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
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)
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

<table>
<thead>
<tr>
<th></th>
<th>Fatigue life</th>
<th>Stress level</th>
<th>Crack opening</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-cycle fatigue</td>
<td>Short</td>
<td>High</td>
<td>Large</td>
</tr>
<tr>
<td>High-cycle fatigue</td>
<td>Long</td>
<td>Low</td>
<td>Small</td>
</tr>
</tbody>
</table>

Challenges for monitoring high-cycle fatigue

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

- Four-step procedure: 1) data collection; 2) frequency analysis; 3) computing Crack Growth Index (CGI); and 4) crack growth monitoring.
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 $R = 0.1, 0.4, \text{ and } 0.6$

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

- Three tests and five datasets.
Small-scale Testing

Crack growth under new loading protocols

- Limited plastic deformation at the crack tip

<table>
<thead>
<tr>
<th>Test number</th>
<th>Number of cycles</th>
<th>Specimen fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>1,810,000</td>
<td>No</td>
</tr>
<tr>
<td>Test 2</td>
<td>660,000</td>
<td>No</td>
</tr>
<tr>
<td>Test 3</td>
<td>605,000</td>
<td>No</td>
</tr>
<tr>
<td>Previous Low-cycle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fatigue Test</td>
<td>14,500</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Low-cycle fatigue

- Crack tip, 38.1 mm (24/16 in)

High-cycle fatigue

- Crack tip, 46.0 mm (29/16 in)
Small-scale Testing

SEC measurements – first dataset
Small-scale Testing

CGI for all datasets

- Test 1: $R = 0.1$
- Test 2: $R = 0.4$
- Test 2: $R = 0.6$
- Test 3: $R = 0.4$
- Test 3: $R = 0.6$

Graphs showing the relationship between Crack length (mm) and CGI for different tests.
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

Existing out-of-plane 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 in²
  - 1.5 x 1.5 in²
- 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

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