THE ELECTROCHEMICAL FATIGUE SENSOR: A NOVEL SENSOR FOR ACTIVE FATIGUE CRACK DETECTION AND CHARACTERIZATION

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Abstract

In the early 1990's work was initiated to develop a testing technique for identifying fatigue cracks in aircraft airframes. Initial efforts focused on the measurement of corrosion fatigue. The initial effort revealed that a technique based upon electrochemical principles could measure corrosion current with unusual precision. With this fundamental basis and a basic understanding of the fatigue cracking process, the initial developmental work focused on a crack detection technique that was actually based on the detection of the growth of corrosion products. The resulting technology has a remarkable capability at detecting very small fatigue cracks that are actively growing and is known as the Electrochemical Fatigue Sensor (EFS).

This paper describes the EFS system including a detailed discussion of the fundamentals. In addition, usage of the EFS system is presented through a case study. Additionally, commentary is provided on the cost-effectiveness of the use of the EFS system in an active bridge management approach.

INTRODUCTION

Fatigue crack detection is a very difficult task. In fact, a study conducted at the Federal Highway Administration NDE Validation Center in which 49 State Department of Transportation bridge inspectors were asked to inspect two steel girder bridges with fatigue crack indications revealed just how difficult crack identification can be. This study indicated that fatigue cracks are only likely to be correctly identified less than ten percent of the time with current inspection techniques.

In the early 1990's work was initiated to develop a testing technique for identifying fatigue cracks in aircraft airframes. Initial efforts focused on the measurement of corrosion fatigue. The initial research on a testing 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 developmental work focused on a crack detection technique that was actually based on the detection of the growth of corrosion products. The resulting technology has a remarkable capability at detecting very small fatigue cracks that are actively growing and is known as the Electrochemical Fatigue Sensor (EFS) system.

THE EFS SYSTEM

The EFS system is a nondestructive fatigue crack testing system. Specifically, EFS is a method for determining if a previously unidentified actively growing fatigue crack is present in the inspection area or if known fatigue cracks are actively growing. During an EFS test, an EFS sensor is applied to each location of interest and crack detection occurs for areas under, or in the immediate vicinity of, the sensor. The EFS system consists of an electrolyte filled sensor, a potentiostat that applies a constant polarizing voltage between the structure and the sensor, and data collection and analysis software.

The EFS system works on fundamental electrochemical principles. During testing, the inspection area is anodically polarized to create a passive film on the area of interest. The polarizing voltage produces a DC base current in the electrochemical cell. When the structure being tested undergoes a cyclic stress, the current flowing within the cell fluctuates in a complex relation to the variation of the mechanical stress. As a result, an AC current is superimposed on the base DC current. Dependent upon the structural material, the loading conditions, as well as the state of the fatigue damage in the structure, the transient current within the cell provides information on any fatigue crack activity.

The electrochemical conditions imposed during an EFS test are designed to induce a stable, passive oxide film on the surface of the material. During cyclic loading, the fatigue process causes micro-plasticity and strain localization on a very fine scale. The interaction of the cyclic slip and the passivating process causes temporary and repeated alterations to the passive films. These alterations, including both dissolution and repassivating processes, give rise to transient currents. The resulting EFS transient currents are complex and result from cyclic changes in the electrical double layer at the interface of the metal and the EFS electrolyte. The transient currents generally possess the same frequency as that of the mechanical stress, but also have a complex phase relationship. In addition, the disruption of the surface oxide film by the cyclic slip causes an additional component of the transient current which has double the frequency of the elastic current. This occurs because plasticity effects occur during both the tensile and compressive portions of the loading cycle. As fatigue damage develops, the cracks induce localized plasticity at different parts of the fatigue cycle from those in which the background micro-plasticity occurs and in locations where cracks have not yet formed. The crack-induced plasticity, thus, introduces higher harmonic components into the transient EFS current. It is the analysis of these various current components that allows determination of whether a growing crack is present or not. The EFS technique offers several distinct advantages over other methods of nondestructive evaluation because of the inherent ability to detect active fatigue crack growth and because of the very small detectable crack size.

To enhance the sensitivity of the EFS system, a configuration known as differential EFS is employed. Differential EFS uses two sensors, one as the reference (R) and one as the crack measurement (CM) sensor. The two sensors are both installed near the location of interest. The CM sensor is specifically located over the area to be inspected while the R sensor is located near the CM sensor – but in a location where a crack is not probable. Using signal processing, the two signals are compared to determine if a crack is present. In this configuration and in the presence of a growing crack the CM measurement sensor provides a larger frequency content magnitude than the R sensor data and also contains extra frequency content. Several proprietary data analysis techniques have been developed and are contained within the EFS system software.

The EFS hardware system consists of three major components: the EFS sensor, the EFS electrolyte, and the EFS potentiostat. The following sections briefly discuss each of these components.

EFS Sensor

The basic EFS sensor consists of several parts as shown in Figure 1. Each sensor has a convenient contact adhesive on one side for attachment to the structure. The open area in the middle of the sensor holds the subsequently described EFS electrolyte. The sensor is filled with electrolyte through the lower filler tube while air escapes out of the upper bleeder tube. The EFS sensor electrode – a stainless steel mesh – is sandwiched between the upper and lower sensor sections. When the sensor is filled with electrolyte, the electrode is completely covered. Depending on the area to be tested, EFS sensors can be custom-made to fit any three-dimensional geometric requirements (including size, shape, orientation, etc.).

EFS Electrolyte

The EFS electrolyte is a proprietary, water-based solution that has been tested on multiple materials including aluminum, titanium, copper, and steel. The EFS electrolyte has been found, in all cases, to be benign to metals. The U.S. Air Force, in fact, has conducted extended fatigue tests with EFS installed on steel, aluminum, and titanium components and has found that EFS did not cause premature failure or impact the fatigue life. The EFS electrolyte is chemically inert and environmentally safe.

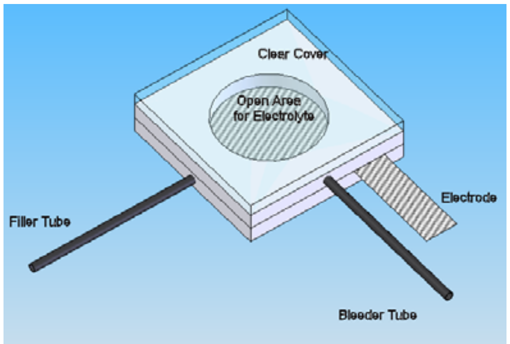

Figure 1 Basic schematic of an EFS sensor.

EFS Potentiostat

The EFS potentiostat is an electronic device that controls the voltage difference between the working electrode and a reference electrode. In the case of use during an EFS inspection, both electrodes are contained within the previously mentioned electrochemical cell. The specific variable controlled by the EFS potentiostat is the cell potential and the measured variable is the cell current. The EFS potentiostat has been custom-designed to not only control the voltage but to also measure the current flow between the working and reference electrodes. During testing, the working electrode is the structure and the reference electrode is the previously mentioned EFS sensor electrode which is sandwiched within the EFS sensor (i.e., the stainless steel mesh).

The battery-powered, wireless MATECH potentiostat, shown in Figure 2, provides all of the features necessary to collect data in the field. The potentiostat is compact, lightweight, and provides isolated channels for the R sensor and the CM sensor. The MATECH potentiostat features onboard A/D conversion, data collection to a removable MMC card, wireless data streaming, and an easy to use wireless setup for bias, gain, and sample rate.

APPLICATION CASE STUDY

MATECH was retained by the Pennsylvania Department of Transportation (PENNDOT) to test three steel girder bridges using its EFS system. The three structures were located on the following major highways: I-476 over the Schuylkill River, PA; I-81 over the Susquehanna River; and I-80 over Canoe Creek. Each structure has documented cracks at fatigue sensitive details. PENNDOT was interested in utilizing the EFS system to determine whether the documented fatigue cracks were continuing to grow and to determine the effectiveness of previously implemented repairs. The following briefly describes the tested bridges and the testing that was conducted. A brief discussion of the results of the testing then follows. Additional, more detailed information on this application can be obtained from the author.

Figure 2 The EFS Potentiostat.

Test Details

The dual 15-span steel bridges running north-south on I-476 over the Schuylkill River in West Conshohocken, PA was inspected by MATECH preliminarily on May 1, 2006 and with the EFS system on October 5, 2006 and is shown in Figure 3. The structure was constructed in the early 1970's and cracking was reported at the toes of the welds above the bearing locations on the northbound and southbound spans at Pier 11 and within the girder webs at the same locations. The following locations were evaluated with the EFS system:

NORTHBOUND SPAN

- Girder 1, Pier 11, Span 12 at a transverse weld toe crack on the outer side of the girder at the floorbeam at Pier 11
- Girder 7, Pier 11, Span 12
  - One location is at a vertical weld toe crack which has propagated into the base metal of the floorbeam web.
  - One location is a weld toe crack at the same weld several inches above the first location.

SOUTHBOUND SPAN

- Girder 1, Pier 11, Span 12
  - Four crack locations along the toe of weld at the girder to floorbeam connection on both sides of the girder.
  - One location adjacent to a stop drill in the web of the Girder 1.


Figure 3. The I-476 bridge.

The second tested bridge was the southbound span of a dual 23-span bridge system located on I-81 over the Susquehanna River just north of Harrisburg, shown in Figure 4. A preliminary inspection was performed on May 2nd with the EFS inspection performed on October 10 and 12, 2006. The structure was built in 1972 with the first full year of traffic in 1976. Fatigue cracking was reported during a biennial inspection. The cracking is the result of out-of-plane bending in the girders and high stress range levels. The following locations were tested on the southbound span:

Span 9, Girder 5, Floorbeam 1 - cracked
Span 9, Girder 5, Floorbeam 3 – cracked
Span 9, Girder 5, Floorbeam 4 - cracked
Span 10 Girder 5 Floorbeam 1 – cracked
Span 19, Girder 1, Floorbeam 7 - cracked
Span 20, Girder 1, Floorbeam 4 – cracked


Figure 4. The I-81 bridge.

The third bridge inspected is the I-80 eastbound 6-span bridge located west of Clarion, PA in Clarion County over the Canoe Creek shown in Figure 5. A preliminary inspection was performed on May 4 with the EFS inspection performed on October 2 and 3, 2006. The following locations were inspected with the EFS system:

Two crack locations at Girder 1, Floorbeam 22.
Two locations beyond stop drills at Girder 2, Floorbeam 26 from the outside.
Three locations beyond stop drills at Girder 1, Floorbeam 21 from the outside.
Four locations where cracks have propagated beyond the stop drill holes at Girder 2, Floorbeam 19.

Figure 5. Bridge I-80

Results

Specific results of the tests are summarized in Tables 1 through 3. Note that crack location refers to the sequential inspection location followed by a potentiostat identifier. For reference, the term X in Tables 1 through 3 describes the ratio of the CM output to the R output. This is one, but not the only, factor used in determining the activity of a given crack.

The results summarized in Tables 1 through 3 lead to some important findings. First, on the I-476 Bridge, the stop drill holes appear to be of a large enough diameter to have arrested crack growth. However, cracks along the toes of the welds are continuing to grow at a fairly accelerated pace.

At the I-81 Harrisburg Bridge, it should be noted that the MATECH team detected a crack not previously reported at Girder 5, Span 10, Floorbeam 1. This location contained a connection detail similar to those which exhibited crack growth elsewhere on the bridge. Results indicate that microplasticity is already occurring in this area and that there is a good chance of crack initiation.

The I-80 Canoe Creek bridge cracks have, in general, been stabilized. The numerous drill stops and retrofits seem to have slowed the crack growth. Additionally, it is possible that the cracks had gotten so long that the stress field around the area of the crack tip is now below critical levels. It should be noted that testing at one location, the connection of Girder 2 to Floorbeam 26, revealed that there is microplasticity in the area of the crack and that future crack growth is likely in this area.

Table 1. Inspection results, Bridge I-476

Crack Location	Crack Visually Detected?	X, (X=CM/Ref)	Activity
1-53	Yes	5.5	Active Growth
2-60	Yes	2.8	Active Growth
3-56	No	1.5	Growth not observed
4-57	Yes	2.3	Little growth
5-63	Yes	3.4	Active Growth
6-52	Yes	3.5	Active Growth
7-54	Yes	3.5	Active Growth
8-62	No	1.5	Growth not observed

Table 2. Inspection results, Bridge I-81

Crack Location	Crack Visually Detected?	X, (X=CM/Ref)	Activity
1-52	Yes	16.0	Active Growth
2-53	Yes	11.0	Active Growth
3-54	Yes	5.0	Active Growth
4-63	No	1.8	Little to no growth
5-57	Yes	8.4	Active Growth
6-62	Yes	5.6	Active Growth

Table 3. Inspection results, Bridge I-80

Crack Location	Crack Visually Detected?	X, (X=CM/Ref)	Activity
1-58	No	<1.3	Growth not observed
2-53	No	1.9	Little to no growth
3-57	No	<1.3	Growth not observed
4-59	No	<1.3	Growth not observed
5-62	No	<1.3	Growth not observed
6-60	No	<1.3	Growth not observed
7-63	No	<1.3	Growth not observed
8-52	No	<1.3	Growth not observed
9-56	No	<1.3	Growth not observed
10-56	No	<1.3	Growth not observed
11-52	No	<1.3	Growth not observed

COST EFFECTIVENESS OF EFS INSPECTIONS

The overriding purpose for utilizing EFS as a condition assessment tool for the above described testing was to help PENNDOT meet one of the objectives set forth in a report recently released by the Pennsylvania Transportation Funding and Reform Commission. This report states that one reform that will significantly contribute to PENNDOT's goal of saving $120M per year is "…taking the right maintenance steps at optimum intervals to extend the life of highways and bridges…" by identifying growing cracks in highway bridges. Using the EFS system, it was determined that some of the inspected areas had growing cracks (both at previously repaired and at unrepaired locations) and that in other areas repairs had been successful. The inspection results at the known cracks allowed PENNDOT to prioritize repairs dollars to those most in need, to eliminate planned repairs to areas that do not need repair, and to avoid very costly bridge closures/load restrictions/failures. In addition, because actively growing cracks that had not previously been documented were identified by the EFS system, the agency could make minor repairs before they become more expensive problems. All together this resulted in a more efficient deployment of funds.

To illustrate the cost-effectiveness of conducting an EFS inspection, the three bridges inspected for PENNDOT can be used as a case-study. Working with PENNDOT data and following PENNDOT advice, policy, and practice, the following savings were estimated and realized:

I-80 Canoe Creek Bridge (Total savings = $67,420)

Cause of savings – Elimination of planned cross-girder repairs
Savings:

Repair mobilization	$10,000
Maintenance and protection of traffic	$22,920
Repair	$34,500
Total	**$67,420**

I-476 in West Conshohocken (Total savings = $81,800)

Cause of savings – Elimination of planned stop drill repairs
Savings:

Repair mobilization	$1,800
Repair	$5,000
Total	**$6,800**

Additional cause of savings – Cost of needing to restrict traffic due to ineffective repairs
Savings: **Estimated to be $75,000** for disruption to commerce and the traveling public

I-81 over the Susquehanna River (Total savings = $100,000)

Cause of Savings – Prioritization of repairs to avoid bridge load restriction
Savings: **Estimated to be $100,000** for disruption to commerce and the traveling public

In total, these tests saved over $200,000 and cost just a fraction of that to conduct. As a result of these savings and the increase in safety resulting from the EFS inspections, PENNDOT has initiated an on-call contract with MATECH to provide these tests statewide.

CONCLUDING REMARKS

The EFS system is a novel NDE technique capable of detecting active fatigue cracks that are smaller than those detectable by other currently available techniques. Further, the fact that EFS can detect whether a crack is actively growing gives bridge owners never before available information that allows for active prioritization of bridge repair/rehabilitation funds. The ability to know which cracks require attention and which cracks can conceivably be left as-is without structural impact has the potential of allowing significant dollars to be more efficiently allocated to fixing problems that could continue escalating in scale.

EFS has been examined in side-by-side comparisons with currently available NDE techniques during several field bridge inspections. These comparisons have revealed that EFS consistently identifies all cracks identified by other technologies and is able to detect cracks that others can't (even once their presence and location is known). Additionally, EFS has been shown to give owners information that no other technology can. Combined, it is clear that EFS is an effective and cost-saving tool within any active bridge management system.