Thin-Film Sensor for Fatigue Crack Sensing and Monitoring in Steel Bridges under Varying Crack Propagation Rates and Random Traffic Loads

Xiangxiong Kong
University of Kansas

Jian Li
University of Kansas

Caroline Bennett
University of Kansas

See next page for additional authors

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Abstract
Fatigue cracks are critical structural concerns for steel highway bridges, and fatigue initiation and propagation activity continues undetected between physical bridge inspections. Monitoring fatigue crack activity between physical inspections can provide far greater reliability in structural performance and can be used to prevent excessive damage and repair costs. In this paper, a thin-film strain sensor, called a soft elastomeric capacitor (SEC) sensor, is evaluated for sensing and monitoring fatigue cracks in steel bridges. The SEC is a flexible and mechanically robust strain sensor, capable of monitoring strain over large structural surfaces. By deploying multiple SECs in the form of dense sensor arrays, it is possible to detect fatigue cracks over large regions of a structural member such as a bridge girder. Previous studies have verified the SEC’s capability to monitor fatigue cracks under idealized harmonic load cycles with a constant crack propagation rate. Here, an investigation is performed under more complex and realistic situations to translate the SEC technology from laboratory testing to field applications—specifically, as cracking propagates under (1) a decreasing crack propagation rate, and (2) random traffic load cycles with stochastic peak-to-peak amplitudes and periods. An experimental program was developed which included an efficient data collection strategy, new loading protocols, and crack-sensing algorithms. The experimental results showed an increasing trend of the fatigue damage feature, crack growth index (CGI), under crack initiation and propagation, despite decreasing crack propagation rates or random traffic load cycles. In addition, the results also showed that the SEC did not produce false-positive results when cracks stopped growing. The findings of this study significantly enhance the SEC’s fatigue sensing and monitoring capability under more realistic loading conditions, which is a critical step toward field applications of this technology.

Keywords
Fatigue crack sensing and monitoring, Steel highway bridges, Structural health monitoring, Thin-film sensors, Compact specimen, Power spectrum density, Traffic load, Capacitive strain sensor

Disciplines
Civil and Environmental Engineering | Electro-Mechanical Systems | Structural Engineering | Transportation Engineering | VLSI and Circuits, Embedded and Hardware Systems

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1Ph.D. Candidate, Department of Civil, Environmental and Architectural Engineering, University of Kansas, 1530 W. 15th St., Lawrence, KS 66045.

2Assistant Professor, Department of Civil, Environmental and Architectural Engineering, University of Kansas, 1530 W. 15th St., Lawrence, KS 66045 (Corresponding Author). Email: jianli@ku.edu

3Associate Professor, Department of Civil, Environmental and Architectural Engineering, University of Kansas, 1530 W. 15th St., Lawrence, KS 66045.

4Assistant Professor, Department of Civil, Environmental and Architectural Engineering, University of Kansas, 1530 W. 15th St., Lawrence, KS 66045.

5Associate Professor, Department of Civil, Construction, and Environmental Engineering and Department of Electrical and Computer Engineering, Iowa State University, Town Engineering #416A, Ames, IA, 50011.

6Assistant Professor, Department of Civil Engineering and Engineering Mechanics, University of Arizona, 1209 E. 2nd Street, Tucson, AZ, 85721

ABSTRACT

Fatigue cracks are critical structural concerns for steel highway bridges, and fatigue initiation and propagation activity continues undetected between physical bridge inspections. Monitoring fatigue crack activity between physical inspections can provide far greater reliability in structural performance and can be used to prevent excessive damage and repair costs. In this paper, a thin-film strain sensor, termed a soft elastomeric capacitor sensor (SEC), is evaluated for sensing and monitoring fatigue cracks in steel bridges. The SEC is a flexible and mechanically-robust strain sensor, capable of monitoring strain over large structural surfaces. By deploying multiple
SECs in the form of dense sensor arrays, it is possible to detect fatigue cracks over large regions of a structural member such as a bridge girder. Previous studies verified the SEC’s capability to monitor fatigue crack under idealized harmonic load cycles with a constant crack propagation rate. Here, an investigation is performed under more complex and realistic situations to translate the SEC technology from laboratory testing to field applications, specifically, as cracking propagates under 1) a decreasing crack propagation rate, and 2) random traffic load cycles with stochastic peak-to-peak amplitudes and periods. An experimental program was developed which includes an efficient data collection strategy, new loading protocols, and crack sensing algorithms. The experimental results showed an increasing trend of the fatigue damage feature, termed as crack growth index \((CGI)\), under crack initiation and propagation, despite the decreasing crack propagation rate or random traffic load cycles. In addition, the results also showed that the SEC does not produce false-positive results when the crack stopped growing. Findings of this study significantly enhance the SEC’s fatigue sensing and monitoring capability under more realistic loading conditions, which is a critical step towards field applications of the technology.

**KEYWORDS**

Fatigue crack sensing and monitoring, Steel highway bridges, Structural health monitoring, Thin-film sensors, Compact specimen, Power spectrum density, Traffic load, Capacitive strain sensor

**INTRODUCTION**

Monitoring of fatigue cracks is critical for detecting and preventing excessive damage that can lead to bridge failure (Haghani et al. 2012). Visual inspection is the most commonly-used approach for detecting crack activity; however, it is labor-intensive, potentially dangerous, and allows the potential for crack propagation over long periods of time between inspections (Zhao
Nondestructive testing (NDT) and other advanced approaches such as acoustic emission (Roberts and Talebzadeh 2003), piezoelectric sensors (Ihn and Chang 2014), vibration analysis (Blunt and Keller 2006), and computer vision-based methods (Kong and Li 2018) have shown various levels of success for detecting and/or monitoring fatigue cracks. Nevertheless, these techniques usually rely on extensive human involvement and/or complex data processing algorithms, which may limit their success and level of applicability.

Strain-based methods coupled with thin-film sensors have shown potential for continuous detection and monitoring of fatigue cracks over large-scale structural surfaces (Burton et al. 2017; Loh et al. 2007a; Loh et al. 2009). The methodology is aimed at capturing abrupt strain change induced by cracking in the local region by deploying large-area strain sensors over fatigue-susceptible regions of structural components. The concept of using thin-film sensors is an appealing one, since this approach provides the opportunity to detect crack activity over an entire fatigue-susceptible region, rather than only gathering data at discrete points. Several types of thin-film sensors have been developed for the purpose of crack detection in civil infrastructure applications, using various sensing principles. Examples include: resistance sensing sheets (Tung et al. 2014), patch antenna sensors (Yi et al. 2013), carbon nanotube sensors (Kang et al. 2006; Loh et al. 2007b), and soft elastomeric capacitor (SEC) sensors (Laflamme et al. 2012). One particular advantage of the SEC is its ability to measure a wide range of strain (up to 20%) (Laflamme et al. 2013) over a large sensing area, typically 63.5 mm × 63.5 mm (2.5 in. × 2.5 in.).

The features of large-area sensing and wide strain range make the SEC a suitable candidate for fatigue crack sensing and monitoring. By deploying multiple SECs in the form of dense sensor arrays over fatigue-susceptible regions, the SEC technology greatly increases the chance of capturing fatigue crack initiation and propagation over large structural surfaces without accurate
prior knowledge about crack locations. In addition, because of the large measurement range, the SEC would remain functional as cracks propagate beneath it, providing continuous monitoring over long term.

Previous investigations have experimentally evaluated the SEC’s performance for crack detection using compact, C(T), specimens (Kharroub et al. 2015; Kong et al. 2016), which were single edge-notched plates loaded in tension. Results indicated that the SEC was capable of detecting and monitoring low-cycle fatigue cracks. Later research (Kong et al. 2017) established a robust data processing strategy and greatly enhanced the SEC’s ability to monitor high-cycle fatigue cracks, which represent cracks commonly occurring in steel highway bridges.

Before the SEC-based crack sensing technology can be translated from laboratory to field applications, two research questions need to be addressed. The first research question is whether the SEC can be expected to produce false-positive results during long-term monitoring. Crack propagation in the field is likely to be driven by more complex loadings than the simple scenarios previously studied (Kong et al. 2017). The stress intensity factor range at the crack tip, $\Delta K$, which is the driving force behind crack growth, can be expected to fluctuate due to changing loading and structural conditions in the field. As a result, the crack propagation rate may fluctuate, and in some cases, the crack may stop growing when $\Delta K$ approaches its threshold for crack growth. Previous experimental investigations (Kong et al. 2017) applied loading protocols that resulted in constant crack propagation rate. To ensure that the SEC is capable of consistently monitoring crack growth over the long-term without false-positive results, it is critical to evaluate the SEC-based crack sensing technology under varying crack propagation rates.

The second research question is whether the SEC is still functional as a fatigue crack sensing device under more realistic loading cycles occurring in steel highway bridges. In field
applications, traffic loads are composed of a series of load cycles due to passing vehicles. These load cycles can be expected to have different peak-to-peak amplitudes and periods. The load cycles used in previous tests (Kong et al. 2017) were based on a harmonic time series with a single period and a constant peak-to-peak amplitude, which does not fully capture realistic traffic load cycles in steel highway bridges.

In this study, we examined these two research questions through fatigue test of a steel C(T) specimen. First, a new loading protocol was created to generate and propagate a fatigue crack under a decreasing $\Delta K$, eventually diminishing all the way to the material threshold for crack growth. As a result, the crack propagation rate continued to decrease until crack growth arrested. Measurements of the SEC under harmonic load cycles were collected, from which crack growth features were extracted using the previously-established crack sensing algorithm (Kong et al. 2017). The SEC’s crack monitoring performance under the decreasing crack propagation rate was then assessed. The result was also investigated when the crack stopped growing (i.e. when $\Delta K$ approached the threshold for crack growth). Second, new stochastic traffic load was established using random peak-to-peak amplitudes and periods, designed to simulate realistic features of traffic loads of steel bridges. An updated crack sensing algorithm was established for extracting crack growth features to investigate the SEC performance under the simulated random traffic load cycles.

BACKGROUND

In this section, the fundamental sensing principle of the SEC is first introduced. It is then extended for fatigue crack sensing of steel bridge structures.

SEC Technology

The SEC is a large-area flexible capacitor comprising a dielectric sandwiched between two
conductive layers (electrodes), as illustrated in Figure 1a. The dielectric (i.e. electrical insulator) is fabricated by a styrene-ethylene/butylene-styrene (SEBS) block co-polymer filled with titania, while the conductive layers are fabricated from the same SEBS, but filled with carbon black. Two copper tapes are attached on the top and bottom conductive layers to connect to the data acquisition (DAQ) system for capacitance measurement.

The SEC can be used as a large-area strain gauge by deploying it on a structural surface using off-the-shelf bi-component epoxy (Figure 1a). Equation 1 describes the sensing principle of the SEC. A change in strain on the monitored structure induces changes in the SEC geometry, i.e. changes in length \( l \), width \( w \), and thickness \( h \) (Figure 1a and 1b). These changes then cause a capacitance change \( C \) of the SEC, where \( \varepsilon_0 \) and \( \varepsilon_r \) in Equation 1 are the permittivity of air and the dielectric, respectively.

\[
C = \frac{\varepsilon_0 \varepsilon_r lw}{h}
\]  

(1)

The SEC is a highly-scalable technology and can be fabricated into different sizes. A typical size of 3 in. \( \times \) 3 in. was adopted in this study. Figure 1c shows a picture of the SEC. The effective sensing area (i.e. the area of the conductive layer) was approximately 63.5 mm \( \times \) 63.5 mm (2.5 in. \( \times \) 2.5 in.). A detailed description regarding the fabrication procedure of the SEC is provided in (Laflamme el al. 2012).

SEC-based Fatigue Crack Sensing in Steel Bridges

The strain sensing principle of the SEC can be adapted to fulfil the purpose of fatigue crack detection and monitoring in steel bridges. Figure 2 illustrates this concept using dense SEC arrays. Suppose a large-scale structural surface of a steel girder bridge (Figure 2a) is subjected to fatigue damage under repetitive traffic loads \( F \). To enable fatigue damage sensing over the large structural area, an SEC array is deployed over the fatigue-susceptible region (Figure 2b). If fatigue crack
initiates within the sensing area, the tiny crack opening driven by the external load would periodically stretch the material of the SEC (SEC #6 in this case), leading to a higher capacitance response $C$ occurring in this particular SEC. By monitoring the increasing trend of capacitance $C$ in SEC #6, the initiation of the fatigue crack can be successfully identified.

The SEC arrays can also monitor crack propagation. As the crack propagates longer, the crack opening would become larger under the same load due to the local stiffness reduction. This larger crack opening will result in additional increments of capacitance response $C$ in SEC #6, which can be used as a robust indicator of fatigue crack propagation. Once the crack grows beyond SEC #6, other SECs in the arrays (e.g. SEC #5 and #1) will capture and continuously monitor the fatigue crack propagation using the similar principle, as illustrated in Figure 2c and 2d. Hence, the SEC array as a whole offers a continuous fatigue crack detection and monitoring solution over a large structural surface without accurate prior knowledge about crack locations. In practice, the number of SECs for sensing fatigue cracks in a steel bridge varies depending on crack locations, structural layout, existing crack lengths, and the estimated crack growth rates. For instance, a single SEC would be enough for monitoring a short, slow-propagating crack; while for a long, fast-growing fatigue crack, multiple SECs would be necessary. In case of sensing potential fatigue damage over a large structural region, multiple SECs would also be required. The computational cost for processing data taken by one or multiple SECs is discussed separately in this paper. It should be noticed the proposed approach through the SEC arrays demonstrated in Figure 2 can also be applied for monitoring multiple cracks. However, the experimental investigation presented in this paper is targeted at the case when a single fatigue crack exits beneath an SEC at any given time. Further investigation is needed to understand better the behavior of a single SEC when covering more than one crack.
Our previous study (Kong et al. 2016) demonstrated that both the mean and peak-to-peak amplitude of capacitance \( C \) of the SEC (denoted in Figure 2e) increase during crack propagation. However, the later investigation (Kong et al. 2017) verified that, compared with mean capacitance, the peak-to-peak capacitance is more robust and less sensitive to capacitance drift over long term. Therefore, the peak-to-peak capacitance was adopted as the means for sensing fatigue crack in this study.

**EXPERIMENTAL METHODOLOGY**

**Test Setup**

A C(T) specimen was used for investigating the capability of the SEC to detect and monitor a fatigue crack under variable-amplitude loading. The specimen was fabricated from a 6.4 mm (1/4 in.) thick A36 steel plate. The dimensions of the C(T) specimen are shown in Figure 3d, which are adopted from ASTM E647 (ASTM, 2015a). A notch was fabricated in the specimen to initiate a fatigue crack. To apply the fatigue load, the specimen was mounted in a uniaxial load frame (Instron model 1334) through two clevises (Figure 3b). On the front face of the specimen, two adhesive measuring tapes with 1.6 mm (1/16 in.) marks were attached next to the crack path to visually measure crack length during the test. On the reverse side, an SEC was attached to the specimen using JB-Weld bi-component epoxy (Figure 3c). An off-the-shelf DAQ system (ACAM PCAP02) was used to measure capacitance (Figure 3a).

**Data Collection Strategy**

Because fatigue cracks in steel highway bridges may take years to initiate and propagate before they reach critical sizes (Zhao and Haldar 1996), continuously collecting data throughout the entire life of the structure is impractical. An effective data collection strategy in the field would be based on multiple timescales (Gupta and Ray 2007): a fast timescale for data collection when
the SEC is exposed to different crack lengths and a slow timescale for tracking crack growth over long-term. In the fast timescale data collection, short-time measurements of the SEC and applied load are obtained, during which the fatigue crack length is assumed unchanged. The damage feature related with crack length can be extracted from this particular dataset. By continuously extracting damage features through multiple fast timescale datasets, the fatigue crack growth can be monitored along the slow timescale.

For the laboratory test in this study, we adopted a similar strategy through a multi-rate loading protocol, illustrated in Figure 4. The specimen was initially loaded harmonically with a 10 Hz loading rate to accelerate the process of crack propagation between data collection intervals. No data was collected while the test was expressly focused on crack propagation. Each time the crack length $l$ grew an additional 1.6 mm (1/16 in.), two types of load cycles, a harmonic load $F_H(t)$ and a traffic load $F_T(t)$, were applied to the specimen. The harmonic load cycle $F_H(t)$ was applied at 0.5 Hz, while the traffic load $F_T(t)$ contained cycles with different peak-to-peak amplitudes and periods, further explained later in this section. Under these two types of load cycles, two sets of measurements of SEC capacitance, $C_H(t)$ and $C_T(t)$, were collected for extracting crack growth features using the proposed algorithm. After SEC data collection was complete, loading resumed at the 10 Hz rate until the crack propagated another 1/16 in. By repeating this procedure, two datasets were collected for different crack lengths $l$ under both harmonic and traffic loading.

**Loading Protocol Design**

**Load Range**

Load range is a critical parameter that governs fatigue crack propagation. Given that one of the research questions being investigated was whether the SEC would produce “false-positive” readings at low load ranges, our objective in selecting a loading protocol was to determine the upper and lower bounds of a load cycle ($F_{\text{max}}$ and $F_{\text{min}}$ denoted in Figure 4), and to adjust those
bounds during crack propagation to achieve a decreasing crack propagation rate throughout the test. To accomplish this, the stress intensity factor range, $\Delta K$, was chosen as the design criteria. $\Delta K$ represents the change of stress state in one load cycle around the crack tip, hence governs the crack propagation rate (Klingerman and Fisher 1973).

As shown in Figure 5, an initial $\Delta K = 22.0$ MPa$\sqrt{\text{m}}$ (20 ksi$\sqrt{\text{in.}}$) was assigned at the beginning of the test. Each time the crack propagated an additional 4.8 mm (3/16 in.), as visually identified by the measuring tape in Figure 3b, $\Delta K$ was decreased by 2.2 MPa$\sqrt{\text{m}}$ (2 ksi$\sqrt{\text{in.}}$). As a result, $\Delta K$ was incrementally decreased while the crack propagated, generating a decreasing crack propagation rate. Ultimately, the crack was expected to stop growing when $\Delta K$ dropped to 4.4 MPa$\sqrt{\text{m}}$ (4 ksi$\sqrt{\text{in.}}$), which is below the crack growth threshold of the A36 steel.

Once the relation of $\Delta K$ versus crack length was determined, the corresponding $F_{\text{max}}$ and $F_{\text{min}}$ of the load cycles was calculated using the recommended method in the ASTM E1820 (ASTM 2015b). The stress intensity ratio $R = F_{\text{min}} / F_{\text{max}}$ was also induced in this calculation, and its initial value was set as 0.6. The resulting $F_{\text{max}}$ and $F_{\text{min}}$ were equal to 29 kN (6.52 kip) and 17.3 kN (3.88 kip), respectively at the beginning of the test. The mean load, $F_{\text{mean}} = 0.5 \times (F_{\text{max}} + F_{\text{min}})$, was maintained as 23.1 kN (5.2 kip) throughout the fatigue test. A detailed explanation on calculating $F_{\text{max}}$ and $F_{\text{min}}$ using $\Delta K$ and the $R$ ratio can be found in (Kong et al. 2017). The crack length in Figure 5 was measured from the notch of the C(T) specimen as denoted in Figure 3d.

**Traffic Load Cycles**

In the study, traffic load cycles refer to the load cycles applied to the C(T) specimen to simulate the stress cycles in steel bridges induced by realistic moving traffic loading, rather than the moving vehicle loading itself. When designing the loading protocol for the laboratory test, the goal was to mimic features of the stress response under realistic traffic loads in steel highway bridges. The stochastic nature of the peak-to-peak amplitude and period are two important
characteristics of the stress cycles induced by traffic load. In steel highway bridges, the peak-to-peak amplitude of stress response is governed by vehicle weight. Lu et al. (2012) found that among all type of vehicles, only fully-loaded heavy trucks were critical for fatigue crack propagation, while excitation forces from lighter-weight vehicles were below the threshold of fatigue crack growth. Vrouwenvelder and Waarts (1993) measured 16,000 vehicles in the Netherlands in the 1970s and found the weights of fully-loaded heavy trucks followed normal distributions with coefficients of variation (COVs) from 0.12 to 0.22, depending on specific truck types. To simplify the laboratory loading, only one type of fully-loaded truck was considered in this study, and the peak-to-peak amplitude of load cycles was taken to have a normal distribution with a COV = 0.13.

The period of the stress cycles under traffic load, on the other hand, is governed by bridge geometric configuration such as span length, and vehicle speed. Note that the period refers to the duration of the stress cycle included by a vehicle passing the bridge, instead of the period of vehicle arrivals. For a specific steel highway bridge with known geometric configurations, vehicle speed becomes the only factor that affects the loading period. Different statistical distributions have been reported for highway vehicle speed, including bimodal distribution (Dey et al. 2006), normal distribution (McLean 1978), and gamma distribution (Haight and Mosher 1962). In this study, the period of traffic load cycles was assigned a normal distribution. The mean period was taken as 2.49 sec, while the COV of the period was taken as 0.20.

Figure 6 shows the generated traffic load cycles for the beginning of the test. In total 20 cycles were generated following the previously-determined statistical distributions of peak-to-peak amplitude and period. The generated waveform was combined with the load range, $F_{max}$ and $F_{min}$ shown in Figure 5, to produce the final traffic load for the whole test. The corresponding power
spectral density (PSD) of the generated load cycles is illustrated in Figure 6b. Instead of a single dominant peak at the loading frequency, which was the case for the previous harmonic load cycles, a wide plateau can be observed around 0.5 Hz due to the variation of frequency content in the time series of loading signal.

Crack Sensing Algorithm

Once the C(T) specimen was tested under the above loading protocol and measurements were collected using the proposed data collection method, the fatigue crack growth was monitored using the crack sensing algorithms illustrated in Figure 7.

Figure 7a illustrates the algorithm for fatigue crack sensing under harmonic load cycles. As mentioned previously, compared with the mean capacitance, the peak-to-peak capacitance is a robust indicator of crack growth. However, accurately identifying the peak-to-peak capacitance in the time domain could be challenging due to the noise content in the measurement. To address this, frequency analysis is proposed to convert $C_H(t)$ to the frequency domain by computing its power spectral density (PSD). Since $C_H(t)$ is a harmonic signal, the peak of the PSD curve $PeakC$ robustly indicates the magnitude of the peak-to-peak capacitance in the time series signal. In addition, the PSD of the applied load $F_H(t)$ is also needed to normalize $PeakC$, because the amplitude of the applied load governs the peak-to-peak capacitance. For example, the SEC would produce a larger peak-to-peak capacitance under a higher load range even if the crack does not grow. The applied load is directly obtained from the actuator in the test of this study, while it could be indirectly inferred by deploying strain gauges on steel bridges (e.g. at cross frames) in field test. Finally, the normalized peak-to-peak capacitance is termed as the crack growth index ($CGI$), which can be correlated with crack length $l$ for sensing fatigue crack growth.

The crack sensing algorithm for harmonic load cycles was modified for the case of traffic load cycles. A moving-average filter (i.e. low-pass filter) was applied in the frequency domain to
smooth the PSD curves as shown in Figure 7b. The PSD curves of the applied load $F(t)$ and capacitance measurement $C(t)$ both exhibited a broad-band feature due to multiple frequency contents in the traffic load cycles. To obtain robust results, the moving-average filter is necessary to smooth the PSD curves. With adequate order of the filter, flat plateaus can be achieved and the magnitudes of the flat plateaus ($Peak_c$ and $Peak_r$) are adopted for computing the CGI.

RESULTS AND DISCUSSIONS

Crack Growth Characteristics

Under the aforementioned test setup with the newly-designed loading protocol, the experimental test was conducted in the Fatigue and Fracture Laboratory at the University of Kansas. During the test, the number of cycles for propagating the crack each additional 1.6 mm (1/16 in.) was recorded. This information was converted to the crack propagation rate in terms of $da/dN$ (increment of crack length per load cycle). Table 1 summarizes typical crack propagation rates and number of cycles under each $\Delta K$ throughout the test.

The crack propagation rate, $da/dN$, was found to be $8.0 \times 10^{-5}$ mm/cycle (3.13x10^{-6} in./cycle) at the beginning of the test when $\Delta K = 22.0$ MPa√m (20 ksi√in.), after which it decreased as the crack propagated. Then the crack length reached 38.1 mm (1-1/2 in.) when $\Delta K = 6.6$ MPa√m (6 ksi√in.), $da/dN$ became $2.0 \times 10^{-6}$ mm/cycle (7.81x10^{-8} in./cycle), which was significantly lower than the initial crack propagation rate. A total of 4.73 million cycles had been applied to the specimen at this point. $\Delta K$ was then further reduced to 4.4 MPa√m (4 ksi√in.), and the crack propagation rate was found to be extremely low, after which the crack stopped growing. These observations indicate that the newly designed loading protocol successfully generated a varying crack propagation rate in the fatigue test.

To evaluate whether the SEC would produce a false-positive result, five additional
measurements, taken at increments of 0.2 million load cycles, were recorded under harmonic load cycles. Figure 8 shows a photograph when the crack reached 38.1 mm. Despite the visible crack opening shown in the photograph, the crack propagation rate was extremely slow at this point because $\Delta K$ had decreased below the crack growth threshold for A36 steel.

**Typical Measurements**

During the test, short-time measurements were collected for both SEC and applied load once the crack propagated each additional 1.6 mm (1/16 in.). All measurements were sampled at 50 Hz. Measurements under harmonic load cycles contained about 100 cycles, while measurements under traffic load cycles contained 20 cycles as previously determined in Figure 6a. For demonstration purpose, only measurements at three typical stages of the test are illustrated in this section including: 1) the beginning of the test where the crack length was 0 mm; 2) the crack reached 19.1 mm (3/4 in.) in length; and 3) the end of the test when the crack reached 38.1 mm (1-1/2 in.). Frequency spectra of the above measurements in terms of PSDs are also illustrated. For the time series measurements under harmonic load cycles (Figure 9a and b), instead of showing the full-length measurements containing 100 cycles, only 5 representative cycles are presented. Finally, the procedure for applying a moving-average filter to smooth the PSD curves under the traffic load cycles are demonstrated.

**Measurements under harmonic load cycles**

Figure 9 shows responses of the SEC and the applied load in time series as well as their PSDs in frequency domain. The designed load intended to limit the size of the crack opening, leading to small capacitance change of the SEC. As a result, noise content in the SEC’s raw measurements makes it difficult to visualize the 0.5 Hz harmonic signal (Figure 9a) and identify the accurate peak-to-peak amplitudes. Meanwhile, the mean capacitance experienced drift during the crack
propagation: it started around 918 pF at the beginning of the test, drifted to 916 pF when the crack reached 19.1 mm (3/4 in.), and moved back to 918 pF when the crack propagated to 38.1 mm (1-1/2 in.). The drift may be attributed to environmental factors such as temperature and humidity change over long term, or the intrinsic electrical behavior of the SEC which can be found in thin-film sensors fabricated from smart materials (Cai et al. 2013; Kang et al. 2006). Our previous study (Kong et al. 2017) revealed that compared with mean capacitance, peak-to-peak capacitance is more robust and less sensitive to signal drift, hence is proposed for crack monitoring.

Figure 9b shows the driving force of the corresponding SEC’s measurement. A decreasing load range can be found in the figures, following the pre-defined loading protocol in Figure 5. Figure 9c and 9d show the PSDs of the SEC signals and the applied load, respectively. Dominant peaks can be found in the PSD curves around the loading rate (0.5 Hz). These peaks are a robust indicator of the peak-to-peak amplitudes of the time series measurements. As the crack grows, the increase of the dominant peak amplitudes in Figure 9c indicates larger peak-to-peak capacitance of the SEC in Figure 9a, while the decrease of the dominant peak amplitude in Figure 9d indicates the load range reduces in Figure 9b.

**Measurements under traffic load cycles**

Figure 10 shows similar measurements of the SEC and applied load under traffic load cycles. Full-length time series measurements containing 20 traffic load cycles are shown in Figure 10a and 10b. Compared with measurements under harmonic load cycles, extracting damage features is more challenging for measurements under random traffic load cycles due to the varying amplitude and period as shown in Figure 10b.

As shown in Figure 10d, unlike the harmonic load case, the PSDs of the applied loads show broad-band feature. As explained previously, this is because multiple frequency contents exist in the traffic load cycles. The decreasing magnitude of the PSD indicates the applied load range
reduces when the crack grows longer (Figure 10b). On the other hand, the PSDs of the SEC signals in Figure 10c are noisy due to noise contents in the time series signals as well as the small number of load cycles (Figure 10a). Instead of showing smooth broad-band PSD curves, scattered peaks are located around the loading rate (0.5 Hz), making it challenging for direct extraction of the PSD magnitudes. Additional data processing is therefore necessary to ensure robust computation of CGIs, which will be discussed in the next paragraph.

Figure 11 illustrates the additional smoothing process for the noisy PSD curves. A frequency band of interest is first defined based on the traffic load characteristic. The raw PSD data of the SEC (square-dotted lines in Figure 11a) is then truncated to remove the frequency contents outside of the defined frequency band of interest. For this test, the PSD data between 0.21 Hz and 0.60 Hz is preserved as they reflect the SEC’s response under traffic load excitation. The PSD data outside of this range is removed because it is induced by noise contents in the time series signals. The truncated PSD curves are shown as diamond-dotted lines in Figure 11a. Next, a moving-average filter is applied to the truncated PSDs to smooth out the scattered peaks to achieve flat plateaus, shown as triangle-dotted lines in Figure 11a. Similar processing method is applied to the PSDs of the measured load (Figure 11b). However, the raw PSD curves are smoothed using the same moving-average filter without truncation due to less noise content in the load measurements. Similar flat plateaus can be achieved as shown in the triangle-dotted lines in Figure 11b.

Determination of the frequency band of interest is a critical step to ensure the success of the above data processing method. Essentially, the frequency range should cover the frequencies of most load cycles. For this test, 0.21 Hz to 0.60 Hz is selected based on the raw PSDs of the applied loads in Figure 11b. In field deployments where the direct traffic loads are difficult to obtain, the frequency range could be estimated based on vehicle speeds and the bridge span length, or inferred
through indirect load indicators such as the strain measurements of the structural member under the load path.

**CGI Extraction and Crack Sensing Results**

By following the proposed crack sensing algorithm shown in Figure 7, the CGIs can be extracted from the measurements taken at different crack lengths. Figure 12 shows the CGIs under both harmonic and traffic load cycles.

Figure 12a illustrates CGI versus crack length. The crack length was measured from the notch of the C(T) specimen (denoted in Figure 3d). In general, the CGIs under both harmonic and traffic load cycles have a similar increasing trend. The lowest CGI occurred at the beginning of the test when the crack length was 0 mm, after which CGI gradually increased as the crack grew longer. This result validates the SEC’s ability to detect fatigue crack initiation and monitoring crack propagation, regardless the loading scenarios. In particular, the SEC and its data processing algorithm remained effective under 20 traffic load cycles with random peak-to-peak amplitudes and periods.

Figure 12b shows CGI versus the number of load cycles, in which the number of cycles is shown in log scale. As described previously, the crack propagation rate continuously decreased during crack propagation. The same behavior was also observed in the CGI, which increased rapidly at the beginning of the test but slowed after approximately 1 million cycles. Importantly, the CGI continued exhibiting an increasing trend toward the end of the test during the period of extremely low crack propagation rate. This result demonstrates the crack monitoring capability of the SEC under a varying crack propagation rate.

Finally, five CGIs under harmonic load cycles and three CGIs under traffic load cycles after the crack growth had stopped at 38.1 mm (1-1/2 in.) are marked in Figure 12b, with the details
shown in Figure 12c. The CGI remained stable during the additional 1.8 million load cycles applied to the specimen, indicating that the SEC does not produce false-positive results under both harmonic and traffic load cycles when the crack is not growing.

**Computational cost**

Matlab (MathWork 2016) was adopted for performing the majority of signal processing in this study. The total processing time for computing the CGIs of a single SEC shown in Fig. 12 is similar between harmonic and traffic loads, which was about 1 minute for each case on a desktop computer (16 GB RAM, 3.1GHz CPU). The computational cost would proportionally increase if multiple SECs are used for crack monitoring.

**CONCLUSIONS**

This study evaluated the SEC, a flexible thin-film strain sensor, for sensing and monitoring fatigue cracks in steel highway bridges by simulating realistic stress conditions in a steel compact, C(T), specimen. Emphasis was placed on performance evaluation of the SEC applied over a fatigue crack with varying propagation rates and random traffic load cycles. To facilitate the investigation, we developed an experimental methodology including three components:

- An efficient data collection strategy was developed by taking multiple short-time measurements during crack propagation, and then extracting crack growth features, the CGIs, to monitor fatigue crack growth in a long-term fashion;
- A new loading protocol was developed for generating a fatigue crack with decreasing crack propagation rates, and random load cycles that can reflect realistic stochastic features of traffic load of steel highway bridges;
- Crack sensing algorithms based on frequency analysis was developed to extract CGIs under harmonic and traffic load cycles.
Experimental results showed an increasing trend of CGI during the process of crack initiation and propagation, despite continuously decreasing crack propagation rate or random traffic load cycles. Furthermore, the SEC produced constant CGIs after the crack stopped growing, indicating no false-positive results. Results of this study verified the capability of the SEC to detect and monitor fatigue cracks under more complex and realistic loading conditions, which is a critical step towards field applications of the technology. By integrating the SEC-based fatigue sensing methodology demonstrated in this study with the concept of dense sensor arrays, it would be possible to achieve a fatigue crack sensing solution over large structural surfaces in steel bridges without accurate prior knowledge about crack locations. Our future work will focus on deploying dense SEC arrays on large-scale structures for monitoring distortion-induced fatigue cracks in steel bridges.

ACKNOWLEDGEMENTS

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REFERENCES


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<table>
<thead>
<tr>
<th>$\Delta K$</th>
<th>Number of cycles (million)</th>
<th>Crack length</th>
<th>da/dN</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.0 MPa √ m (20 ksi √ in.)</td>
<td>0.08</td>
<td>3.2 mm (1/8 in.)</td>
<td>8.0×10^{-5} mm/cycle (3.13×10^{-6} in./cycle)</td>
<td></td>
</tr>
<tr>
<td>15.4 MPa √ m (14 ksi √ in.)</td>
<td>0.27</td>
<td>15.9 mm (5/8 in.)</td>
<td>3.2×10^{-5} mm/cycle (1.25×10^{-6} in./cycle)</td>
<td>Decreasing crack propagation rate</td>
</tr>
<tr>
<td>11.0 MPa √ m (10 ksi √ in.)</td>
<td>0.79</td>
<td>27.0 mm (1-1/16 in.)</td>
<td>1.6×10^{-5} mm/cycle (6.25×10^{-7} in./cycle)</td>
<td></td>
</tr>
<tr>
<td>6.6 MPa √ m (6 ksi √ in.)</td>
<td>4.73</td>
<td>38.1 mm (1-1/2 in.)</td>
<td>2.0×10^{-6} mm/cycle (7.81×10^{-8} in./cycle)</td>
<td></td>
</tr>
<tr>
<td>4.4 MPa √ m (4 ksi √ in.)</td>
<td>6.37</td>
<td>38.1 mm (1-1/2 in.)</td>
<td>0</td>
<td>Crack propagation stopped</td>
</tr>
</tbody>
</table>
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