Evaluation of the Metal Fatigue Solutions Electrochemical Fatigue Sensor System

Final Report
March 2018

BRIDGE ENGINEERING CENTER

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Technical Report Documentation Page

1. Report No. InTrans Project 15-560	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title Evaluation of the Metal Fatigue Solutions Electrochemical Fatigue Sensor System		**5. Report Date** March 2018	
		6. Performing Organization Code	
7. Author(s) Yaohua "Jimmy" Deng (orcid.org/0000-0003-0779-6112) and Brent Phares (orcid.org/0000-0001-5894-4774)		**8. Performing Organization Report No.** InTrans Project 15-560	
9. Performing Organization Name and Address Bridge Engineering Center Iowa State University 2711 South Loop Drive, Suite 4700 Ames, IA 50010-8664		**10. Work Unit No. (TRAIS)**	
		11. Contract or Grant No.	
12. Sponsoring Organization Name and Address Iowa Department of Transportation 800 Lincoln Way Ames, Iowa 50010	Federal Highway Administration 1200 New Jersey Avenue, SE Washington, DC 20590	**13. Type of Report and Period Covered** Final Report	
		14. Sponsoring Agency Code SPR RB12-016	

15. Supplementary Notes

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16. Abstract

The electrochemical fatigue sensor (EFS) was developed to detect very small fatigue cracks that are actively growing. To evaluate the fatigue crack capabilities and gain a better of understanding of implementation needs, a laboratory test and a field monitoring program were developed to evaluate the EFS system using the CrackChek and FatigueWatch sensors, respectively.

The laboratory test program consisted of evaluating the adequacy of CrackChek sensors for crack detection. The CrackChek sensors were installed on a standard steel plate specimen. An electrical discharge machining (EDM) notch was induced in the mid-length of the steel plate and a pair of sensors (i.e., crack and reference sensors) were installed adjacent to the notch tip.

The field monitoring program consisted of evaluating the adequacy of the FatigueWatch sensors for crack detection and the general capabilities of the system for use in field applications. The sensors were installed on the Cherry Creek Bridge near Newton, Iowa, on a sacrificial specimen and on a bridge girder web in a known fatigue-sensitive location. The sacrificial specimen was a standard steel plate exactly the same as the one used for evaluating the CrackChek sensors. The EDM notch was also generated in the edge and mid-length of the specimen and a pair of sensors were installed near the notch tip. After a 13-month data collection and analysis period, no crack formed in either the sacrificial specimen or the bridge girder web where the sensors were installed.

In summary, the CrackChek and FatigueWatch sensors perform well for crack detection.

17. Key Words		18. Distribution Statement	
CrackChek—electrochemical fatigue sensor (EFS)—FatigueWatch—fatigue cracks—metal fatigue sensing devices		No restrictions.	
19. Security Classification (of this report) Unclassified.	**20. Security Classification (of this page)** Unclassified.	**21. No. of Pages** 32	**22. Price** NA

Form DOT F 1700.7 (8-72)   **Reproduction of completed page authorized**

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EXECUTIVE SUMMARY

Identifying fatigue cracks in bridges and other structures is very difficult. An even more difficult task is identifying whether something that looks like a fatigue crack is an actively growing crack that could induce serious structural damage. The technology known as the electrochemical fatigue sensor (EFS) has the reported capability to detect very small fatigue cracks that are actively growing. To evaluate the fatigue crack monitoring capabilities and readiness for field implementation, a baseline set of EFS equipment was purchased for evaluating these fatigue crack monitoring technologies. Classroom and laboratory training were provided by Metal Fatigue Solutions (MFS), Inc. To assess the two fatigue crack monitoring technologies, a laboratory test and a field monitoring program were developed to evaluate the EFS system using the short-term (CrackChek) and long-term (FatigueWatch) sensors, respectively.

The laboratory test program consisted of evaluating the adequacy of CrackChek sensors for crack detection. The CrackChek sensors were installed on a steel plate specimen. An electrical discharge machining (EDM) notch was induced at mid-length of the steel plate where the crack was expected to form at the notch location after cyclic loadings. A pair of sensors (i.e., crack and reference sensors) were installed adjacent to the notch tip. After more than 120,000 loading cycles, a crack formed at the bottom of the steel plate instead of the notch tip. A pair of sensors were again installed adjacent to the crack location. Analysis of the results and the measured data showed that the CrackChek Sensors successfully detected the crack in the steel plate.

The field monitoring program consisted of evaluating the adequacy of the FatigueWatch sensors for crack detection. The FatigueWatch sensors were installed on the Cherry Creek Bridge (located near Newton, Iowa) on a sacrificial specimen and on a bridge girder web. The sacrificial specimen was a standard steel plate exactly the same as the one used for evaluating the CrackChek sensors in the laboratory. The EDM notch was also generated in the edge and mid-length of the specimen. A pair of sensors were installed near the notch tip. The specimen was clamped to the girder bottom flange of the Cherry Creek Bridge. Additionally, a pair of sensors were also installed at the top region of a girder web near the diaphragm location known to be fatigue-sensitive. A strain gage was also installed on the steel plate to evaluate the stress levels in the monitored location. According to the strain magnitudes, it was found that the collected EFS signal would be sufficient for data analysis in terms of crack detection, but stress levels may not be large enough to cause crack growth. A sensor install verification test was also conducted, and verified that the installed sensors on the Cherry Creek Bridges functioned well after installation.

1. INTRODUCTION

Background

Identifying fatigue cracks in bridges and other structures is very difficult. An even more difficult task is identifying whether something that looks like a fatigue crack is an actively growing crack that could induce serious structural damage. In the early 1990s, work was begun to develop a nondestructive evaluation (NDE) technique for identifying fatigue cracks in small, inaccessible aircraft parts. Initial efforts focused on the measurement of corrosion fatigue. The initial research on a NDE technique based upon electrochemical principles quickly revealed that corrosion current could be measured with unusual precision. With this fundamental basis and a basic understanding of the fatigue cracking process, the initial efforts focused on developing a crack detection technique that was actually based on the detection of the growth of corrosion products. The resulting technology has a reported capability for detecting very small fatigue cracks that are actively growing and is known as the electrochemical fatigue sensor (EFS).

Objective and Scope

The main objective of this work is to evaluate the short-term (CrackChek) and long-term (FatigueWatch) fatigue crack monitoring technologies and understand how, when, and where to deploy the EFS system most effectively. To achieve the project goal, a laboratory test program and a field monitoring program were developed to evaluate the EFS system using the CrackChek and FatigueWatch sensors.

Work Plan

The following tasks were completed for this work.

Task 1 – Purchase EFS System

Working with Metal Fatigue Solutions, Inc., (MFS), the EFS system manufacturer, the research team purchased a baseline set of EFS equipment. This baseline system provided the research team and the Iowa Department of Transportation (Iowa DOT) with the tools needed to perform long-term (FatigueWatch) and short-term (CrackChek) fatigue crack monitoring as needed. The proposed system included the following components:

- 5 Potentiostat Data Links (PDL)
- 1 Potentiostat Communication Node (PCN)
- 32 CrackChek sensors
- 32 FatigueWatch sensors

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Task 2 – Training

The equipment manufacturer (MFS) provided approximately 4 to 8 hours of training to interested Iowa State University staff. This training covered the basics of fatigue, crack initiation and growth, the EFS system operational characteristics, and tutorials on how to collect and analyze data. This training had both classroom and laboratory components.

Task 3 – System Evaluation

The research team developed and fabricated several controlled test specimens to which the EFS system was applied. These test specimens included details that will result in the growth of fatigue cracks when placed under cyclic loads. Variables to be considered during the investigation included load application intensity and type of excitation (regular or variable). Additionally, a long-term (FatigueWatch) fatigue crack monitoring system was installed on a bridge.

Task 4 – Documentation and Information Dissemination

All of the work completed during this project is summarized in this final report.

2. LABORATORY PROGRAM

EFS System Purchase

A baseline set of EFS equipment was purchased for evaluating the fatigue crack monitoring technologies from the MFS, Inc. This baseline system included the tools needed to perform long-term (FatigueWatch) and short-term (CrackChek) fatigue crack monitoring as needed. The system included the following components:

- 5 Potentiostat Data Links (PDL)
- 1 Potentiostat Communication Node (PCN)
- 32 CrackChek sensors (crack detection)
- 32 FatigueWatch sensors (long-term monitoring)

The Potentiostat Data Links (PDL) collect and store the data from the sensors and the Potentiostat Communication Node (PCN) is used to access to the PDLs and the collected data. The PCN has the additional capability of transmitting the data to a computer or a data storage location.

Classroom and Laboratory Training

MFS, Inc. provided approximately 6 hours of training to the staff of the Iowa State University Bridge Engineering Center. This training covered the basics of fatigue, crack initiation and growth, the EFS system operational characteristics, and tutorials on how to collect and analyze data. The training included both classroom and laboratory components. The classroom component illustrated the fundamentals of EFS technologies and how to use the software to collect and process the collected data as shown in Figure 1(b). The laboratory component demonstrated how to connect different components of the systems and install sensors as shown in Figure 1(a).
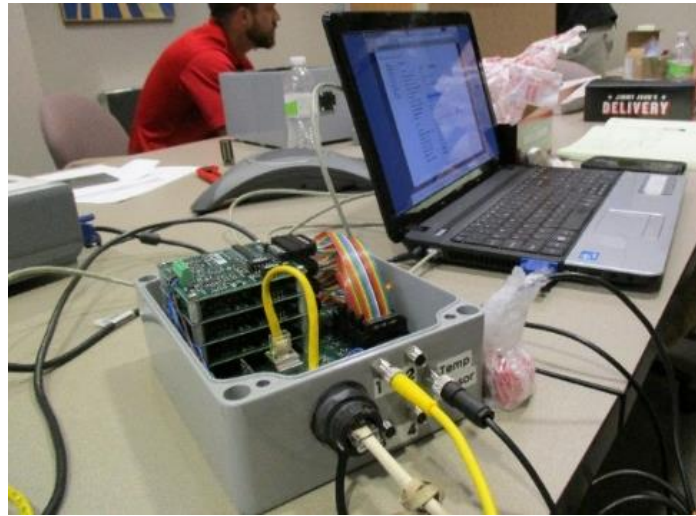
<table>
<tr><td>(a) Sensor Installation</td><td>(b) Data process and System Components</td></tr>
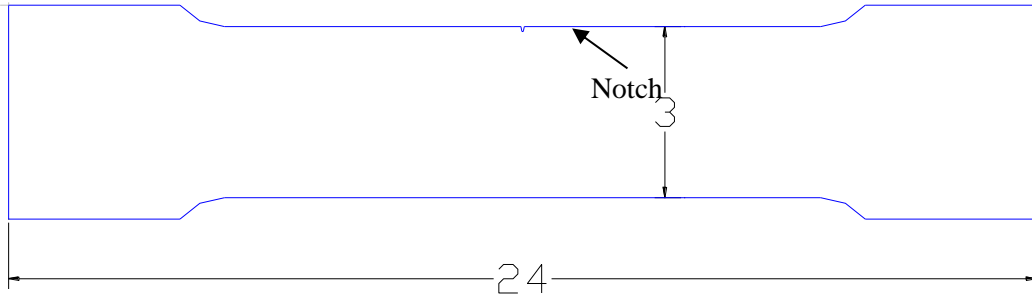</table>

Figure 1. Training and demonstration of EFS system

Laboratory Evaluation of CrackChek Sensors

A laboratory program was developed to evaluate the adequacy of the CrackChek sensors for crack detection. For the laboratory evaluation, a small, standard steel plate specimen was designed and fabricated as shown in Figure 2.

(a) Specimen View

(b) Drawing of Specimen and Notch (in.)

Figure 2. Steel plate specimen for crack detection

The steel plate specimen has a thickness of 1/4 in., a width of 3 in., and a length of 24 in. A full-depth EDM notch was created on the edge and mid-length of the specimen as shown in Figure 2(b). The notch has a width of 0.01−0.06 in. and a length of 0.09 in.

Each CrackChek sensor consists of a pair of sensors (i.e., crack and reference sensors). Since a crack was expected to occur at the notch tip, the crack sensor was placed adjacent to the notch tip as shown in Figure 3.
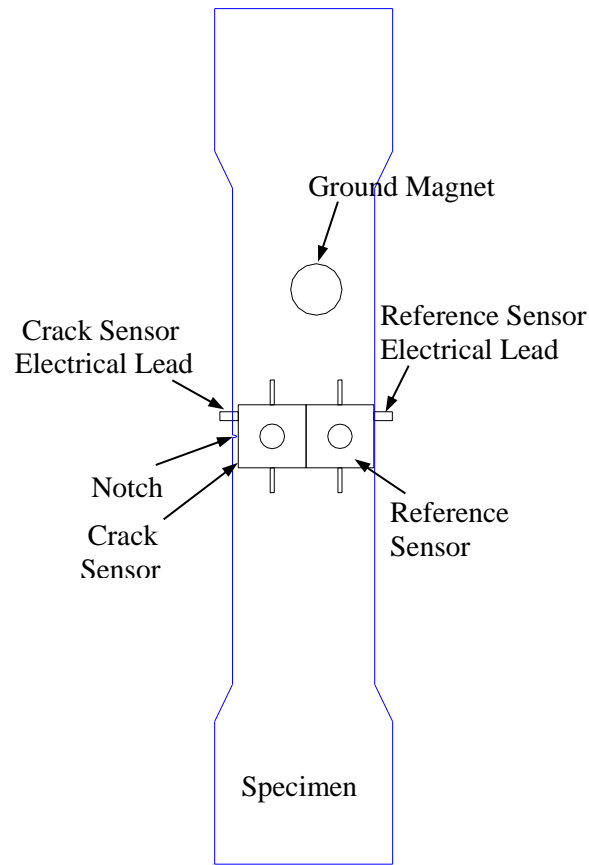
(a) Sketch Illustration

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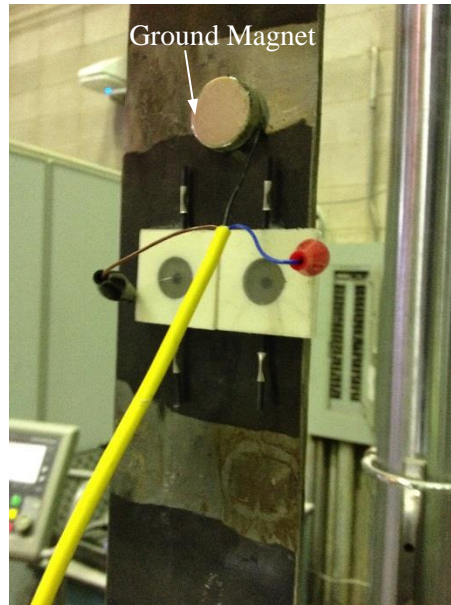
(b) View of Ground Magnet and Sensors on Specimen

Figure 3. CrackChek sensor installation

If a crack occurred, the crack tip should enter the sensor window and be detected. The reference sensor was placed adjacent to the crack sensor for the purpose of crack detection as shown in Figure 3(a). A ground magnet was attached to the steel plate for connecting to the ground as shown in Figure 3(b). Before the sensor was installed, the steel plate was cleaned to smooth the surface, and all debris under the ground magnet and sensors were removed.

Once the sensors were installed, the sensors were connected to a PDL, and then to a PCN. The data acquisition system was set up and the parameters of the software for the data collection were set to the appropriate values shown in Figure 4.

Program ID	Program name	Sample Rate (Hz)	Repeat Times (#)	Time Between (sec.)	Program Start (hour:minute)	Duration (sec.)	ADC threshold	Bias (V)	PGA (ohm)	DigiPOT	LZMA	
0	Time1	100	0	0	13:33	200	0	0.4 ↑ ↓	2	5000	No	configure / start
1	Time2	100	0	0	11:00	200	0	0.4 ↑ ↓	2	5000	No	configure / start
2	Time3	100	0	0	12:00	200	0	0.4 ↑ ↓	2	5000	No	configure / start
3	Time4	100	0	0	13:00	200	0	0.4 ↑ ↓	2	5000	No	configure / start
4	Time5	100	0	0	14:00	200	0	0.4 ↑ ↓	2	5000	No	configure / start
5	Time6	100	0	0	15:00	200	0	0.4 ↑ ↓	2	5000	No	configure / start
6	Time7	100	0	0	16:00	200	0	0.4 ↑ ↓	2	5000	No	configure / start
7	Time8	100	0	0	17:00	200	0	0.4 ↑ ↓	2	5000	No	configure / start
8	Time9	100	0	0	18:00	200	0	0.4 ↑ ↓	2	5000	No	configure / start
9	Time10	100	0	0	19:00	200	0	0.4 ↑ ↓	2	5000	No	configure / start
10	Time11	100	0	0	20:00	200	0	0.4 ↑ ↓	2	5000	No	configure / start

Figure 4. Parameter settings for data acquisition

The start of the data collection was controlled by the software. As shown in Figure 4, each program ID represents one data collection. The sample rate is commonly set to 100 Hz. "Program Start" and "Duration" represent the start time and duration of data collection. The "configure" button is to ensure that the parameter settings become effective. The "start" button is to initiate the start of the data collection.

For testing, the steel plate specimen was clamped in the test equipment. To induce a fatigue crack near the notch region of the specimen, a sinusoidal cyclic fatigue loading test was applied to the two ends of the specimen as shown in Figure 5.
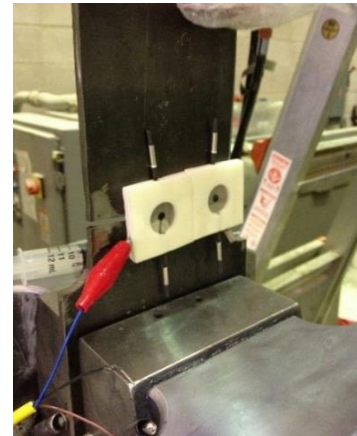

Figure 5. Fatigue load test setup

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Initially, a fatigue load with a range of 0.5-10 kips, an amplitude of 4.25 kips, and a frequency of 10 Hz was applied to the specimen. Data from the CrackChek sensors were collected every 10 minutes, and the results of processing the preliminary data indicated no cracking in the specimen. After 100,000 load cycles, and based on the data processing results, no crack was found in the specimen. In order to quickly induce a crack in the specimen, the load range and amplitude were increased to 0.5-18 kips and 8.75 kips, respectively. The load frequency was kept the same at 10 Hz.

After approximately 20,000 additional load cycles, a crack formed at the bottom of the specimen instead of the notch location, as shown in Figure 6(a). CrackChek sensors were then installed at the crack tip for the crack detection purposes as shown in Figure 6(b).


(a) Crack (b) Sensors installed at the crack location

Figure 6. Crack detection at the induced crack location

To simulate real truck loading on bridges, a fatigue load with a range of 0.5-4 kips, an amplitude of 1.75 kips, and a frequency of 1 Hz was applied to the specimen.

For the no-cracking scenario, the data from the crack sensor in time and frequency domains are plotted in Figure 7(a) and Figure 7(b), respectively.
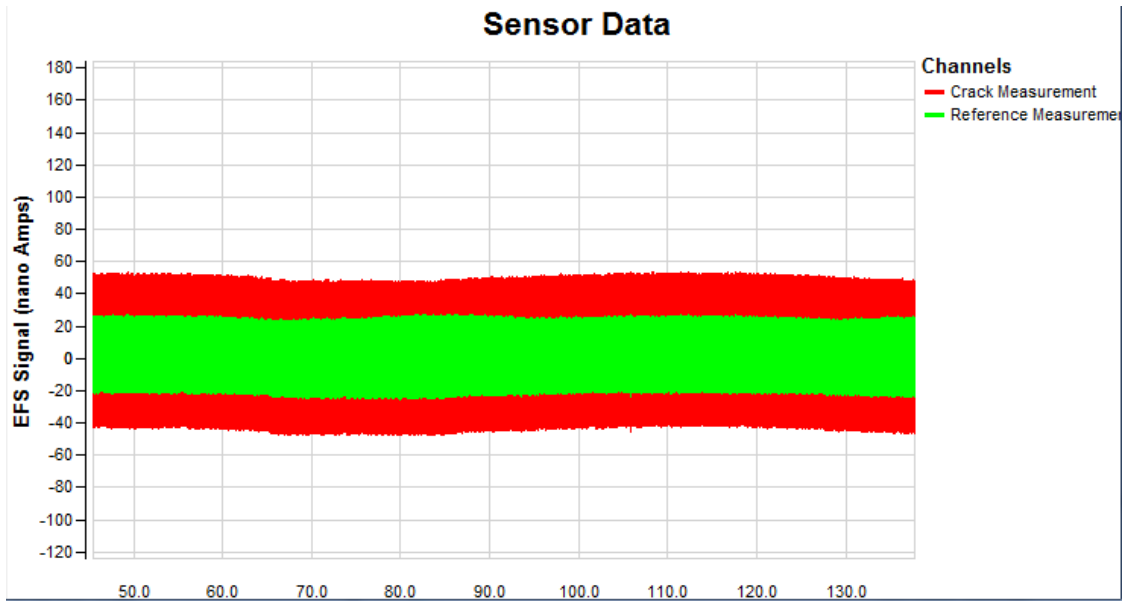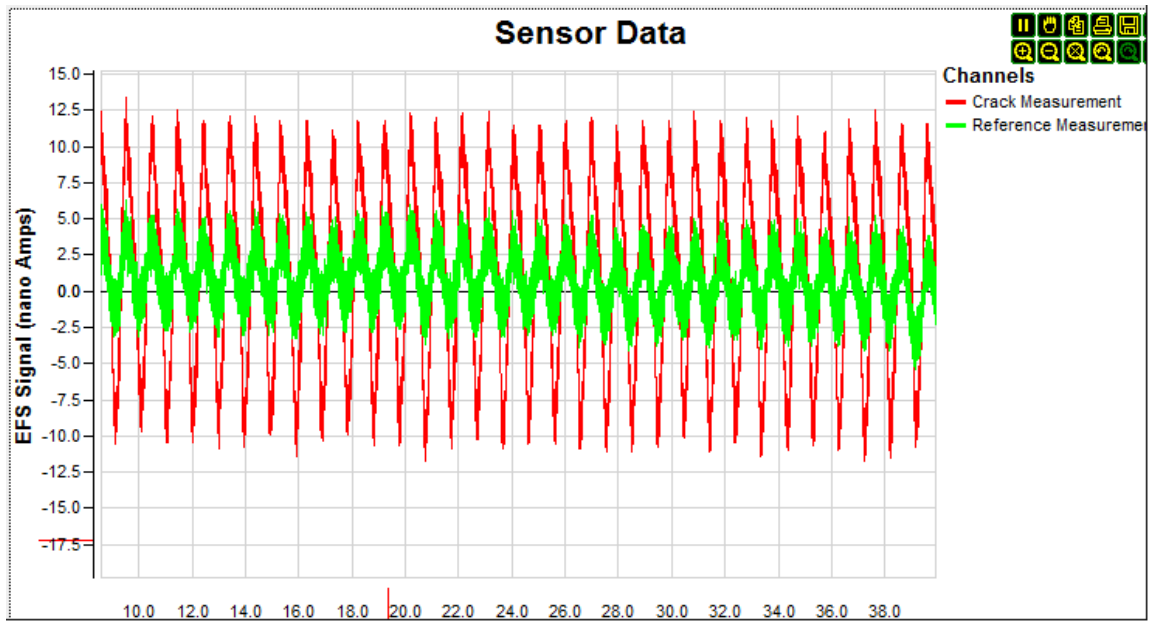
(a) Time Domain
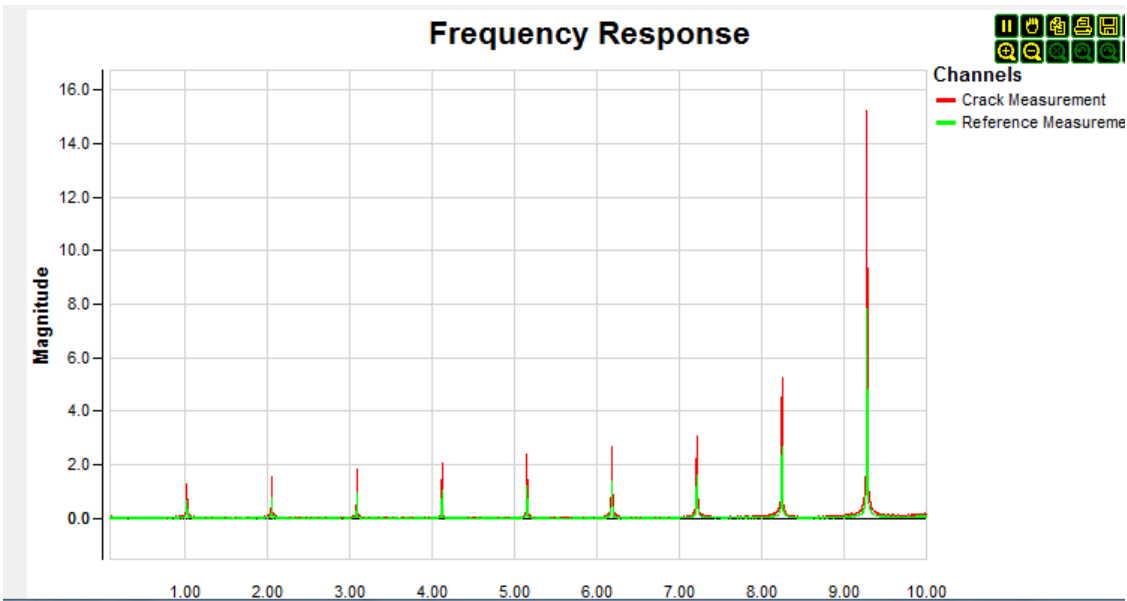
(b) Frequency Domain

Figure 7. Data collected without a crack

For the scenario with a crack, the data from the crack sensor in time and frequency domains are also plotted in Frequency Domain
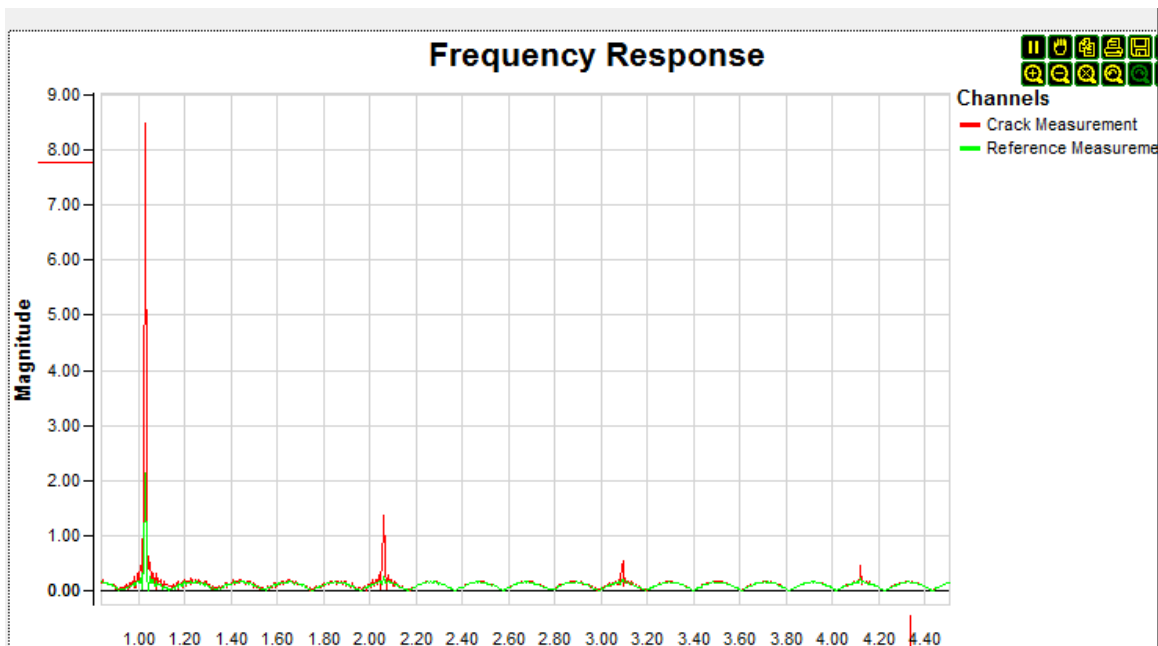
Figure 8(a) and Frequency Domain

Figure 8(b), respectively. The harmonics in the data plots (especially the frequency plot) from the crack sensor as shown in Frequency Domain

Figure 8 indicate the presence of a growing crack.

(a) Time Domain

(b) Frequency Domain

Figure 8. Data collected near the crack location

**Field Evaluation of FatigueWatch Sensors**

The FatigueWatch system, a more durable version of the CrackChek system, is designed to be a long-term monitoring system. The current response, corresponding to the traffic dynamic

loadings, is utilized to detect existing or initiation/growth of potential cracks in steel bridges (MFS 2016b). The PDLs store the data from the data system and have connectivity via Ethernet to a connection node, PCN. The user is able to remotely monitor the live data by transferring data from PDLs/PCNs to the office server (MFS 2016b).

The eastbound Cherry Creek Bridge was selected for instrumentation with the FatigueWatch system. The Cherry Creek Bridge, located on Interstate 80, crosses Cherry Creek near Newton, Iowa. The bridge has three spans with a 24-deg skew, a total length of 158 ft and a roadway width of 30 ft as shown in Figure 9(a) and Figure 9(b).

(a) View

Sensor installation location
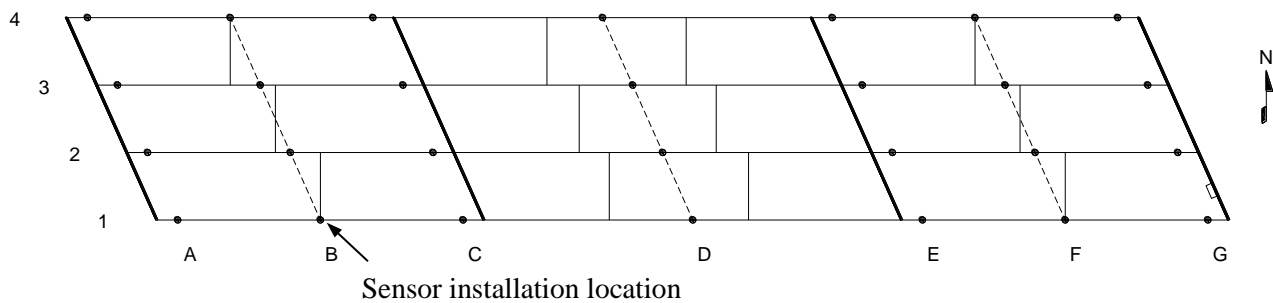
(b) Plan view

(c) Abutment

(d) Pier
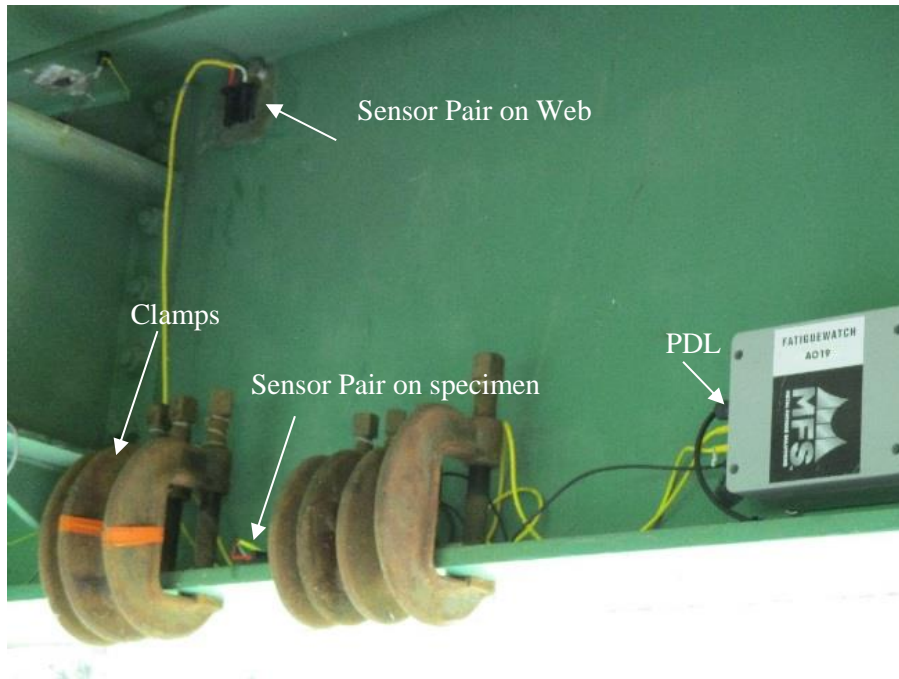
Figure 9. Cherry Creek Bridge

The bridge supports two eastbound traffic lanes with a posted speed limit of 70 mph. The nominal 7.125-in. thick cast-in-place reinforced concrete deck is supported by four steel girders, two pier diaphragms, and four intermediate diaphragms. The girders are embedded into the abutment and are continuous over the three spans with 49-ft end spans and a 60-ft center span. Both abutments are stub concrete and the two piers are open two-column, concrete cantilevers as shown in Figure 9(c) and Figure 9(d).

Similar to the CrackChek sensors, several steps for installing the FatigueWatch sensors were required (MFS 2016a) as follows:

1. Grind the location for the sensor installation to remove paint or oxidation from the installation area and then clean with acetone to remove any dirt and grease.
2. Mark the sensor installation area through placing a crack gage on the specimen.
3. Dispense some adhesive around the edge of the sensor.
4. Mount the sensor at the marked area.
5. Fill in more adhesive around the edge of the sensor.
6. Clean and remove excess adhesive.
7. Repeat steps 2 through 6 for the reference sensor.
8. Inject the electrolyte into the inlet port of the sensors using the cartridge dispenser.
9. Connect the sensors with a PDL.
10. Check the sensors for leakage.

To verify the adequacy of the system, the FatigueWatch sensors were installed on the Cherry Creek Bridge at two locations: (1) a sacrificial specimen and (2) a bridge girder web. The sacrificial specimen is a steel plate exactly the same as the one used to verify the adequacy of the CrackChek system in the laboratory. The EDM notch was also generated in the edge and mid-length of the specimen. A crack sensor was installed near the notch location. A reference sensor was installed adjacent to the crack sensor. The two ends of the steel plate specimen were clamped to the bottom flange of Girder 1 and mid-span of the west span of the Cherry Creek Bridge as shown in Figure 9(b). Based on the strain and forces compatibilities, the steel plate also sustains forces induced by the traffic loading. Additionally, a pair of sensors were installed at the top region of the web of Girder 1 near the diaphragm location. This is due to the fact that cracks were commonly found in this region for steel bridges.

As shown in Figure 10(a), the two pairs of sensors were installed on the girder web and specimen, and the two ends of the sacrificial specimen were clamped to the girder bottom flange. The crack and reference sensors were mounted on the sacrificial specimen as shown in Figure 10(b). The sensors were connected to the PDL placed on the girder web, and the PDL was connected to the PCN placed at the abutment location as shown in Figure 10(c).

(a) Sensor Installation Locations

(b) Sensors on the sacrificial specimen
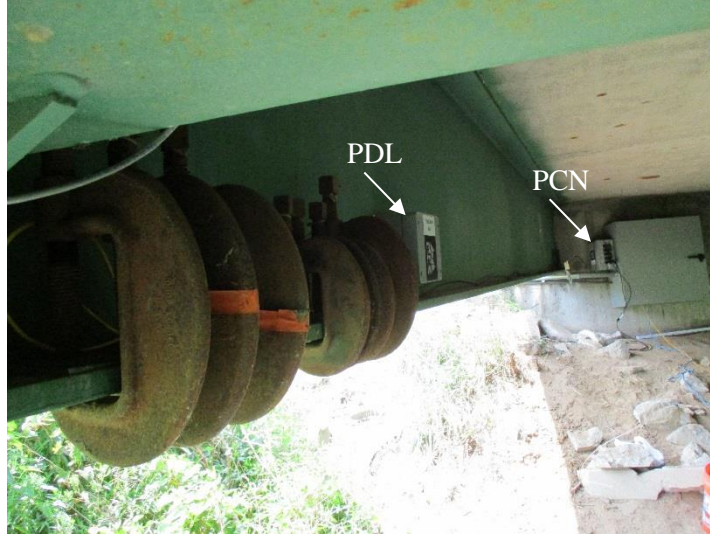
(c) PDL and PCN

Figure 10. Sensor installation on Cherry Creek Bridge

In addition to the EFS sensors installed in the sacrificial specimen, a strain gage was also installed to verify that the specimen was being adequately stressed. The strain response is plotted for lighter and heavier trucks in Figure 11(a) and Figure 11(b), respectively.
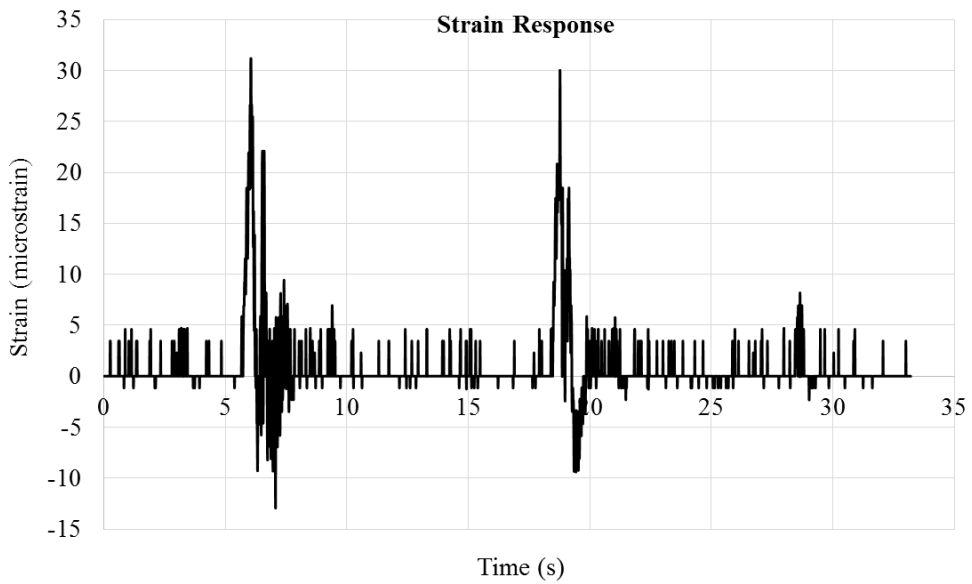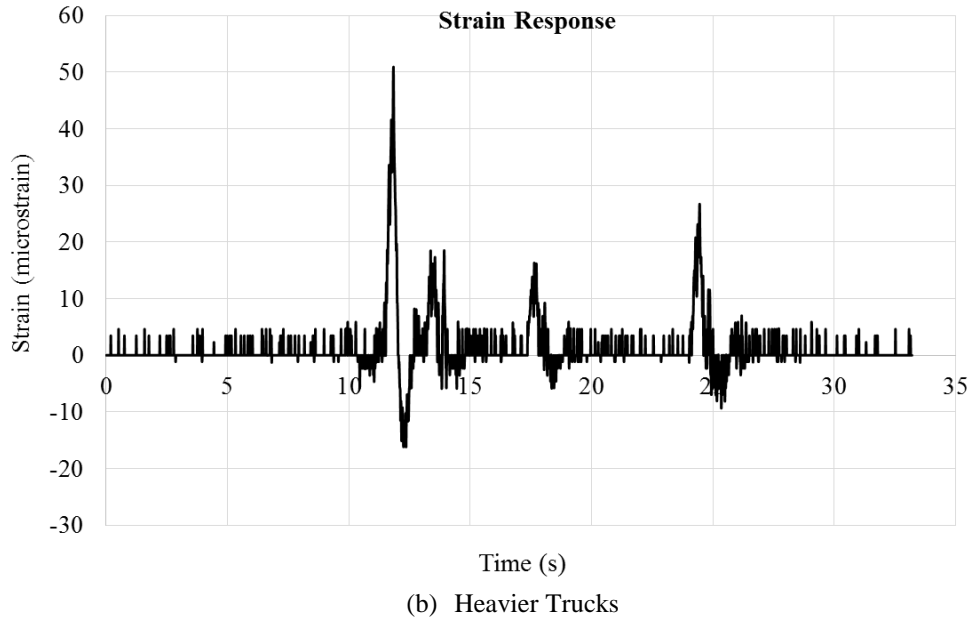

(a) Lighter Trucks

(b) Heavier Trucks

Figure 11. Strain response in sacrificial specimen

The peak strains in the sacrificial specimen are around 30 and 50 micro-strains due to the lighter and heavier trucks. Those collected strains are fairly comparable to the strain magnitudes in the girder bottom flange. This also verifies that the clamps are well tightened to ensure sufficient structural response in the steel plate specimen. Accordingly, it is expected a crack will form at the notch location and the collected EFS signal will be sufficient for data analysis in terms of crack detection.

In order to confirm that there is electrolyte in the sensors and that they are responding in a predictable manner, the sensor install verification test was conducted following the procedure below (MFS 2016b):

1. Start data collection (i.e., run a program, ideally about 5 minutes long).
2. Switch to the "Configure" tab on the web interface.
3. Decrease the Bias voltage to 0.0 V and press "submit." (It is important that the data are collected during this process.)
4. Wait for approximately 45 seconds.
5. Increase the Bias voltage to 0.4V and press "submit."
6. Wait for approximately 45 seconds.
7. Repeat Steps 3-6.

The data from the sensor install verification test was plotted as shown in Figure 12(a). The sample plot of EFS signal from well-installed sensors is shown in Figure 12(b). Figure 12 indicates that the installed sensors on the Cherry Creek Bridges function well after installation.

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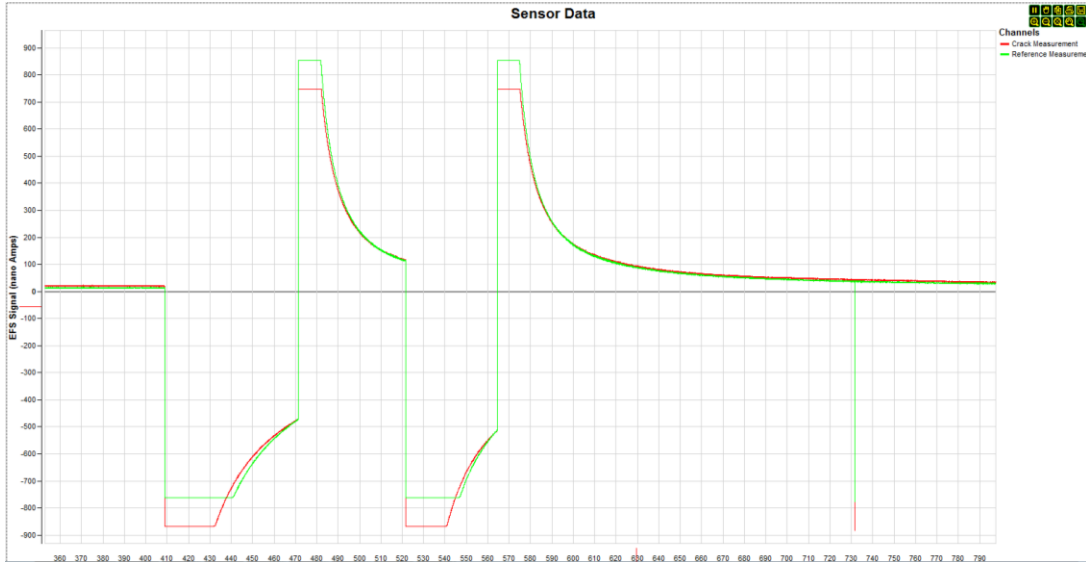
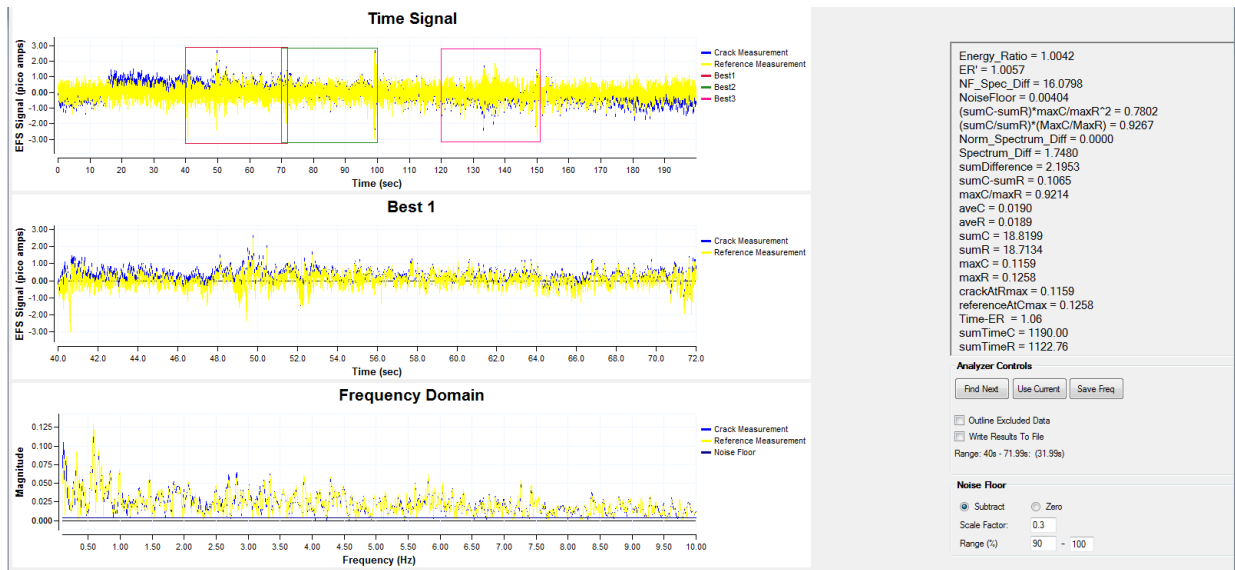(a) Collected EFS Signal from the installed sensors
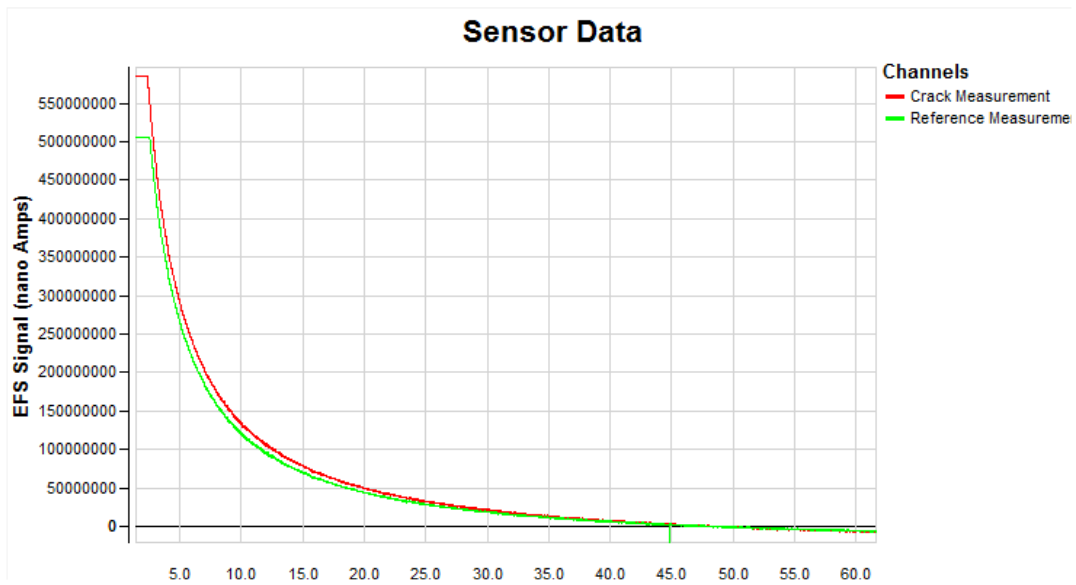
(b) Sample EFS Signal

Figure 12. EFS signal from verification test

Commonly, when analyzing the data collected for bridge response in the frequency domain, the frequency content is spread fairly evenly across the 10 Hz range as shown in Figure 13.
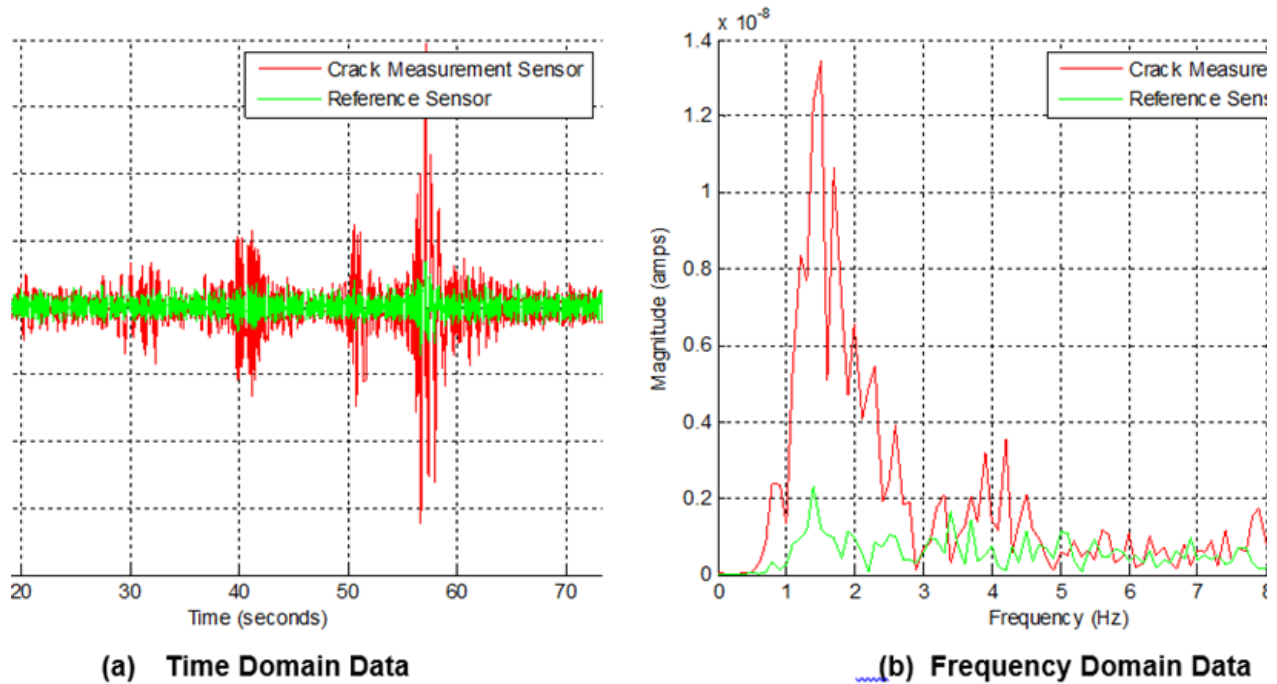
(a) Sensors on Sacrificial Steel Plate Specimen

(b) Sensors on Girder Web

Figure 13. Plots in time and frequency domains without cracking

If there was a crack, a frequency amplitude in the lower 1–3.5 Hz to be 3 to 4 times greater than the higher 3.5-10 Hz range as shown in Figure 14.

MFS 2016a

Figure 14. Sample plots in time and frequency domains with cracking

Nine months after the sensors were installed, the data plot in the frequency domain from the installed sensors is shown in Figure 13. Figure 13 indicates that no crack had formed in the sacrificial specimen and bridge girder web where the sensors were installed. Several trips were made to the bridge site and no visually observable cracks were found to have formed in the girder web or in the sacrificial specimen.

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3. SUMMARY AND CONCLUSIONS

To evaluate the short-term (CrackChek) and long-term (FatigueWatch) fatigue crack monitoring technologies, a laboratory test and a field monitoring program were developed to evaluate the EFS system using the CrackChek and FatigueWatch sensors, respectively.

The laboratory test program consisted of evaluating the adequacy of CrackChek sensors for crack detection. The CrackChek sensors were installed on a standard steel plate specimen. An EDM notch was created at the mid-length of the steel plate and a crack was expected to form at the notch location after cyclic loadings. A pair of sensors (i.e., crack and reference sensors) were installed adjacent to the notch tip. After more than 120,000 loading cycles, a crack formed at the bottom of the steel plate instead of the notch tip. A pair of sensors were again installed adjacent to the crack location. The analyzed results from the measured data indicated that the CrackChek sensors successfully detected the crack in the steel plate.

The field monitoring program consisted of evaluating the adequacy of the FatigueWatch sensors for crack detection in a field environment. The FatigueWatch sensors were installed on the Cherry Creek Bridge for crack detection; one was placed on a sacrificial specimen and the other on a bridge girder web. The sacrificial specimen is a standard steel plate exactly the same as the one used for evaluating the CrackChek sensors. The EDM notch was also generated in the edge and mid-length of the specimen. A pair of sensors were installed near the notch tip. The specimen was clamped to the girder bottom flange of the Cherry Creek Bridge. Additionally, a pair of sensors were installed at the top region of a girder web near the diaphragm location. A strain gage was also installed on the steel plate to verify that the specimen experienced sufficient structural forces. According to the strain magnitudes, it was found that the collected EFS signal would be sufficient for data analysis in terms of crack detection. A sensor install verification test was also conducted and verified that the installed sensors on the Cherry Creek Bridge functioned well after installation. After 13 months of data collection and analysis, it was found that no crack formed in either the sacrificial specimen or the bridge girder web where the sensors were installed.

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MFS, Inc. 2016a. *FatigueWatch Sensor Installation Manual*. Metal Fatigue Solutions, Inc., Las Vegas, NV.

MFS, Inc. 2016b. *Potentiostat Data Link Manual*. Metal Fatigue Solutions, Inc., Las Vegas, NV.

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