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Remote Structural Health Monitoring and Corrosion-Rate Modeling of Steel Bridges

Final Report on Project F08-AR13

Steven C. Sweeney, Richard G. Lampo, Vincent F. Hock,
and Robert B. Mason Jr.

June 2018

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Final report

Approved for public release; distribution is unlimited.

Prepared for Office of the Secretary of Defense for
 Acquisition, Technology, and Logistics (OUSD(AT&L))
 3090 Defense Pentagon
 Washington, DC 20301-3090

Under Project F08-AR13, "Remote Structural Health Monitoring and Corrosion-Rate
 Modeling of Bridges"

Abstract

The U.S. Army maintains over 200 steel bridges. Conventional bridge inspections do not always detect cracks or corrosion nor determine if a crack is growing. The Office of the Secretary of Defense's Corrosion Prevention and Control (CPC) program funds demonstration and validation of technologies that reduce corrosion and related costs. Thus, there is an urgent need to assess state-of-the-art technologies and approaches for remote structural health monitoring (SHM) of steel bridges with strategically placed sensors, reliable data acquisition, and analytical software. These components measure critical parameters and reduce risks of catastrophic failure through advance warning. This report discusses successful demonstration/validation of a novel SHM system at two bridges. The systems monitored corrosion using several types of sensors and monitoring systems that transmitted data and alerts via web-connected computers. The ROI for this project is less than breakeven (breakeven ROI=1) due to high research and development costs associated with first-of-their-kind systems. Even so, the SHM system is recommended for implementation on bridges critical for Department of Defense (DoD) use. However, standardization of SHM systems across the DoD is not recommended due to rapidly changing technology. Systems must be designed for specific applications, and each design is greatly influenced by the target structure's existing issues and concerns.

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Preface

This demonstration was performed for the Office of the Secretary of Defense under Department of Defense Corrosion Prevention and Control (CPC) Project Fo8-AR13, “Remote Structural Health Monitoring and Corrosion-Rate Modeling of Bridges.” The proponent was the U.S. Army Office of the Assistant Chief of Staff for Installation Management (ACSIM) and the stakeholder was the Army Installation Management Command (IMCOM). The technical monitors were Daniel J. Dunmire (OUSD(AT&L)), Ismael Meléndez (IMPW-FM), and Valerie D. Hines (DAIM-ODF).

The work was performed by the Materials and Structures Branch of the Facilities Division (CEERD-CFM), U.S. Army Engineer Research and Development Center-Construction Engineering Research Laboratory (ERDC-CERL), Champaign, IL. ERDC-CERL’s CPC Program Manager was Michael K. McInerney. At the time this report was published, Vicki L. Van Blaricum was Chief, CEERD-CFM; Donald K. Hicks was Chief, CEERD-CF; and Kurt Kinnevan, CEERD-CZT, was the Technical Director for Infrastructure for Combat Operations. The Deputy Director of ERDC-CERL was Dr. Kirankumar Topudurti, and the Director was Dr. Lance D. Hansen.

The following personnel are gratefully acknowledged for their assistance. For work at the Arsenal Bridge, the authors thank:

- Christian Hawkinson—Rock Island Arsenal Directorate of Public Works (DPW)
- Dana Johnson, Rock Island DPW
- R. Mike Dunne, Bridge Supervisor

For work at the Vicksburg I-20 Bridge, the authors thank:

- Vincent Chiarito and Dr. Paul Mlakar, U.S. Army ERDC
- R. Kirk Gallien P.E., P.T.O.E., Louisiana Department of Transportation
- Mitchell K. Carr, Mississippi Department of Transportation

The Commander of ERDC was COL Bryan S. Green, and the Director was Dr. David W. Pittman.

Unit Conversion Factors

Multiply	By	To Obtain
degrees Fahrenheit	$(F-32)/1.8$	degrees Celsius

(Intentionally blank.)

1 Introduction

1.1 Problem statement

The structural health of bridges has become an increasing area of concern in recent years, because the factors of structural age, aggressive environments, and increased traffic volume have all taken their toll on many bridge structures. The potential for catastrophic failure of public bridges has facilitated studies and surveys of bridge structural health that provide a grim picture. In December 2008, the U.S. Department of Transportation (DOT) reported that, of over 601,000 U.S. highway bridges in the inventory, as many as 151,000 may be either structurally deficient or functionally obsolete (Ingold 2009; Speed 2009). The situation becomes even more concerning when one considers that a number of these bridges may be fracture critical (i.e., they may contain a single component whose failure could lead to failure of the entire structure). These studies, as well as incidents such as 2007's catastrophic collapse in Minneapolis of the Interstate 35 (I-35) West Bridge over the Mississippi River, have refocused public attention upon the age and condition of bridges.

Steel bridges have become a particular concern in recent years, as metal fatigue can combine with corrosion on steel bridges to accelerate structural deterioration. These conditions have been implicated in several recent failures of steel bridges (NTSB 2008). And, of the more than 500 U.S. bridges that failed over an 11-year period, 100 were found to be due to corrosion (Ingold 2009).

The U.S. Army has over 200 steel bridges in its inventory (Ingold 2009). As with all bridges in public use, these Army bridges have seen increased utilization in recent years (one large Army bridge has an average daily traffic of 30,000 vehicles). Should one of these bridges fail due to these issues, the health, safety, cost, and readiness implications would obviously be significant.

The ability to monitor the structural health of bridges, however, is somewhat constrained by current bridge inspection practices. For example, the engineering investigation following the collapse of the I-35 bridge demon-

strated that conventional inspection techniques employed during the routine assessment of steel bridges (e.g., visual, dye penetrant, ultrasonic, and/or radiographic nondestructive testing methods) may not always detect cracks in hidden or hard-to-reach areas such as those in built-up structures (NTSB 2008). Current inspection techniques also may be unable to determine if a crack in a critical location or component is actively growing. Sensors and sensing systems could alleviate all of these issues, but these systems are not currently in widespread use for the structural monitoring of bridges.

In view of this information, there is an urgent need to examine and assess the latest state-of-the-art technologies and approaches to the remote monitoring of the degradation of steel bridges by means of strategically positioned sensors, reliable data acquisition systems, and advanced analytical software. This type of monitoring system should greatly reduce the risk of a catastrophic failure by providing advance warning of a growing structural problem caused by corrosion/materials degradation, with an opportunity for repair before catastrophic failure that would likely result in significant economic and human costs such as the 2017 collapse of I-35W Mississippi River Bridge in Minneapolis, Minnesota, in which 13 people died and 145 people were injured (detailed in Section 4.2.1).

1.2 Objective

The objectives of this project are to demonstrate and validate state-of-the-art and emerging innovative technology approaches for possible use by the DoD for the remote structural health and corrosion degradation monitoring of steel bridges.

1.3 Approach

Under this effort, innovative structural health monitoring (SHM) systems were designed, installed, and demonstrated/validated on two existing steel bridges that span the Mississippi River: (1) the Government Bridge at Rock Island Arsenal, Rock Island, IL, * and (2) the Interstate 20 (I-20) Mississippi River Bridge between Mississippi and Louisiana. These SHM systems employed a variety of sensors which, when installed on the subject bridges, simultaneously and remotely measured such critical parameters

* In this report, the Government Bridge is referred to as the Arsenal Bridge, as it is commonly called.

as corrosion rate, strain, vibration, tilt, and acoustic emissions. Sensor selection was based on the specific needs of each bridge, and the bridges' requirements, parameters, and locations were confirmed through structural analyses. All sensors were integrated into a single control system at each bridge for recording data, performing condition assessment analysis, receiving programming, and transmitting data and alerts to/from an internet-accessible computer.

The Arsenal Bridge (Figure 1) was built in 1896, making it one of the oldest in the Army inventory (Jackson 1988) and a vital access route to the Rock Island Arsenal. A steel-truss structure with two decks, it incorporates a swing section to accommodate river vessel traffic. At the time of demonstration, loading included over 18,000 vehicles per day (lower deck) and approximately three trains per day (upper deck) (Weeks 2008a).

Figure 1. Arsenal Bridge, Rock Island, IL.

The I-20 Bridge opened to traffic in 1973. Like the Arsenal Bridge, it is also a steel truss through-deck structure (Figure 2). Bridge traffic consists of over 28,000 vehicles per day (Weeks 2008b).

Figure 2. Interstate 20 Bridge, Vicksburg, MS (looking west).

The maintaining organizations for the I-20 Bridge have performed work in recent years to compensate for westward movement of bridge piers E-1 and E-2 (Figure 3) on the east side. The piers' movement is due to an active geological fault running along the river near the east bank. It is noted that the span between piers E-1 and E-2 has two expansion joints, each located approximately one quarter of the span length.

Figure 3. Interstate 20 bridge elevation, looking north (Louisiana Department of Transportation and Development).

Due to the advanced nature of SHM system technology, it is not addressed currently or specifically by government or industry standards or specifications. However, some commonly used corrosion standards were employed for corrosion test coupons that were installed as part of the system, and software should conform to IEEE 12207, “Systems and Software Engineering: Software Life Cycle Processes.” The Institute of Electrical and Electronics Engineers (IEEE) standard establishes a common framework for software life-cycle processes.

1.4 Metrics

To measure corrosion rate data as compared to ASTM Standards, one corrosion test coupon rack was installed, along with the SHM system, on the Arsenal Bridge. The rack was removed every three months and analyzed for mass loss in accordance with ASTM Standard G11 (1999) and for chlorides in accordance with ASTM B825 (2002). The purpose of the test rack was to determine the corrosivity of the site and to correlate this with corrosion sensors that were being installed.

In a workshop held by ERDC-CERL at the beginning of this project, several characteristics of a successful SHM system were identified and are listed below as project metrics:

- Monitor the most critical section of each bridge structure.
- Operate in all environments and situations (e.g., while the swing span of the Arsenal Bridge is operating).
- Remain robust and durable.
- Consume low power.
- Require low maintenance.
- Report immediate and useful information if an accident should occur on the bridge or between the bridge and river traffic.

The various technologies used in this project had varied success at meeting some or all of the above metrics; more discussion is presented in Section 3.1.4.

Chapter 4 discusses all first costs of the system and cost avoidance as compared with the current costs. Several cost-related aspects were discussed. Cost information related to bridge inspection was sought from the relevant authorities for both bridges that included, but is not limited to, the following:

- Typical cost of inspection.
- Frequency of inspection.
- Manpower used for inspection.
- Equipment used for inspection.
- Duration of inspection.
- Frequency of inspection.
- Cost of shutting bridge down for inspection and/or repairs, as applicable.

All available data and facts related to the SHM system installation were gathered that included, but were not limited to, the following:

- Actual costs and quantities of material used during installation.
- Costs of equipment and mobilization for installation (and one year of monitoring, if needed).
- Operating costs, including electrical power, during one year of monitoring.
- Actual person hours by trade required to install and maintain the SHM system.

Data was collected related to cost avoided by utilizing the SHM system. These costs included, but are not limited to, the following:

- Reduced maintenance in both labor and materials costs related to using the system to pinpoint exact areas that require attention.
- Savings related to using the system to monitor the structure remotely instead of having inspection personnel do so on site.
- Savings related to avoidance and/or reduction of bridge shutdowns to affect critical repairs.
- Savings related to avoidance of bridge structural failure.

1.5 Scope

The initial project proposed installing a small SHM system on a composite bridge being constructed at Fort Bragg, South Carolina. After the 1 August 2007 collapse of the I-35W bridge in Minneapolis, Minnesota, significant interest was generated for SHM of steel bridges. Thus, the scope of the project was expanded to develop and implement an SHM system to monitor—in real time—the performance of a steel bridge structure. The goal was to be able to identify immediate problems that might occur as well as to detect long-term degradation that might impact bridge performance and bridge safety.

2 Technical Investigation

2.1 Technology overview

The following sections detail the SHM system design and bridge-specific design information.

2.1.1 SHM system description

SHM system design incorporated the following criteria:

- monitor the most critical section of each bridge structure
- operate in all environments and situations (e.g., while the swing span of the Arsenal bridge is operating)
- remain robust and durable
- consume low power
- require low maintenance

The key sensors and other components of both demonstrated SHM systems are listed below:

- corrosion test rack
- fiber Bragg grating (FBG) technology in
 - accelerometers
 - strain sensors
 - tilt sensors
 - displacement sensors

The Arsenal Bridge also included the following:

- acoustic emission sensors
- experimental corrosion sensor

the i-20 bridge also included the following:

- video capture technology
- weather station
- FBG security sensor at computer cabinet

These components are described, and their purposes are explained in Appendix B. The components were integrated into two unified, application-specific, interactive systems. Sensors were located along the bridges and linked as a system using an unobtrusive single-trunk design in which cabling from all sensors emanate from a single large bundle running the length of the bridge. This design greatly reduced the amount of cabling needed and took advantage of the long-distance data-transmission capabilities of fiber Bragg grating technology (see Appendix B). Figure 4 shows a conceptual diagram of the SHM system as applied to a generic bridge.

Figure 4. Conceptual diagram of SHM system installation on an example, generic bridge structure.

2.1.2 Bridge-specific design assumptions

The following assumptions and conditions were considered during the design of the bridge-specific SHM systems:

- The placement of sensors, as previously mentioned, was critical. The sensors had to be placed in such a way as to monitor potential issues at key areas (e.g., corrosion sensors had to be placed in corrosion-prone areas, such as the torrent and floor panels). Placement was less of an issue with the acoustic emission sensors for the Arsenal Bridge, which monitored entire areas (see Section 2.2.2.1).
- The SHM system on the Arsenal Bridge was designed to operate while the swing span is in any operating position as well as while the swing span is in motion.
- All sensors had to be robust and durable such that they remained calibrated and functional throughout the wide outdoor temperature swings experienced by the both bridges. Both SHM systems had to be able to translate the data into a simple graphical user interface (see Section 2.3), that can be quickly and easily interpreted by inspectors and/or engineers.

- Additional sensors (possibly two or three strain gauges) were useful to determine railroad and highway floor beam stress levels, since some of these beams are fracture-critical members.

In a functional system, the sensors must work together to describe a potential or actual structural event in real time. The project team drafted a matrix indicating how each type of sensor might react for a given event. A number of possible events were considered using hypothetical readings or measurements to which the system would respond. The matrix helped the project team and stakeholders to understand how the system components would interact in various scenarios. The matrix is shown in Figure 5.

Figure 5. SHM system scenarios and sensor matrix.

Bridge Structural Health Monitoring System Scenarios and Sensors Matrix									
Scenarios	Corrosion Sensors	FBD Strain Sensors	FBG Temperature Sensors	Deflection/ Displacement Sensors	Acoustic Emissions Sensors	Tilt Meters	Camera system	Water Level Gage	Accelerometers
Accident on bridge with damage to truss	No	Yes (DES-1)	Maybe	Yes (DES-2)	Maybe	Maybe	Yes	No	Yes
Bridge overload - high strain	Maybe	Yes	No	Yes	Maybe	Maybe	Yes	Maybe	No
Creep of Bridge Structure	Maybe	Yes (A)	No	Yes (A)	No	Maybe	Yes	No	No
Excess deflection	Maybe	Yes	Maybe	Yes (DES-3)	Maybe	Maybe	Yes	Maybe	Yes
Extreme corrosion - reduced cross section	Yes (DES-4)	Yes (DES-5)	No	Maybe	No	Maybe	Yes (DES-6)	No	Maybe (DES-7)
Extreme temperature due to fire on bridge	No	Maybe (DES-8)	Yes	Maybe	No	No	Yes	No	Maybe (DES-9)
High water condition	No	No	No	No	No	No	No	Yes	No
Lightning	Maybe	No	No	Maybe	Maybe	Maybe	Maybe	Maybe	Maybe
Loss of any individual signal	Maybe	Maybe	Maybe	Maybe	Maybe	Maybe	Maybe	Maybe	Maybe
Natural Frequency Shift of Bridge Structure	Maybe (DES-10)	Maybe (DES-11)	Maybe (DES-11)	Maybe	Maybe	Maybe	Yes (DES-12)	Maybe (DES-13)	Yes (DES-14)
Pier Rotation	No	Maybe	No	Maybe	Maybe	Yes	Yes	Maybe	Yes (DES-15)
Seismic Activity	No	Yes (DES-16)	No	Maybe	Maybe	Yes	No	Maybe	Yes
Structural crack growth	Maybe	Maybe	No	Maybe	Yes (DES-17)	Maybe	Yes	Maybe	No
Train accident/derailed	No	Yes (DES-18)	No	Maybe	Maybe	Maybe	Yes	No	Yes
Total System Failure (DES-19)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Yes = Event will affect sensor									
Maybe = Might affect sensor, depending on circumstances and hardware									
No = Unlikely to affect sensor									
Footnote (A) - System performance would need to be tracked using a run chart and program logic to check for trends or shifts in data.									
DES-1: If the accident damages the truss, some indication should be given in at least one of the sensors, most likely more than 1									
DES-2: It should be likely that a displacement sensor somewhere would register an accident causing damage to the truss									
DES-3: Would this depend on the location of the excess deflection compared with sensors--might be Maybe									
DES-4: It seems that the "Yes" should be restricted to members that are being monitored for corrosion									
DES-5: Strain sensors mounted on corroded members or around corroded members in a parallel resistance situation should respond									
DES-6: This is an unconditional "yes." But, how will the camera system react to a corroded member unless the corroded member can be seen by the camera?									
DES-7: A corroded member could change the member stiffness which should be detectable as a frequency shift if not confused with a thermal change									
DES-8: Presumably, a strain sensor would react to a fire because of thermal expansion effects from increased member temperatures from the fire.									
DES-9: Thermal expansion effects from a fire could be sufficient to change member length and the effects of fire on steel may also change the stiffness so that frequencies may change									
DES-10: See DES-7									
DES-11: If a frequency shift can be created by thermal expansion, strain and temperature sensors could detect a frequency shift									
DES-12: It is not clear to me how a camera can detect small changes in natural frequency unless it is very high speed (many, many fps)									
DES-13: While rare, if a fundamental mode involves pier movement, then water level could affect that modal frequency since a change in water level changes the water mass that moves with the pier									
DES-14: An accelerometer should detect a frequency shift, particularly the first mode unless it is mounted at a point that is a modal node									
DES-15: If acceleration records can be integrated twice with respect to time, accelerometers can show pier movements									
DES-16: Strain sensors that can read dynamic strains should show strains due to seismic activity									
DES-17: Installing crack monitoring sensors after a crack initiation has been found can also provide a quantitative measure of crack growth									
DES-18: Strain sensors recording dynamic strains should detect impact/dynamic responses to a train accident or derailment									
DES-19: Not sure what total system failure means, all sensors or the data processing/collection system or all of the above. If everything goes black will we know why?									

2.2 Field work

2.2.1 Structural evaluation

Before initiating a specific design for each of the bridges, a structural evaluation was necessary to establish the current structural health of each

bridge, identify any potential issues, and determine any critical failure points, load paths, etc. The evaluation's results were also used to identify the best available locations for sensor placement. To accomplish this, structural engineers evaluated both bridges based on 3D finite element models. In addition, bridge inspection and maintenance reports were reviewed. For full reports of these analyses, see Appendix A.

2.2.2 Installation of sensors and exposure coupons

2.2.2.1 Arsenal Bridge

During the first year of this effort, the Arsenal Bridge was outfitted with its SHM system. Span II of the Arsenal Bridge—the swing span—was instrumented and monitored. The overall intent of the SHM system on this bridge was to monitor corrosion and to detect existing structural irregularities and changes in the bridge over time. Monitored parameters included peak accelerations by using accelerometers; strain response by using strain gauges; acoustic emissions by using ultrasonic sensors; and corrosion activity by using both electrical resistance (ER sensors) and exposure coupons.

Experimental corrosion sensors from the Cooperative Research Centre for Integrated Engineering Asset Management (CIEAM) of Brisbane, Australia, were installed on the Arsenal Bridge by CIEAM personnel in December 2009. Due to a number of sensor communication issues, the corrosion sensors were eventually removed from the Arsenal Bridge and returned to CIEAM. The issues are summarized in the monitoring contractor's final report, found in Appendix F of this report. The sensors were replaced with COTS ER corrosion sensors, which performed acceptably throughout the monitoring period.

2.2.2.2 I-20 Bridge

Under the second year of this effort, the I-20 Bridge was outfitted with its purpose-designed SHM system. This bridge has experienced westward movement of bridge piers E-1 and E-2 on the east side of the main river navigational channel. The purpose of this SHM system was to monitor previous movement of piers E-1 and E-2 (refer to Figure 3) and distress to structural members on the bridge structure, while also assessing the overall condition of the span across the navigation channel between piers E-1 and W-1. The main parameters monitored were as follows: movement at

piers and expansion joints by using tiltmeters and displacement gauges; stresses in bridge superstructure by using strain gauges; peak accelerations by using accelerometers; and corrosion by using both ER sensors and exposure coupons.

2.3 SHM interface and controls

The basic layout of the Arsenal Bridge SHM system data interface is presented in Figure 6.

Figure 6. Arsenal Bridge SHM system data interface.

The basic layout of the I-20 Bridge SHM system data interface is presented in Figure 7.

Figure 7. I-20 Bridge SHM system data interface.

The SHM control system provides data integration, analysis, and output for all sensors incorporated into the sensor system. The control system consists of two major components: (1) a data recorder and analysis system located on each bridge for recording and performing the analysis, and (2) a remote computer which can store data, perform additional analyses, send alerts via e-mail and telephone, and serve as a web-based access portal for visualizing the data and generating reports.

The SHM software is developed from the IntelOptics™ software platform and consists of a graphic user interface (GUI) that is compatible with the Windows® operating system. The software records and archives data provide real-time graphical presentation of data in an innovative “color code” system. Rather than providing a data readout that must be interpreted and understood before action can be taken, the system shows an image of the monitored structure overlaid with a color code (green, yellow, or red) for each sensor. In this way, the software performs real time analysis of the

structure for the purpose of detecting potential problems or safety concerns. The system allows two-way communication between the data recorder and analysis system on each bridge and the remote computer such that programming and querying of instrumentation may be performed remotely. If any sensor area maintains a yellow/red status or if an actual event is detected, the system will automatically transmit warnings to designated personnel via e-mail and cell phone, so that data can be reviewed and an appropriate response can be quickly determined. Data for both the SHM systems are accessed via the Chandler Monitoring Systems website. After the user's ID and password are entered, the user is brought to a summary screen, showing the output of all sensors (Figure 8).

Other screens provide the readings from specific sensors in each of the four zones. The sensor placement in each of the sectors was selected from optimum placements derived from the engineering analysis (see Appendix A). The screenshot in Figure 9 shows the sensor readout by zone.

Figure 8. Arsenal Bridge SHM system's summary screen.

Figure 10. Arsenal Bridge SHM system report screen.

Figure 11. Typical data readout from a zone.

Figure 12. Arsenal Bridge SHM system corrosion readout screen.

Figure 13. Arsenal Bridge SHM system acoustic emission readout screen.

3 Discussion

3.1 Results

The installation of the Arsenal Bridge SHM system was completed in December 2009. It was necessary to return to the bridge in January 2010 to resolve communication issues related to the CIEAM corrosion sensors and return again in May 2010 to install alternative corrosion sensors (Section 3.2.3).

The installation of the I-20 Bridge SHM system was completed in November 2010. The system was revisited several times during the subsequent one-year monitoring period to affect updates and repairs.

3.1.1 Data reports

One full year of SHM data were reported for the I-20 Bridge, and two years of SHM data were reported for the Arsenal Bridge during the performance period. Typical data for the Arsenal Bridge SHM system is presented in Figure 14–Figure 17.

Figure 14. Arsenal Bridge SHM system, typical data from optical accelerometers.

Figure 15. Arsenal Bridge SHM system, typical data from optical strain sensors.

Figure 16. Arsenal Bridge SHM system, typical data from optical strain sensors.

Figure 17. Arsenal Bridge SHM system, typical data from acoustic emission sensors.

Typical data for the I-20 Bridge SHM system is presented in Figure 18–Figure 20.

Figure 18. I-20 Bridge SHM system, typical data from optical strain sensors.

Figure 19. I-20 Bridge SHM system, typical data from weather station.

OPTICAL SENSORS SUMMARY ZONES ADVANCED SETTINGS REPORTS REPORT OUTPUT DISCUSSION BOARD WEATHER STATION CAMERA CORROSION

POWER SECURITY IMAGE GALLERY DATA STREAM

Vicksburg I-20 Bridge
Vicksburg, Mississippi

IntelliOptics™ Weather Station

Barometric Trend: 0.812

Parameter	Value	High	Time	Low	Time	Average	Rate	Rate Hi	Time	Rate Lo	Time
Wind Direction	W	359.00	12:36am	1.00	3:18am	263.85	8.1	258.0	2:15am	-127.0	9:29am
Wind Speed	13	17	12:29pm	8	5:29am	10	2.4	11.3	1:52am	-6.1	12:32pm
Gust	17	17	12:29pm	8	5:22am	13	4.4	16.6	1:48am	-6.5	4:51am
In Humidity	0	0	12:00am	0	12:00am	0	0.0	0.0	12:00am	0.0	12:00am
Out Humidity	85	85	7:28am	62	9:34am	67	-1.9	7.6	12:34am	-12.2	8:34am
In Temp	17.78	17.78	12:00am	17.78	12:00am	17.78	0.00	0.00	12:00am	0.00	12:00am
Out Temp	14.70	14.70	12:03pm	2.50	1:05am	11.07	1.63	4.33	9:34am	-1.90	12:33am
Barometer	757.76	760.38	12:00am	757.76	12:53pm	758.96	-0.812	0.390	10:00am	-0.858	12:50pm
Rain	831.31	831.31	12:00am	831.31	12:00am	831.30	0.000	0.000	12:00am	0.000	12:55pm
Ch 1 Temp	0.00	0.00	12:00am	0.00	12:00am	0.00	0.00	0.00	12:00am	0.00	12:00am
Ch 1 Hum	0	0	12:00am	0	12:00am	0	0.0	0.0	12:00am	0.0	12:00am
Ch 2 Temp	0.00	0.00	12:00am	0.00	12:00am	0.00	0.00	0.00	12:00am	0.00	12:00am
Ch 2 Hum	0	0	12:00am	0	12:00am	0	0.0	0.0	12:00am	0.0	12:00am
Ch 3 Temp	0.00	0.00	12:00am	0.00	12:00am	0.00	0.00	0.00	12:00am	0.00	12:00am
Ch 3 Hum	0	0	12:00am	0	12:00am	0	0.0	0.0	12:00am	0.0	12:00am
ET	0.81	0.81	12:00pm	0.00	12:00am	0.54	0.271	0.875	12:00pm	-0.520	12:00am
UV Index	13.51	13.34	1:20am	13.50	12:49pm	13.99	-0.0	0.0	1:20am	-0.1	9:29am
Solar	858.6	735.6	10:51am	0.0	12:00am	584.0	74.0	473.2	10:40am	-440.1	12:32pm
Wind Chill	13.95	14.08	12:41pm	0.21	12:54am	12.35	1.00	4.80	9:34am	-3.92	12:50am
Air Heat Index	-19.01	-19.01	12:00am	-19.01	12:00am	-19.01	0.00	0.00	12:00am	0.00	12:00am
Heat Index	16.02	16.00	12:53pm	4.73	1:05am	14.53	1.51	3.52	9:34am	-1.44	12:30am
Dew Point	8.20	8.35	12:53pm	-1.90	12:29am	7.13	1.13	1.90	9:22am	-0.51	12:29am
Baron Sea-level	758.91	761.53	12:00am	758.91	12:53pm	759.71	-0.812	0.390	10:00am	-0.858	12:50pm
Parameter	Month High	Date	Month Low	Date	Year High	Date	Year Low	Date	Yesterday High	Yesterday Low	24 Hour Difference

Figure 20. I-20 Bridge SHM system, camera shot.

OPTICAL SENSORS SUMMARY ZONES ADVANCED SETTINGS REPORTS REPORT OUTPUT DISCUSSION BOARD WEATHER STATION CAMERA CORROSION

POWER SECURITY IMAGE GALLERY DATA STREAM

Camera 1 Camera 2 Camera 3

IntelliOptics™

auto

Set 1 2 3 4 5 6

Digital I/O

Input 1 Input 2 Input 3 Input 4 Relay 1

System log

29.12.2011 09:32:39 MPEG ActiveX
Version: 4.27 - Register UDP: 1756

Event log

MPEG-4 Stream 1 MPEG-4 Stream 2 M-JPEG

Typical raw acoustic emission sensor data are presented in Appendix D of this report. When processed, the processed acoustic emission data are shown as a green, yellow, or red dot depending on the data's severity (with green indicating no cracking and red indicating a potential issue), as seen in Figure 21.

Figure 21. Processed acoustic emission sensor data.

Sensor positions are shown as numbered crosses. The data can be put onto a picture, so that the processed acoustic emission data can be superimposed on a 2D picture of the trusses or on a 3D drawing of the bridge, as shown in Figure 21. Each green, yellow, or red dot is an acoustic emission event location whose color shows its severity. Each event has coordinates, time of occurrence, and severity information associated with it.

The final data derived from the corrosion coupons installed at the two bridges is presented in Figure 22. The environments at both bridges were judged to be mild (compared to similar structures and materials at various sites worldwide). Of the two bridges, the I-20 Bridge was found to be the more corrosive site. The full report of corrosion data can be found in Appendix F of this report.

Figure 22. Summary of response of passive corrosion coupons at the two bridges.

3.1.2 SHM system performance during I-20 bridge barge impact

The I-20 Bridge SHM system was demonstrated during an actual event on Wednesday, 23 March 2011, which was several months after the SHM system had been installed on the I-20 Bridge. A barge hit the railroad bridge adjacent to the I-20 Bridge about 3:30 pm EST. A large piece of the barge split off and hit the E1 Pier (refer to diagram in Figure 3). At the time, the I-20 Bridge authority at the Louisiana DOT and all of his inspectors were in training at a facility two hours away. Naturally the DOT sent engineers to inspect the bridge, but they also were able to use the SHM system while enroute to direct engineers when they arrived to specific points of concern, based on the sensor data and camera shots. In this case, the SHM system greatly enhanced the efficiency and effectiveness of the DOT personnel who responded to this incident.

Furthermore, when the piece of the barge that hit E1 hung up on the pier and had to be removed, DOT personnel were able to remotely monitor efforts to remove the barge by utilizing the output of the SHM's cameras.

3.1.3 SHM system performance for Arsenal Bridge

The Arsenal Bridge SHM system had multiple issues with both installation and performance, which are discussed in the lessons learned (Section 3.2). The overall issue is that the system required more attention and maintenance than was intended. This was in part due to the significant mixing of sensor technologies that complicated the system architecture. One unfortunate incident involved a Trojan virus that was able to attack the system. The system had to be wiped and reloaded to resolve the problem.

3.1.4 Metrics

Five characteristics of a successful SHM system were presented in Section 1.4. To review, the system should (1) monitor the most critical section of each bridge structure, (2) operate in all environments and situations (e.g., while the swing span of the Arsenal Bridge is operating), (3) be robust and durable, (4) consume low power, and (5) require low maintenance. Each of these is discussed below.

3.1.4.1 Monitoring sections

Monitoring critical sections of each bridge was determined by engineering analysis of the structures. While it is impossible to know in advance how and where a properly designed structure might fail, critical sections were monitored and sensors were distributed to detect movement or change in structural behavior.

3.1.4.2 System operation

The systems generally performed well in their operational environments. One significant problem occurred with communications on the swing span of the Government Bridge. No hard line communications existed to this span. Computer connectivity was provided via a wireless modem located in the shop at the base of the structure and an antenna placed on the swing span connected to the SHM system. Because the bridge could swing 180 degrees, antenna placement could not be optimized so communications were sometimes interrupted. No data was ever lost, and data was transferred whenever communications were reestablished. The only negative

aspect of this was the loss of immediate notification if a critical event occurred. No other environmental issues were identified with either installation. The acoustic emission sensor system for crack detection installed on the Government Bridge never was successfully developed to achieve the intended objectives. Issues with environmental noise and the wide distribution of sensors could not be overcome adequately within the limitation of this effort.

3.1.4.3 Robustness and durability; low maintenance

The issues of robustness and durability are directly related to requiring low maintenance. In these areas, some issues were identified. The initial corrosion sensor system used on the Government Bridge never functioned properly. The issue was determined to relate to the wireless communication system incorporated in the sensor system and not to the sensors themselves; however, the sensor system was replaced with a COTS system. The fiber-optic sensors and system performed very well throughout the project. Two sensors had to be replaced due to corrosion that occurred within the sensor. This corrosion was attributed to the adverse environmental conditions at the time of installation that caused moisture to be trapped within the sealed sensor. These sensors were easily replaced. Insufficient virus protection of the computer system also resulted in the need to upgrade protection and reset the system due to malware intrusion.

3.1.4.4 Low power

The low power requirements issue was indirectly addressed through the primary use of fiber optic sensors. These sensors do not require an external power source, so their use greatly simplify installation and reliability.

3.2 Lessons learned

Lessons learned during the course of this project were numerous, and related to site selection, installation of the sensor system, and interfacing with the system. Issues related to these items, as well as access equipment, data transmission, and sensor integration, were encountered and resolved through constant interaction with stakeholders (primarily the relevant bridge authorities). Finally, the need for alternative power sources and updated antivirus protection, as well as security measures such as bulletproof casings for the cameras, was also found to be very important.

3.2.1 Site selection

3.2.1.1 Know and prepare for potential delays

It was found to be important for the team installing the SHM to take into account and prepare for any and all types of potential delays inherent to the site (weather, trains, equipment delivery, etc.) and to report expected delays as soon as possible. One example of an unanticipated delay was the need for the Arsenal Bridge to open and close for trains and barges during the day. It is noted that, due to the nature of these delays, a partial closure of the Arsenal Bridge (for a few days of the week or on weekends) would have significantly reduced the elapsed time and labor-hours spent on installing the SHM.

3.2.1.2 Establish and maintain traffic control

Establishing and maintaining traffic control at all times is a lesson to be learned during any bridge maintenance or installation procedure, but that control was particularly important for the Arsenal Bridge SHM installation. Access to the Arsenal Bridge was extremely limited because the team only had partial access in 24-hour period (from 9 p.m. to 4:30 a.m.) and although the bridge was closed to traffic during the stated hours, the bridge remained open to trains, which the team was expected to work around with sufficient warning given. After learning the lesson of establishing traffic control at the Arsenal Bridge, the team made an effort to proactively seek support from the proper authorities versed for the I-20 Bridge SHM system installation.

3.2.1.3 Consider site's climate

An important lesson was learned about considering a site's local climate when installing the SHM system. Inclement weather (largely influenced by the time of year in which installation occurs) severely impacted the installation schedule for the Arsenal Bridge installation. The Arsenal Bridge installation was originally scheduled for August/September 2009. However, the project was modified to include additional sensors, and the approvals for the modifications delayed the installation to November/December 2009. As a result of the delay and the bridge's northern Illinois location, the team was required to work in freezing rain, sleet, high winds, and extremely cold conditions. The severe weather conditions resulted in the SHM's installation taking longer than originally proposed because there

were seven days in which the team could only work periodically and four days in which they could not work at all.

3.2.2 Technology selection

Because of the high research component of this project, multiple sensor types were selected that could provide useful information on the bridge performance. These varying sensor types required a very complex data acquisition and analysis architecture. In future installations, the sensor systems should be designed to minimize these complexities and simplify the system architecture. The specific sensor systems selected will be dependent on what is determined to be the critical condition to be monitored.

3.2.3 Technology installation

3.2.3.1 Install equipment in areas inaccessible to public; communicate locations to vendors

The most important lesson learned for installing a SHM system's technology was having all equipment and sensors placed in areas on the bridge that are inaccessible to both the public and non-DOT bridge maintenance personnel (e.g., painting contractors) for prevention of theft and/or vandalism. A need for this lesson became apparent in August 2012, when the SHM team returned to the Arsenal Bridge to complete repairs and perform a final inspection of the system. At that time, they discovered that major portions of the system, including sensors and wiring, had been damaged and/or removed from the bridge structure. It was theorized that painting contractors caused this damage during the course of cleaning and painting the bridge. As a result, the system was not fully operational at the end of the contract and could not be turned over to the Directorate of Public Works (DPW). Thus it is essential that sensors and cabling be concealed on the bridge structure, and that other contractors be made aware of the system. In addition, all equipment should be hardened (e.g., bulletproof casings for cameras) to prevent vandalism. This lesson applied to both bridges.

3.2.3.2 Consider physical environment, operation, and type of bridge

Another lesson learned was to consider the physical operation and type of bridge before attempting to install technology. An example is the necessity to find an alternative means to transmit the data from the Arsenal Bridge to the web portal. A traditional hard computer line could not be installed

on the Arsenal Bridge to transfer data, due to the fact the monitored span must remain free to swing on this style of bridge. It was originally envisioned to place a satellite dish on top of the monitoring station located at the top center of the bridge. Instead, wireless transmission of data had to take place. Although first seeming to be promising, satellite dish transmission methodology could not be realized. The dish could not be placed near power lines, and the lockmaster at the Arsenal Bridge told the team during the system installation that a satellite dish could not be placed on the lock island. Originally, cell cards were placed in the acoustic emission and optical equipment, providing two sources to feed needed data remotely. Due to the slow transfer of data, various software changes needed to be made, and those changes somewhat compromised the originally intended performance of the system. Specifically, the rate at which the data was streamed to the server had to be reduced to accommodate the slower acquisition speed. In addition, a different type of virtual network communication (VNC) had to be used. Finally, a digital subscriber line (DSL) was installed to facilitate improved data transmission from the Arsenal Bridge SHM system. Data interruptions still occurred in this configuration, as there was no ideal location for the system antenna due to the rotation aspect of the bridge and the bridge's ability to lock in place with the stairs in either the upstream or downstream position. Still, with the DSL configuration, the system can be easily upgraded as communication technology advances.

3.2.3.3 Establish contact with bridge authorities

Another lesson learned was that proactive contact with bridge authorities will minimize delays, optimize installation time, and even alleviate some safety concerns. For example, Louisiana DOT personnel quickly responded to a problem on the I-20 Bridge by implementing more safety controls when workers reported that large trucks occasionally were ignoring reduced-speed warning signage. This constant interaction optimizes the time spent during the installation and also helps to ensure the safety of the installation crew.

3.2.4 Access equipment

3.2.4.1 Monitor rental equipment

Use of any rented access equipment must be monitored at all times, with no unauthorized use by personnel other than the installation team. Issues with rental equipment led to train and road traffic delays and problems on

the road below the embankment. The team must ensure that the rental company for any access equipment has spare parts and repair personnel readily available. Lessons learned from the Arsenal Bridge installation were applied to the I-20 Bridge SHM system installation, and no issues were encountered there.

3.2.4.2 Find alternative data transmission

The team found it valuable to have an alternative means of data transmission available, if feasible and affordable. As mentioned in Section 3.2.3.2, a satellite dish could not be placed on the Arsenal Bridge, and it was decided to place cell cards in both the acoustic emission and optical equipment, providing two sources to feed needed data remotely. Due to the slow transfer of data, various software changes needed to be made. For example, the team adapted the software from polling information remotely to streaming information. Doing this enabled cell communications to perform in a manner more suitable for the SHM system (but yet compromised as compared to the original satellite dish configuration described in Section 3.2.3.2).

3.2.4.3 Validate sensors independently

Finally, the correct installation of all sensors needs to be validated independently during installation. The displacement gauges on the expansion joints of the I-20 Bridge functioned properly throughout the evaluation period, but the software interpreted the data in a way that made the data look “backwards.” Thorough, unbiased checks should be made to the data and ensure that the system is working properly.

3.2.5 Operational lessons

3.2.5.1 Communicate frequently with contractors and vendors

To keep abreast of the team’s progress during the installation of the system on the Arsenal Bridge, daily teleconferences were conducted. These teleconferences were required to be held biweekly in the contract, but contractor Concurrent Technologies Corp. (CTC) exceeded this requirement by holding teleconferences on a daily basis (including weekends). The daily teleconferences were found to be very helpful to stakeholders, by providing input on the progress of the installation team as well as resolving issues in a timely fashion.

When a number of different sensors are integrated into a singular system, vendors should provide the system integrator with as much information and support as possible. The original corrosion sensors were prototypes and did not initially perform as expected. While the first units received by the team worked as expected, the final prototypes to be installed on the Arsenal Bridge would not transmit the data successfully and eventually had to be removed. Similarly, the acoustic emissions sensors also demonstrated limited applicability for the overall SHM system. While the sensors did indicate areas of concern, the related alarms have yet to be independently validated in terms of degree of damage severity being indicated. Validation was not possible due to data-transmission problems from the bridge and various difficulties with integrating the alarms into the SHM software.

3.2.5.2 Utilize back-up power sources

Back-up power sources should be utilized wherever possible. The I-20 Bridge SHM sensor system shut off numerous times when it was first installed, due to a failing transformer on the bridge. The use of alternative power sources (specifically solar power and battery backup), as well as installing automating power rest switches and replacing the transformer, resolved the issue.

3.2.5.3 Install and update software protection

Finally, it was confirmed that system operators must be diligent in seeing that any SHM software must utilize the best available protection against viruses, adware, malware, etc., and this virus protection must be updated frequently.

4 Economic Analysis

4.1 Costs and assumptions

The cost of this project for both bridges was \$1,706,625. It is not possible to completely break out the costs between the two structures, so the ROI is computed considering both bridges equally.

The following assumptions were made for both bridges:

- Inspections performed on each bridge every two years, costing \$205,000 in total (based on information for the Arsenal Bridge).
- With the SHM system in place, inspection times would be reduced, resulting in inspection costs of \$123,000.

As seen when the barge impacted the I-20 bridge, the SHM system proved beneficial in monitoring the bridge during an incident, thereby reducing the closure time required. It is assumed that between these two bridges, one such event would happen on average every 5 years, with a SHM system reducing bridge closure by 3 days for each event. The cost of closure per day is assumed to be \$61,432 based on Example Problem Three of the New Jersey Department of Transportation Road User Cost Manual (NJ DOT 2001), which assumes 22,000 vehicles per day and a 9-mile detour.

4.2 Projected return on investment (ROI)

Using the above assumptions, the ROI was calculated in accordance with OMB Circular A-94 (OMB 1992) and is summarized in Table 1.

Table 1. ROI summary.
Return on Investment Calculation

Investment Required		1,706,625
Return on Investment Ratio	0.73	Percent 73%
Net Present Value of Costs and Benefits/Savings	1,411,314	2,652,654 1,241,340

A	B	C	D	E	F	G	H
Future	Baseline	Baseline	New System	New System	Present Value of	Present Value of	Total Present
Year	Costs	Benefits/Savings	Costs	Benefits/Savings	Costs	Savings	Value
1							
2	205,000		123,000		107,428	179,047	71,619
3	205,000		123,000		100,405	167,342	66,937
4	205,000		123,000	61,432	93,837	203,261	109,424
5	205,000		123,000	61,432	87,699	189,966	102,267
6	205,000		123,000		81,955	136,592	54,637
7	205,000		123,000	61,432	76,592	165,907	89,315
8	205,000		123,000		71,586	119,310	47,724
9	205,000		123,000	61,432	66,900	144,912	78,013
10	205,000		123,000		62,521	104,202	41,681
11	205,000		123,000		58,437	97,396	38,958
12	205,000		123,000	61,432	54,612	118,296	63,684
13	205,000		123,000		51,045	85,075	34,030
14	205,000		123,000	61,432	47,699	103,322	55,623
15	205,000		123,000		44,575	74,292	29,717
16	205,000		123,000	61,432	41,660	90,241	48,580
17	205,000		123,000		38,942	64,903	25,961
18	205,000		123,000	61,432	36,396	78,837	42,442
19	205,000		123,000		34,010	56,683	22,673
20	205,000		123,000	61,432	31,783	68,846	37,063
21	205,000		123,000		29,705	49,508	19,803
22	205,000		123,000		27,761	46,269	18,507
23	205,000		123,000	61,432	25,941	56,191	30,250
24	205,000		123,000		24,243	40,406	16,162
25	205,000		123,000		22,657	37,761	15,104
26	205,000		123,000	61,432	21,181	45,880	24,699
27	205,000		123,000		19,791	32,985	13,194
28	205,000		123,000		18,499	30,832	12,333
29	205,000		123,000	61,432	17,294	37,460	20,167
30	205,000		123,000		16,162	26,937	10,775

As can be seen, this project had an ROI of 0.73 due to the high initial cost and low immediately identifiable savings. This project had significantly high costs due to the high level of research and development involved. Also, the significant benefits of an SHM system are not easily quantifiable due to the disaster-avoidance nature of the benefits. These points are discussed further in the next section.

4.2.1 Data and example savings

A SHM system is an important, useful item of equipment that might serve as an alarm for detecting unnoticed, critical damage to the bridge. An alarm thereby could save lives and/or avoid complete bridge replacement, but data are not available to quantify such savings. However, even minor

events such as the barge impact on the I-20 Bridge (Section 3.1.2) demonstrate the usefulness of the SHM system in confirming structural integrity and optimizing repair efforts.

While examples of the monetary impacts of casualties and the cost of bridge replacement exist, the missing data required to incorporate the costs of lives into an ROI calculation is the incidence rate of those costs. Without such savings factored into the calculations, the ROI is less than 1.0.

Because of the large research and development costs of this project and the lack of incident/event avoidance data, the ROI value does not reflect costs and benefits of the SHM system alone, but there are other bridge scenarios for consideration. For example, for the 1 August 2007 collapse of the I-35W Mississippi River Bridge in Minneapolis, Minnesota, the direct replacement cost of the bridge was \$234 million and due to longer commutes, there were indirect costs of \$400,000 a day to the local economy until the bridge was replaced (Haugen 2008). The Twin Cities Red Cross alone incurred costs of \$203,000 (Eischer 2008), but costs incurred by the remaining large disaster-response groups (75 federal, state, and local entities) are not available, nor is the cost of the NTSB investigation and debris clean-up. A lawsuit against the firm that had performed a fatigue analysis of the bridge prior to collapse was settled for \$52.4 million (James 2010), and a lawsuit against the successor of the bridge's design company was allowed to move forward after the U.S. Supreme Court decision in May 2012 declined to hear the case (Associated Press 2012). The lawsuit was settled in November 2012, with the company paying \$8.9 million to the State of Minnesota without admitting wrongdoing (Sepic 2012).

Most tragically important is the loss incurred when 13 people died, and 145 people were injured from the Minneapolis bridge collapse.

In short, the collapse of a major bridge is worth the cost of SHM installations. Even if such a system is only able to provide a timely closure/evacuation warning (and thus avoid any casualties in advance of the bridge's collapse), the system is likely to pay for itself.

5 Conclusions and Recommendations

5.1 Conclusions

Under this effort, two innovative SHM systems were designed, implemented, and demonstrated on two steel bridges. The project was deemed successful overall because the SHM system sensors were able to measure such critical parameters as corrosion rate, strain, vibration, tilt, and acoustic emission. At each bridge, all sensors were integrated into a single control system that successfully recorded data, performed condition assessment analysis, received programming, and transmitted data and alerts to and from an internet-accessible computer. The systems required minimum service and maintenance during the demonstration period. The SHM systems also provided remote monitoring of other degradation issues such as cracking, fatigue, and movement. No major structural problems were noted on either structure with respect to corrosion/materials degradation. When an event occurred that could have damaged one of the bridges—specifically, the barge hitting the I-20 Bridge—the SHM system successfully provided remote monitoring during and after the event. The SHM's remotely transmitted and received data allowed bridge authorities to monitor the situation and optimize the deployment of support personnel for evaluation and action.

Using direct costs and savings measurements provides a small rate of return. However, when assumptions are made to optimize maintenance procedures and facilitate condition-based maintenance, a larger ROI may be realized. It is recognized that the benefits of the SHM system are related more to incident/event avoidance rather than maintenance cost avoidance.

Lessons learned during the project included the need to install system components (sensors, wiring, etc.) in concealed locations to prevent theft and/or vandalism. It was also found important for scheduling accuracy to account for delays, traffic, and weather associated with each subject bridge. Issues regarding access equipment installation, data transmission, and sensor integration were encountered but were resolved through consistent, frequent interaction between the team and bridge stakeholders (primarily the relevant bridge authorities).

Several portions of the system required additional development and/or evaluation. The SHM system on the Arsenal Bridge required repairs due to damage and vandalism. In addition, the original corrosion sensors for this SHM system would not communicate with each other during the evaluation period and had to be removed. In the interim, a suitable replacement corrosion sensor was deployed. With the acoustic sensor system, the sensors were functional; however, further evaluation is required to determine if they can actually distinguish an active crack and alert the user that there is a green/yellow/red condition.

5.2 Recommendations

5.2.1 Applicability

The SHM system is applicable to all steel DoD structures in general and to bridges in particular. Applicability specifics will be determined when considering additional structures and scenarios.

At the end of the one-year evaluation period, the Louisiana Department of Transportation and Development (LA DOTD) recognized the utility of the I-20 Bridge SHM system and agreed to take control of the system and continue to monitor it under DOT funding. The system's key function will be to monitor movement of the E-1 and E-2 piers and to assess the overall condition of the span across the navigation channel between piers E-1 and W-1.

The SHM system on the Arsenal Bridge required repairs due to vandalism and improperly working sensors. After repairs, the system was fully functional, but communications were sometimes intermittent due to the wireless connectivity required because it is a rotating bridge.

Based on this work, the demonstrated SHM system is deemed applicable for structures where there are known concerns or defects that would benefit from continuous monitoring.

5.2.2 Implementation

Based on the work conducted under this project, it is suggested that the SHM system be implemented for monitoring large structures that are critical for DoD use. However, standardization of SHM systems across the DoD is not recommended due to the rapidly changing state of the art and

associated technology. Systems must be designed for each specific application, and that design is greatly influenced by existing issues and concerns related to the target structure. However, it is recommended that research and development continue to devise methodologies for evaluating the long-term condition and degradation of bridge structures.

Because the SHM system concept is an emerging structural engineering technology, there are very few government or industry standards, specifications, or methods that are applicable to the FBG sensors, the acoustic emission sensors, or the ER sensors. It is recommended that all SHM components conform to available industry, instrumentation, and communication standards. One applicable standard was found to be IEEE 12207, "Standard for Information Technology-Software Life Cycle Processes." This standard establishes a common framework for software life-cycle processes; it officially replaced MIL-STD-498 for the development of DoD software systems in May 1998. The SHM software that was developed under this activity (Section 2.3) conforms to this standard.

Several portions of the SHM system require additional development and/or evaluation. The SHM system on the Arsenal Bridge will require additional funding outside this effort to affect repairs that occurred near the end of the project to return the system to full functionality. It is suggested that repairs be implemented as soon as such funding becomes available. When these repairs occur, the acoustic emission sensors that are part of this system should be re-evaluated. These acoustic emission sensors were functional during the course of this effort, but they require additional evaluation to ascertain their utility as part of this system. In addition, original corrosion sensors for the Arsenal Bridge SHM system would not communicate with each other during the evaluation period and had to be removed. These sensors may require additional development and evaluation. In the interim, a suitable replacement was deployed.

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Appendix A: Structural Engineering Report on Demonstration Bridges

OCE 08-677

STRUCTURAL ANALYSIS
OF THE
I-20 BRIDGE IN VICKSBURG, MS
AND THE
GOVERNMENT BRIDGE AT ROCK ISLAND, IL

Report

August 17, 2009

by

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**STRUCTURAL ANALYSIS
OF THE
I-20 BRIDGE IN VICKSBURG, MS
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Analysis of the I-20 Vicksburg Bridge and Rock Island Arsenal Government Bridge

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Structural Analysis of the I20 Bridge in Vicksburg, MS and the Government Bridge at Rock Island, IL

Report

August 17, 2009

1.0 INTRODUCTION

Finite element analyses of the I-20 Bridge and the Government Bridge at Rock Island, Illinois were performed in order to determine critical members for placement of sensors as part of the Remote Structural Health and Corrosion Degradation Monitoring System. The results of the finite element analyses were limited to investigations to determine critical bridge members for monitoring and were not used for performing a design code check on either bridge. The critical issue to be determined was what would happen regarding bridge stability in the event of failure of various members.

2.0 I-20 BRIDGE**2.1 Description of Finite Element Model**

A finite element model of the I-20 Bridge was created using Version 11.0 of the ANSYS finite element software. The model was based on drawings of the bridge provided by the U.S. Army Corp of Engineers and included modification to the bridge structures up to the present time as appropriate. Due to the size of the bridge, the model did not include the entire length of the bridge, but only specific pertinent spans.

The finite element model of the I-20 Bridge included the two cantilever spans and the suspended span between Piers W-2 and E-2. The model consisted of the superstructure. The substructure (piers) was not modeled. However, a dynamic analysis was made to determine changes in natural frequencies and mode shapes if the piers had been included. Springs with the appropriate stiffness were used to model the piers. The results indicated essentially no change in frequency or mode shapes compared to neglecting the piers.

The various chords, verticals, diagonals, cross-members, floorbeams, diaphragms, and stringers were modeled with three-dimensional elastic beam elements. The hangers and other pinned connections were modeled with three-dimensional spar elements. The reinforced concrete deck was modeled with three-dimensional elastic shell elements. The model included the offset distances between the centroids of the various members. The effects of the bearings were taken into account through boundary conditions. The model of the I-20 Bridge consisted of approximately 21,000 elements and 23,000 nodes. Figures 1 through 4 show the model of the I-20 Bridge.

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The material properties used in the analyses for the steel members were

Young's Modulus	29×10^6 psi
Poisson's Ratio	0.3
Weight Density	0.283 lb/in^3

The material properties for the reinforced concrete used in analyses were

Young's Modulus	3.6×10^6 psi
Poisson's Ratio	0.2
Weight Density	0.084 lb/in^3

2.2 Loading Conditions

The finite element model of the I-20 Bridge was subjected to various loading scenarios to determine its response. These scenarios included:

- Deadweight
- Automotive and truck traffic based on an HS20 truck with automotive traffic (equal to 0.64k/ft lane load) ahead and behind the truck axle loads.
- Temperature

The automotive and truck traffic loading scenarios were evaluated using both static and transient dynamic analyses. Modal analyses were also conducted to determine the natural frequencies of the bridge.

2.3 Analysis Results

The results of the analyses of the I-20 Bridge showed that the deadweight loading scenario produces the largest stresses and deflections in the bridge. The resulting stresses from the other loading scenarios are an order of magnitude smaller. Figures 5 and 6 show the stresses in the bridge for loading due to deadweight.

The stresses due to deadweight provided on the U.S. Army Corp of Engineers drawings were about 15% higher than those calculated using finite element analysis. These differences can be attributed to the finite element model having a more accurate representation of the stiffness of the members and joints in comparison to the hand calculations used in the original design of the bridge.

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Since the deadweight loading scenario resulted in the largest stresses for the I-20 Bridge, the critical members were determined using this loading scenario. In order to determine the critical members, analyses of the I-20 Bridge subjected to deadweight, were conducted. To simulate complete member failure, members of the bridge were individually removed from the model and an analysis of the bridge for deadweight loading was conducted. Critical members were determined by evaluating the stress and displacement in the bridge. Members whose removal resulted in an unacceptable increase in stress in the other members or resulted in an unacceptable increase in displacement, were considered critical members. Figures 7 and 8 show typical stress plots for the I-20 Bridge when certain structural members have been removed. Table 1 lists the locations of sensors to be placed on critical members of the I-20 Bridge. In addition to those members identified as fracture critical from the analyses, Table 1 also includes locations for sensors on members with a history of problems on the I-20 Bridge. A total of 37 sensors were specified. Although more sensors could have been specified, the number of the sensors was restricted to approximately 30 sensors for the I-20 Bridge. Figures 9 and 10 show the approximate locations for sensor placement.

The natural frequency of the bridge was determined using a modal analysis. Figure 11 shows the first natural frequency of the I-20 Bridge. This natural frequency is for vertical oscillations as 0.8 Hz.

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Table 1: I-20 Bridge Sensors

Member	Type of Sensor	Location	No. of Sensors	Notes
M7-U8	Strain Gage	Midpoint along length, on web at neutral axis	2	One sensor on north member, other on south
M7'-U8'	Strain Gage	Midpoint along length, on web at neutral axis	2	One sensor on north member, other on south
U8-U10	Strain Gage	Midpoint between Panel Points 9 and 10, on web at neutral axis	2	One sensor on north member, other on south
U8'-U10'	Strain Gage	Midpoint between Panel Points 9' and 10', on web at neutral axis	2	One sensor on north member, other on south
U10-U12	Strain Gage	Midpoint between Panel Points 10 and 11, on web at neutral axis	2	One sensor on north member, other on south
U10'-U12'	Strain Gage	Midpoint between Panel Points 10' and 11', on web at neutral axis	2	One sensor on north member, other on south
U12'-M13'	Strain Gage	Midpoint along length, on web at neutral axis	2	One sensor on north member, other on south
U12-M13	Strain Gage	Midpoint along length, on web at neutral axis	2	One sensor on north member, other on south
U15-L15	Strain Gage	Midpoint along length, on web at neutral axis	2	One sensor on north member, other on south
U15'-L15'	Strain Gage	Midpoint along length, on web at neutral axis	2	One sensor on north member, other on south
L19-L20	Strain Gage	Midpoint along length, on bottom flange	2	One sensor on north member, other on south
Longitudinal Strut	Strain Gage	Midpoint along length, on web at neutral axis	1	Longitudinal strut is between Panel Points 14' and 15'
Floor Beam 7 (FBM7)	Strain Gage	At ends and center	6	FBM7 is located on suspended span at Panel Points 15 and 15'
Hanger Pins	Strain Gage	At mid-span of pin at bottom	8	One sensor on upper and lower pins at Panel Point 15 and 15'
Piers E1, E2, and W1	Tilt Meter	At north and south edges of pier	6	

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ANSYS

Figure 1: Finite Element Model of I-20 Bridge in Vicksburg, MS

ANSYS

Figure 2: Finite Element Model of I-20 Bridge in Vicksburg, MS

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ANSYS

Figure 3: Finite Element Model of I-20 Bridge in Vicksburg, MS

ANSYS

Figure 4: Finite Element Model of I-20 Bridge in Vicksburg, MS

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Figure 5: Axial Stresses in I-20 Bridge due to Deadweight

Figure 6: Axial + Bending Stresses in I-20 Bridge due to Deadweight

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Figure 7: Excessive Stresses in I-20 Bridge when Member U12-M13 is Removed

Figure 8: Excessive Stresses in I-20 Bridge when Member M7-U8 is Removed

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Figure 9: Locations of Sensors (shown as red dots) on the I-20 Bridge

Figure 10: Locations of Sensors (shown as red dots) on the I-20 Bridge

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Figure 11: First Natural Frequency of I-20 Bridge Depicting Vertical Oscillations at 0.8 Hz

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3.0 GOVERNMENT BRIDGE**3.1 Description of Finite Element Model**

A finite element model of the Government Bridge at the Rock Island Arsenal was created using Version 11.0 of the ANSYS finite element software. The model was based on drawings of the bridge provided by the U.S. Army Corp of Engineers which included modifications to the bridge structure up to the present. Due to the size of the bridge, the model did not include the entire length of the bridge, but only Span 2, which is the swing span of the bridge. Figure 12 shows the actual bridge.

The finite element model of the Government Bridge included the railroad deck above the vehicle roadway deck as shown in Figure 13. The model consisted of the superstructure. The substructure (piers) was not modeled. The various chords, verticals, diagonals, cross-members, floorbeams, diaphragms, and stringers were modeled with three-dimensional elastic beam elements. To determine the distribution of the train load, the railroad deck consisting of mainly c-channels was modeled using shell elements. The roadway deck made of steel grating filled with concrete was modeled with three-dimensional elastic shell elements. The model included the offset distances between the centroids of the various members. Effects of pinned connections were modeled by releasing the rotational degree of freedom about the pin axis. The effects of the bearings at either end of the bridge were taken into account through boundary conditions. The model of the Government Bridge consisted of approximately 132,000 elements and 140,000 nodes. Figures 13 through 15 show the model of the Government Bridge.

The material properties used in the analyses for the steel members were

Young's Modulus	29×10^6 psi
Poisson's Ratio	0.3
Weight Density	0.283 lb/in^3

The material properties for the reinforced concrete used in analyses were

Young's Modulus	3.6×10^6 psi
Poisson's Ratio	0.2
Weight Density	0.084 lb/in^3

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3.2 Loading Conditions

The finite element model of the Government Bridge was subjected to various loading scenarios to determine its response. These scenarios included:

- Deadweight
- Automotive and truck traffic
- Temperature
- Train traffic

The automotive, truck, and train traffic loading scenarios were evaluated using both static and transient dynamic analyses. The Government Bridge has two sets of tracks on the top deck but only one track is operational and subjected to train loading on one side of the bridge at a time. The loads applied to the one side of the bridge consisted of an AREMA E80 train loading which was moved across the bridge to determine the effects of load versus distance on individual bridge members. On the roadway deck, one HS20 truck loading was applied midspan of two supports in addition to the 0.64k/ft lane load on the remaining roadway surface. Modal analyses were also conducted to determine the natural frequencies of the bridge.

There are two possible deadweight loading conditions since this span can swing to allow boat traffic. The first scenario is when the bridge is in the closed position and supported at the ends and in center of the span. A second scenario consists of the bridge in the open position or swinging which utilizes only the center support leaving the ends of the span cantilevered.

3.3 Analysis Results

The stresses in members for the two deadweight scenarios, while the bridge is closed and open, are provided in Figures 16 and Figure 17.

The deflection at the end of the swing span for deadweight loading agreed well with measurements reported by the U.S. Army Corp of Engineers at Rock Island, Illinois.

The results of the analyses of the Government Bridge showed that the live loading scenario, as opposed to the deadweight only scenario, produces the largest stresses and deflections in the bridge. Figures 18 through 28 show the stresses in the bridge for loading scenarios involving deadweight + live loads (E80 train moving and H20 truck loading), which have exaggerated displacements to more easily see the bridge deflections.

Due to redundancy in the Government Bridge, removal of individual members (such as that done in evaluating the I-20 Bridge) did not produce significant increases in stress in the remaining members under deadweight loading. Therefore, since the live loading scenario resulted in the largest stresses for the Government Bridge, the critical members were determined using this loading scenario. In order to determine the critical members, analyses of the Government Bridge

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subjected to deadweight + live loads, were conducted. Critical members were determined by evaluating the stress and displacement in the bridge.

Table 2 lists the locations of sensors to be placed on the Government Bridge. In addition to strain gages, accelerometers were also specified. The accelerometers at the ends of the bridge (near supports on Table 2) are intended for use in determining the dynamic movement at the ends of the bridge during swing. It is anticipated that the accelerogram from the accelerometers will be integrated twice with respect to time to determine the dynamic displacement as the bridge swings which will serve as a model verification. Due to the relative symmetry of the bridge, Figure 29 shows their locations for $\frac{1}{4}$ of the bridge. Details of sensor locations for various member cross-sections are provided in Figure 30. A total of 34 sensors were specified. Although more sensors could have been specified, the number of the sensors was restricted to approximately 30 sensors for the Government Bridge.

The natural frequency of the bridge was determined using a modal analysis. Figure 31 shows the first natural frequency of the Rock Island Arsenal Bridge at 4.6 Hz. This natural frequency is for vertical oscillations as 0.8 Hz. Displacements are exaggerated to visualize the oscillations of the structure. Individual members may have much lower frequencies and can also be excited near the same frequency as the main structure, as indicated in Figure 31.

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Table 2: Sensor Locations

Member	Type of Sensor	Location	No. of Sensors on Member	Total No. of Sensors on Bridge	Notes
L0 - M0	Strain Gage	Midspan of member	1	4	See Fig. 30 -2(a)
L2 - U3	Strain Gage	Midspan of Railroad Deck and U2	1	4	See Fig. 30 -2(d)
L3 - L4	Strain Gage	Midspan of member	1	4	See Fig. 30 -2(a)
M5 - U6	Strain Gage	Midspan of member	1	4	See Fig. 30 -2(c)
L8 - M7	Strain Gage	Midspan of member	1	4	See Fig. 30 -2(a)
L6 - M7	Strain Gage	Midspan of member	1	4	See Fig. 30 -2(d)
M7	Strain Gage	Middle of pin length	1	4	
M7 - U7	Strain Gage	Midspan of member	1	4	See Fig. 30 -2(d)
U8 - U8'	Strain Gage	Midspan of member	1	2	See Fig. 30 -2(c)
L0	Accelerometer	Near support	1	2-4	
L4 - L5	Accelerometer	Midspan of member	1	4	
L7 -U7	Accelerometer	Near or on Railroad Deck	1	4

Figure 12: Government Bridge at Rock Island Arsenal, Span 2

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Figure 13: Government Bridge Model

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Figure 14: Government Bridge Model

Figure 15: Government Bridge Model

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Figure 16: Axial+Bending Stresses in Bridge Members, Closed Position

Figure 17: Axial+Bending Stresses in Bridge Members, Open Position

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Figure 18: Axial+Bending Stresses (lb/ft²) in Bridge Members, Deadload+Liveload

Figure 19: Axial+Bending Stresses (lb/ft²) in Bridge Members, Deadload+Liveload

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Figure 20: Axial+Bending Stresses (lb/ft²) in Bridge Members, Deadload+Liveload

Figure 21: Axial+Bending Stresses (lb/ft²) in Bridge Members, Deadload+Liveload

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Figure 22: Axial+Bending Stresses (lb/ft²) in Bridge Members, Deadload+Liveload

Figure 23: Axial+Bending Stresses (lb/ft²) in Bridge Members, Deadload+Liveload

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Figure 24: Axial+Bending Stresses (lb/ft²) in Bridge Members, Deadload+Liveload

Figure 25: Axial+Bending Stresses (lb/ft²) in Bridge Members, Deadload+Liveload

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Figure 26: Axial+Bending Stresses (lb/ft²) in Bridge Members, Deadload+Liveload

Figure 27: Axial+Bending Stresses (lb/ft²) in Bridge Members, Deadload+Liveload

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Figure 28: Axial+Bending Stresses (lb/ft²) in Bridge Members, Deadload+Liveload

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Figure 29: The Government Bridge Sensor Locations (Only ¼ Bridge Shown)

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Figure 30: The Government Bridge Sensor Locations Details

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Figure 31: Modal Analysis, Frequency 4.6 Hz (Displacements Exaggerated)

OCE Response to CTC Questions on Bridge SHM Report

October 6, 2009

Question 1: Pier Rotations

The measurements of pier movements from Modjeski and Masters¹ show only horizontal displacements associated with the geologic movements. Also tiltmeter measurements made by Modjeski and Masters² show pier rotations that are consistent with thermal expansions of the spans between the piers with no additional or permanent tilts. Also studies of the geologic movement indicate that the movement is horizontal toward the west of strata overlying a horizontal slip plane.³ Therefore, rotations other than those due to thermal expansion are unlikely. Also, hinges in the bridge supports atop the piers provide an ability for pier rotations to not affect the bridge.

As indicated above the approach of the finite element analysis was to identify members which are critical to bridge safety such as fracture critical members. It was not to investigate potential load cases which are unknown in magnitude and any resulting stresses could not be separated from other environmental or live loadings. Thus, as indicated in the report on thresholds, the thresholds were established based on the existing margin over and above the existing dead load stresses determined by analysis regardless of the source of those additional stresses.

In theory the finite element model could be used to investigate patterns of threshold readings and the loading conditions that produced the patterns. But in practice an extremely large number of analyses would be required and the possibility that a unique loading cause could not be found remains substantial. If event loadings could be independently quantified, finite element analyses might then be used to try to correlate the loads with sensor data from which stresses at other locations could be determined. But that would require knowing not only quantitative information on event loading but also other loading conditions such as live loads, thermal conditions and wind making such analyses very difficult and most likely impractical.

¹ Modjeski and Masters, Presentation, *Structural Health Management (SHM) of Steel and Composite Bridges, Workshop*, May 1 and 2, 2008

² Ibid

³ "Flat slip surfaces that developed in clayey strata during block displacements have facilitated recent movements as the meandering river impinged on the bluff. The foundations of two bridges at Vicksburg have experienced such creep-like movements in recent years. Localized plastic deformation has complicated the geologic picture near the bridges. Deformation features are confined to a single bed of marly limestone and the underlying layer of clayey marl." Lutton, Richard J., "Past Valley Widening and Recent Creep beside the Lower Mississippi Valley," *Environmental & Engineering Geoscience, Vol. XII, No. 1*, February 2006, pp. 13–24

Question 2: Government Bridge at Rock Island

The railroad deck is composed of many thousands of shell elements that comprise the “C-sections” that make up the deck. While it would be theoretically possible to revise the properties of single elements at corrosion locations, it is doubtful that it would show significant effect. The rail and end supports provide a mechanism to bridge any “C-section” members that might be significantly corroded in spatial extent. Loads on such members would decrease and loads on neighboring members would increase, but the change in stresses would be small unless even if spatial corrosion were fairly extensive. Practically, such analyses would be tedious and numerous and might not yield significant information.

As to the decking structure corrosion getting worse and its condition today, it is our understanding the bridge has been load rated based on the last inspection results. If additional corrosion is believed to exist, another inspection and load rating evaluation in accordance with AASHTO and AREMA load evaluation procedures should be conducted.

Model and Sensor Symmetry

The model is symmetric about both the transverse and longitudinal axes. The sensor placement is also symmetric about both of those axes. One reason for this is that because the bridge rotates, maximum stresses due to train loading even with only one track will affect both sides of the bridge depending on the rotational configuration.

Appendix B: SHM System Components

The components of both demonstrated SHM systems are discussed here. Several critical sensors represent innovative applications of fiber Bragg grating (FBG) technology, as described below.

Corrosion sensors

For this activity, three types of corrosion sensor technologies were selected. Two types of ER corrosion sensors were selected to measure atmospheric corrosion rates on each bridge structure. The first type was an experimental sensor developed by the Australian Defense Science and Technology Organization (DSTO) and licensed to an Australian consortium, the Cooperative Research Centre for Integrated Engineering Asset Management (CIEAM). Commercial-off-the-shelf (COTS) corrosion sensors were also selected for each bridge; the results of these sensors were compared to those of experimental ER sensors. In addition, an assessment of atmospheric corrosion on each bridge location was made using a test rack of coupons. Bare metal coupons mounted on a polymer sample card (using non-metallic fasteners that suspend the samples 1/4" above the polymer sample card) were employed.

The COTS ER sensors and the corrosion coupons were incorporated into both SHM systems. The CIEAM corrosion sensors were employed for the Arsenal Bridge only.

Fiber Bragg grating technology

Most sensors employed in the SHM system use *fiber Bragg grating* (FBG) technology. FBGs are reflectors that are photo-imprinted into a fiber optic cable. They are tuned to either reflect or transmit specific light wavelengths for application-specific purposes. A representative FBG in a fiber optic cable is diagrammed in Figure B1.

Figure B1. Diagram of fiber optic cable with fiber Bragg gratings.

Each FBG sensor in the system is tuned to a specific wavelength to measure a specific parameter. When a laser light source is used to project light through the fiber, a portion of the light is reflected back from the FBG. As this wavelength changes over time with respect to temperature and stress of the fiber, each FBG sensor returns information on these parameters, which are in turn a function of the state of the structure (Yolken and Matzkanin 2009). The nature of FBG sensors makes them well suited for outdoor infrastructure monitoring; they consume lower power than standard sensor systems and are immune to electromagnetic effects, corrosion, and most chemicals. Optical sensors have been previously demonstrated for infrastructure applications using this technique (Yolken and Matzkanin 2009; Kersey 1994).

The versatility of FBG sensors lends them to a number of useful applications with respect to the bridge SHM system. For both bridges, an assessment of bridge peak accelerations, to evaluate changes in the overall structural behavior, was determined using three-dimensional FBG accelerometers, placed such that the natural frequencies and vibration mode shapes can be determined for the structure. An assessment of strain, to monitor stresses in critical structural members of the superstructure, was measured using FBG strain gauges adhered directly to the bridge structure.

A number of different types of FBG sensors were employed for the two SHM systems, including accelerometers, strain sensors, tiltmeters, and

displacement gauges. These sensors are described in the following sections.

FBG accelerometers

Acceleration measurement on bridge structures are typically determined using accelerometers, placed at specific points on the structure such that the natural frequencies and vibration mode shapes can be determined. Changes in peak acceleration, vibration, and inclination can then be measured as a function of time. Modal response in particular is considered to be a useful method for determining changes in the overall structural behavior of bridges, in that changes in the bridge's natural frequency may be indicative of damage to the structure (Ingold 2009; Yolken and Matzkanin 2009). FBG accelerometers were incorporated into both bridge SHM systems for this purpose. Installed FBG accelerometers are shown in Figure B2.

Figure B2. Installed FBG accelerometers.

Strain sensors

An assessment of strain, to monitor tensile and compressive loading in critical structural members of the superstructure, can be derived using

strain gauges adhered directly to the bridge structure. Important data related to stresses in critical bridge members, particularly those that are not redundant, can be obtained using strain gauges. FBG strain gauges were incorporated into both SHM systems. FBG strain sensors as installed (i.e., not painted) are shown in Figure B3; a strain sensor that has been installed and then painted to protect it from environmental effects is shown in Figure B4.

Figure B3. Installed strain sensors, uncovered.

Figure B4. Installed strain sensor, after painting.

Tilt sensors

Tilt sensors were employed to determine rotational displacement on free-standing structural members such as bridge piers. Movement at piers is measured and monitored using tiltmeters. FBG tilt sensors were incorporated into the I-20 Bridge SHM system.

Displacement sensors

Deflection/displacement sensors were employed to measure movement between structural members, such as displacement between deck joints and displacements at bridge bearings. Measured deflections, like strain readings, are helpful in determining whether a structure is responding as expected and can serve as an early warning if unanticipated trends (e.g., sudden large shifts due to movement from an event such as an earthquake) are observed. FBG displacement sensors were incorporated into the I-20 Bridge SHM system.

Acoustic emission sensors

Acoustic emission technology detects and monitors ultrasonic waves produced by materials when they crack (Yolken and Matkanin 2009). Acoustic emission sensors inspect the monitored areas for defects (cracks, corrosion, and other events that emit sounds when they occur), covering beams, gussets, stringers, and all hidden structural members. The technique has previously been thoroughly demonstrated for the structural health assessment of bridge systems (Pollock and Carlyle 1995; Carlyle 1993a, 1993b; Carlyle and Leaird 1992; Carlyle and Ely 1992).

For this effort, acoustic emission sensors were utilized to detect active crack growth in selected pins that connect truss members on the Arsenal Bridge. This portion of the SHM system consisted of piezoelectric sensors and specialized signal processing to separate, in real-time, the acoustic defect signal from typical traffic noise. At each pin, sensors actively listened for distress or cracking. In addition, the sensors actively emitted a signal (ping) upon command, in order to detect degradation of the sensitivity of the sensors monitoring the pin connectors. An acoustic emission sensor that has been installed on a bridge member is shown in Figure B5.

Figure B5. Acoustic emission sensor (weatherproof cover removed) installed on Arsenal Bridge.

Other technologies

The SHM system on the I-20 Bridge also incorporated three video cameras placed on and adjacent to the structure to allow remote viewing and to

save video images when the camera system is triggered by an event. The video cameras were set in such a way as to allow remote viewing of the length of the structure, as well as the main navigation channel and piers E-1 and W-1. Video capture from the remote computer was enabled through the SHM software.

A weather station was also incorporated into the I-20 Bridge SHM system, so that weather events could be correlated with the structural data.

Finally, FBG sensors were used to provide security measures for the I-20 Bridge system. Sensors were placed on a mat directly in front of the computer to detect the presence of unauthorized people.

Appendix C: Diagrams of Arsenal Bridge SHM System

Drawings prepared by Chandler Monitoring Systems.

Figure C1. Overall system diagram.

Figure C2. Locations of sensors and wireless units (control tower views).

Figure C3. Photos of individual units.

Photos of Units 3 and 4

Photo showing the locations of Units 3 and 4

Photo taken from beneath Unit 3 looking upward towards master antenna

Photo showing the locations of Units 3 and 4, rail deck in background

Photos of Unit 2

Photo showing the location of Unit 2

Photo showing the location of Unit 2 with rail deck in background

Photo showing the location of Unit 2 looking up towards master antenna

Photos of Unit 5

Photo of Unit 5 taken from Control Tower deck

Photo of Unit 5 taken from Control Tower deck, master antenna a couple of meters above where photo taken

Photo of Unit 5 taken from Control Tower deck

Appendix D: Design Details for the I-20 Bridge SHM System

This system was designed to provide advance warning of various structural problems on the I-20 Bridge caused by corrosion/materials degradation. The SHM system design monitors the movement of piers and the associated distress affecting structural members on the I-20 Bridge, and assesses the overall condition of the span across the navigation channel between piers E-1 and W-1 of the structure (Figure D1). To accomplish this, the SHM system was designed to monitor movement at piers and expansion joints; stresses in bridge superstructure; and displacements, strains, modal response, and corrosion activity.

Figure D1.. I-20 Bridge south elevation (Louisiana Department of Transportation and Development).

The sensors were placed along the bridge by using an unobtrusive single-trunk design, in which cabling from all sensors were part of a single large bundle running along the length of the bridge. This design greatly reduces the space required for cabling and takes advantage of the ability of FBG sensor technology to transmit data over long distances. A conceptual diagram of a representative SHM system implemented with periodic continuous monitoring subsystems is shown in Figure D2.

Figure D2. Representative SHM system Installation on generic bridge.

This SHM system design was based on results of the structural analysis of the I-20 Bridge* and the conceptual configuration shown above in Figure D2. After review and modification of the preliminary design, the final design was derived and completed, as diagrammed in Figure D3.

Figure D3. Sensor placement for I-20 Bridge SHM system.

* Editor's note: See Appendix A of this dem/val report.

The sensors were installed to monitor five distinct zones (Figure D4), with each zone shown in Figures D5 through D9, as represented in the monitoring application program interface.

Figure D4. Diagram of five SHM monitoring zones (image has been rotated counter-clockwise).

Figure D5. SHM system Zone 1.

Figure D6. SHM system Zone 2.

Figure D7. SHM system Zone 3 (oblique bottom view of sensor locations).

Figure D8. SHM system Zone 4.

Figure D9. SHM system Zone 5.

Appendix E: White Paper on CIEAM Corrosion Sensor Performance

Performance of CIEAM Corrosion Sensors as Part of the Structural Health Monitoring System on the Government Bridge

November 10, 2010

Revision February 4, 2011

Contract No. W9132T-06-D-0001

Order No. W9132T-CTC-002

Submitted to:

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INTRODUCTION

This White Paper is a minor deliverable for the project, Remote Structural Health and Corrosion Degradation Monitoring of Steel Bridges. This document describes the performance of corrosion sensors supplied by the Cooperative Research Center for Integrated Engineering Asset Management (CIEAM) in Brisbane, Australia, as part of a bridge structural health monitoring (SHM) system. The SHM system, including the CIEAM corrosion sensors, was installed on the Government Bridge at Rock Island Arsenal, Illinois by a team led by Concurrent Technologies Corporation (CTC)³. The installation and performance of the CIEAM corrosion sensors as part of the SHM system, including all efforts to get these sensors to operate as part of the system, are described in this document.

Background

The United States (U.S.) Army has over 200 steel bridges in its inventory; virtually every Army installation has at least one steel bridge. As with bridges in public use, these Army bridges have seen increased utilization in recent years (one large Army bridge has an average daily traffic of 30,000 vehicles [Ref. 1]). In its role as a lead engineering organization, the U.S. Army Corps of Engineers, Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL) has a responsibility to ensure that these bridges are well-maintained and safe. The key challenges faced by ERDC-CERL in this mission directly parallel those faced by the Federal Highway Administration (FHWA) for bridges in public use: metallic corrosion and fatigue combined with a potentially fracture critical design.

The efforts of ERDC-CERL and the FHWA to monitor and maintain steel bridges are constrained to some degree by current bridge inspection practices. The engineering investigation following the collapse of the I-35 Bridge demonstrated that the conventional inspection techniques employed during the routine assessment of steel

³ This team included personnel from ERDC-CERL, Mandaree Enterprise Corporation, CTC, O'Donnell Consulting Engineers Inc., Chandler Monitoring Systems Inc., Carlyle Consulting, CIEAM, and the Rock Island Directorate of Public Works.

bridges – including visual, dye penetrant, ultrasonic, and/or radiographic nondestructive testing methods – may not always be capable of detecting cracks in hidden or hard-to reach areas (such as those in built-up structures), and also may be unable to determine if a crack in a critical location or component is actively growing. There is an urgent need to examine and assess the latest state-of-the-art technologies and approaches to the remote monitoring of the degradation of steel bridges by means of strategically positioned sensors, reliable data acquisition systems, and advanced analytical software.

Project Objectives

The overall objectives of this project are to demonstrate and validate state-of-the-art and emerging innovative technology approaches for the remote structural health and corrosion degradation monitoring of steel bridges. The intent of a monitoring system is to greatly reduce the risk of a catastrophic failure by providing advance warning of a growing structural problem caused by corrosion/materials degradation with an opportunity for repair before catastrophic failure. This project will help demonstrate the capabilities of such systems and validate the potential benefits for future possible application by the Army and the rest of the Department of Defense (DOD) on mission-critical bridges and similar load-bearing structures.

To this end, the purpose of the effort with respect to the CIEAM corrosion sensors was to demonstrate that the technology could detect corrosion on the bridge structures to which they were attached, and that the resulting data could be integrated into the overall SHM system.

SUBJECT CORROSION SENSORS

As part of the SHM system, corrosion sensors were installed on the Government Bridge. The sensors were electrical resistance (ER) corrosion sensors that were designed and built by CIEAM. Information on these sensors was provided in a special report to CTC and ERDC-CERL [Ref 2]. The information is presented in its entirety in Appendix A of this report and is summarized briefly in this section.

The corrosion sensors are comprised of boards that consist of thin strips of mild steel and a weather proof connector for resistance measurements. The ER sensor boards include an onboard correction to account for the temperature dependence of the resistance of the sensor elements. The sensors that were deployed on the Government Bridge incorporated special steel sensing elements to more accurately match the properties of the material used to construct the bridge. An example of the CIEAM corrosion sensor is presented in Figure 1 [Ref. 2].

Figure 1. Example of Electrical Resistance-Based CIEAM Corrosion Sensor Board.

A simple stop-and-go protocol using a single master unit and multiple slave units reportedly enables the automatic collection of sensor parameters and transmission to a central location for processing. The units communicate using radio frequency (RF) at 916 Megahertz (MHz). The sensors, when used in conjunction with the associated software, give a direct measure of the corrosion damage experienced by the structure.

The CIEAM corrosion sensors were installed on the Government Bridge, along with the other sensors and technologies that were to be incorporated as part of the SHM system, in October 2009. CTC's subcontractor, Chandler Monitoring Systems, Inc. (CMSI) installed the corrosion sensors under the supervision of CIEAM personnel. Photographs taken from the installation are presented in Appendix B of this report. The sensors were installed at locations on the bridge such that they would be exposed to a wide range of corrosive conditions.

These locations were guided by CIEAM's experience from previous installations of these sensor boards at a range of locations with varying levels of corrosivity across Australia.

An overview diagram of the resulting corrosion sensor system and how it was installed on the Government Bridge is presented in Figure 2. A series of pictures that present a more thorough representation of the corrosion sensors on the Government Bridge is presented in Appendix C of this report.

Figure 2. Corrosion Sensor System Configuration on Government Bridge.

CORROSION SENSOR PERFORMANCE

From the installation date in October 2009, the corrosion sensors did not function properly. The issue was the communication between the master and slave nodes; the slaves would not transmit data to the master, or would transmit data initially and then shut down. ERDC-CERL and CTC, along with CMSI, spent countless man hours, communicating with CIEAM through emails and after-hours conference calls and engaging in development trials and multiple trips to the bridge site, to resolve the issue. A full summary of CMSI's attempts to get the sensors to function properly, along with the associated costs, is presented in Appendix C of this report and is summarized in this section.

At first, attempts were made to use new CIEAM corrosion sensors (meant for the I-20 Bridge) to integrate with the system. This worked initially, so CIEAM sent new sensors to replace the old ones on the Government Bridge. These were installed on the Government Bridge by CIEAM personnel (with the assistance of CMSI personnel) in December 2009. These worked initially, but failed to communicate soon thereafter.

Efforts were then directed toward modification of the CIEAM sensors to repair inherent flaws that could be preventing their communication. New transceivers (identified and procured by CMSI personnel) were installed, and attempts were made to re-program the units following instructions provided by CIEAM. CMSI loaded the new firmware and modified the configuration files to change the power levels and get the units to communicate. However, the units would not accept certain power levels, and when CMSI finally got them on the same power levels, they still would not communicate; this was observed on multiple occasions.

In March 2009, CMSI reported the findings to date to both CTC and ERDC-CERL and proposed two options. The first option was to realign the corrosion sensors to the master antenna using a frequency finder. This option was successful at CMSI facilities, but did not work on the sensors on the bridge. The second solution was to interconnect

the feeds manually (essentially converting the units to a cabled system) with a booster to the antenna. Although various types of cable were tested, this option was also unsuccessful.

It should be noted that CIEAM never provided the proper software interface to CMSI (which was requested numerous times) so that the software engineer could integrate the sensor data into CMSI's proprietary data acquisition and analysis software (IntelOptics). Consequently, the CMSI software engineer also spent many hours attempting to extract data from the CIEAM system.

Finally, the idea to connect the corrosion sensor boards independently of the rest of CIEAM's system was discussed. As mentioned in Section 2.0, the boards are comprised of strips of metal for which change of resistance is recorded as the cross-section of material is corroded away. CMSI indicated that they could design a data collection system that would employ these boards if CIEAM would permit them to do so. However, CMSI mentioned that this option would take considerable time and effort, possibly longer than the period of performance of the Bridge SHM activity, and is outside of their current scope of work.

After eight months of attempts, ERDC-CERL instructed CTC and CMSI to remove the corrosion units from the Government Bridge (and forego installation of these sensors on the I-20 Bridge also under this Contract). The units were removed in May 2010 by CMSI and were returned to the Australian Defense Science and Technology Organisation (DSTO) in November 2010.

SUMMARY

While the CIEAM corrosion sensors may perform in stand-alone configurations (as reportedly demonstrated by both CIEAM and DSTO), they did not function when integrated into the Government Bridge SHM system. The issue was not the ability to interface with the SHM system, but rather the inability of the sensors to transmit data from the slave nodes to the master. Despite many hours of ef-

fort, numerous replaced components, countless telephone conversations, emails with CIEAM personnel, and many software modifications, CMSI were unable to determine why the sensors were unable to maintain communication with each other. After months of unsuccessful attempts, the corrosion sensors were removed and returned to DSTO.

RECOMMENDATIONS

It is suggested that future work should focus on the identification of the failure mode(s) that did not permit the CIEAM sensors to communicate and transmit data. CMSI could not ascertain why the sensors would not communicate, and so it may require considerable effort from and/or interaction with DSTO personnel to determine why their sensors did not work in this application.

In addition, the idea to connect the boards independently of the rest of CIEAM's system should be explored. CMSI indicated that they could design a data collection system that would employ these boards if DSTO would permit them to do so. However, it must be understood that this option would take considerable time and effort, possibly longer than the period of performance of the Bridge SHM activity, and is outside of their current scope of work.

Finally, relative to data collection, it is suggested that DSTO be employed to retrieve the data that was collected on the units that were installed on the Government Bridge and operating at least temporarily. As CMSI were unable to retrieve the data working on their own, it is suggested that CTC, ERDC-CERL, CMSI, and DSTO work together to determine the best path to retrieve the data.

REFERENCES

- 1) R. Lampo, S. Sweeney, and V. Hock, "Remote Structural Monitoring and Corrosion Degradation Modeling of Bridges," 2008 U.S. Army Corrosion Summit, Clearwater, FL, February 2008.
- 2) S. Wade and A. Trueman, "Electrical Resistance Corrosion Sensor Units for Installation on Government Bridge," addendum to Monthly Progress Report for Remote Structural Health and Corrosion Degradation Monitoring of Steel Bridges project, October 2009.

APPENDIX A

Electrical Resistance Corrosion Sensor Units for Installation on Government Bridge

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²Defence Science and Technology Organisation, Fishermans Bend, Victoria, Australia

The following document provides some background information on the electrical resistance-based corrosion sensors to be installed on the Government Bridge as part of a United States (U.S.) Army Corps of Engineers, Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL) project “*Remote Structural Health and Corrosion Degradation Monitoring of Steel Bridges*.” This part of the project is being carried out under a subcontract to the CRC for Integrated Engineering Asset Management with Chandler Monitoring Systems (CMS).

The electrical resistance (ER) method of corrosion sensing is based on the change in the electrical resistance of a conductor due to the reduction of thickness as corrosion takes place [1, 2]. The resistance of a conductor is described by:

$$R = \frac{\rho l}{A} \quad (1)$$

where R is the resistance, ρ is the resistivity, l is the length and A is the cross-sectional area of the conductor (i.e. A = width $\times$ thickness, for a thin flat strip of metal). The relative change in the resistance of the conductor in a

corrosive environment will depend upon the initial thickness of the material. Thinner materials will initially be more sensitive but will also corrode through and ultimately fail in a shorter time frame.

Corrosion sensor boards based on the electrical resistance method have been developed, an example of which is shown in Figure 1. The sensor boards (dimensions 105×110 mm) consist of thin strips of mild steel and a weather proof connector for resistance measurements. Steel shims with thicknesses ranging from 25 μm to 250 μm have been used in this work. The resistances of the sensor elements are currently measured using hand held meter, however automatic data logging devices are being developed. The ER sensor boards include an inbuilt correction to account for the temperature dependence of the resistance of the sensor elements. The sensors to be deployed on Government Bridge have special steel sensing elements incorporated to more accurately match the properties of the material used to construct the bridge.

Figure 1: Example of Electrical Resistance-Based Corrosion Sensor Board

The sensors when used in conjunction with the associated software give a direct measure of the corrosion damage experienced by the structure. To record sensor data wireless logger units designed for simplicity, low power, low cost and high customizability have been developed. The units communicate using RF at 916 MHz; and a simple stop-and-go protocol with a one master/multiple slave's configuration enables automatic collecting of sensor parameters and transmission to a central location for processing. In addition to measurements from the corrosion sensors the wireless logger units incorporate a combined relative humidity/temperature sensor the data from which can be useful in the interpretation of corrosion measurements.

The logger units also have the capability of expansion for additional sensor measurements.

For the corrosion sensor installations carried out as part of the United States (U.S.) Army Corps of Engineers, Engineer Research & Development Center, Construction Engineering Research Laboratory (ERDC-CERL) project four corrosion sensor boards will be installed on the two bridges being investigated. To this end the sensors will be installed at locations on the bridge such that they are:

- a) exposed to a wide range of corrosive conditions, and,
- b) where possible for one of the sensors to simulate the exposure conditions described in the ASTM standard for conducting corrosion tests on metals (ASTM G50[3]).

These locations will be guided by experience gained from previous installations of these sensor boards at a range of locations with varying levels of corrosivity across Australia.

References:

- 1 M. McKenzie and P.R. Vassie, British Corrosion Journal, 20, pp117-124 (1985)
- 2 G.L. Cooper, "Sensing Probes and Instruments for Electrochemical and Electrical Resistance Corrosion Monitoring", ASTM STP 908, pub ASTM, pp237-250 (1986)
- 3 G50-76 (2003) Standard Practice for Conducting Atmospheric Corrosion Tests on Metals. In Vol 03.02 of Annual Book of ASTM Standards. Philadelphia, ASTM International, 2008: 353-359.

APPENDIX B

Photographs of CIEAM Corrosion Sensor System at the Government Bridge, Rock Island Arsenal, IL

Locations of ER Sensors and Wireless 1

View of Arsenal bridge from side 1

Photos of Units 3 and 4

Photo showing the locations of Units 3 and 4

Photo taken from beneath Unit 3 looking upward towards master antenna

Photo showing the locations of Units 3 and 4, rail deck in background

Photos of Unit 2

Photo showing the location of Unit 2

Photo showing the location of Unit 2 with rail deck in background

Photo showing the location of Unit 2 looking up towards master antenna

Photos of Unit 5

Photo of Unit 5 taken from Control Tower deck

Photo of Unit 5 taken from Control Tower deck, master antenna a couple of meters above where photo taken

Photo of Unit 5 taken from Control Tower deck

APPENDIX C

Summary of CMSI Attempts to Repair CIEAM Corrosion Sensor Communication Issues

CMS Time For Installation Of CIEAM Corrosion Sensors :

Date	Installer Name	Description	Total Hours
10/24/2009	Kenyon Carter, Jose Velasquez	Made mount bracket for 45° angle board (4 Hours Each)	8
10/24/2009	Kenyon Carter, Jose Velasquez	Mount antenna (1 Hour Each)	2
10/25/2009	Kenyon Carter, Jose Velasquez	Welding bolts for sensors (5 Hours Each)	10
10/25/2009	Kenyon Carter, Jose Velasquez	Mount sensors on road deck (2 Hours Each)	4
10/25/2009	Kenyon Carter, Jose Velasquez	Mount the master rod on wall (3 Hours Each)	6
10/26/2009	Kenyon Carter, Justin Chandler	Mount sensor on deck (1 Hour Each)	2
10/26/2009	Kenyon Carter, Jose Velasquez	Make a cable cat 5 for master rod (1 Hour Each)	2
11/1/2009	Kenyon Carter, Jose Velasquez	Temporary re-mounted corrosion sensor power (1 Hour Each)	2
11/1/2009	Kenyon Carter, Jose Velasquez	Powered up and down boards for power cycle. (1 Hour Each)	2
Total Hours :			38

CMS Time For On-Site Networking Of CIEAM Corrosion Sensors :

Date	Name	Description	Total Hours
10/24/2009	Kevin Chandler	On-Site Support : Monitoring Sensor Data and Power Cycling	2
10/25/2009	Kevin Chandler	On-Site Support : Monitoring Sensor Data and Power Cycling	2
10/26/2009	Kevin Chandler	On-Site Support : Monitoring Sensor Data and Power Cycling	2
10/27/2009	Kevin Chandler	On-Site Support : Monitoring Sensor Data and Power Cycling	3
10/28/2009	Kevin Chandler	On-Site Support : Monitoring Sensor Data and Power Cycling	2
10/31/2009	Kevin Chandler	On-Site Support : Monitoring Sensor Data and Power Cycling	2
11/1/2009	Kevin Chandler	On-Site Support : Monitoring Sensor Data and Power Cycling	2
11/2/2009	Kevin Chandler	On-Site Support : Monitoring Sensor Data and Power Cycling	3
11/3/2009	Kevin Chandler	On-Site Support : Monitoring Sensor Data and Power Cycling	2
11/11/2009	Kevin Chandler	On-Site Support : Monitoring Sensor Data and Power Cycling	1
11/12/2009	Kevin Chandler	On-Site Support : Monitoring Sensor Data and Power Cycling	1
11/13/2009	Kevin Chandler	On-Site Support : Monitoring Sensor Data and Power Cycling	2
11/14/2009	Kevin Chandler	On-Site Support : Monitoring Sensor Data and Power Cycling	2
11/15/2010	Kevin Chandler	On-Site Support : Monitoring Sensor Data and Power Cycling	2
11/18/2009	Kevin Chandler	On-Site Support : Monitoring Sensor Data and Power Cycling	2
11/21/2009	Kevin Chandler	On-Site Support : Monitoring Sensor Data and Power Cycling	2
Total Hours :			32

CMS Time For Remote Networking Of CIEAM Corrosion Sensors :

Date	Installer Name	Description	Total Hours
	Abbee Zeleke	100 Hours To Date (December 10, 2009)	100
	Abbee Zeleke	112 Hours January 2010 – May 2010	112
Total Hours :			212

CMS Secondary Trip For Troubleshooting CIEAM Corrosion Sensors :

Date	Installer Name	Description	Total
12/15/2009 – 12/19/2009	Justin Chandler	Airfare	
12/15/2009 – 12/19/2009	Justin Chandler	Hotel	
12/16/2009	Justin Chandler	Labor Hours	7.0 Hours
12/17/2009	Justin Chandler	Labor Hours	6.0 Hours
12/18/2009	Justin Chandler	Labor Hours	8.0 Hours
Total Labor Hours :			21 Hours

CMS Correspondences

Date	Name	Description	Total Hours
03/31/10 – 04/08/10	Jennifer Chandler	Emails, Phone calls coordinating re-programming and slave node shipment and updates	1
4/6/2010	Kat Furrow	researching the 4 Way Combiner/Divider	1
4/7/2010	Kat Furrow	ordered the 4 way Combiner/Divider from InStock Wireless	1
4/8/2010	Kat Furrow	researching and asking questions regarding the Connectors from Allied Electronics to fit cable needed for job	2
4/9/2010	Kat Furrow	ordered products from Allied Electronics	1
4/21/2010	Kat Furrow	ordered additional male connectors from Allied Electronics	1
Total Labor Hours :			7 Hours

CMS Support Time For Modifications To CIEAM Corrosion Sensors

Date	Name	Description	Total Hours
3/10/2010	Matt Doerr	Connected wire to each corrosion sensor to control unit to try and enhance signal between sensors.	1.5
4/8/2010	Jose Velasquez	Ordered the parts needed to make all the cables for the sensors with.	4
4/10/2010	Jose Velasquez, Justin Chandler	Went to Fry's to buy SMA connectors to try slave node programming. (4 Hours Each)	8
4/16/2010	Jose Velasquez, Justin Chandler	Made the modifications to remove the wireless communications to hard wire per instructions provided to us by Bruce Thomas. (16 Hours Each)	32
4/21/2010	Jose Velasquez	Reordered more SMA connectors for the sensors at Arsenal.	1
4/21/2010	Jose Velasquez	Took slave nodes apart and Soldered 39k resistor on slave node #6, 7, 8, 9.	4
4/21/2010	Justin Chandler	Put slave nodes together after JC soldered 39k resistor on slave node #6, 7, 8, and 9	4
4/23/2010	Jose Velasquez	Went to Fry's electronics to purchase ribbon cable to make harness for programmer. Built harness for and tested harness, gave to Kevin when complete	12
4/26/2010	Jose Velasquez	Took slave nodes apart and Soldered 39k resistors on slave nodes #6, 7, 8, 9.	4
4/29/2010	Jose Velasquez	Took slave nodes apart to remove hardwire antenna and replace with wireless receiver boards. Placed antenna back on master node to see if it would communicate with slave node and gave to Kevin to run program.	10
4/29/2010	Justin Chandler	Put slave nodes back together after JC removed hardwire antenna and replaced with wireless receiver boards	8
Total Labor Hours :			88.5

CMS Programming Time Following Modification to CIEAM Corrosion Sensors :

Date	Name	Description	Total Hours
4/20/2010	Kevin Chandler	Began reading up on programming Corrosion units	5
4/21/2010	Kevin Chandler	Finished reading on Programming downloaded and installed software for reprogramming. Began reprogramming	5
4/23/2010	Kevin Chandler	Continued working on reprogramming and testing sensors	12
4/25/2010	Kevin Chandler	Continued working on reprogramming and testing sensors	4
4/26/2010	Kevin Chandler	Continued working on reprogramming and testing sensors	5
4/27/2010	Kevin Chandler	Continued working on reprogramming and testing sensors	10
4/28/2010	Kevin Chandler	Continued working on reprogramming and testing sensors	6
4/29/2010	Kevin Chandler	Continued working on reprogramming and testing sensors using the new transceivers and firmware	6
4/30/2010	Kevin Chandler	Continued working on reprogramming and testing sensors using the new transceivers and firmware	6
5/1/2010	Kevin Chandler	Continued working on reprogramming and testing sensors using the new transceivers and firmware	6
5/2/2010	Kevin Chandler	Continued working on reprogramming and testing sensors using the new transceivers and firmware	6
5/3/2010	Kevin Chandler	Continued working on reprogramming and testing sensors using the new transceivers and firmware	6
5/4/2010	Kevin Chandler	Continued working on reprogramming and testing sensors using the new transceivers and firmware	6
5/5/2010	Kevin Chandler	Continued working on reprogramming and testing sensors using the new transceivers and firmware	6
5/6/2010	Kevin Chandler	Continued working on reprogramming and testing sensors using the new transceivers and firmware	6
5/7/2010	Kevin Chandler	Continued working on reprogramming and testing sensors using the new transceivers and firmware	6
5/8/2010	Kevin Chandler	Continued working on reprogramming and testing sensors using the new transceivers and firmware	6
5/9/2010	Kevin Chandler	Continued working on reprogramming and testing sensors using the new transceivers, firmware, and New Dlogger	6
5/10/2010	Kevin Chandler	Continued working on reprogramming and testing sensors using the new transceivers, firmware, and New Dlogger	6
5/11/2010	Kevin Chandler	Continued working on reprogramming and testing sensors using the new transceivers, firmware, and New Dlogger	6
Total Labor Hours :			125

CMS Materials Purchased For Modifications To CIEAM Corrosion Sensors :		
Company Name	Description	Total
Texas Instrument	USB Debugging Interface for CIEAM - Programming Corrosion Sensors - Arsenal	\$128.70
Fry's Electronics	Crimp Tool, Blue Wick, LF Solder wick, 3/8" blk heat shrink, 3/4' white heat shrink - Corrosion Sensor Board Rework - Arsenal	\$110.99
Allied Electronics	Connectors & 500 Ft cable for Arsenal Bridge - (10) connector, RF Coaxial SMA Bulkhead crimp jack for RG 174, 316, LMR100 Cable, 50 OHM	\$68.51
Allied Electronics	(10) connector, RF Coaxial, SMA crimp plug, for RG 174, 316, LMR100 Cable, 50 OHM/Mate to 132119	\$46.93
Allied Electronics	(1) CX/500) cable, Coaxial; 26 AWG; 7/34; 0.110 in; 90% Polyvinylchloride – Type 1 Black	\$274.69
Allied Electronics	Shipping	\$46.14
Allied Electronics	(10) Connector Housing; CPC Receptacle; AMP Series 2; 11; 8 Mounting Holes; Wire, (80) Pin Contact	\$81.30
Allied Electronics	connector, RF Coaxial, SMA crimp plug, for RG 174, 316, LMR100 Cable, 50 OHM/Mate to 132119 / Male Connector	\$61.36
Allied Electronics	Shipping	\$8.43
InStock Wireless	4-Way Power Divider Combiner, SMA Female Connectors, 350 - 1000 MHz, 30W, 50 Ohm, 0 Degree, RoHS	\$104.13
Fry's Electronics	Hand Crimp tool,	\$12.99
Fry's Electronics	(2) molex interconnection system for PC boards	\$7.25
Fry's Electronics	(2) female crimp pin	\$4.39
Fry's Electronics	5 pin molex non polarized housing	\$3.23
Fry's Electronics	(2) 24 gauge solid wire pvc jacket/tinned copper	\$12.97
Fry's Electronics	(2) flat ribbon cable	\$3.09
Fry's Electronics	4" diagonal cutters	\$20.46
Fry's Electronics	(4) female crimp pin	\$21.71
Fry's Electronics	extractor tool	\$11.68
	Total Amount Of Materials Purchased :	\$1,028.95

CMS Third Trip For Troubleshooting CIEAM Corrosion Sensors :

Date	Installer Name	Description	Total
5/17/2010	Jose Velasquez	Removed slave nodes # 3, 4, 5, 6, from bridge. Brought them next to the panel and ran program to see if there was any communication between them. Slave node #3 responded once then stopped. Ran program about 4 times.	10
5/18/2010	Jose Velasquez	Made the modifications to remove the wireless communications to hardwire per instructions provided to us by Bruce Thomas. Removed antenna, place a IP fitting for cable, soldered 39k resistor for programming.	10
5/18/2010	Justin Chandler	Downloaded all necessary software to program arsenal units, attempted to download all stored data off slave nodes, did trouble shooting to find out why data could not be received, attempted to reprogram all slave nodes.	10
5/19/2010	Jose Velasquez	Connected slave node # 5 to master node before programming started and ran program and to my amazement it was communicating the hardwire cable connected straight to the master node. Mounted slave node outside after testing was complete and ran the cable to panel.	18
5/19/2010	Justin Chandler	Connected slave node # 5 to master node before programming started and ran program, ran cable outside for slave node #5 after testing was complete.	18
05/17/2010 - 05/19/2010	Hotel	Hotel accommodations for Justin Chandler, Jose Velasquez, and Keith Chandler for three nights	
05/17/2010 - 05/19/2010	Meals	Meals for Justin Chandler, Jose Velasquez, and Keith Chandler for three nights	
05/17/2010 - 05/19/2010	Misc. Materials	Materials Needed For CIEAM Sensors: Heat Shrink , and Step Drill	
Total Labor Hours :			66

CMS Project Management Time Spent Of CIEAM Corrosion Sensors :

Name	Description	Total Hours
Keith Chandler	15 Conferences with Corp of Engineers, Job site re-visits, on site visit with Corp Of Engineers, Phone and Email Correspondences, including with Robert with CIEAM at very late hours and technical input added to project scope of work	160
Total Labor Hours :		160

Appendix F: Report of Corrosion Coupon Data*

December 24, 2011
Mr. Robert Mason
Concurrent Technologies Corp.
7995 114th Ave.
Largo, FL 33773

Dear Mr. Mason:

This letter is a Final Report on work we have been conducting for CTC on the subject of Corrosion Monitoring on Two Bridges. At the time this report is being written, one set of samples remains on the I-20 bridge in Vicksburg. This set is not scheduled to be removed until mid-January. However, since this contract expires at the end of December 2011, we are sending this report with over 9 months of exposure data for this location. In the event that it appears the last set would add any new understanding, we will plan to update the graphs contained in this report.

This report covers the period from about November 2009 through December 2011, during which time monitoring was conducted.

Objectives

This work was conducted in support of the CTC project to instrument and monitor two bridges. Battelle's role in this was to use Battelle's corrosion monitoring methods to quantify the corrosive severity on the same two bridges.

Experimental

The procedures used in this work were identical to the monitoring techniques that Battelle has been using for the government to conduct similar corrosion monitoring worldwide for the last decade. This consists of the placement of 4"x 5" plastic cards in a small plastic rack at test sites. Each card holds a series of 0.5" x 3.0" metallic coupons. The coupons are silver,

* Text of signed letter from W.H. Abbott, Senior Research Scientist at Battelle of Columbus, OH.

copper, steel (1010), 6061 T6 aluminum, 2024 T3 aluminum, and 7075 T6 aluminum.

The general strategy that has been adopted is for a test card to remain in place for about 3 months. At that point the card is replaced, and this procedure is repeated over the course of about 1 year. The installations and card replacements are usually done by an on-site POC. The cards are returned to Battelle where the corrosion products are chemically removed for the determination of weight loss as the corrosion metric. The exception to this is the silver. Here the film(s) are analyzed by a technique known as cathodic reduction for the determination of the levels of atmospheric chlorides.

The two bridges that were monitored in this work were (1) the Government (Arsenal) Bridge at the Rock Island Arsenal, Illinois, and (2) the I-20 Bridge over the Mississippi river at Vicksburg, Mississippi. The intent was for Battelle to have samples installed to coincide with the installation of other instrumentation. The Rock Island Bridge was started first in December 2009. Due to lengthy delays associated with the I-20 Bridge this contract was extended several times. As a result, Battelle provided some additional samples to the rock Island location resulting in monitoring for more than the planned 1 year period. The monitoring on the I-20 bridge was finally started in October 2010.

During the course of this work, Battelle did several additional things beyond what was originally planned. First, an additional test package was added on the underside of the bridge at Rock Island. This location will be referenced as “Downstairs.” It is understood that the original placement was on the topside of the bridge (Upstairs). The reason for this addition was to determine if there might be any substantial difference in severity associated with winter deicing operations.

The second addition was the use of some Battelle passive corrosion sensors that were attached to the backside of the corrosion test cards. The sensors were read initially at Battelle and then measured again when the card was returned. The purpose was to add other sensors to the test system to determine if they might provide sufficient sensitivity for monitoring purposes at either or both locations.

Experimental Results

The data from these studies will be shown in graphical form to track the kinetic responses for the various metals. These data will be shown as cumulative weight loss for most of the metals and cumulative AgCl film thickness obtained from the silver.

The Battelle sensor data will be shown in terms of the cumulative change in digital voltage referenced to the starting sensor output.

Figure F1 shows the results from the silver coupons for the formation of AgCl. The fact that AgCl was found even for the inland site at Rock Island is not surprising as all Battelle studies have shown that atmospheric chlorides at some levels are ubiquitous.

Figure F1. Atmospheric chlorides at two bridges.

The data show large differences between the two locations. Since the levels at Vicksburg are higher it would not be surprising if the corrosion data show this location to be the more severe. Atmospheric chlorides are one of

the major drivers of corrosion, but this will be dependent also on the synergistic effects of several measures of water in the environment.

Figure F2 shows similar results for steel. As just discussed, it is not surprising to find a higher corrosion rate at Vicksburg. However, the differences are not as great as might be expected based on the differences in atmospheric chloride. Unfortunately, data were not obtained for humidity and rainfall from which estimates of corrosion rates might have been made.

With this said, it is useful to examine the absolute magnitudes of these values compared to data obtained in a similar manner around the world. Typical values for steel at sites judged to be severe might fall in the range above about 100,000 microgm/cm²/yr.

Figure F2. Corrosion of 1010 steel at two bridges.

The values for both of these locations are well below that. In fact based on Battelle data, both of these locations would fall below the median worldwide

levels with the Rock Island site below even the 25th percentile (i.e., mild severity).

Figures F3–F5 show similar results for three aluminum alloys at these bridges. The results are generally consistent with the expectations, based on the previous findings.

The kinetics as shown do not appear to follow any simple rate law. This is not surprising and could be due to seasonal effects. However, as a first approximation, the data might be judged as linear approximations, with the exception of the 6061 Al.

It is noted that the data are consistent with all other data obtained by Battelle for the relative reaction rates of these 3 aluminum alloys. Typically 2024 and 7075 are somewhat similar and 6061 is considerably lower. However, all rates are consistent with those for sites judged to be mild severity.

Figure F3. Corrosion of 2024 T3 aluminum at two bridges.

Figure F4. Corrosion of 7075 T6 aluminum at two bridges.

Figure F5. Corrosion of 6061 T6 Aluminum at Two Bridges.

The final data involve those for the corrosion sensors, as shown in Figure F6. In order to put these data in perspective, two comments should be made. First, on the vertical output scale, the minimum level of reliable detection is regarded as about 0.02 volts. The data are well above this level. Second, the output is directly proportional to the cumulative corrosion of the sensor material, and it has been shown from extensive field calibration work that these data are also proportional to the corrosion of steel and aluminum.

In summary, this work has successfully demonstrated that a simple passive corrosion sensor could be used for similar monitoring purposes.

Figure F6. Response of Battelle passive corrosion sensors at two bridges.

Conclusions

This work has successfully determined the corrosive severity at the two bridges being instrumented in the CTC studies. There were no surprises or

unusual features in the data. The environments at both bridges were judged to be mild in Battelle terms. This does not mean that bare metals will not corrode. Instead, it means that the rates were quite low compared to various sites worldwide.

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) June 2018		2. REPORT TYPE Final		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Remote Structural Health Monitoring and Corrosion-Rate Modeling of Steel Bridges: Final Report on Project F08-AR13				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER DoD Corrosion Prevention and Control	
6. AUTHOR(S) Steven C. Sweeney, Richard G. Lampo, Vincent F. Hock, and Robert B. Mason, Jr.				5d. PROJECT NUMBER F08-AR13	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Engineer Research and Development Center (ERDC) Construction Engineering Research Laboratory (CERL) PO Box 9005 Champaign, IL 61826-9005				8. PERFORMING ORGANIZATION REPORT NUMBER ERDC/CERL TR-18-10	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of the Secretary of Defense for Acquisition, Technology, and Logistics 3090 Defense Pentagon Washington, DC 20301-3090				10. SPONSOR/MONITOR'S ACRONYM(S) OUSD(AT&L)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT The U.S. Army maintains over 200 steel bridges. Conventional bridge in-spections do not always detect cracks or corrosion nor deter-mine if a crack is growing. The Office of the Secretary of Defense's Corrosion Prevention and Control (CPC) program funds demonstration and validation of technologies that reduce corrosion and related costs. Thus, there is an urgent need to assess state-of-the-art technologies and approaches for remote structural health monitoring (SHM) of steel bridges with strategically placed sensors, reliable data acquisition, and analytical software. These components measure critical parameters and reduce risks of catastrophic failure through advance warning. This report discusses successful demonstration/validation of a novel SHM system at two bridges. The systems monitored corrosion using several types of sensors and monitoring systems that transmitted data and alerts via web-connected computers. The ROI for this project is less than breakeven (breakeven ROI=1) due to high research and development costs associated with first-of-their-kind systems. Even so, the SHM system is recommended for implementation on bridges critical for Department of Defense (DoD) use. However, standardization of SHM systems across the DoD is not recommended due to rapidly changing technology. Systems must be designed for specific applications, and each design is greatly influenced by the target structure's existing issues and concerns.					
15. SUBJECT TERMS Iron and steel bridges—Corrosion, Iron and steel bridges--Maintenance and repair, Structural health monitoring, Structural analysis (Engineering), Detectors					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (in-clude area code)