Remote Monitoring of Fatigue-sensitive Details on Bridges

(Appendices)

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Department of Civil & Construction Engineering
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APPENDIX A

ABBREVIATIONS
<table>
<thead>
<tr>
<th><strong>A</strong></th>
<th>Amperage (Amps)</th>
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<tr>
<td>AASHTO</td>
<td>American Association of State Highway and Transportation Officials</td>
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<tr>
<td><strong>AC</strong></td>
<td>Alternating Current</td>
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<td><strong>ADT</strong></td>
<td>Average Daily Traffic</td>
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<td><strong>ADTT</strong></td>
<td>Average Daily Truck Traffic</td>
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<td><strong>AE</strong></td>
<td>Acoustic Emission</td>
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<td><strong>Ah</strong></td>
<td>Amp hours</td>
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<tr>
<td><strong>ASTM</strong></td>
<td>American Society for Testing and Materials</td>
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<td><strong>C</strong></td>
<td>Constant-Amplitude Fatigue Threshold</td>
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<td><strong>CFRP</strong></td>
<td>Carbon Fiber Reinforced Polymer</td>
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<td><strong>D</strong></td>
<td>Direct Current</td>
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<tr>
<td><strong>DFT</strong></td>
<td>Department for Transport</td>
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<td><strong>DIC</strong></td>
<td>Digital Image Correlation</td>
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<tr>
<td><strong>DMRB</strong></td>
<td>Design Manual for Roads and Bridges</td>
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<td><strong>DoD</strong></td>
<td>Depth of Discharge</td>
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<td><strong>DOT</strong></td>
<td>Department of Transportation</td>
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<td><strong>E</strong></td>
<td>Eastbound</td>
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<td><strong>EFS</strong></td>
<td>Electrochemical Fatigue Sensor</td>
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<td><strong>F</strong></td>
<td>Fracture Critical Members</td>
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<td><strong>FD</strong></td>
<td>Fatigue damage sensor</td>
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<td><strong>FE</strong></td>
<td>Finite Element</td>
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<td><strong>FHWA</strong></td>
<td>Federal Highway Administration</td>
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Remote Monitoring of Fatigue-sensitive Details on Bridges

FF  Fatigue Fuse
FHC  First-Hit Channel

H  Hot Spot
HS  Hot Spot Stress
HSS  Hot Spot Stress

I  International Institute of Welding
IIW  International Institute of Welding
LVD  Low-Voltage Disconnect
LVR  Low-Voltage Reconnect

L  Linear Elastic Fracture Mechanics
LEFM  Linear Elastic Fracture Mechanics
Ly  Langley

M  Manual for Bridge Evaluation
MBE  Manual for Bridge Evaluation
MDOT  Michigan Department of Transportation
MPPT  Maximum Power Point Tracking

N  National Bridge Inventory
NBI  National Bridge Inventory
NCHRP National Cooperative Highway Research Program
NTD  Nondestructive Testing
NREL  National Renewable Energy Laboratory
NLM  Non-Linear Mapping

O  Oregon Department of Transportation
ODOT  Oregon Department of Transportation
Remote Monitoring of Fatigue-sensitive Details on Bridges

P
PE  Photoelasticity
PLB  Pencil Lead Break
PV  Photovoltaic

R
RFID  Radio Frequency Identification

S
SG  Strain Gauges
SHM  Structural Health Monitoring

T
TS  Temperature Sensor

U
UIT  Ultrasonic Impact Treatment
USGW  Ultrasonic Guided Wave

V
V  Voltage (Volts)

W
WB  Westbound
WEU  Waveform Extraction Utility
WIM  Weight-In-Motion

X
XRD  X-ray Diffraction
APPENDIX B
NOTATIONS
Δf  Stress range

(Δf)_{eff}  Effective stress range

Δf_i  Particular stress range

(Δf)_{max}  Maximum stress range

(Δf)_{TH}  Threshold stress

ΔK  Stress intensity factor range

ρ  Radius of crack-stop hole

σ  Stress

σ_{hs, assess}  Hot spot stress of the detail to be assessed

σ_{hs, ref}  Hot spot stress of the reference detail

σ_y  Yield strength

γ_i  Percentage of cycles at a particular stress range

A  Present age of a detail; Detail category constant

ADT  Average daily traffic

ADTT  Average daily truck traffic

(ADTT)_{SL}  Average daily truck traffic in a single lane averaged over fatigue life

[(ADTT)_{SL}]_{PRESENT}  Present average daily truck traffic in a single lane

CAFT_{assess}  Constant-amplitude fatigue threshold of the detail to be assessed

CAFT_{ref}  Constant-amplitude fatigue threshold of the reference detail

D  Damage sum/index, 0 ≤ D ≤ 1.0

E  Modulus of elasticity of the material

f_y  Yield Strength

g  Average yearly increase in traffic

i  Stress range

k  \((σ_{hs, ref})/(σ_{hs, assess})\)

n  Number of stress-range cycles per truck passage

n_i  Number of cycles at stress range i

N_i  Theoretical fatigue life at stress range i

Q  Fatigue Serviceability Index

R_R  Resistance factor specified for evaluation
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<tr>
<td>Rs</td>
<td>The stress-range estimate partial load factor</td>
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<tr>
<td>SYY</td>
<td>Stress in y-direction</td>
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<tr>
<td>t</td>
<td>Plate thickness</td>
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<tr>
<td>T_{fat}</td>
<td>Remaining fatigue life</td>
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<tr>
<td>V_{mp}</td>
<td>Maximum power point voltage</td>
</tr>
<tr>
<td>W</td>
<td>Longitudinal attachment thickness + 2\times weld leg length</td>
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<tr>
<td>Y</td>
<td>Finite fatigue life</td>
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APPENDIX C

TECHNOLOGY FOR FATIGUE-SENSITIVE DETAIL MONITORING
C OVERVIEW

While a few technologies are successfully implemented in the field, a limited number of technologies are evaluated under laboratory and field conditions for fatigue event detection, crack growth monitoring, and for capturing strain profile at or around sensitive details. A limited number of these studies are documented in this appendix. Further, the working principles of a few technologies are also presented.

C.1 TECHNOLOGIES AND PRACTICE – CASE STUDIES

C.1.1 Low-power wireless sensor network (WSN) for strain data acquisition (Fasl 2013, Fasl et al. 2012).

Fasl et al. studied a 900 ft long bridge with the maximum span of 230 ft and twin trapezoidal 78 in. deep box girders. A monitoring system was implemented to record the strains at fatigue-sensitive details of the bridge. The monitoring system included four strain gauge nodes, two thermocouple nodes, and a real-time low-power wireless sensor network (WSN). The system was used for continuous acquisition of temperature and traffic-induced strains. A standard rainflow counting algorithm was implemented, and real-time strain data analysis was performed. The processed data was transmitted through the WSN gateway, which was connected to a cellular gateway, to transmit the data to a cloud-based service for storing, further analysis, and sharing (Figure C-1). The data acquired from the system was primarily used to calculate the remaining fatigue life.

Figure C-1. Schematic of the monitoring system (Fasl et al. 2012)
The strain gauge nodes were programmed to run in five different modes as described below:

- **Idle**: Node acquisition is inactive; waiting for a command.
- **Streaming**: Periodically acquires and transmits strain waveforms.
- **Rainflow**: Continuously acquires dynamic data, performs real-time rainflow counting, and transmits a histogram of the results at a predefined time interval (typically every 30 minutes).
- **Trigger**: Transmits strains as a time-series when a predefined trigger level is exceeded.
- **Rainflow+Trigger**: Execute rainflow counting algorithm and trigger modes simultaneously.

The key features of this system include the capability of the system to process data before transmission, the flexibility in configuring the system to transmit processed data as well as raw data, and the system activation capability through a predefined trigger level.

**C.1.2 Multi-sensor network system for steel bridge fatigue crack monitoring (Zhao et al. 2013)**

Fatigue events and crack growth were monitored using a multi-channel and multi-sensor network system with acoustic emission (AE), strain, and ultrasonic guided wave (USGW) sensors. Once a possible damage event is captured by AE and strain sensors, the USGW sensors were triggered to perform in-situ inspection of the damaged location to characterize the cracks. The triggering thresholds were set for AE signal and strain change amplitude. Also, the monitoring system included the capability to trigger the USGW sensors to inspect the area as needed. The sensor data was remotely accessible via a Global System for Mobile (GSM) communication network. The monitoring system included the capability to send a Short Message Service (SMS) after detecting a damage event.

The system was implemented on a four-span, multi-girder bridge built in 1966. The primary objective of technology implementation was to monitor the growth of existing fatigue cracks at a diaphragm and girder web connection. The AE sensor was mounted on the girder web near a web gap, a fatigue-sensitive detail (Figure C-2a). The USGW sensors were mounted as a rectangular array, enclosing an existing crack, to monitor growth (Figure C-2b). The arrows in
the USGW sensor array (Figure C-2b) indicate the wave propagation path between the pulsers, located on the left, and the receivers, located on the right. Both the AE and USGW sensors were calibrated after being mounted near the crack.

Figure C-2. Sensor locations of (a) AE sensor and (b) USGW sensor array (Zhao et al. 2013)

The USGW sensor array included 4 sensors mounted to capture an activity of a crack located within the array (Figure C-3a). The signals from the USGW sensors were categorized based on the sensor location, wave propagation path, and crack tip location (Figure C-3b). As an example, (i) the pair-wise data between sensors 1 and 2 is named as ‘crack’ when the direct transmission of signals from sensor 2 to 1 is disturbed by a crack; (ii) the pair-wise data between sensors 2 and 3 and 4 and 1 are named as ‘crack tip’ when the pairwise data between sensors 2 and 3, and 4 and 1 represent a specific signal pattern demonstrating the reach of crack tip closer to the direct signal transmission between these sensors; and (iii) the pairwise data between sensors 3 and 4 was named as ‘normal’ when the direct signal transmission between those two sensors is not interrupted.

Figure C-3. Field implementation of the system for fatigue crack monitoring (a) sensor system mounted on the bridge and (b) schematic of the USGW sensor array (Zhao et al. 2013)
A GSM cellular network was used for wireless data transmission to a remote computer. The field data from the AE and USGW sensors was used to characterize the crack and also to evaluate the impact of loads on the structure and traffic noises. The traffic noises rarely triggered the AE sensors due to low energy levels generated by the loads (Figure C-4).

![Figure C-4. Difference in wave pattern from AE signal for (a) simulated crack and (b) external noise (Zhao et al. 2013)](image)

The major improvement of this monitoring system compared to a traditional AE sensor system is the use of automated triggering of USGW sensors to monitor status and growth of cracks once a fatigue event is captured by the AE sensors. Also, the USGW sensors can be triggered to inspect the details, as needed. However, the effectiveness of the system depends on the USGW sensor arrangement and the proximity to the crack location. The drawback of the wireless system compared to the wired system is the delay in triggering USGW sensors for data collection.

C.1.3 Fatigue testing and SHM of retrofitted steel highway bridge web stiffeners (Ghahremani et al. 2013)

Ghahremani et al. (2013) evaluated a retrofitted detail using strain gauges, an alternating current potential drop technique (which is commonly known as eddy current method for crack depth measurement) and direct current differential transducers for displacement measurement. The approach was to predict fatigue crack depth using local strain data supported with 2D and 3D finite element analysis results. The eddy current method was used to calibrate and validate the methodology.
One of the major challenges of this study was to accurately measure the strain near the crack location. This challenge was overcome with the help of detailed FE analysis. The other challenge was to eliminate the effect of environmental and experimental conditions. This challenge was overcome by having additional sensors (guard sensors) mounted away from the critical area to record the effects due to ambient and experimental conditions, and eliminating them from the data recorded from the sensors mounted in the vicinity of the crack locations.

C.1.4 Field monitoring of a fatigue crack on a highway steel I-girder bridge (Zhang et al. 2013)

The piezoelectric film sensors, also referred as the piezoelectric paint sensors, are used in AE sensors (Barut 2006; Yang and Fritzen 2011). These piezoelectric film sensors are made using a composite piezoelectric material that is developed by mixing small piezoelectric particles in a polymer matrix. The piezoelectric powder used in developing these sensors is mainly composed of Lead Zirconate Titanate, with the chemical formula Pb[Zr\(_x\)Ti\(_{1-x}\)]O\(_3\), of which \(x\) varies between 0 to 1 (i.e., \(0 \leq x \leq 1\)). The sensors with Lead Zirconate Titanate are called PZT (Yang and Fritzen 2011). The PZT sensors have several advantages when compared to the traditional sensors made of brittle piezoelectric ceramic material. The flexibility of PZT composite material allows mounting these sensors on curved surfaces (Figure C-5). In addition, light weight, small size, and wide bandwidth are the other advantages of these sensors.

![Figure C-5. (a) PZT sensor sample and (b) PZT sensor sample on a curved surface](image)

Zhang et al. (2013) used a health monitoring system with PZT AE wideband low profile (i.e., small and lightweight) sensors to monitor an existing fatigue crack on a weld at the diaphragm connection plate of a 140 ft single span multi-girder steel bridge. The fatigue crack initiated due to live load induced stresses in the welds resulting from differential deflections of adjacent...
girders. The monitoring system was comprised of three PZT AE sensors, wireless accelerometers, laser distance sensors, and strain transducers (Figure C-6 and Figure C-7). The growth of the crack was monitored using AE sensors while the wireless accelerometers and laser distance sensors measured the vibration responses and differential deflection of adjacent girders (expected cause of the fatigue cracking).

Average frequency spectrums of triggered signals from the three AE sensors were used to cancel out ambient noise effect instead of using a guard sensor. In addition, a band-pass filter was used to filter out low frequency noises induced by bridge vibration.
C.1.5 Acoustic emission monitoring of a cantilever through truss bridge (Kosnik 2008)

An AE sensor array was used to monitor a 5 in. long, full depth, fatigue crack in a cantilever through truss bridge. As a maintenance activity, an inch diameter crack-stop hole was drilled at the tip of the crack. The objective of the instrumentation was to monitor the effectiveness of the crack-stop hole in preventing crack growth. Four sensors were mounted in a rectangular array around the crack-stop hole while one of them mounted opposite the crack tip (Figure C-8). The system continuously collected and transmitted data to monitor crack growth beyond the crack-stop hole. Even though a threshold value of 40 dB was set to eliminate the noises, the noise levels generated from the bolted connection near the crack were greater than the threshold. Hence, the first-hit channel (FHC) analysis approach was used to filter out the noises from the bolted connection near the crack. Also, the AE hardware was mounted on rubber to avoid noises from the enclosure itself.

![Image](image1.png) ![Image](image2.png)

Figure C-8. Field monitoring of a fatigue crack using an AE sensor array (Kosnik 2008)

Few AE activities were identified near the crack-stop hole using the FHC analysis technique. These events were identified using signals with amplitude lower than the threshold. Further investigations revealed that the signals originated due to fretting of the existing crack.

Even though the monitoring system was designed to locate and characterize damage events, complicated geometry and low strength signals made the tasks unattainable. Hence, effective use of AE sensors at a particular structure requires having adequate signal strength to negate the noises or implementation of advanced signal enhancing and processing techniques to minimize the noise effects. Further, a long-term implementation of a monitoring system on a particular structure is required to identify the noise sources and establish thresholds to capture fatigue events.
C.1.6 Fatigue crack detection and monitoring techniques for steel bridges (FHWA 2009, FHWA 2012)

The Federal Highway Administration (FHWA) conducted a multi-year project to evaluate currently available NDE technologies for crack detection and crack growth monitoring in steel bridges, including subsurface flaws as small as 0.01 in. in length or depth. The laboratory studies used plate specimens with surface and subsurface cracks. Field evaluation included monitoring a crack at a web gap of a 3-span, continuous, multi-girder bridge.

Phased array ultrasonic testing (PAUT) and eddy current (EC) capabilities were evaluated for detecting existing cracks or flaws. The parameters considered for the evaluation are crack length, depth, and orientation. The PAUT system was able to detect and characterize subsurface and internal crack length and depth more effectively than an EC system that could only measure the length. Even though the geometry of the crack posed difficulties in sizing the cracks, the PAUT system could locate the crack tip with sectorial scan images. These technologies are not suitable for remote monitoring purposes because both techniques require access to the specific bridge details to perform inspection. Hence, no further information on these technologies is presented.

AE and electrochemical fatigue sensors (EFS) were evaluated for detecting crack growth or the status of a crack (i.e., an active or a dormant crack). A comparative study was carried out using EFS and AE systems using a cruciform specimen test. The conclusions of the study are as follows:

- AE takes almost twice the time of EFS to detect major crack activity. Hence, the EFS has a greater sensitivity in detecting low energy cracking events.
- AE sensors can continuously record crack growth activity.
- AE is suitable for local as well as global structural monitoring whereas the EFS is suitable for local monitoring.
- Frequent refill of chemicals (i.e., every 1-3 days) is needed for proper operation of EFS under hot weather conditions. Hence, an AE system is suitable for long-term monitoring since it does not require direct access to a crack or the sensors once the sensors are installed.
• Even though AE can only detect crack growth activity, it can be used with other NDE methods to characterize the crack.

• The detection of smaller cracks, less than 0.04 in. in length, with AE and EFS can be severely affected by the bridge coating.

C.1.7 Acoustic emission for non-destructive testing of bridges (Parmar and Sharp 2009)

Bridge cables were monitored during low and high traffic volumes as well as during winter and summer (Figure C-9) to evaluate potential use of an AE system to ensure the integrity of the bridge cables. The objective was to detect active cracks and flaws located in hidden areas where visual inspection is difficult.

The field implementation results show that the AE technique can be used to monitor, record, and analyze real time data remotely from the bridge for structural health monitoring of the cables. AE data was used to identify damage activities of the bridge cable once the noises arising from sources such as rain and wind are eliminated through signal analysis techniques or using data from guard sensors.

C.1.8 AE system development and field implementation plan for a tied arch bridge (Schultz and Thompson 2010)

Schultz and Thompson (2010) presented a system development and field implementation plan of an AE monitoring system for the Cedar Avenue/MN 77 tied arch bridge in Minnesota. The bridge is classified as fracture-critical due to lack of redundancy. The instrumentation plan was
developed for monitoring fatigue crack initiation and crack growth at critical locations such as the steel connections, box ties, floor beams, and the cables. The AE system was chosen as the most applicable monitoring system for the particular bridge after reviewing technical literature for commercially available technologies. The implementation plan recommended following up with visual inspection when an event is detected by the monitoring system.

The FE model was used to identify critical or high stress concentration areas (hot spots) for sensor array design. The hanger plate and diaphragm connection to the box girder web developed high stresses. For this particular detail, three different sensor arrays with two, three, and four sensors were suggested (Figure C-10). The capabilities of three sensor arrays were evaluated with respect to the detail to be monitored. The two sensor array provides linear source location detection capability. The three sensor array is capable of detecting the source location in two-dimension. The advanced four sensor array is capable of detecting the 3D location of a source. After considering the specific detail of the Cedar Avenue bridge and the monitoring system cost, Schultz and Thompson (2010) recommended using a two sensor linear array system.

The signal attenuation rate was calculated by performing several pencil lead break tests while changing the distance between a hand-held AE sensor and the pencil lead break point. This specific process was needed to place the sensors at optimum locations from the expected source location to capture adequate signal strength for source location detection and event characterization.

The noise generated from fretting of bolted connections can be filtered by selecting a lower bound threshold value. Instead, a guard sensor can be placed just outside the sensor array for fatigue monitoring (or close to the noise source), and the signals recorded by the guard sensor can be filtered out of the signals from the sensor array during analysis. The waveform parameters such as amplitude, energy, signal count, signal rise time, and signal duration are used for location detection and event characterization. In addition to the AE sensors, strain data is needed to correlate AE sensor data for crack growth monitoring.

Even though the bridge selected by Schultz and Thompson (2010) for the technology implementation has shown no evidence of cracking during its life time, the AE system has been continuously collecting AE counts which are below the threshold values set in the system.
C.1.9 Field implementation of acoustic emission (AE) sensors on railway steel bridges (Hay et al. 2009; Ledeczi et al. 2009)

The AE method has been successfully implemented by Hay et al. (2009) for over 20 years to monitor fatigue sensitive details in railway bridges (Figure C-11). An AE monitoring system with strain correlation was implemented to monitor the growth of existing cracks at the bottom of intermediate stiffeners on a 1,233 ft (376 m) open deck bridge with welded girders built in 1910. A similar system was implemented to monitor a link-pin connection of a 320 ft (97.5 m) long open deck bridge built in 1913. The link-pin connection is subjected to out-of-plane bending stresses caused by lateral sway from wind and train motion. The AE system was used
for timely scheduling of the retrofit of the link-pin connection when a crack initiates behind the pin nut that would not be detected by visual inspection. Another example of an AE system installation by Hay et al. (2009) is the monitoring of a 107 spans, 3,444 ft (1050 m) long bridge with various structural configurations such as through trusses and timber pile trestles. The primary objective of monitoring was to help bridge managers make risk-informed decisions to schedule retrofit activities.

Ledeczi et al. (2009) implemented a wireless monitoring system with AE and strain sensors on a railway bridge for fatigue event and location detection. The objective of the field implementation was to benchmark the wireless system against a wired system (Figure C-12). The system consists of 4 AE channels and one strain gauge. A strain sensor was used to trigger AE sensors when traffic is detected on the bridge. This approach makes the system capture only the AE and strain data at the time of traffic passing the bridge, so that the stresses on the monitored component can be correlated to the active fatigue cracks.

Both a wired and wireless system had some sensitivity issues related to fatigue event detection due to sensor location, surface preparation, and sensor coupling to the structure. The accuracy of the fatigue event source location detection had 1-3 in. error due to the complexity of the detail. The detail had multiple fasteners that affected the line-of-sight between the sensors and the
source. However, all the events detected were clustered around the crack tip area within the margin of the location error.

![Image](image.png)

**Figure C-12. The monitoring systems wired and wireless (marked in circles) AE sensors (Ledeczi et al. 2009)**

### C.1.10 Electrochemical fatigue sensors (EFS)

Electrochemical fatigue sensors (EFS) are developed in response to limitations of other fatigue monitoring technologies. As an example, AE technology has widely been used to detect fatigue events by monitoring the stress waves generated due to rapid release of energy. Stress wave propagation is affected by several factors as discussed in section C.2.1.7. Further, the threshold levels established after evaluating the noise levels limit the AE sensor system sensitivity. Above all, the AE sensors cannot predict the potential for future crack growth. This limitation is generally addressed by placing strain gauges at critical locations and monitoring strain profile (or load history). However, this approach may be limited by the sensitivity of the strain gauges.

Two major applications of EFS are (i) monitoring fatigue crack growth by mounting the sensor over a crack tip and (ii) monitoring strain localization and/or micro plasticity to evaluate the potential for crack growth. Monitoring strain localization or micro plasticity is important for evaluating the effectiveness of a retrofit (e.g., crack-stop hole) or for prioritizing or scheduling repair activities (Moshier et al. 2009).

EFS were deployed in the field to monitor growth or growth potential of existing cracks, effectiveness of crack-stop holes in arresting crack growth, and potential for crack initiation or
growth of unidentified cracks at sensitive locations identified through previous experience with similar details (MFS 2013).

The Pennsylvania Department of Transportation implemented an EFS system to monitor three steel girder bridges with cracks at fatigue-sensitive details (Phares 2007). Fatigue cracks were located at the weld toe of the girder above the floorbeam as well as on the floorbeam web. These cracks were initiated due to out-of-plane distortion in the girders and high stresses developed at the floorbeam-girder connection. The objectives of EFS system implementation was to monitor the state of the existing cracks and to determine the effectiveness of crack-stop holes that were installed to arrest further growth. The inspection results from the EFS system indicated continuous growth of weld toe cracks and the effectiveness of the large crack-stop holes in arresting the growth. The system also revealed microplasticity in some potential future crack growth locations.

Several other successful field implementations on highway and railway bridges are documented (MFS 2013). These implementations include three bridges in Australia, the Manahawkin Bay Bridge and George Washington Bridge in New Jersey, and Steven’s Point Rail Bridge owned by the Canadian National (CN) Railway. The results of these implementations demonstrated the capability of the technology in detecting actively growing cracks, evaluating the effectiveness of crack-stop holes, and identifying early signs of crack growth.

C.1.11 Fatigue crack monitoring of orthotropic steel bridge deck using piezoelectric (PZT) paint sensors and commercial acoustic emission (AE) sensors (Yi et al. 2012)

Yi et al (2012) evaluated PZT paint AE sensors by comparing the results with commercially available AE sensors. Please refer to section C.1.4 for more information on PZT paint sensors. The fatigue-sensitive details used for the evaluation included orthotropic steel bridge deck details such as longitudinal stiffener to deck plate weld connections, longitudinal stiffener to diaphragm weld connections, through splice butt welds and diaphragm cutout. The full-scale test structure was subjected to static and cyclic loading by using a servo-hydraulic actuator fixed to a load frame (Figure C-13).
The PZT paint and commercial AE sensor array used for the experimental set up is shown in Figure C-14. A 45 dB threshold level was set to the AE system to minimize the effect of external noise. The PZT paint sensors were connected to a signal conditioning circuit containing a preamplifier and a low and high pass filter. The voltage gain of the preamplifier was set to be at 40 dB. A pencil lead break (PLB) test was performed to calibrate the sensors. In addition, the waveform from the PLB test was used as a reference for identifying the other AE data acquired from the experiment. The experimental test results demonstrated the capability of PZT paint sensors to detect AE events associated with fatigue cracks compared to commercial AE sensors.
C.1.12 Strain and crack monitoring using radio frequency identification (RFID) based antenna sensor (Yi et al. 2012b)

Yi et al. (2012b) developed and evaluated a wireless crack sensing system under laboratory conditions. The system is designed as a folded patch antenna that consists of a radiofrequency identification (RFID) chip for signal modulation and collision avoidance (i.e., to prevent potential for reading multiple sensors at the same time which will eventually leads to data loss). The system is capable of detecting change in strain or deformation based on the electrical length change and its electromagnetic resonance frequency. This system can also be used for crack detection using the radiofrequency (RF) that will be described later. The schematic of the system is shown in Figure C-15. The system is passive; it obtains power from RF signals emitted by the wireless reader by means of interrogation. The passive RFID tags are smaller and lighter compared to the active RFID sensors, but the range is limited to several feet. The system has been tested for measuring strain in the range of 20 µε - 10,000 µε. In addition, the system working principles and capabilities were evaluated by Yi et al. (2012b) through simulations by using an electromagnetic software package.

![Figure C-15. Schematic of the RFID system (Yi et al. 2012b)](image)
The RFID tag has an electromagnetic antenna and an RFID chip that reflects the RF signal emitted by the RFID reader. The signals received by the RFID tags are amplitude-modulated and reflected back to the RFID reader. The signals captured by the RFID reader are demodulated by the reader to distinguish between other reflected signals from the surrounding environment. The folded patch antenna in the RFID tag is designed to function as a wireless strain sensor. The antenna is folded to reduce the sensor size which is typically 0.04 in × 0.04 in (1 mm x 1 mm). When the electrical current flow in the RFID tag antenna that is induced by the RFID reader is cut off due to cracked folded antenna, the current flow takes a different route around the crack. This new elongated electrical passage causes a shift in the resonance frequency of the sensor indicating the presence of a crack. Figure C-16 shows the variation of interrogation power (P) and the resonance frequency of cracked and uncracked specimens.

An experimental set up used by Yi et al. (2012b) is shown in Figure C-17. The crack was simulated on an aluminum plate (8 in. × 4 in. × 0.5 in.) by tightening a screw to open the crack. The sensor was mounted right on top of the expected crack location. The RFID reader was located at 12 in. away from the RFID tag. The reader is capable of automatically recognizing the interrogation power threshold and the resonance frequency of the RFID tag by analyzing different frequencies. This is performed five times for each crack opening size to eliminate external noise effects.

![Figure C-16. Resonance frequency shift due to cracking at the folded patch antenna (Yi et al. 2012)]
As shown in Figure C-18, the resonance frequency gradually reduces as the crack size increases. Further, resonance frequency vs. the crack size and resonance frequency vs. equivalent strain show linear relationships (Figure C-19).

![Figure C-17. Experimental set up of the RFID sensor system (Yi et al. 2012)](image)

![Figure C-18. Interrogation power threshold values at different crack opening size (Yi et al. 2012b)](image)
Figure C-19. Relationship between the resonance frequency and (a) crack size and (b) equivalent strain (Yi et al. 2012b)

One drawback of the system is that the frequency shift can be recorded even when the sensor is not cracked. The electromagnetic disturbance developed by the presence of conductive material such as steel near the sensors is another challenge for implementation of this technology (Kaur et al. 2011). However, Li et al. (2011) used steel specimens to evaluate an RFID sensor that they developed, but they do not discuss any impact of steel on the data. The thermal sensitivity of the material used for fabrication of the antenna component in the RFID system has an impact on the measurements. For example, glass microfiber-reinforced PTFE substrate shows a relatively high temperature sensitivity when compared with ceramic-filled PTFE substrate material. This aspect has been investigated by Yi et al. (2012b). Also, the transmission efficiency, crack pattern, location of the crack with respect to the sensor, growth of multiple simultaneous cracks, and impact of exposure conditions need to be investigated for this system to be practically ready for field implementation.

C.1.13 Structural health monitoring using digital image correlation (DIC) (Iadicola et al. 2012)

As part of the NCHRP 12-84 project, FHWA used digital image correlation (DIC) technique for measuring displacements and strains of a large gusset plate. The experimental setup consisted of 5 members that were connected by two gusset plates and loaded with hydraulic actuators (Figure C-20 and Figure C-21). The gusset plates were labeled as north and south. Moreover, the unloaded structure was used as the reference for all measurements. DIC results were compared with the results from laser point tracking, photoelastic imaging, and traditional foil strain gauges.
The laser tracker was used to compare the measured displacement while the DIC strain profiles were compared with the photoelastic imaging and strain gauge data.

The experimental setup of the DIC is shown in Figure C-20. The system consists of two cameras mounted on an aluminum bar as a rigid support for measuring 3D displacement and surface strain on the north gusset plate. The DIC measurement technique needs a random pattern (speckles) on the surface. The random pattern consisted of approximately 0.2 in. (5 mm) wide black and white areas (Figure C-22). The gusset plate surface was illuminated, and the shadowing was reduced by using two photographic lights mounted behind the cameras.

Figure C-20. Digital image correlation experimental setup (a) general view, (b) plan view, and (c) elevation view (Iadicola et al. 2012)
Figure C-21. Experimental set up of the large-scale test specimen (Iadicola et al. 2012)

Figure C-22. Speckle pattern used for DIC method (a) full-filed view and (b) close up of the pattern (Iadicola et al. 2012)
As the first step, the unloaded configuration of the plate was measured using DIC and laser tracker systems. The expected accuracies of the laser tracker system are 0.0012 in. (0.03 mm) and 0.0004 in. (0.01 mm) in plane and out-of-plane, respectively. The data points or the measurement locations for both DIC and the laser tracker are shown in Figure C-23. The data from the area covered by the washers and nuts were not considered for the analysis (Figure C-23, Figure C-24). The comparison of data from these two technologies yielded the following findings.

- DIC can acquire more data points in less than 1s time compared to laser tracker which took more than 300 s to cover a similar area.
- The accuracy of the laser tracker is higher than the DIC.
- As shown in the Figure C-24, the laser tracker system can trace the edge of the plate more accurately than the DIC system. (The grey area along the edges of the DIC contour plot shows the inability of the DIC system to trace the edges accurately.)
- The DIC system tracks specific points on the surface so that the strain measurements can be derived.
- The laser tracker can be used to track the initial shape of the plate. However, it cannot track the same point repeatedly for strain measurements unless specific targets are placed on the surface.
- Both methods are capable of capturing out of plane deformations but with different accuracies.

![Figure C-23. Measurement locations for (a) DIC and (b) laser tracker (Iadicola et al. 2012)](image-url)
The second step was designed to compare the elastic strains calculated using the displacement field measurements of DIC with the results from strain gauges and the photoelastic method. Five strain gauges, with a range of measurement $\pm 2 \mu e$, were mounted on each plate. They were placed in a horizontal line at 14.8 in. (368 mm) from the bottom of the plate. Small circles on Figure C-26 depict the strain gauge locations. A stress photonics grey-field polariscope photoelastic camera was used for strain measurement on the south plate while the DIC method was implemented on the north plate. The south plate surface was prepared using a special epoxy (photoelastic material) to develop fringe patterns to calculate strains (Figure C-25).
The maximum in-plane shear strain contour plots from DIC and photoelastic methods are shown in Figure C-26. The photoelastic measurement captured only a T shaped region because the photoelastic coating was applied only within that region to view the fringes. In general, both methods were able to capture hot-spot strains and locations. Due to high resolution, the photoelastic method was able to capture the strains between the bolts (Figure C-26).

Figure C-26. Comparison of maximum in-plane shear strain of the elastically loaded connection by (a) DIC and (b) photoelastic method (Iadicola et al. 2012)

Figure C-27a shows the comparison of DIC, photoelastic, and strain gauge results. Since all the strain gauges are located in a horizontal line, DIC and photoelastic results were averaged over a 1 in. (25.4 mm) wide strip (Figure C-27b and c) for the comparison. Further, the upper and lower bounds of DIC and photoelastic results were also calculated. Two of the north rosettes failed during the experiment and recorded almost zero strains. Figure C-27a shows that the measurement of elastic strains from all three methods can be closely related within their noise levels. For an example, the noise level of DIC and photoelastic methods are around +/-150 με and +/- 50 με, respectively. Another preliminary finding from this study is the capability of the DIC system to measure a plastic strain that the photoelastic method cannot measure. However, this conclusion needs to be supported by further analysis of plate curvatures and their effect on the measured strain values.

Even though DIC technology has been extensively used for strain and displacement measurement under lab conditions (Cintron and Saouma 2008, Yang et al. 2010), field implementation has been scarcely reported (Bell et al. 2012, Yoneyama et al. 2007).
X-ray diffraction (XRD) technology is generally used for material characterization under laboratory conditions. Recent advances in the technology have allowed measuring strain in crystalline material such as steel. The strain is determined by calculating the atomic lattice spacing \( d \) using Bragg’s law presented by the \( n\lambda = 2d \sin \theta \) equation. The XRD equipment measures the wavelength of the incident x-ray \( \lambda \) and the angle of diffracted x-ray beam \( \theta \). The variable \( n \) represents the order of diffraction, and \( n=1 \) is used for first order diffraction. The XRD equipment can be equipped with multiple detectors to capture a diffracted signal to enhance the measurement accuracy. Strain is calculated using the change in lattice spacing \( d \). Then the stress is calculated by multiplying with the material modulus of elasticity. Since the
strain is calculated using the change in lattice spacing, corrections for thermal induced strains are required for accurate calculation of stresses.

Once the stresses are calculated, forces and moments can be calculated using member cross-section properties. As an example, axial force is calculated by multiplying XRD measured strain value, elastic constant of the material, and the cross-section area of the member (i.e., elastic stress multiplied by cross sectional area of the member). The member forces calculated using the XRD measured strain can be compared with the original design values to track the changes due to maintenance, repair, or other damages to the structure that might have caused redistribution of loads or change in load path. Further, this approach can also be used in critical high-stress or fatigue-sensitive areas to measure the stresses due to applied loads, fabrication tolerances, and out-of-plane deformation (distortion). Hence, the capability of the XRD equipment in measuring strain allows performing in-service dead load measurement, load path determination, crack-stop hole validation by checking the stresses around it, baseline stress measurement for enhanced structural monitoring, and residual stress measurement before and after retrofit.

The technology has been implemented in California’s Oakland Bay Bridge and New York’s Brooklyn Bridge.

C.1.15 Fatigue damage (FD) sensor and the fatigue fuse (FF)

Kujawski et al. (2011) developed the fatigue damage (FD) sensor. MFS (2014) has developed the fatigue fuse (FF). Both the FD sensor and the FF work on the same principle. Both sensors have a series of parallel metal strips (fuses) with different geometric patterns. Each fuse is designed to represent a finite and predictable fatigue life at which the respective fuse is broken. Hence, a sensor can be designed with multiple fuses, each representing a fraction of a component’s fatigue life, to detect degradation in fatigue life of a component. The sensor can be mounted at a crack tip to monitor the growth of the crack. Also, the sensor can be mounted at a remote location from the fatigue sensitive detail, and once calibrated, it can calculate the degradation of the fatigue life of the sensitive detail. At present, there is no documentation on field implementation of these sensors for monitoring fatigue life degradation at bridge details.
C.2 FUNDAMENTALS OF THE TECHNOLOGY

Review of the state-of-the-art technology and practice shows that acoustic emission (AE) is the most promising technology for development and field implementation of a remote monitoring system. In addition to AE, the electrochemical fatigue sensor has been used at experimental level as well as in limited field applications for fatigue event detection and detection of early signs of crack growth. Also, the ultrasonic guided wave technique has been used at the experimental level in remote monitoring systems to characterize fatigue cracks. Hence, the fundamentals of these three technologies, AE, EFS, and USGW are presented herein.

C.2.1 ACOUSTIC EMISSION TECHNIQUE

The acoustic emission technique is a potential NDE tool for real-time monitoring to detect and locate active fatigue damage events. AE is the development of transient elastic waves by the rapid release of energy from a localized source or sources within a material when subjected to external stress or other stimuli such as load, deformation, pressure, and temperature (Huang et al. 1998; Nair and Cai 2010; NDT 2014; FHWA 2012; Hay and Nyborg 2000). AE sensors detect elastic waves generated by plastic deformation, initiation and growth of cracks (fatigue and fracture), and slip and dislocation movements in the order of picometers (1.0 x 10^{-12} m) or smaller (Hay and Nyborg 2000; NDT 2014; FHWA 2012). AE sensors are passive and continuously listen to the sounds from active damage events. The data acquisition systems used with AE sensors can be programmed to continuously gather signals from the sensors. Since AE sensors capture stress waves generated from all the sources, it is vital to identify the noise sources and set up appropriate thresholds for the specific application. In general, the signals that exceed the threshold are used for further analysis (Nair and Cai 2010).

C.2.1.1 AE mechanisms and signal sources

Acoustic emission can be classified into two different modes: burst emission or AE event and continuous emission (Figure C-28). The burst mechanism is related to the plastic deformation mechanisms (dislocation, slipping or gliding of portions of the crystal over on another) occurring in materials at or near the yield stress. Internal or external crack growth is a phenomenon based on the separation of interatomic bonding between the materials along the crack growth path due to the externally applied loads. This may occur even before complete failure/fracture; hence, AE
emission will be an indication of an active damage event. The continuous emission may occur from external noises such as mechanical and electromagnetic interference. The mechanical noises can occur due to the rubbing or fretting of structural components. The electromagnetic interference may arise due to electrical equipment near the AE sensors. Hence, these noises need to be well understood for a particular monitoring environment and conditioning; furthermore, proper filtering techniques need to be incorporated into the system to gather useful data.

![Figure C-28. Temporal AE modes (Hay and Nyborg 2000)](image)

**C.2.1.2 Wave propagation basics for AE detection**

An AE event generates three types of elastic waves: dilatational (longitudinal waves), distortional (shear waves), and Rayleigh or surface waves (Figure C-29). In an ideal scenario, a transducer mounted on the surface typically captures these waves at different times due to difference in speed. As an example, longitudinal, shear, and surface wave speeds in steel are 19,422 ft/s (5,920 m/s), 10,663 ft/s (3,250 m/s), and 9,711 ft/s (2,960 m/s), respectively. However, during field applications, the signal detection and analysis becomes complicated due to presence of multiple AE sources, complexity of the details, and signal attenuation. The attenuation is a phenomenon that is described as the gradual reduction in signal amplitude (strength) with the distance from the source to the transducer. Signal strength may be reduced due to geometric attenuation, energy dissipation, dispersion, scattering, and diffraction. As an example, geometric attenuation can occur when the source is located near an edge or a surface. Therefore, an attenuation survey needs to be conducted to determine the optimal placement of AE sensor for monitoring a specific detail (DFT UK 2006).
C.2.1.3 AE event detection and monitoring

AE sensors are commonly made of piezoelectric material that generates electrical current due to deformations. Stress waves, which are generated within the material due to sudden energy release from a crack, generate surface deformations. These deformations are detected by the surface mounted piezoelectric sensors and converted into electrical signals (voltage) (FHWA 2012). These signals are conditioned, filtered, and recorded for further analysis. Depending on the monitoring system features, signal analysis results are presented in various formats to be useful to the intended user (Figure C-30). The AE signal parameters such as amplitude, counts, decay time, duration, energy, and rise time are extracted from a recorded signal to evaluate damage events such as the location and growth rate (Nair and Cai 2010; Parmer and Sharp 2009; Huang et al 1998).

C.2.1.4 AE source location identification and sensor layout

The location of an AE signal source can be calculated using a pre-defined sensor array network. The time difference of arrival between the received signals from two or more sensors mounted near the area of concern can be used to locate the source. The planer location can be precisely
detected using three or more sensors. However, when there is a source with continuous emission of acoustics, the time difference method cannot be adopted. In such cases, use of advanced signal analysis techniques, such as time series analysis using cross correlation, is required. The time difference of arrival can be defined based on the first threshold crossing (FTC) time and peak time (PT) depending on the material and the damage/source being monitored. For accurate location identification in complex situations, the sensor array network should be designed accordingly by combining other sensors such as strain gauges to correlate with the load matrix. The sensors can be arranged in rectangular, triangular, open-ended, and close circular arrangement depending on the complexity of the component being monitored and the sensitivity of the sensors. AE detection sensitivity is discussed in section C.2.1.7.

C.2.1.5 AE monitoring systems

AE monitoring systems can be classified as single channel systems and multi-channel systems. The basic components of these systems are shown in Figure C-31. A single channel system is preferred when a portable system is required to monitor if acoustic events are generated. The multi-channel system is used when source location measurement and data processing are required. AE sensors and instruments typically consist of integrated or external preamplifiers and external noise cancelation or filtration components to improve the signal-to-noise ratio or to filter out unwanted signals from other sources close to the damage location (Nair and Cai 2010; FHWA 2012). However, the amplification needs to be optimized to filter out the noises that are amplified simultaneously with the AE signals. The use of guard sensors just outside the area of concern can also be used for filtering emissions from outside the monitoring area. In addition to the data acquired from the AE transducers, parametric data such as strain, displacement, and temperature can also be measured with the use of other techniques. This parametric data is used for correlation with AE activities. Once the data is stored and transmitted from the job site, the signals can be further analyzed for identifying damage events such as crack initiation and growth precisely by extracting key features of the waveform or pattern.
C.2.1.6 AE transducers

The transducers or sensors are the most important elements of an AE monitoring system as they convert the mechanical energy into electrical energy (signals). The sensitivity of the monitoring system and the availability of quality data for post-processing heavily depend on the transducer. The sensing element of these transducers is made of piezoelectric material mainly composed of Lead Zirconate Titanate; hence these sensors are called piezoelectric PZT transducers or simply PZT transducers. Sensor technology is evolving, and the latest sensors are made of flexible piezoelectric sensing elements instead of the commonly used brittle ceramic sensors (Barut 2006; Yang and Fritzen 2011).

The transducer can be connected to the detail to be monitored using a couplant such as silicone, glycerin, stopcock grease, and oil to create a uniform acoustic path between the transducers and the testing material. Silicone provides temperature stability and adequate ductility to tolerate a certain degree of deformation (Hay and Nyborg 2000).

C.2.1.7 Parameters affecting AE detection sensitivity

Currently available transducers can detect AE events in the order of picometers (1.0 x 10^-12 m) or smaller. The factors affecting the transducer sensitivity are frequency, size, material, and QA/QC of the manufacturing process. The damage detection from an AE source depends on the type of transducers/sensors, number of sensors, and the sensor arrangement around the damage event source. Two types of sensors are used in AE monitoring systems: resonant or narrow-band
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and broadband (Hay and Nyborg 2000). Resonant AE sensors are commonly used due to their greater sensitivity to sources at a particular frequency. Among the other benefits of narrow-band sensors, larger spacing of sensors and minimized background noise capturing by filtration are significant. Contrarily, the broadband AE sensors have reduced sensitivity and require closer sensor spacing (DFT UK 2006). Location sensitivity can also be increased by using higher frequency sensors (DFT UK 2006). Depending on the monitoring objectives, a narrow-band and wide-band sensor integrated system may be required.

The damage event detection sensitivity also depends on the magnitude of the energy released from the damage source as well as the signal strength at the sensor location. Hence, the factors that affect signal strength are the component dimensions, exposure conditions, the path between the sources and the transducer, load or stress levels that generated the elastic waves, and the noise level that establishes the signal thresholds.

C.2.2 ELECTROCHEMICAL FATIGUE SENSORS

The Electrochemical Fatigue Sensor (EFS) was developed by Moshier and Berks (2009) based on the electrochemical working principle. Once the sensor containers are filled with the electrolyte through the fill tube and sealed, a constant voltage is applied by a Potentiostat Data Link (PDL) unit to form an electrochemical film over the monitored steel surface area by anodically polarizing the sensor to produce a DC base current in the sensor (Figure C-32). When the sensor is mounted on the tip of an actively growing crack, the DC current within the cell fluctuates, and an AC current is superimposed on the base DC current. The transient current within the cell provides information on crack growth depending on the structural material, the loading conditions, as well as the state of the fatigue damage in the structure (Phares 2007).

![Figure C-32. Electrochemical fatigue sensor configuration (FHWA 2012)](image_url)
It is necessary to mount two sensors to monitor a specific area or a crack. These two sensors, named crack measurement (CM) sensor and reference (R) sensor, are connected to a portable data logger (PDL unit) (Figure C-33). When the system is used to monitor the growth of an existing crack, the CM sensor is mounted on the crack tip while the R sensor is mounted close to the CM sensor within the same stress zone. The crack growth monitoring is calculated based on the energy ratio (ER) (FHWA 2012). This ratio is calculated taking the ratio of the areas under the frequency domain spectrum curves of the CM sensor and the R sensor. As per the manufacturer’s information, an actively growing crack is predicted by the system when the energy ratio is greater than 2.0.

Figure C-33. Configuration of a monitoring system with electrochemical fatigue sensors (FHWA 2012)

C.2.3 ULTRASONIC GUIDED WAVE ACTUATOR-SENSOR SYSTEM

Ultrasonic guided wave (USGW) technology has been experimented and implemented for damage detection in sign support structures (Zhu et al. 2010), fatigue crack monitoring of a steel bridge (Zhao et al. 2013), health monitoring of an aircraft wing (Zhao et al. 2007), and defect growth monitoring in a welded plate (Rose et al. 2008).

Ultrasonic guided waves are based on the principle of elastic wave propagation in solids. The waves are guided by the component surface boundaries or advanced algorithms. The USGW sensors come in two different configurations: (i) a packaged sensor, which consists of the pulser and receiver in the same transducer and (ii) individual transducers that work as either a pulser or receiver. When a packaged sensor is used, the emitting and receiving signals can be captured from the same surface. Otherwise, a receiver can be located at another location to capture the signal. The energy is generated by applying an AC voltage to the transducers in different
frequencies. This pulser-receiver system can be mounted on the surface of the area of concern, such as one with fatigue-sensitive details, in a pre-defined array (Figure C-34). Consequently, the data acquired from the system can be used to develop topographic images by combining every possible data acquired from the sensor combination (i.e., pair-wise comparison) of the array (Figure C-35) for fatigue event detection and damage characterization (Rose et al. 2008).

![Figure C-34. USGW sensor array configurations and computed tomography (Rose et al. 2008)](image)

The tomography approach for damage detection, growth monitoring, and location mapping can be performed by using wave speed, attenuation, and/or energy from the acquired data (Zhao et al. 2007). As an example, tomography mapping for damage location of a crack (shown in Figure C-36) was calculated from the linear summation of the signal changes of pair-wise data between sensors and the relative position of the damage to those sensors (Zhao et al. 2007). In this approach, the wave propagation pattern was assumed to have an elliptical distribution function, in which the most significant pair-wise signal change is assumed to be occurring when the
damage is located along the direct path (Figure C-37). The indirect path of the signal can occur due to reflection of the wave from discontinuities (e.g., edges and corners) in the component being monitored.

The USGW technique requires additional research in data analysis and interpretation for effective damage location detection and characterization in field applications due to complex geometries of fatigue sensitive details that lead to wave propagation in multipath, reflection or echo from the edges, wave scattering, and attenuation (Zhao et al. 2007).

Figure C-36. Damage location mapping using tomography approach with circular array of 8 USGW sensors (Zhao et al. 2007)

Figure C-37. Wave propagation distribution function (Zhao et al. 2007)