Sensing distortion-induced fatigue cracks in steel bridges with capacitive skin sensor arrays

Xiangxiong Kong a, Jian Li a*, William Collins a, Caroline Bennett a, Simon Laflamme b,c, and Hongki Jo d

a Department of Civil, Environmental and Architectural Engineering, University of Kansas, Lawrence, KS 66045, USA
b Department of Civil, Construction, and Environmental Engineering, Iowa State University, Ames, IA, 50011, USA
c Department of Electrical and Computer Engineering, Iowa State University, Ames, IA, 50011, USA
d Department of Civil Engineering and Engineering Mechanics, University of Arizona, Tucson, AZ, 85721, USA

Abstract

Distortion-induced fatigue cracks represent the majority of fatigue cracks in steel bridges in the United States. Currently, bridge owners, such as the state departments of transportation (DOTs), rely on human inspection to detect, monitor, and quantify these cracks so that appropriate repairs can be applied before cracks reach critical sizes. However, visual inspections are costly, labor intensive, and may be prone to error due to inconsistent skills among bridge inspectors. In this study, we represent a novel strain-based approach for sensing distortion-induced fatigue cracks in steel bridges using soft elastomeric capacitor (SEC) arrays. Compared with traditional foil strain gauges, the SEC technology is a large-area and flexible skin-type strain sensor that can measure a wide range of strain over a large surface. Previous investigations have verified the suitability of a single SEC for sensing an in-plane fatigue crack in a small-scale steel specimen. In this paper, we further demonstrate the ability of SECs for sensing distortion-induced fatigue cracks. The proposed strategy consists of deploying an array of SECs to cover a large fatigue-susceptible region and establishing a fatigue sensing algorithm by constructing a crack growth index (CGI) map. The effectiveness of the strategy was experimentally validated through fatigue tests of bridge girder to cross-frame connection models with distortion-induced fatigue cracks. Test results verified that by deploying an SEC array, multiple CGIs can be obtained over the fatigue-susceptible region, offering a more comprehensive picture of fatigue damage. Furthermore, by monitoring a series of CGI maps constructed under different fatigue cycles, the fatigue crack growth can be clearly visualized through the intensity change in the CGI maps.

Keywords: distortion-induced fatigue; sensing skin; structural health monitoring; capacitive strain sensor; large area electronics; steel bridges; web-gap

*Assistant Professor; Email: jianli@ku.edu
1. INTRODUCTION

Civil infrastructure systems are critical for maintaining vital societal functions. Many older bridges in the United States are prone to structural damage due to carrying significant amount of service loads over long periods of time. According to the recent infrastructure report [1] issued by the American Society of Civil Engineers (ASCE) in early 2017, the overall score for American bridges is a C+ with over 9% of the nation’s bridges rated structurally deficient. These bridges require significant investment in maintenance, rehabilitation, or replacement. Otherwise, structural damage (e.g. cracks, corrosion, or excessive deformation) in critical structural members could impair structural integrity and lead to catastrophic failures [2].

Among the various damage mechanisms in steel bridges, fatigue cracks are extremely common [3]. In the United States, one predominate type of cracking on steel bridges is distortion-induced fatigue, which is caused by out-of-plane loading in the web-gap region under differential movement between adjacent girders [4]. Due to the lack of consideration in early bridge design specifications, distortion-induced fatigue cracks are a common issue in many steel bridges built prior to the mid-1980s in the United States [5].

Bridge owners, such as state departments of transportation (DOTs) in the United States, typically rely on trained bridge inspectors to visually inspect steel bridges for fatigue cracking [6] so that appropriate repairs can be applied before cracks reach critical sizes. However, visual inspections can be prone to error due to inconsistent skills and results interpretation among inspectors [7]. For instance, a study by the Federal Highway Administration (FHWA) reported that only 2 of 49 bridge inspectors across the United States correctly identified fatigue cracks in steel bridges in Virginia and Pennsylvania [8].

Advanced approaches for detecting and/or monitoring of fatigue cracks have been investigated in both the structural health monitoring (SHM) and nondestructive testing (NDT) communities. As a result, both the accuracy and robustness of crack detection can be improved by using sensing technologies. In the context of distortion-induced fatigue crack detection, Yu et al. [9] reported an acoustic emission approach for identifying fatigue damage at the fillet weld in representative cruciform joints of steel bridges; Alavi et al. [10] demonstrated a self-powered sensing approach based on a piezo-floating-gate (PFG) sensor for detecting distortion-induced fatigue cracks; and Kong and Li [11] adopted a computer vision-based method to detect distortion-induced fatigue cracks through video feature tracking. An important challenge with these methods is their reliance on extensive human operations to collect critical measurements (acoustic emission data, voltage, or digital videos) in the field, making it challenging to implement long-term continuous crack monitoring of steel bridges.

Strain-based sensing methods, on the other hand, have demonstrated the ability to detect distortion-induced fatigue cracks in steel bridges. By directly deploying strain sensors over crack-susceptible regions, fatigue damage can be inferred by the abrupt strain change induced under cracking. For instance, Ghahremani et al. [12] adopted strain gauge measurements on a large-scale bridge girder
to evaluate the depth characteristics of distortion-induced fatigue cracks, and Bennett et al. [13] successfully used strain gages to detect the initiation of distortion-induced fatigue cracks in a test of a scaled bridge. However, a general limitation of traditional metal foil strain gauges is their relatively small footprint, making them less cost-effective when attempting to monitor fatigue damage over a large structural surface.

Novel large-area strain sensing technologies, often referred to as skin sensors or sensing skins, have recently attracted much attention in the SHM community, mainly attributed to their ability to measure strain over a much larger area than traditional foil strain gauges. Examples include carbon nanotube-based sensors [14, 15], resistive sensing sheets [16], printable conductive polymer [17], patch antenna sensors [18], electrical resistance tomography [19], and so forth. These technologies are all large size but rely on different sensing principles, and are used in different applications in civil engineering.

The authors previously developed a novel skin sensor, known as soft elastomeric capacitor (SEC) [20] for monitoring and detecting damage in civil structures. The SEC is a large and flexible strain gauge capable of measuring up to 20% strain change over a large area [21]. SEC technology has been applied in many engineering applications including: condition evaluation of wind turbine blades [22], reconstruction of in-plane strain maps [23], and dynamic nondestructive testing [24]. The features of large sensing area and wide measurement range also make the SEC a suitable candidate for crack detection and monitoring. Past research had verified the SEC’s crack sensing ability through numerical investigations [25] and experimental tests [26, 27, 28]. These studies were mainly focused on the examination of a single SEC on a small-scale specimen with an in-plane fatigue crack. However, the effectiveness of SEC technology when applied to distortion-induced fatigue cracks in large-scale structures has not been investigated, and therefore remains unknown.

In this study, we investigated the SEC’s crack monitoring performance on bridge girder to cross-frame connections subjected to distortion-induced fatigue. Multiple SECs were deployed over a large structural region to form an SEC array. A new fatigue damage sensing approach was then established in terms of crack growth index (CGI) map, which is a 2D image constructed by signals from the SEC array. The CGI map offers more comprehensive fatigue-related information about the monitored structural region than relying on discrete values from individual SECs. The effectiveness of the SEC array and the CGI map were validated through laboratory tests on scaled bridge girder to cross-frame connection models.

The rest of this paper is organized as follows: Section 2 briefly introduces the technical background of distortion-induced fatigue cracks in steel bridges, the sensing principle of the SEC, and the algorithm for CGI extraction; Section 3 establishes the methodology for constructing the CGI map; Section 4 describes the experimental configurations; Section 5 illustrates the experimental results; Section 6 further discusses the results of folded SECs from the sensor array; and Section 7 summarizes conclusions of the study.
2. BACKGROUND

This section introduces the background of this study including: a brief review of the mechanism of distortion-induced fatigue cracking, sensing principle of the SEC, and previous work on extracting fatigue sensitive features from SEC measurements.

2.1 Distortion-induced fatigue cracks

Figure 1 shows the mechanism of distortion-induced fatigue at web-gap regions in steel girder bridges built prior to the mid-1980s in the United States. Cross-frames and diaphragms are used to provide lateral stability to girders, as shown in a skewed bridge configuration in Figure 1(a). As illustrated in Figure 1(b), the traffic load $F$ applied on top of Girder A leads to a differential vertical movement $\Delta$ between the two adjacent girders, which would in turn provoke an out-of-plane bending moment at the top web-gap region in the adjacent girder (i.e. Girder B). This repetitive out-of-plane loading leads to the initiation and propagation of fatigue cracks. A more detailed discussion about the mechanism of distortion-induced fatigue cracks can be found in [29].

Figure 1. Schematic of a girder bridge under traffic load: (a) plan view; and (b) elevation view and detail of the web-gap region.

Figure 2(a) is a photo that illustrates a common structural layout of a steel highway girder bridge. Many fatigue cracks have been identified at the web-gap region in this bridge during routine bridge inspections. Figure 2(b) shows a typical example where Crack A was found between the top flange and web, while Crack B initiated at the top end of the fillet weld between the connection plate and the web. Depending on the skew angle of the cross frame (denoted as $\theta$ in Figure 1(a)), Crack B could propagate into the web region, or grow along the fillet weld between the connection plate and the web.
2.2 Soft Elastomeric Capacitor

The SEC technology is described in detail in [20]. Briefly, as shown Figure 3(a), the SEC is a large-area capacitor consisting of a dielectric layer sandwiched between two conductive layers. The two sizes of SECs adopted in this study (Figure 3(b)) are 76.2 mm by 76.2 mm (3 in. by 3 in.) and 38.1 mm by 38.1 mm (1.5 in. by 1.5 in.), with respective nominal capacitance values of approximately 900 pF and 150 pF. Two copper tapes were adhered onto both conductive layers for measuring capacitance of the sensor.

Equation 1 shows the sensing principle of the sensor, where $C$ is the capacitance of the SEC, $\varepsilon_0$ and $\varepsilon_r$ are the vacuum and polymer relative permittivity, respectively, and $l$, $w$, and $h$ are the length, width, and thickness of the SEC (Figure 3(a)), respectively. A change in surface strain on the monitored surface will provoke a change in the geometry of the SEC (i.e. $l$, $w$, and $h$), hence changing the capacitance $C$.

$$ C = \frac{\varepsilon_0 \varepsilon_r lw}{h} $$

Figure 3. (a) Schematic of the SEC; (b) photo of an SEC of dimension 76.2 mm by 76.2 mm; (c) photo of an SEC of dimension 39.1 mm by 39.1 mm.
2.3 Crack growth index

Previous work [27, 30] have proposed and demonstrated a crack detection and monitoring algorithm by extracting a crack-sensitive feature, termed the crack growth index (CGI), from the SEC’s capacitance measurements. This feature extraction method is briefly reviewed here as it serves as the basis for constructing the CGI map to be introduced in Section 2.4.

Figure 4(a) shows the procedure for computing CGI. In the figure, a fatigue crack in a steel plate is generated by the fatigue load $F$. An SEC is deployed onto the steel plate to monitor the crack activity. Our previous investigation [27] verifies that both mean and peak-to-peak capacitances (denoted in Figure 4(a)) of the SEC increase under a growing fatigue crack due to the reduction of local stiffness around the crack. However, the mean capacitance is prone to drift over long-term under changing environmental conditions (e.g. temperature or humidity changes). This is due to an intrinsic electrical behavior found in many sensors fabricated from smart materials [31, 32]. The peak-to-peak capacitance, on the other side, is much less sensitive to changing environmental conditions therefore serves as a robust indicator for fatigue crack growth. Directly identifying the peak-to-peak capacitance from a time-series measurement is challenging because of the noise content in the SEC’s signal. Hence, the power spectral density (PSD) is computed to convert time-series measurement into the frequency domain. The PSD curve represents the energy distribution of the time-series signal, and the peak around the dominant loading frequency (denote as $peak_C$ in Figure 4(a)) can robustly indicate the peak-to-peak capacitance.

The magnitude of the applied load $F$ is also required for CGI extraction. This is because the load range (denote as $Amp_F$ in Figure 4(a)) also directly affects the peak-to-peak capacitance of the SEC. A larger load range would induce higher capacitance response even if the crack does not grow. Hence, the capacitance response needs to be normalized with respect to the load range, which leads to the equation $CGI = \sqrt{peak_C / Amp_F}$. The applied fatigue load can either be directly measured from the actuator in a laboratory setting or indirectly inferred via strain measurements in practical applications.

Once the CGI is extracted from one set of short measurements, crack growth can be monitored through a long-term monitoring strategy as illustrated in Figure 4b. Briefly, a series of short-time measurements of the applied load $F$ and capacitance response $C$ are collected during the fatigue life of the steel plate. If the crack grows between the data collection intervals, the extracted CGI would increase. By collecting the CGIs through repeated measurements over time, the fatigue crack growth can be monitored. It should be noted that the absolute value of CGI is also governed by the type of normalizer. The normalization procedure for computing CGIs could be based on the applied load from the actuator in the laboratory or the strain measurement from the strain gauge installed in the steel bridge. Therefore, directly comparing CGIs from different test set-ups or normalizers is not meaningful. However, for a predetermined test set-up with a fixed normalizer, the relative change of CGIs (i.e. the increasing trend in Figure 4b) is a robust indicator of fatigue crack growth.
Figure 4. (a) Methodology for extracting CGI from a single dataset; and (b) correlating CGI with crack lengths based on multiple datasets. DAQ in Figure 4b represents data acquisition.

3. METHODOLOGY

Previous research has focused on the examination of a single SEC on a small-scale specimen with an in-plane fatigue crack. The method of CGI extraction reviewed in Section 2.3 was developed for single SEC utilization. However, for sensing distortion-induced fatigue cracks in steel bridges, an array of SECs is adopted in this study to cover a larger fatigue-susceptible region. As the number of SECs increases in this application, measurements from the SEC array result in multiple CGIs. Investigating the CGI change for each individual SEC against different crack lengths would be time-consuming and less informative. A better approach is to spatially visualize all CGIs of the SEC array over the fatigue-susceptible region. We do so by extending the CGI index to a CGI map to visually represent the spatial distribution of CGIs.

3.1 CGI map

Figure 5 illustrates the methodology for constructing a CGI map. An array of SECs was deployed on a steel plate to monitor the crack growth, and CGI\(^1\), CGI\(^2\), CGI\(^3\), and CGI\(^4\) are the CGI values for each individual SEC (Figure 5(a)). Where a crack propagates under an SEC (e.g. SEC\(^1\), SEC\(^2\), and SEC\(^3\) in Figure 5(a)), the CGI is a direct indicator of crack growth. On the other hand, where the crack does not grow under an SEC (e.g. SEC\(^3\) in Figure 5a), the SEC serves as a large-area strain gauge for monitoring migration of the strain field caused by the crack growth.

Next, the CGIs of the four SECs in Figure 5(a) were mapped to a 3D coordinate system where the vertical axis is the magnitude of CGI and the two horizontal axes represent the plane of the structural surface. The CGIs are placed at the centroid of each SEC as shown in Figure 5(b). Subsequently, a 3D CGI surface was created using linear interpolation. The 3D CGI surface is a matrix that contains the interpolated CGIs over the zone defined by the four centroids of the SEC array. Finally, by projecting the CGI surface to the structural surface, the 2D image, termed the CGI map, can be constructed as illustrated in Figure 5c.

By constructing a series of CGI maps based on multiple measurements from the SEC array at different crack lengths, fatigue damage in a large region can be monitored. If the fatigue crack
does not grow during the data collection intervals, the corresponding CGI maps would exhibit a similar intensity distribution. Conversely, fatigue crack propagation would provoke intensity changes in the CGI maps, which serve as good features for fatigue damage monitoring.

Figure 5. (a) Methodology for constructing CGI map: (a) individual CGIs from an SEC array; (b) a CGI surface through linear interpolation; and (c) CGI map. The SECs in Figure 5(a) is illustrated as transparent for illustration purpose.

3.2 Special considerations for distortion-induced fatigue cracks

Section 3.1 presented the methodology for constructing CGI maps through a steel plate under an in-plane fatigue crack. However, distortion-induced fatigue cracks in steel bridges usually initiate and propagate along complex paths, as they are subjected to multi-directional states of stress that can vary significantly within the web-gap region. As illustrated in Figure 2(b), distortion-induced fatigue cracks may initiate between the girder web and top flange (e.g. Crack A), or between the connection plate and girder web (e.g. Crack B). In both cases, cracking initiates at the weld toe between two adjacent structural components. Furthermore, depending on the structural geometric layout, the crack may continue to grow along the weld. Hence, special considerations are needed for detecting distortion-induced fatigue cracks.

Previous studies [27, 28] validated that the SEC can effectively sense in-plane fatigue damage if the crack directly propagates under the sensing skin. However, to detect a distortion-induced fatigue crack that grows along the weld, the SEC may need to be deployed in a folded configuration. For instance, an SEC should be folded to cover both the connection plate and the girder web to detect Crack B shown in Figure 2(b).

4. EXPERIMENTAL CONFIGURATION

4.1 Description of the test set-up

A bridge girder to cross-frame connection was adopted for the experimental tests in this study, as shown in Figure 6. To simulate the restraint provided to the top flange of a bridge girder by the deck in the field, the bridge girder was mounted upside-down to the strong floor in the laboratory to constrain the bottom flange of the girder. A cross frame was then installed to the girder through a connection plate. The skew angle $\theta$ between the cross frame and the girder was 40 degrees as shown in Figure 6(b). To represent the structural layout of typical girder bridges built prior to the...
1980s, the connection plate (Figure 6(c)) was only fillet welded to the girder web while the top and bottom of the connection plate were not attached to the flanges. A detailed description of the test specimen can be found in Yu et al. [33].

It should be noticed that the girder to cross-frame connection in this study is a simplified subassembly of the entire bridge system without considering the effect of bridge deck. In addition, the bending behavior of the steel girder due to dead and live loads are eliminated, while only out-of-plane bending imposed by the movement of cross-frame is obtained. Nevertheless, Hassel et al. [34] performed a comparative study through more than 1,000 large-scale finite element (FE) simulations. The study concluded that the stress fields at the web-gap region of the subassembly FE models were similar to the ones extracted from the global bridge FE models. Similar type of subassembly was adopted in the experimental studies in [35] as well.

To apply fatigue load cycles, an actuator was vertically attached to the far end of the cross frame. The actuator was restrained from moving laterally (Figure 6(a)) so that it could only move in the vertical direction and apply vertical load to the cross frame. A 0.5 Hz harmonic load was adopted and a load range of -4.9 kN (-1.1 kip) to 4.9 kN (1.1 kip) was applied.

The dominant frequency of the traffic load cycles in the field depends on multiple factors such as the speed of the passing vehicle, the span length of the steel girder, and girder boundary conditions. The 0.5 Hz frequency adopted in this study is within the range of field measurements performed by McElrath [36]. The load range of fatigue cycles, on the other side, was determined by considering the stress range at the web-gap region, vertical displacement of the cross frame, and crack growth rate. Yu et al. [33] applied a fatigue cycle of 0 kN (0 kip) to 10.2 kN (2.3 kip) to the same test model and demonstrated the rationale for such a load range design. In this study, we adopted the similar load range (2.2 kip) under a symmetric distribution (±1.1 kip) in order to consider the reversal behavior of the traffic load in the field.

As mentioned in Section 2.3, the amplitude of the applied load is required for extracting the CGI from the SEC’s capacitance measurement. For this purpose, a strain gauge was installed on the top horizontal cross frame member (Figure 6(b)) to indirectly infer the amplitude of applied load during the test. A similar strategy could be applied in field applications where the true fatigue load caused by passing vehicles cannot be easily measured.

Figure 6. (a) Exterior view of the test model; (b) interior view of the test model; and (c) detailed view of the connection plate. Figure 6(c) shows the specimen prior to installation of the SEC array.
4.2 Existing fatigue damage

Prior to this study, the test model had been fatigue loaded for 2.7 million cycles under a load range of 0 to 11.2 kN (2.5 kip). As a result, a fatigue crack existed at the interior side of the top web-gap region between the connection plate and the girder web. Due to the small opening of the fatigue crack, a fluorescent dye penetrant was used to accurately identify the locations of the crack tip. As shown in Figure 7, the length of the fatigue crack was measured as 19.1 mm (0.75 in.).

Figure 7(c) shows the detailed layout at the top web gap region of the connection model. The connection plate was not welded to the girder flange, leaving a gap between the flange and connection plate, which was the primary reason for causing distortion-induced fatigue cracks as discussed in Section 2.1.

4.3 Deployment of an SEC array

To detect and monitor distortion-induced fatigue damage in the test girder, an SEC array was deployed at the top web-gap region, as shown in Figure 8(a). SECs with dimensions 76.2 mm x 76.2 mm (3 in. x 3 in.) are termed large SECs, while those with dimensions 38.1 mm x 38.1 mm (1.5 in. x 1.5 in.) are termed small SECs. A total of 11 SECs were deployed on the structural surface using a bi-component epoxy (JB Weld). Figure 8(b) schematizes the sensor layout. Folded SECs (i.e. SEC a1, a5, and a10) were deployed along the weld to detect crack growth at the weld toes. Flat SECs, on the other hand, were intended to serve as large-area strain gauges to sense the strain field migration caused by cracking activity. Small SECs a3, a7, and a8 were deployed at the connection plate in order to avoid the conflict of existing structural bolts (denoted in Figure 8(a)). Our previous studies [25] validated that small SECs were more sensitive to fatigue crack growth by producing higher percentage of capacitance changes. Therefore, in this experimental program, small SEC a1 to a6 were deployed at the top region of the SEC array with aim to better quantifying the crack activities. An off-the-shelf data acquisition (DAQ) system (ACAM PCAP02) was used to collect the capacitance measurements of the SEC array.
The number of SECs in a SEC array for monitoring a fatigue crack in practice varies depending on multiple factors such as: the location of the crack, the layout of the bridge, existing length of the crack, and the crack growth rate estimated by engineering knowledge. For example, a single SEC can be enough for monitoring a short, slow-propagating crack; while multiple SECs are required in order to sense a lengthy, fast-growing fatigue crack, which is the situation in this experimental program. A more detailed discussion can be found in [28].

Figure 8. (a) SEC array arrangement; and (b) a schematic of the sensor layout.

4.4 Experimental procedure

During the test, 130,000 new load cycles were applied to the test girder under the load range of -4.9 kN (-1.1 kip) to +4.9 kN (+1.1 kip). A total of 13 datasets were collected at cycle counts of 0, 15,000, 21,500, 30,000, 43,100, 53,800, 64,900, 79,200, 93,000, 101,300, 110,000, 121,000, and 130,000. Each dataset contained both capacitance measurements from the SEC array and the strain gauge collected over 2-min periods, sampled at 50 Hz and 2000 Hz, respectively. During the test, four inspections were performed to identify crack lengths at cycle counts of 0, 71,000, 101,300, and 130,000 cycles, respectively.

Figure 9(a) presents a photograph of the specimen at the end of the test, in which some of the SECs were removed to clearly identify the crack tip. The locations of the crack tips identified from the four inspections are marked in Figure 9(a) and (b). The length of the crack was measured from the top end of the weld, as annotated in Figure 9(a). Crack lengths were approximately 19 mm (0.8 in.), 42 mm (1.7 in.), 62 mm (2.5 in.), and 84 mm (3.3 in.), respectively at the time of the four inspections. This result indicates how the fatigue crack propagated over the 13 data collection intervals.
Figure 9. (a) Locations of the crack tips at different cycle counts; and (b) illustration of crack tips with respect to the sensor layout.

SEC a1 was removed after 79,200 load cycles, shown in Figure 10. The bonded side (i.e. the side in direct contact with the steel surface) of SEC a1 experienced damage during loading. In particular, a crack was identified in the conductive layer of SEC a1, exposing a white line that revealed the dielectric layer. This crack in the SEC was attributed to the large out-of-plane crack opening displacement under the sensor that repeatedly stretched the sensing skin during the test. Despite the occurrence of the crack in the conductive layer, SEC a1 continued providing capacitance data as to be illustrated in Figure 13.

Figure 10. (a) SEC a1 was removed after 79,200 load cycles for a detailed inspection. On the bonded side (the side in direct contact with the steel surface) of the SEC, a crack was identified in the conductive layer, indicating damage to the SEC. The white color along the crack is the exposed dielectric layer.

5. EXPERIMENTAL RESULTS

5.1 Representative time-series measurements

Figure 11 presents a series of plots of representative time-series measurements of the SEC array taken from SECs a2 and a6. The plots present 10 seconds of measurements collected at 0 cycles (the beginning of the test) and 64,900 cycles. SEC a2 initially exhibited a larger peak-to-peak capacitance \( \Delta C/C \) (Figure 11(a)), which became significantly smaller after 64,900 cycles (Figure 11(c)). This reduction may be attributed to the crack tip propagating away from SEC a2, causing
strain relief around SEC a2 (Figure 9(b)). SEC a6, which was located in front of the crack propagation path, experienced an increased peak-to-peak capacitance, $\Delta C/C$, at 64900 cycles due to higher strain caused by the crack tip moving closer to the sensor.

As discussed in Section 2.3, although peak-to-peak capacitance is a good indicator of fatigue crack growth, it is often times difficult to reliably identify in time-series signals due to the noise content. This can be observed in the signals plotted in Figure 11. Therefore, CGIs were extracted from the time-series signals through frequency analysis described in the next subsection.

Figure 11. Representative time-series measurements from the SEC array. (a) SEC a2 at 0 cycle; (b) SEC a6 at 0 cycle; (c) SEC a2 at 64,900 cycles; and (d) SEC a6 at 64,900 cycles.

5.2 CGIs from the SEC array

5.2.1 CGIs from the flat SECs

CGIs were extracted from the SEC array using the method introduced in Section 2.3. The strain measurement at the top chord of the cross frame was used to normalize the SEC measurements. Figure 12 shows the CGIs from the flat SECs at different numbers of load cycles. For clarity, results have been grouped based on the similarity of amplitude of CGI response.

As shown in Figure 12(a), CGIs from SEC a3 and a4 quickly increased at the beginning of the test and then gradually decreased. This phenomenon was a result of crack propagation which initially brought the crack tip closer to a3 and a4 during the first three datasets collected (0, 15,000, and 21,500 cycles). The stress concentration around the crack tip increased the responses of nearby sensors. As the crack propagated further and the crack tip moved beyond a3 and a4, the stress relief...
along the fatigue crack path led to a decrease in the responses of these two sensors after 21,500 cycles.

Figure 12. CGIs for (a) SEC a3 and a4; (b) SEC a6, a7, a8, a9, and a11; and (c) SEC a2.

Figure 12(b) shows the CGIs from SECs a6, a7, a8, a9, and a11, in which increasing CGIs were observed for all SECs. This increasing trend was due to increases in the strain field at these SECs caused by crack growth. SEC a7 experiences a drop at 21,500 cycles. This is probably due to the noisy content of this particular measurement, leading to a lower energy magnitude at 0.5 Hz in the PSD curve. Figure 12(c) illustrates the CGI change for SEC a2. As the crack propagated downward, stress relief along the crack path led to a decreasing trend of CGI as shown in the figure. This behavior is corroborated by comparing time-series measurements shown in Figure 11(a) and (c), in which the peak-to-peak capacitance decreased significantly at 64,900 cycles.

5.2.2 CGIs from the folded SECs

SECs a1, a5, and a10 were folded at the corner between the connection plate and the girder web. CGIs from these three SECs have been plotted in Figure 13. Only eight datasets were collected for SEC a1, after which the sensor was removed for a detailed inspection (see discussion in Section 4.4). SEC a1 exhibited significantly higher CGI responses than the other SECs. In addition, the CGIs from SEC a1 exhibited fluctuations during the test. This behavior is caused by the damage occurring in the sensing material of SEC a1 (Figure 10) provoked by the distortion-induced fatigue cracking.

SEC a5 also exhibited much larger CGI responses than adjacent flat SECs. The initial CGI from SEC a5 was approximately 14,400 while the CGIs from SEC a6 and a7 were approximately 6,500 and 7,000, as shown in Figure 12(b). This is due to the relative rotation between the connection
plate and the girder web, which periodically stretches the sensing skin around the corner, provoking additional capacitance change to the SEC. In addition, the CGIs from SEC a5 (Figure 12b) steadily increased at the beginning of the test, and then decreased after 43,100 cycles. However, based on the observation illustrated in Figure 9(b), the fatigue crack reached SEC a5 at approximately 100,000 cycles and propagated to the center of SEC a5 at 130,000 cycles (end of the test). The CGI from SEC a5 continuously decreased during this stage despite the fact that the fatigue crack was growing under the sensing skin. A detailed discussion about the possible cause of this phenomenon can be found in Section 6.

Figure 13(c) shows the CGI from SEC a10, which is a folded sensor located far away from the fatigue crack. Large fluctuations were observed in the CGIs collected throughout the test from this SEC. The fluctuations may be attributed to the fact that SEC a10 was far away from the fatigue crack, and hence was less sensitive to the fatigue crack growth.

In summary, CGIs from folded SECs, initially deployed for directly detecting the crack growth, were unable to fulfil such a purpose (i.e. fluctuations of CGIs in SEC a1 and a10; decreasing CGIs when the crack grew into SEC a5). In this regard, only the flat SECs were adopted for constructing CGI maps, presented in the next subsection.

![Figure 13. CGIs from (a) SEC a1; (b) SEC a5; (c) SEC a10](image)

5.3 CGI maps

CGI maps were constructed using CGIs from the SEC array. Figure 14(a) illustrates the flat SECs used in constructing the CGI maps. The dashed lines represent the boundaries of the CGI maps. A 2D coordinate system was created where the origin was at the top of the weld. Figure 14(b) schematizes the 15 cm x 25 cm (6 in. x 10 in.) region used as the boundary for the plots shown in Figure 15.
Figure 14. SECs for constructing the CGI maps.

Figure 15 shows the resulting CGI maps. Due to significant differences in magnitudes of CGIs (e.g. the CGI was as large as 15,000 for SEC a3, and approximately 2,000 for SEC a11), the intensity in the CGI maps is represented in logarithmic scale. The CGI map covers a large area of fatigue susceptible region (10 cm by 20 cm). The crack tip locations were identified multiple times during the test, which are also marked with white x’s in Figure 15a, h, j and m.

Each plot in Figure 15 illustrates the distribution of CGI for the SEC array corresponding to each data collection interval, enabling a clear depiction of the fatigue damage over this large area. As the number of load cycles increases, the intensity in the CGI map changes. For instance, as the crack tip moved downward (shown in the progressions of Figure 15 (a) to (d)), higher intensities/brightness can be observed in the top-left region of the CGI map. However, as the crack continued to propagate, the top-left region became darker due to the stress relief along the crack path, as demonstrated in the progression shown in Figure 15e to h. The bottom-left corner of the CGI map became brighter during crack propagation, evident in a comparison of Figure 15h and m. This is due to the increasing strain field provoked by the propagation of the crack. By comparing the CGI map between the beginning and the end of the test (i.e. Figure 15 (a) and (m)), significant changes in the location of high CGI intensity can be observed, indicating the fatigue crack propagation behavior during these 13 data collection intervals.
6. FURTHER DISCUSSION ON FOLDED SEC SENSORS

This section investigates the potential source of the electromechanical behavior of the folded SEC a5 described in Section 5.2.2. SEC a5 was initially deployed for directly detecting the crack growth, but did not yield increasing CGIs when the crack propagated through the sensor. Figure 16 schematizes the layout of the test model, in which there is a skew angle of 40 degrees between the cross frame and the girder web. Due to the skewed configuration, the fatigue load $F$ creates both a vertical movement of the cross frame and a horizontal rotation around the girder web, as illustrated in Figure 16b. Such a rotational movement could lead to a supplemental change in capacitance of the SEC folded between the connection plate and girder web. As a result, the folded SEC a5 is subject to a combined effect of crack propagation and cross frame rotation, which may have contributed to the behavior of SEC a5.
To further validate this hypothesis, an additional experimental investigation was performed on a non-skewed bridge girder to cross frame connection model, as shown in Figure 17(a). This new model is similar to the skewed one described in section 4.1, except that the cross frame is perpendicular to the girder web, as denoted in Figure 17(a). The test model was symmetric about the cross frame. This non-skewed structural layout allowed the cross frame to maintain the vertical movement under the fatigue loading without being subject to the horizontal rotation around the girder web.

An SEC, denoted SEC b1 in Figure 17(b), was deployed in folded configuration along the weld between the connection plate and the girder web. A foil strain gauge was installed on the top chord of the cross frame for normalizing the SEC’s measurement. Prior to the test, the test model was inspected and no fatigue crack was detected. The test model was then fatigue loaded with 18,900 cycles with a load range of 2.2 kN to 25.5 kN (0.5 kip to 5.75 kip), leading to a newly-initiated fatigue crack beneath SEC b1. After the test, SEC b1 was removed to confirm the crack activity.
(Figure 17(c)). The fatigue crack is shown in Figure 17(d) under fluorescent dye penetrant. Compared with previous skewed test model in Section 4, higher load range is adopted here in order to generate a similar level of stress at the web-gap region. Even though the load ranges are different in these two experimental configurations, the CGI extraction demonstrated in Section 2.3 is based on the normalized peak-to-peak capacitance of the SEC, hence is insensitive with magnitudes of load ranges.

During the test, 13 short time measurements of both the SEC and the strain gauge were collected for computing the CGIs. Utilizing the same CGI extraction method, CGIs of SEC b1 were computed and plotted in Figure 18. A clearly increasing trend of CGIs is observed in the figure, indicating SEC b1 was able to successfully monitor the crack growth, despite its folded configuration.

A comparison between the two tests with folded SECs under the skewed and non-skewed bridge configurations reveals that the rotational movement occurring between the girder web and connection plate led to the inability of the folded SEC a5 to provide consistently increasing CGIs under crack propagation. When no such rotational movement is occurring, as it is the case for the non-skewed configuration, the folded SEC b1 was able to provide robust CGIs to monitor crack growth. Therefore, folded configuration of the SECs is only recommended to use in non-skewed bridge configurations or in ones with small skewness that have limited rotations.

Figure 18. CGIs from SEC b1 in the non-skewed bridge girder to cross frame connection

7. CONCLUSIONS

This study presented a novel strain-based approach for sensing out-of-plane distortion-induced fatigue cracks in steel bridges using soft elastomeric capacitor (SEC) arrays. The SEC is a large-area and flexible sensing skin, able to measure a wide range of strains over large structural surfaces. Previous investigations have verified the ability of a single SEC for sensing an in-plane fatigue crack in a small-scale specimen. In this study, we further demonstrated the ability of the SEC technology in the context of sensing distortion-induced fatigue cracks, which represent the majority of fatigue cracks in aging steel highway girder bridges in the United States.

With the proposed strategy, multiple SECs in the form of a sensor array were deployed to cover a large fatigue-susceptible region. Subsequently, a fatigue sensing algorithm was proposed by
constructing a crack growth index (CGI) map from the measurements of the SEC array. The effectiveness of the SEC array coupled with the CGI map was then experimentally validated through a fatigue test of a bridge girder to cross-frame connection model subjected to distortion-induced fatigue. Test results verified that by deploying the SEC array, multiple CGIs can be obtained over the fatigue-susceptible region, offering a comprehensive picture of the fatigue damage. Furthermore, through monitoring the evolution of CGI maps constructed under different fatigue load cycles, the fatigue crack growth can be clearly visualized by identifying the intensity changes in the CGI maps.

Comparison between the skewed and non-skewed bridge configurations also indicated that the horizontal rotation between the connection plate and the girder web can affect the effectiveness of the folded SEC for directly monitoring crack growth along the corner of the connection. This observation provides an important guideline for applying the SECs in folded configuration in future field applications. A more cost-effective sensor deployment approach in this case would be to attach flat SECs along both sides of the crack path such that the crack growth can be monitored through the migration of the strain field caused by the crack activity. Alternatively, performing fundamental experimental studies regarding the behavior of the folded SEC under rotational movement would also be helpful to address this challenges.

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