit the plastic deformation at the crack tip

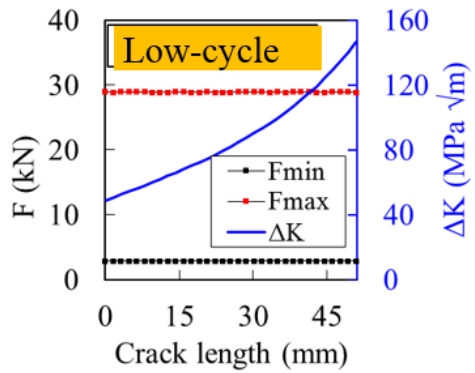
Approach

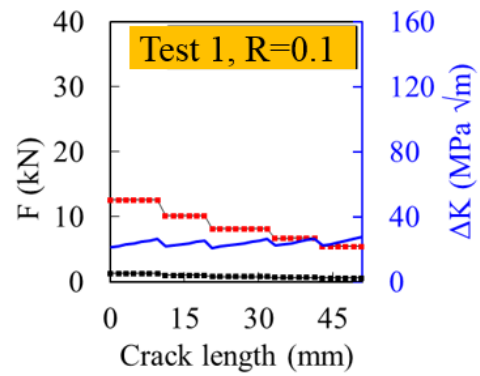
- Based on ASTM E1820-15
- Range R of stress intensity factor remains constant
- Stress intensity ratios R = 0.1, 0.4, and 0.6

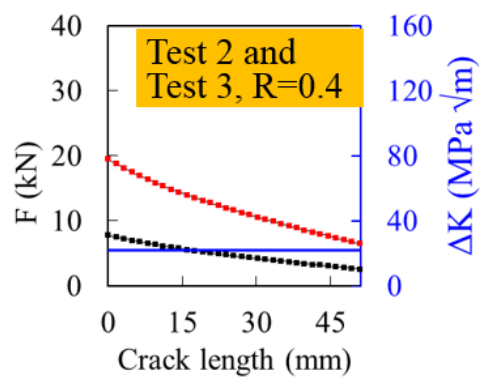
$$R = \frac{F_{min}}{F_{max}}$$

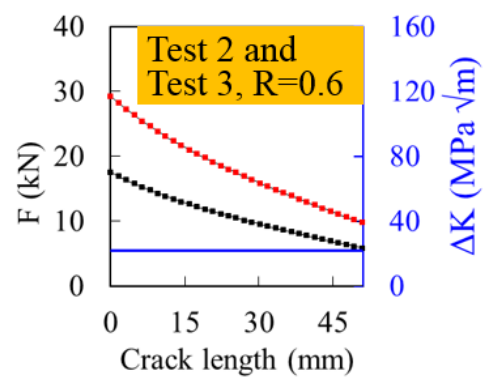


- Three tests and five datasets.





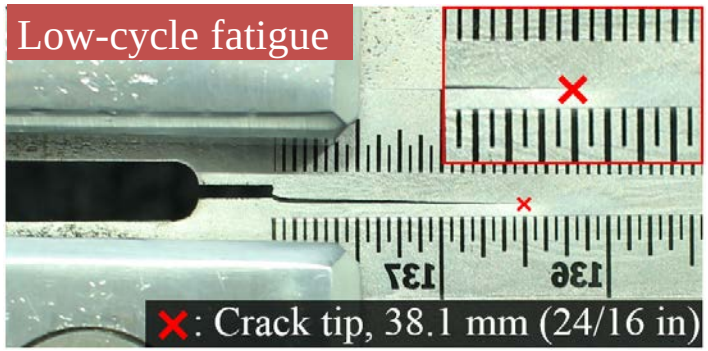


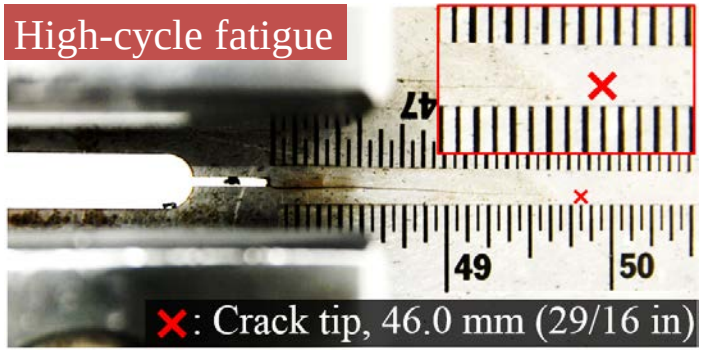


Small-scale Testing

Crack growth under new loading protocols

- Limited plastic deformation at the crack tip

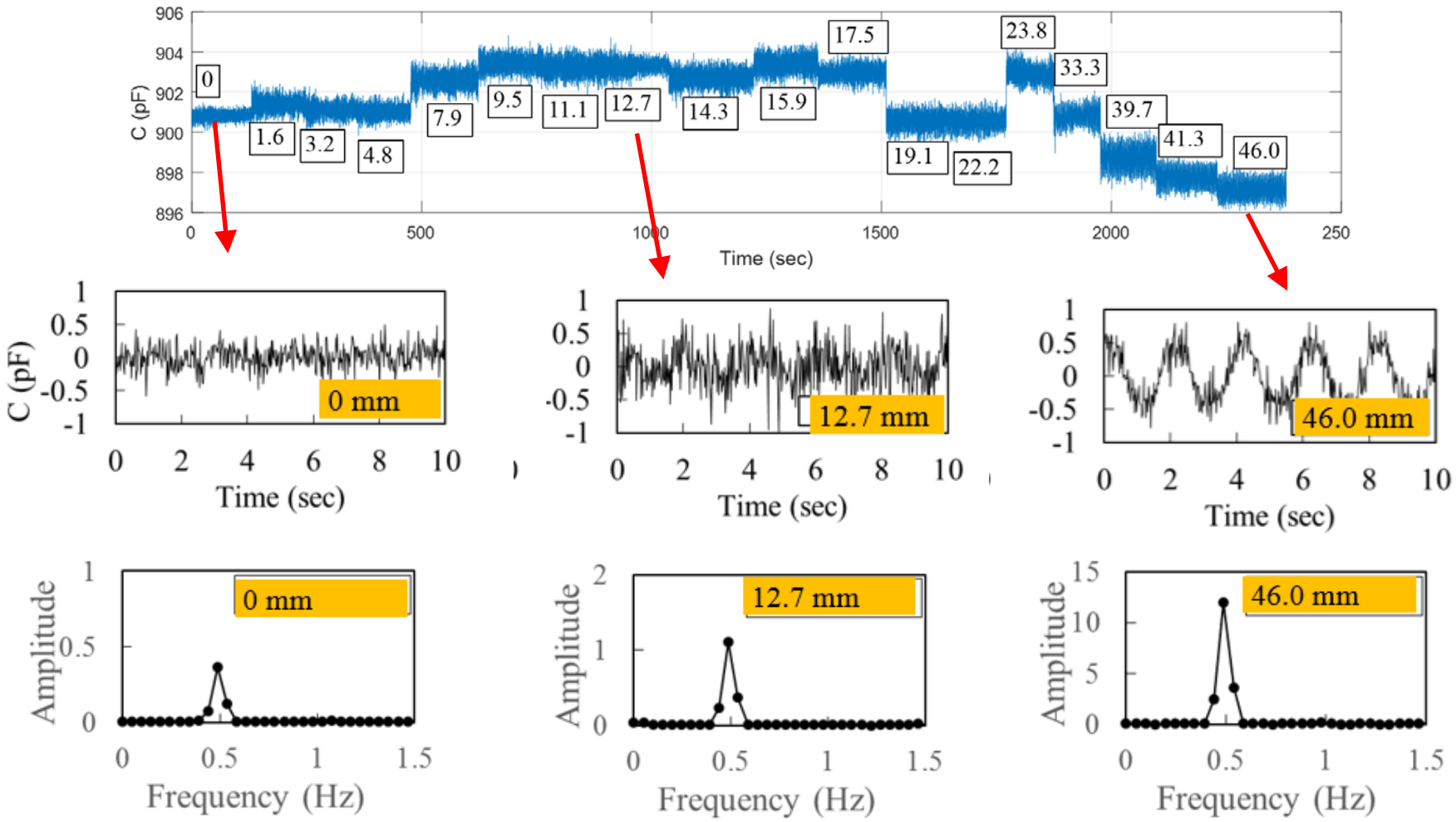




Test number	Number of cycles	Specimen fracture
Test 1	1,810,000	No
Test 2	660,000	No
Test 3	605,000	No
Previous Low-cycle Fatigue Test	14,500	Yes

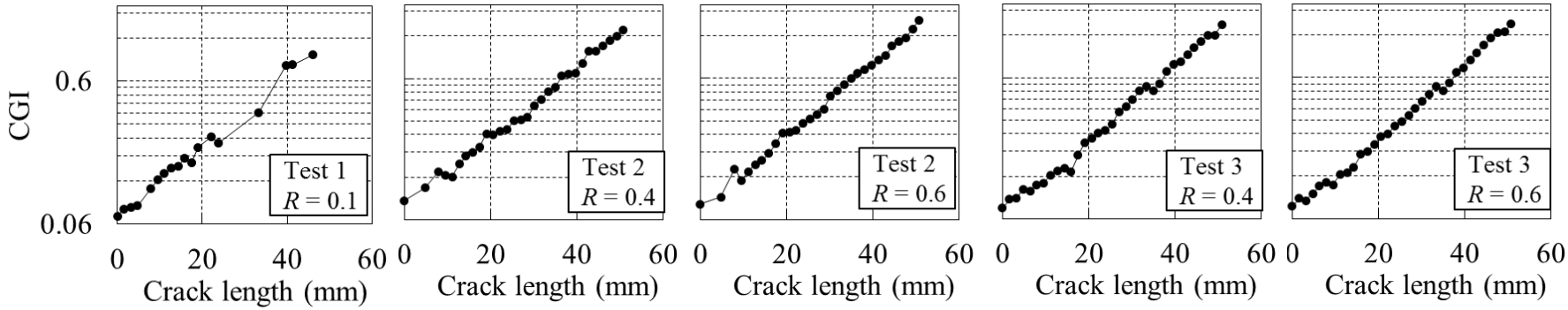
Small-scale Testing

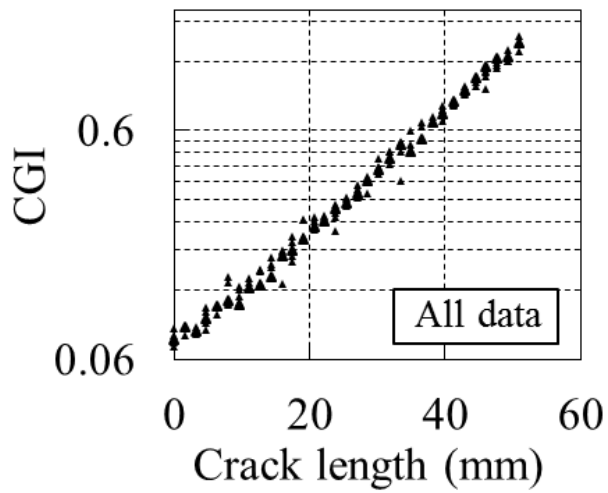
SEC measurements – first dataset



Small-scale Testing

CGI for all datasets





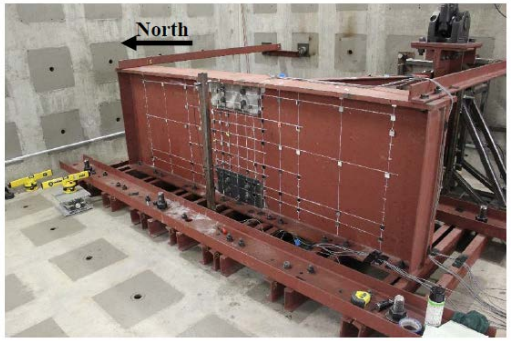
Large-scale Bridge Girder Testing

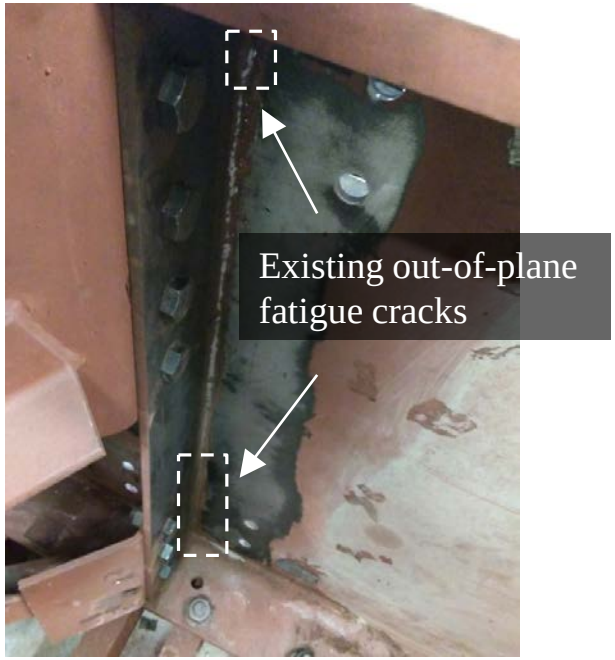
Motivation

- Investigate the SEC's ability for monitoring out-of-plane fatigue crack in a more complex structural configuration

Test structure

- Skewed girder to cross-frame connection
- Existing fatigue cracks

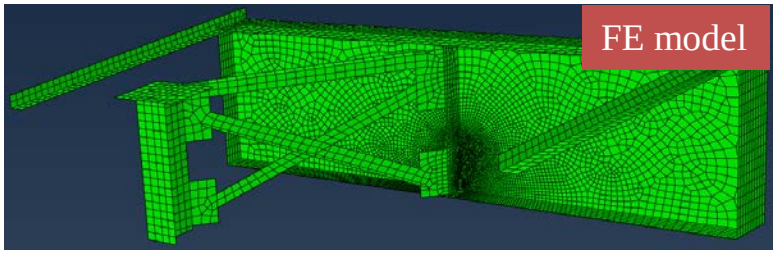


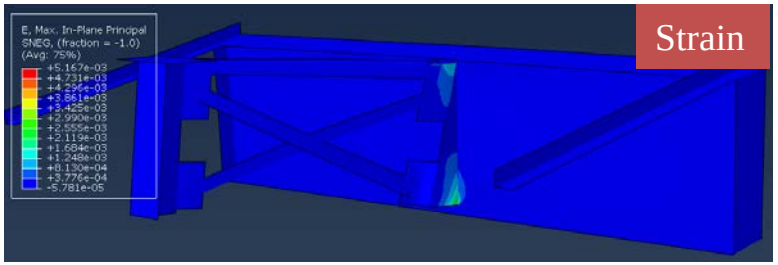


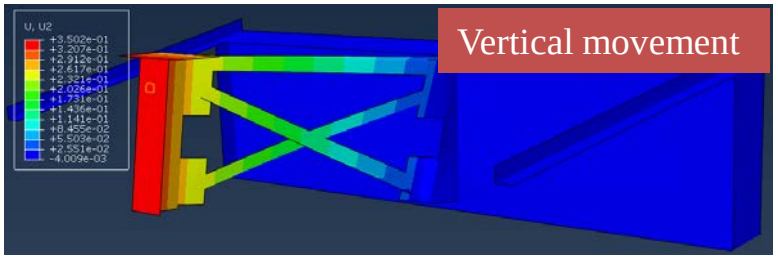
Large-scale Bridge Girder Testing

Finite element analysis

- Goal: capture strain field of the connection under loading
- Shell element-based FE model



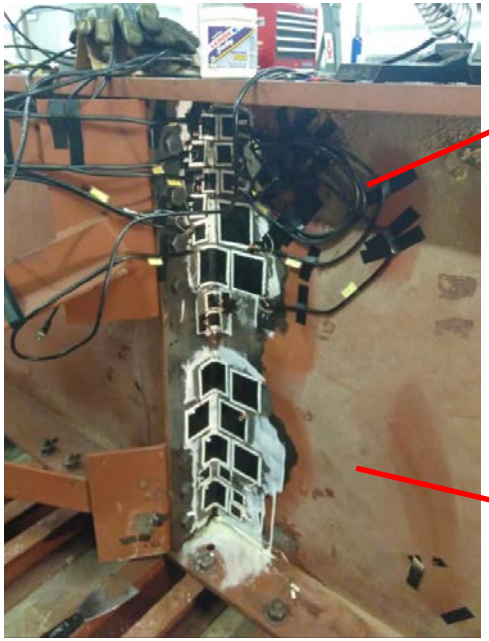


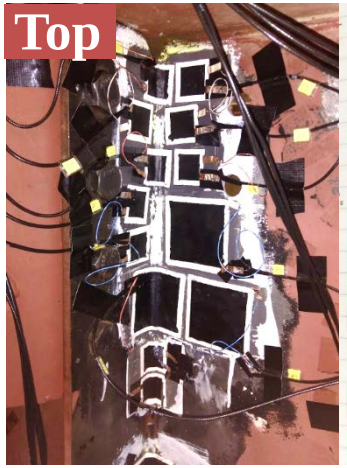


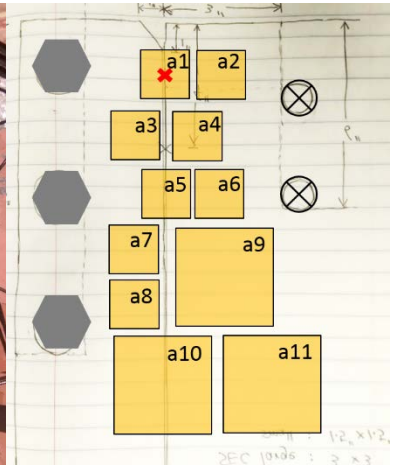
Large-scale Bridge Girder Testing

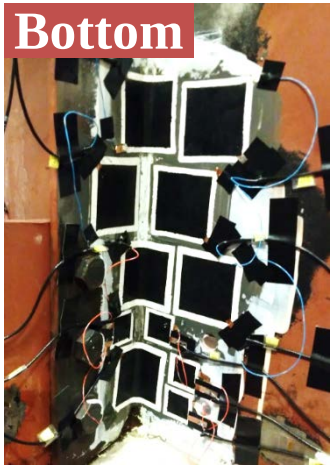
Test setup

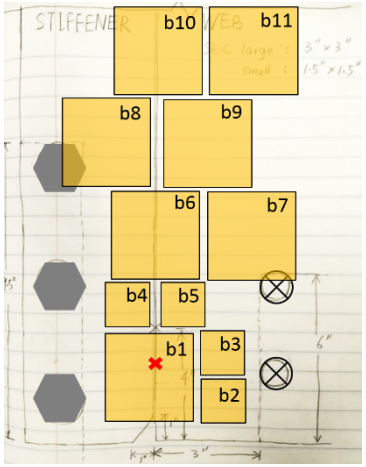
- A SEC array is deployed to cover fatigue critical region
- Two sizes of SEC
  3 x 3 in^2
  1.5 x 1.5 in^2
- 0 to 2.5 kip harmonic load







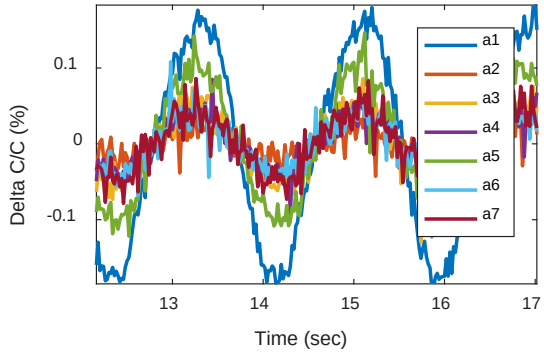


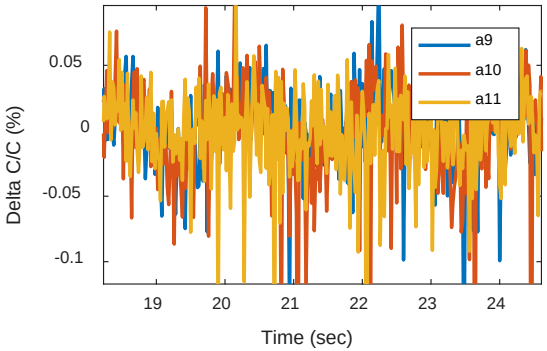


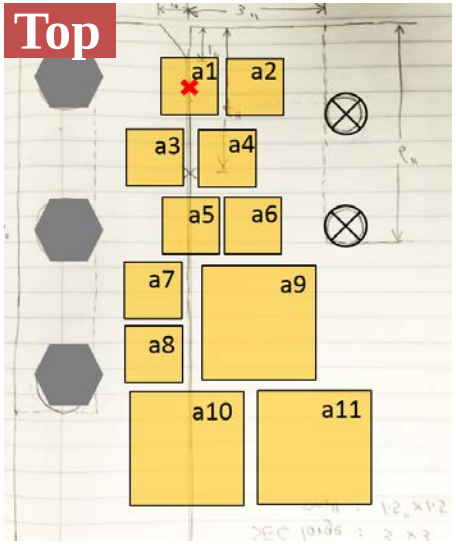
Large-scale Bridge Girder Testing

Typical SEC measurement – Top

- Time series measurements

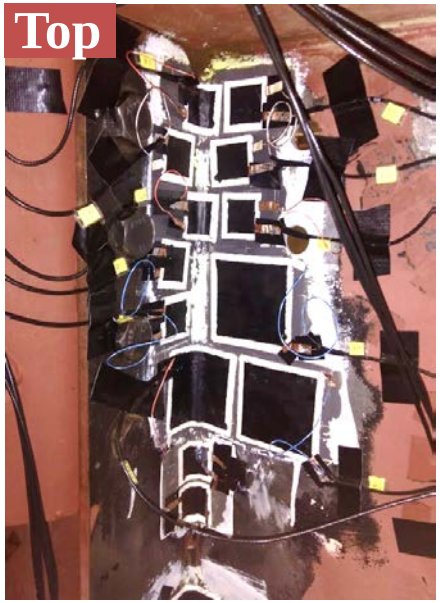


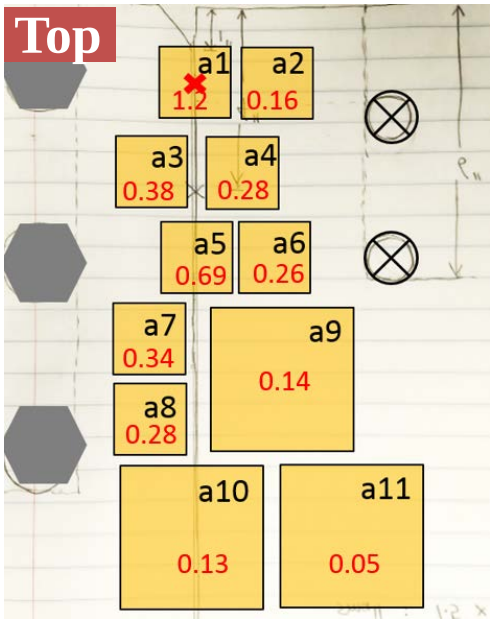




- Map of CGI

(crack growth index)





Conclusion

- The SEC is a large area and flexible strain sensing skin, suitable for monitoring fatigue cracks.
- The pk-pk amplitude is proposed as a robust indicator of crack growth, which is insensitive to the capacitance drift.
- Small-scale testing results verify that the proposed CGI algorithm can robustly monitor the crack growth under various loading conditions.
- Preliminary results on full-scale steel girder demonstrate that the SEC array can detect and localize fatigue cracks.

Acknowledgement

This work is supported by the Transportation Pooled Fund Study, *TPF-5(328)*, which includes the following participating state DOTs: Kansas, Iowa, Minnesota, North Carolina, Pennsylvania, Texas, and Oklahoma.