Implementation of Structural Health Monitoring System

Final Report
February 2020

BRIDGE ENGINEERING CENTER

IOWA STATE UNIVERSITY
Institute for Transportation

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(InTrans Project 16-561)
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16. Abstract
Beginning in approximately 2000, the Bridge Engineering Center at Iowa State University, through projects funded by the Iowa Department of Transportation (DOT), the Iowa Highway Research Board, the Federal Highway Administration, and a transportation pooled fund (TPF) study, began the development of an autonomous structural health monitoring (SHM) system. The development of this system centered around the establishment of a monitoring system that could autonomously monitor and report on the condition of bridges. The first comprehensive SHM bridge project using continuous monitoring was on the US 30 Bridge over the Skunk River in Ames, Iowa in 2007.

It was specifically desired to have a system that could detect changes in structural performance due to damage, etc., allow for the determination of bridge load ratings, and help estimate remaining bridge service life. The system had already been demonstrated on one bridge on I-80 just west of Des Moines, Iowa and one bridge on I-280 just east of the Quad Cities near Milan, Illinois. Another system was scheduled to be installed on US 151 north of Dubuque, Iowa and Kieler, Wisconsin. Also, a portion of the system was installed as part of the reconstruction of the US 65 Bridge over the Iowa River in Iowa Falls, Iowa.

The initial purpose of this work was to further implement the developed SHM system on an additional I-80 bridge (over Cherry Creek) and to fully implement the system on the Iowa River Bridge.

Given the maturity and effectiveness of the developed SHM system validated over a significant time period in cooperation with the Iowa DOT and other states, the timing may be favorable for the Iowa DOT to consider implementing a permanent bridge SHM system program. If so, the most significant decisions for the Iowa DOT would include developing a comprehensive implementation process, including staffing.

Additional needs would require investment in hardware and software, as well as developing an overall effective process to utilize the SHM system.

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IMPLEMENTATION OF STRUCTURAL HEALTH MONITORING SYSTEM

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EXECUTIVE SUMMARY

Overall Goals

The overreaching goals of this project were as follows:

- Demonstrate the usefulness of Iowa's custom-built structural health monitoring (SHM) system on the management of bridges
- Document past and current research and the state-of-the-state related to the SHM of bridges in Iowa
- Outline what is needed to go forward in implementing a long-term SHM program using the system developed and validated to date

Background

The Iowa Department of Transportation (DOT) Office of Bridges and Structures continues to provide safe travel conditions on bridges in the state while maintaining critical infrastructure assets. Beginning about 20 years ago, the Bridge Engineering Center (BEC) at Iowa State University started working toward developing and evolving an autonomous SHM system to assess the safety of bridge structures and to determine the remaining life of bridges.

SHM provides an effective and efficient process to maintain the bridge inventory. The evolution of the SHM system includes monitoring of more than 15 bridges, with additional bridge projects in progress and planned.

While there are other structural health processing systems in the US, we believe our SHM system is the most comprehensive and effective system to date. An important aspect of the success of the SHM system is due to the strong partnership between the Iowa DOT and the BEC.

Project Description

These were the four tasks for this particular project:

- Design, configure, install, and calibrate an SHM system on the eastbound I-80 Bridge over Cherry Creek
- Calibrate the SHM system on the Iowa Falls Bridge
- Monitor trained SHM sites
- Document and disseminate information, including recommendations for long-term SHM implementation

Key Findings, Recommendations, and Implementation Benefits

Integration of SHM Data into a Holistic Bridge Preservation Plan

In general, it is already clear that bridge data collected from the SHM system has provided valuable information and insights. Bridge engineers will be able to develop ideas on how to use the data to understand bridge performance.

For example, the SHM system data could provide insights into the real-time data versus the actual design process used. Critical elements on a bridge could be evaluated using real-time data versus expected design behavior, thus gaining a better perspective. Furthermore, the real-time data can identify anomalies on the bridge (such as fatigue cracks or a bad bridge bearing), and alert bridge engineers that the bridge is not performing correctly.

Once a repair is made for an anomalous problem, subsequent real-time data can determine if the repair is effective. An important aspect of managing bridge performance (usually done by inspections of bridges every several years) is to develop a bridge rating to assure safety. Using the SHM system data, the bridge rating is continuously collected.

A more specific and exhaustive list of the information that the SHM system data can provide to bridge engineers is included in this report. An appendix includes an example of representative data that may be produced by the SHM system for use by Iowa DOT bridge engineers to better understand a bridge's performance.

Establishment of a Bridge Monitoring "Command Center"

A focus on data interpretation and quick response to bridge issues is important for a successful program. One possible format might be to create a new focus area (or similar) within the Iowa DOT.

Implementation Readiness

The Iowa DOT has already invested in implementing an SHM system for their bridges. There are multiple bridges in Iowa that have been "fitted" with the system, and there are considerable data collected to better identify bridge performance.

Given the maturity and effectiveness of the structural health monitoring system for bridges developed and validated over a significant time period in Iowa and other states to date, the timing may be favorable for the Iowa DOT to consider implementing a long-term SHM system program.

The most significant decisions for the Iowa DOT include developing a comprehensive implementation process, including staffing. Additional needs would require investment in hardware and software, as well as developing an overall effective process to utilize the SHM system. These are outlined in more detail in the last chapter of this report.

1. BACKGROUND

Beginning about 20 years ago, the Bridge Engineering Center (BEC) at Iowa State University (ISU) started working toward developing and evolving an autonomous structural health monitoring (SHM) system to assess the safety of bridge structures and to determine the remaining life of bridges. The evolution of the SHM system includes monitoring of more than 15 bridges, with additional bridge projects in progress and planned.

While there are other structural health processing systems in the US, we believe the ISU SHM system is the most comprehensive and effective system to date. An important aspect of the success of the SHM system is due to the strong partnership between the Iowa Department of Transportation (DOT) and the BEC.

Given the maturity and effectiveness of the developed SHM system validated over a significant time period in cooperation with the Iowa DOT and other states, the timing may be favorable for the Iowa DOT to consider implementing a permanent bridge SHM system program. If so, the most significant decisions for the Iowa DOT would include developing a comprehensive implementation process, including staffing.

Additional needs would require investment in hardware and software, as well as developing an overall effective process to utilize the SHM system. Subsequent chapters of this implementation document provide information documenting past and current research related to structural health monitoring of bridges in Iowa.

2. EVOLUTION OF THE DEVELOPMENT OF AN AUTOMATED SHM SYSTEM IN IOWA

The Iowa DOT Office of Bridges and Structures continues to provide safe travel conditions on state bridges while maintaining critical infrastructure assets. SHM provides an effective and efficient process to maintain the bridge inventory. The Iowa DOT partnered with the ISU BEC in conducting research related to developing and implementing SHM system processes. Brief information follows regarding several SHM projects in Iowa in cooperation with the Iowa DOT and the ISU BEC.

2.1 US 30 Bridge over the Skunk River

The first comprehensive SHM bridge project using continuous monitoring was in 2007. The Iowa DOT, in partnership with the BEC, began the process of implementing continuous monitoring of bridges to assure effective and safe bridge performance. The US 30 Bridge over the Skunk River in Ames, Iowa provided a good proving ground and a convenient location. Implementing full-scale testing in developing processes for SHM applications, including hardware and software development, were critical in evolving the SHM systems and processes.

First Generation SHM Bridge in Iowa

The US 30 Bridge has three spans with two equal outer spans (97.5 ft) and a longer middle span (125 ft), a width of 30 ft, and a skew of 20 degrees (see Figure 1).

Figure 1. US 30 Bridge over the Skunk River in Ames, Iowa

The superstructure consists of two continuous welded steel plate girders, 19 floor beams, and two stringers that support a 7.25 in. thick cast-in-place concrete deck. The bridge supports are pinned at the west pier and are roller-type supports at the east pier and at each of the abutments. The abutments are stub reinforced concrete and the piers are monolithic concrete.

This type of bridge is prone to cracks developing in critical connection regions and is typically described as a fracture-critical bridge (FCB). The developed FCB SHM system enables bridge owners to remotely monitor FCBs for gradual or sudden damage formation. This SHM system utilized Fiber Bragg Grating (FBG) fiber optic sensors (FOSs) to measure strains at critical locations.

The strain-based SHM system was trained with measured performance data to identify typical bridge response when subjected to ambient traffic loads, and that knowledge is used to evaluate newly collected data. At specified intervals, the SHM system autonomously generates evaluation reports that summarize the current behavior of the bridge. The evaluation reports are collected and distributed to bridge owners for interpretation and decision-making.

The SHM system consists of two main categories: an office component and a field component (see Figure 2).

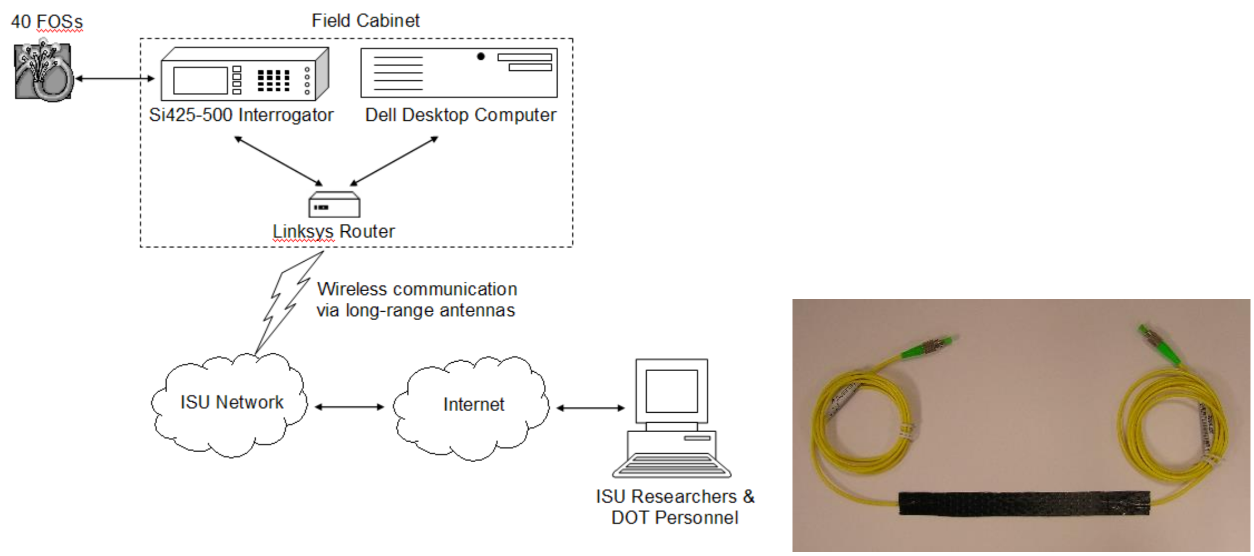


Figure 2. First generation SHM system for bridge monitoring: equipment/hardware (left) and fiber optic sensor (FOS) (right)

The office component has a structural analysis software program that is used to generate thresholds that identify isolated events. The field component includes hardware and field monitoring software that performs data processing and evaluation. The hardware system consists of sensors, data acquisition equipment, and a communication system backbone. The field monitoring software will operate autonomously with minimal user interaction.

In general, the SHM system features two key uses. First, the system can be integrated into an active bridge management system that tracks usage and structural changes. Second, the system helps owners to identify overload occurrence, damage, and deterioration. Online power service is provided at the bridge site.

Damage Detection Algorithm

In this work, a previously-developed, statistical-based, damage-detection approach was validated for its ability to autonomously detect damage in bridges. The damage-detection approach uses statistical differences in the actual and predicted behavior of the bridge caused under a subset of ambient trucks. The predicted behavior is derived from a statistics-based model trained with field data from the undamaged bridge (not a finite element model). The differences between actual and predicted responses, called residuals, are then used to construct control charts, which compare undamaged and damaged structure data.

Validation of the damage-detection approach was achieved by using sacrificial specimens that were mounted to the bridge and exposed to ambient traffic loads and simulated actual damage-sensitive locations. Different damage types and levels were introduced to the sacrificial specimens to study the sensitivity and applicability.

The damage-detection algorithm was able to identify damage, but it also had a high false-positive rate. An evaluation of the sub-components of the damage-detection methodology and methods was completed to improve the approach.

Several of the underlying assumptions within the algorithm were being violated, which was the source of the false-positives. Furthermore, the lack of an automatic evaluation process was thought to potentially be an impediment to widespread use. Recommendations for the improvement of the methodology were developed and preliminarily evaluated. These recommendations are believed to improve the efficacy of the damage-detection approach.

2.2 SHM Pooled Fund Project

A Federal Highway Administration (FHWA) Transportation Pooled Fund (TPF) project (with the Iowa DOT taking the lead) was implemented on the strength of the US 30 Bridge over the Skunk River project. Multiple DOTs and several federal agencies, including the FHWA and the U.S. Department of Agriculture (USDA) Forest Products Laboratory (FPL), were involved.

Three bridges were included in the pool fund project, with one bridge each in Iowa, Illinois, and Wisconsin. (A brief description of the bridge site for each of the bridges that were tested are provided later in this chapter). The multiple projects provided an important platform to continue to enhance the SHM system. Information below provides a summary of further development and evolution of the system through the pooled fund project.

Bridge Engineering Condition Assessment System (BECAS)

As noted above, the three additional bridge research projects funded by the pooled fund study provided opportunities to enhance the SHM system and further evolve the overall processes. The BEC developed advanced SHM software called the Bridge Engineering Condition Assessment System (BECAS).

The software eliminates the subjectivity of current inspection approaches, increases evaluation frequency from once every two years to continuously, virtually removes human error, bias, and limitations, and provides feedback that can be used to perform proactive, rather than reactive, preventive maintenance. An overview of the major components of BECAS, including the hardware and software suite, follows.

The BECAS hardware consists of off-the-shelf components integrated to form a network of state-of-the-art sensors, data collection equipment, data storage, and an N-tier data processing hub.

Three sensor types make up every BECAS installation: resistance strain sensors, temperature sensors, and global positioning system (GPS) signal collectors. In addition, sensors of multiple types can be integrated into the system (tilt, deflection, corrosion, acceleration, etc.) depending on any unique monitoring needs. The sensors are connected to an on-site data logger that has integrated filtering capabilities.

With read speed capabilities that approach 1,000 Hz, the data logger has the ability to collect the data as needed (high speed data collection is needed for vehicle identification and classification). On-board filtering capabilities added to each system helps to ensure that measurement noise is minimized.

To temporarily store, initially process, and then transfer the data to the main data processing hub, a mid-level desktop PC is connected to the data logger via wired Ethernet. An IP-based video camera is also installed at each BECAS site. This camera is set up to record (and temporarily store) a live video feed of the bridge (including traffic crossing the bridge).

One final key piece of the on-site hardware is an IP-based power switch. This power switch has multiple features that make it a useful part of the system. For example, the power switch allows remote users to power up or down individual system components from anywhere in the world. Second, in the event that the on-site system loses its connection with the internet, the power switch automatically reboots the on-site cellular modem until the system comes back on-line fully.

Once transferred from the bridge to the office, the data are stored at a networked location. Then, an N-tier system of computers automatically detects the presence of new data and processes the data. To create redundancy in the system and provide a lower-cost method of analyzing the data in real-time, a typical BECAS processing architecture consists of a workstation-class PC (the parent) plus one or more lower cost desktop PCs (the children). Given that currently available computers have multiple cores (i.e., processing threads), the BECAS described subsequently will parallel-process multiple files at once.

Demonstration Sites

All three bridges (Iowa DOT, Illinois DOT, and Wisconsin DOT) contain similar instrumentation including strain and temperature sensors. The data were collected at the bridge sites that include communication software and hardware to transmit the strain data to the home site (in this case, at ISU). The Iowa and Illinois bridges used solar power at the site and the Wisconsin bridge provided power directly at the site.

I-80 EB Iowa Bridge over Sugar Creek

The I-80 Bridge crosses the Sugar Creek near a weigh station in Dallas County, Iowa (see Figure 3).

Figure 3. I-80 EB Bridge in Iowa over Sugar Creek

The bridge has three spans with an overall span of 150 ft, with two end spans with spans of 61 ft and a center span of 78 ft. The bridge is a three-span continuous steel beam structure. This type of bridge is vulnerable to fatigue cracking in the vicinity of the welded cover plates. The bridge width is 38 ft, with a skew of 15 degrees. The bridge has a 7.5 in. thick concrete slab and steel girder W35x135 for exterior spans and W35x150 for the interior span.

Both abutments are stub concrete and the two piers are open two column concrete cantilever. They are supported on piling. The near abutment bearings are sliding metal plates. The bearings over the far abutment are fixed. The other bearings are rockers.

Figure 4 shows typical hardware associated with the SHM system.

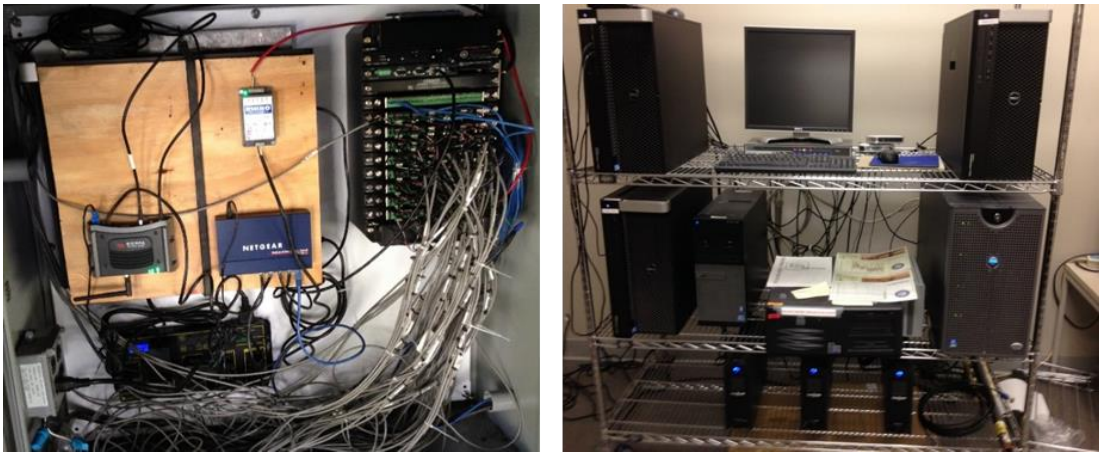


Figure 4. Field site and office site equipment for typical SHM system

The sensor bridge data are collected at the bridge site and stored in cabinets. The hardware at the bridge site includes data loggers and communication devices to transfer data to the office location for data processing.

Solar power may be constructed near the bridge site or power lines may be hooked up to it. If solar power is used, batteries need to store the power (see Figure 5).

Figure 5. Solar panels providing power to bridge sensors (left) and battery storage cabinets under the bridge (right)

Figure 6 shows a schematic plan view and cross-section view of the I-80 Bridge in Iowa over Sugar Creek.

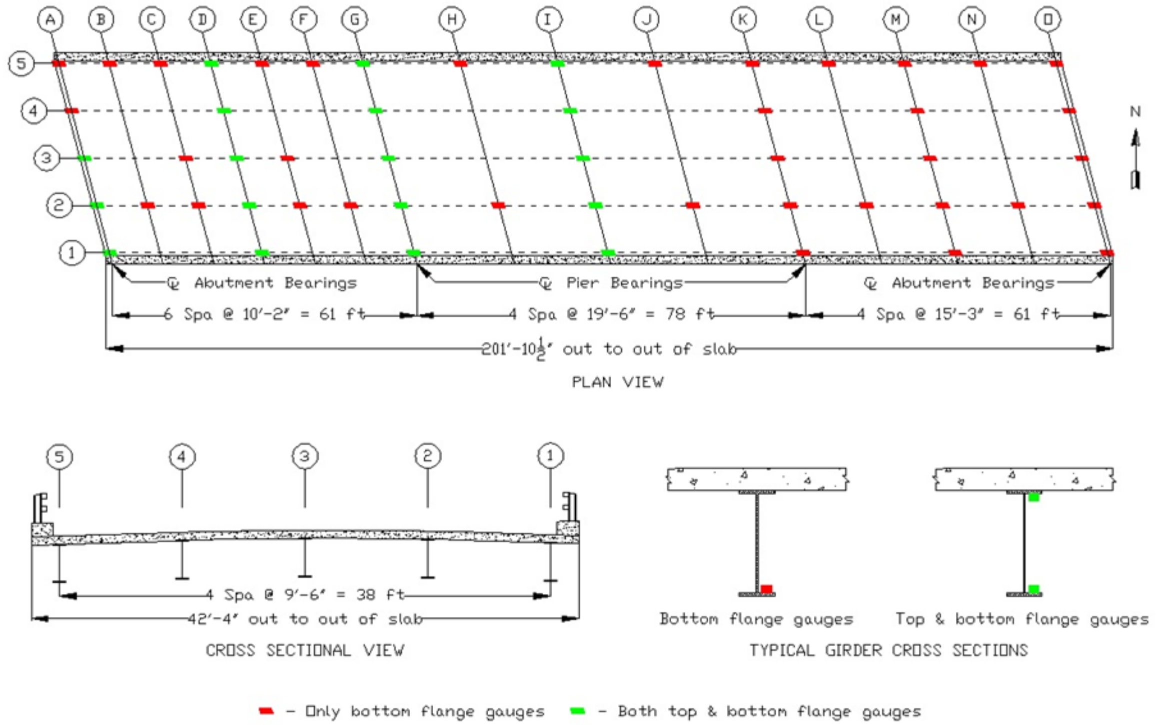


Figure 6. Instrumentation layout plan for girder gauges on I-80 EB Bridge over Sugar Creek

The girder sensor locations on the bridge are shown on the plan view and on a cross-section view for the various data plot locations. Some girder locations have a single strain gauge and the others have top and bottom flange gauges.

I-280 EB Illinois Bridge over US 67

The I-280 EB Bridge crosses US 67 near Milan, Illinois (see Figure 7).

Figure 7. I-280 EB Bridge in Illinois over US 67 near Milan

The structure is a two-span, continuous-steel stringer, multi-girder bridge. The overall span length is 208 ft 7 in. out-to-out of slab; each of the two spans are 103 ft. The bridge deck width is

44.7 ft with a deck slab thickness of 8 in. The bridge is on a 15-degree skew with a curve. The substructure is cast-in-place reinforced concrete units. The abutments are supported on concrete piles, and the piers are supported on spread footings on bedrock.

Figure 8 shows typical hardware associated with the SHM system, similar to the I-80 Bridge in Iowa.

Figure 8. Similar field site with field equipment and solar power for typical SHM system on the I-280 EB Bridge in Illinois over US 67 near Milan

As noted for the I-80 Iowa Bridge, solar panels provided power for the sensors on the I-280 Bridge. The schematic plan and cross-section view for the I-280 Bridge is shown in Figure 9.

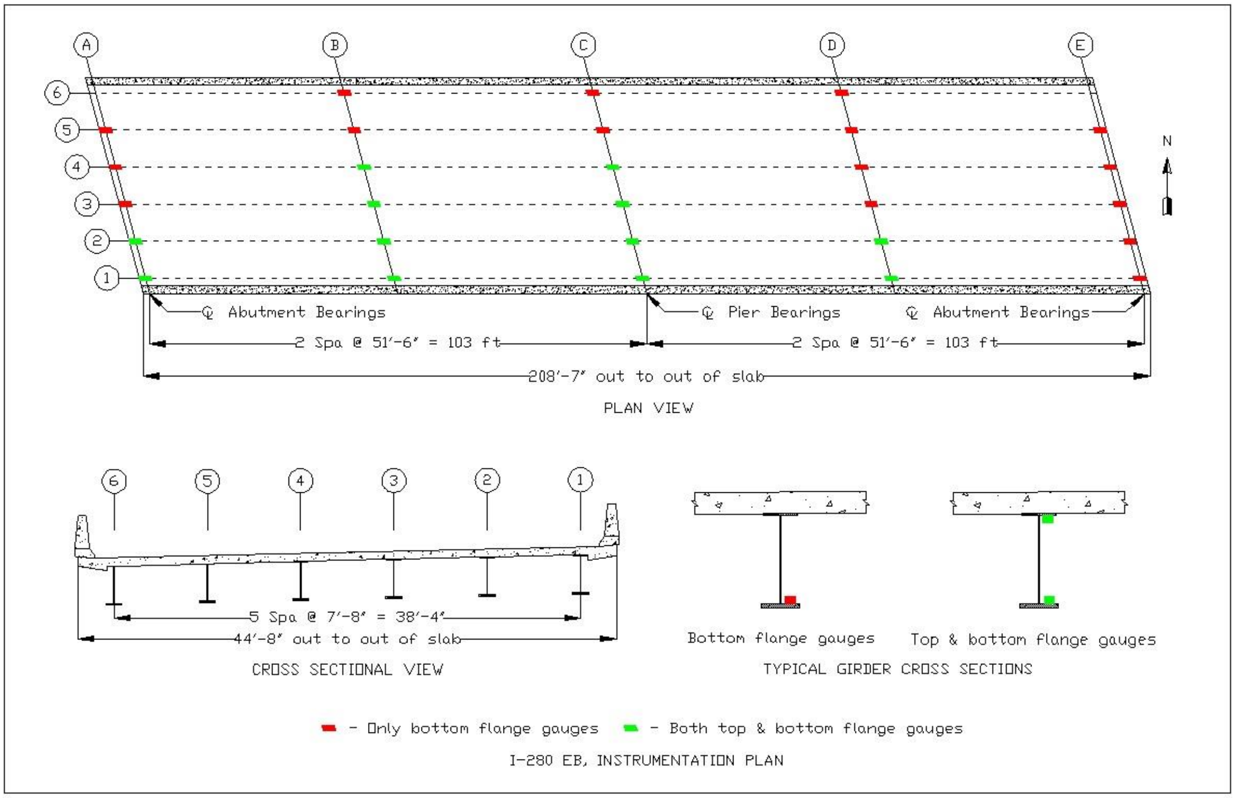


Figure 9. Instrumentation layout plan for girder gauges on I-280 EB Bridge over US 67 near Milan, Illinois

The sensor layout on the girders were arranged similar to the I-80 Bridge over Sugar Creek in Iowa.

US 151 NB Wisconsin Bridge over County Highway H

The US 151 bridge north of Dubuque, Iowa and Kieler, Wisconsin crosses County Highway H in Wisconsin. The overall span length is 127 ft. The structure is a three-span, prestressed girder bridge. The center span is 59 ft and each of the two outer spans are 42 ft long. The out-to-out width of the bridge deck is 43 ft, and the bridge deck is 9 in. in depth. The bridge is constructed on a curve. The two piers are supported on spread footings and both abutments are supported on HP 10x42 steel piles.

Figure 10 includes views of the bridge, and Figure 11 shows typical hardware associated with collecting, processing, and sending data to the office for final processing.

Figure 10. US 151 NB Wisconsin Bridge over County Highway H

Figure 11. Typical hardware equipment

Some of the typical equipment are shown in Figure 11 similar to the other two bridges. Unlike the other two bridges, electrical power service was supplied for the field equipment. Figure 12 shows the cross-section view of the bridge and the plan view with the layout of the strain sensors on the superstructure.

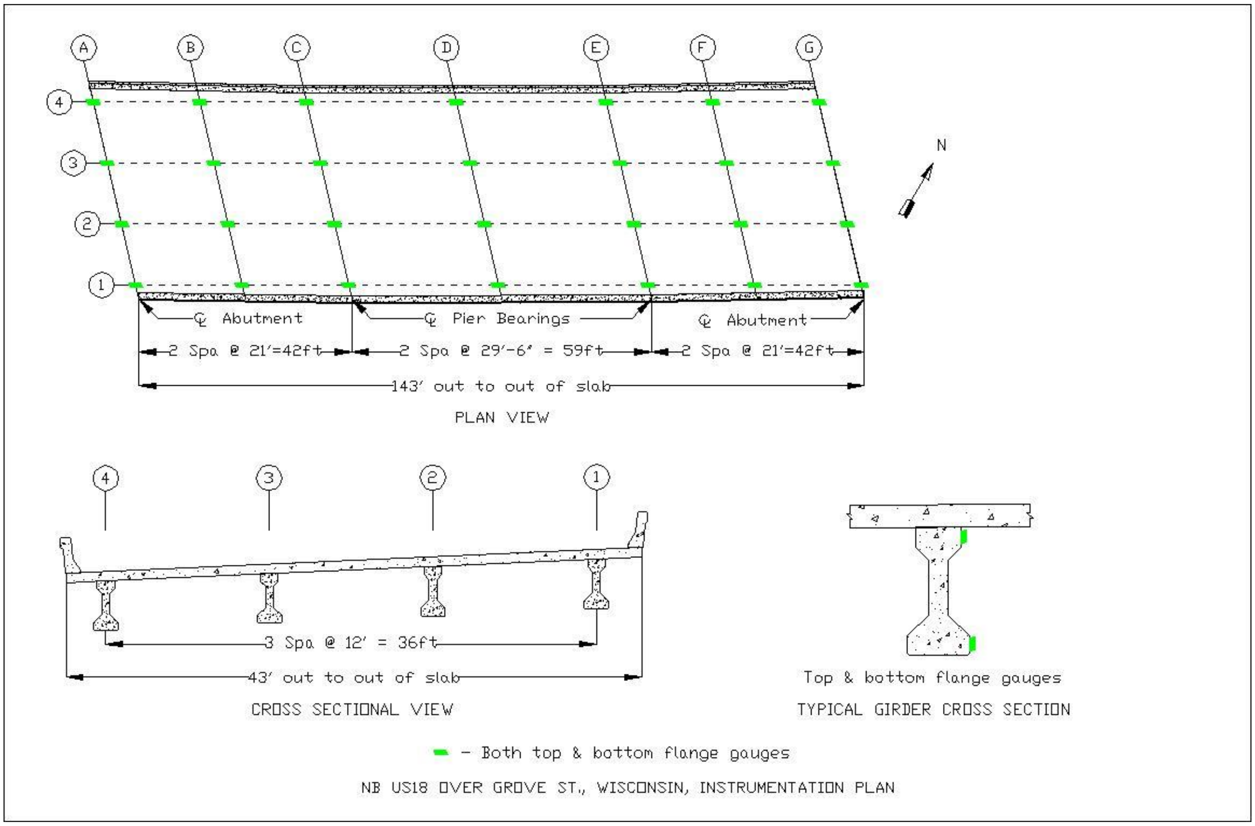


Figure 12. Instrumentation layout plan for girder gauges on US 151 NB Bridge over County Highway H in Wisconsin

3. IMPLEMENTATION PROJECT SITE DESCRIPTIONS

The Iowa DOT provided funding to the BEC for SHM monitoring of two additional bridges: the I-80 Cherry Creek Bridge near Newton, Iowa, and the US 65 (Oak Street) Iowa River Bridge in Iowa Falls.

3.1 I-80 Bridge WB over Cherry Creek near Newton, Iowa

The Cherry Creek Bridge on I-80 in Iowa is located in Jasper County approximately 1.2 miles west of junction IA 14. This bridge is a 158 ft x 30 ft steel beam structure built in 1962 carrying westbound I-80 over Cherry Creek and a waterway. The bridge is a three-span continuous steel girder structure and has a skew of 24 degrees. Both abutments are integral concrete and are supported on steel piling on rock. The piers are steel pile bents encased in a concrete wall with concrete caps. The pier bearings are fixed. This type of superstructure is vulnerable to fatigue cracking in the vicinity of the welded cover plates. The deck is portland cement concrete (PCC) overlaid with dense low-slump concrete in 1981. Both approaches are paved with PCC. Figure 13 shows views of the bridge.

Figure 13. I-80 WB Bridge over Cherry Creek

Overall Monitoring Process

The principal components for the bridge associated with the SHM system include a high-speed data logger, desktop-class PC (to control data acquisition), Ethernet switch and/or Ethernet router, various communication equipment including a 4G cellular modem, internet-based camera, land line power source, and workstation-class PC (for data analysis and strain and temperature sensors). Figure 14 shows equipment and sensors.

Figure 14. Field hardware and components: typical hardware for the SHM system (top), bridge deck strain gauges (center left), steel girder strain gauges (center right), and cabinet containing data and communication under the bridge site with power provided at the site (bottom)

The basic instrumentation plan included 56 strain sensors strategically placed throughout the superstructure, with eight strain sensors placed on the bottom of the bridge deck and 48 strain sensors placed on the top and bottom flange locations at seven cross sections, and three temperature sensors. Figure 15 shows the layout of the strain sensors on the bridge superstructure.

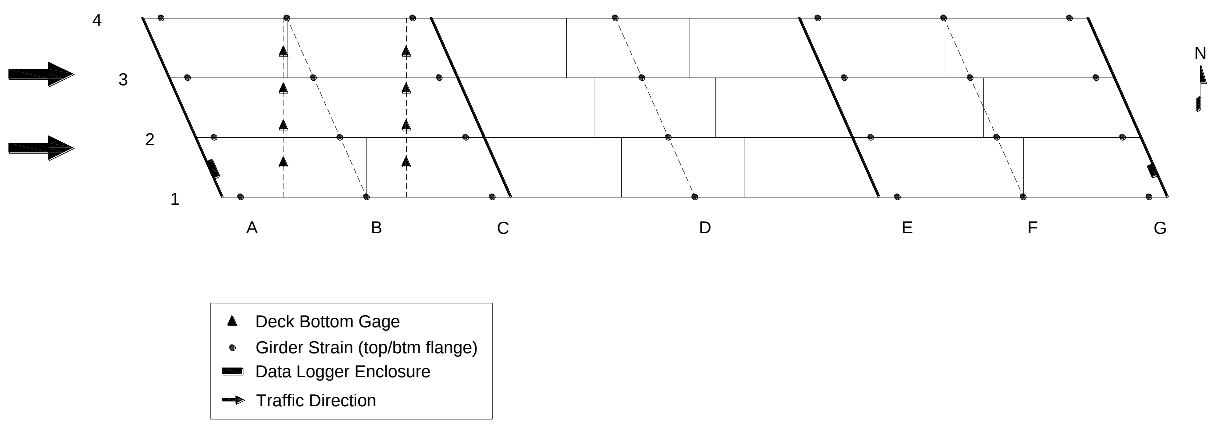


Figure 15. Plan view of the layout of strain sensors on the steel superstructure elements and sensors on the bottom of the concrete deck

The SHM system was trained and calibrated following established protocols. As appropriate, the various software applications mentioned above were installed and site-specific configurations established.

3.2 US 65 (Oak Street) over the Iowa River in Iowa Falls, Iowa

The recently constructed US 65 Iowa River Bridge in Iowa Falls (Hardin County) is a steel arch bridge with a span of 288.5 ft with a width of 42 ft. The bridge carries traffic over the Iowa River on the south side of the Iowa Falls downtown area. The deck is PCC with a 5 ft 2 in. sidewalk and an 11 ft 10 in. multi-use trail. Two lanes of traffic are carried each, northbound and southbound. The steel arch is supported at both ends of the bridge with a skewback foundation using a micropile foundation. The north and south abutments for the roadway also use a micropile foundation (see Figure 16).

Figure 16. US 65 Bridge over the Iowa River in Iowa Falls: view toward the north near downtown (top left), profile view over the Iowa River looking east (top right), and lower level of the superstructure of the bridge including floor beams, stringers, and deck (bottom)

Overall Monitoring Process

The instrumentation components were quite diverse, primarily due to the complexity of an arch bridge and the interest on behalf of the Iowa DOT to test various sensors for structural, environmental, and security data.

Sensor data that contribute to creating a more resilient structural system will provide better life service performance. Some of the sensors implemented on the bridge include monitoring moisture inside the steel arch rib to avoid corrosion, relative movement between the abutments of the bridge, arch rib and hanger forces, and sensors for many other superstructure elements.

The various sensors provided data such as wind speed and direction, bridge deck icing potential, and temperature and humidity, given that winter maintenance practices can contribute to efficient use of de-icing chemicals and reduction of bridge deterioration, increase public safety due to timely application, and reduce the impacts on the environment by using less chemicals if possible. Additionally, sensors monitored the potential for corrosion in the deck, the substructure at expansion joints, and micropiles and concrete anchors.

Data processing is an important part of the SHM system. A separate data logger was used for each application. Measurements from the fast-read gauges were completed using a Campbell

Scientific, Inc. CR9000X data logger, whereas measurements from the slow-read gauges were completed using a Campbell Scientific CR1000 data logger.

In addition to the loggers, other accessory pieces of equipment were needed to complete the data recording and processing. A Campbell Scientific, Inc. AVW200, 2-Channel Vibrating-Wire Interface was required for the data loggers to collect data from vibrating wire instrumentation such as rock bolt strain sensors and tiltmeters. Also, the Campbell Scientific, Inc. AM 16/32B Relay Multiplexer was used to increase the number of sensors that could be measured by the CR1000 data logger.

An HP Compaq 6200 Pro Microtower desktop computer and Campbell Scientific Inc.'s RTDAQ software were used on site to collect, store, and transmit the data from the data loggers. The software is specifically intended for high-speed data acquisition.

All of the equipment, along with other miscellaneous items (modem, Ethernet switch, battery backup, and power supplies), was housed in locked, waterproof cabinets mounted beneath the bridge on the south abutment wall near the southwest arch bearing. A home base, which included PCs and other hardware, accepted and organized the field data. Those data were then processed to provide the detailed bridge performance results. Figures 17 and 18 show the conceptual and actual equipment for the SHM system on the Iowa Falls Bridge.

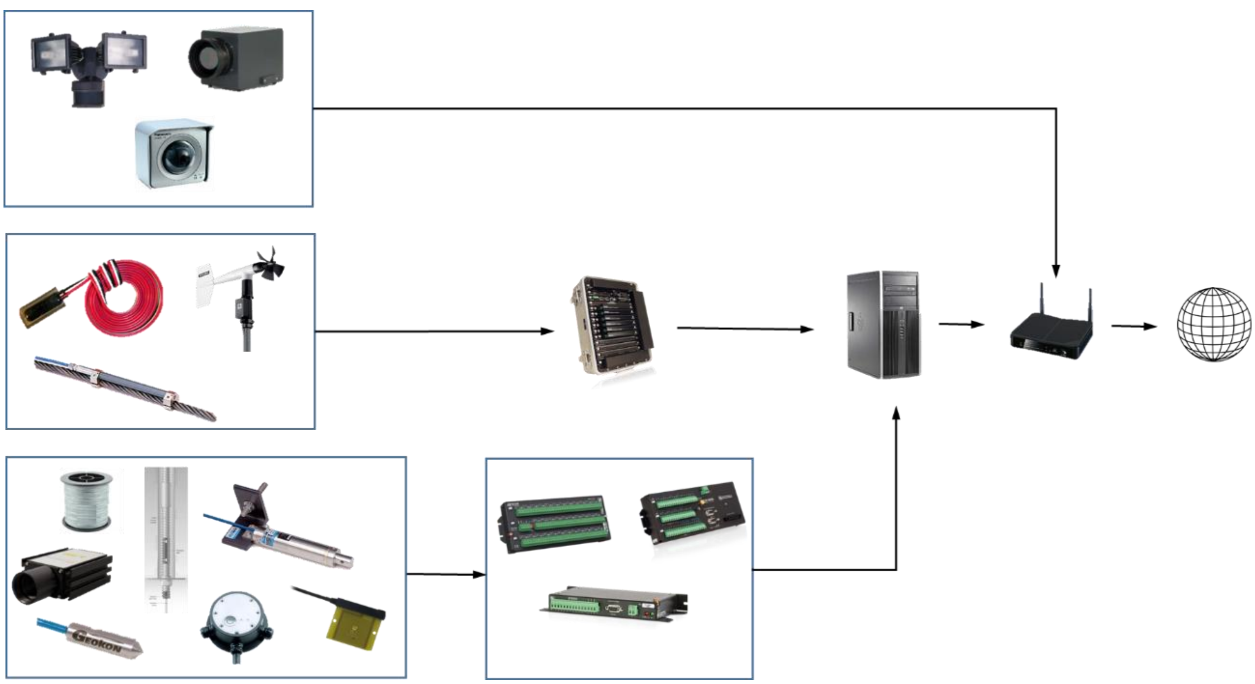


Figure 17. Structural monitoring system equipment and path to receiving the data at the home base (i.e., office)

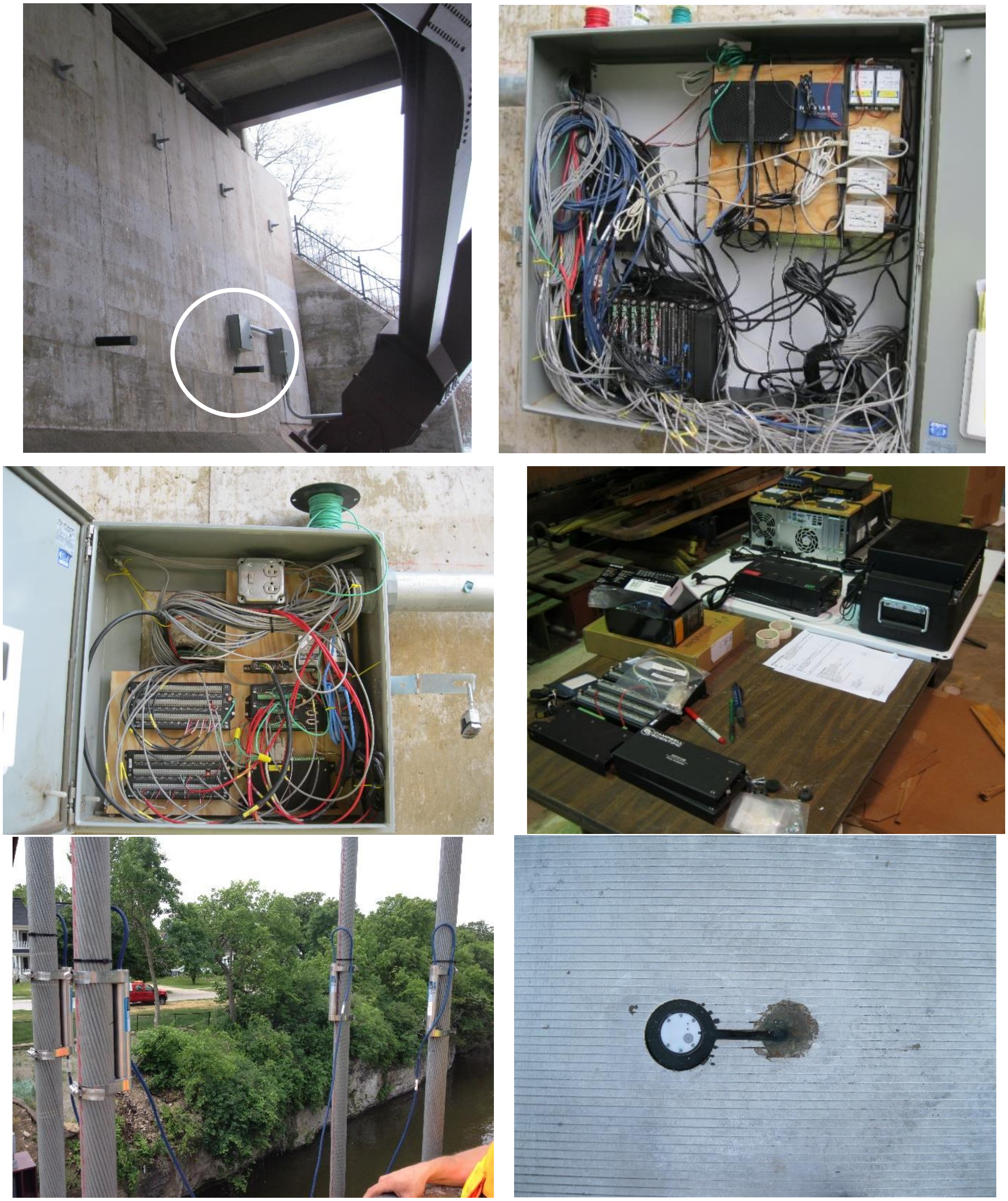


Figure 18. SHM system components associated with the US 65 Bridge over the Iowa River: data collected at the bridge site (top left), data logging equipment (top right), additional hardware (middle left), organizing home base to connect to ISU (middle right), strain gauges on hangers (bottom left), and bridge deck sensor placed in the deck (bottom right)

Figure 19 shows the locations of strain gauges on hanger members and the arch rib.

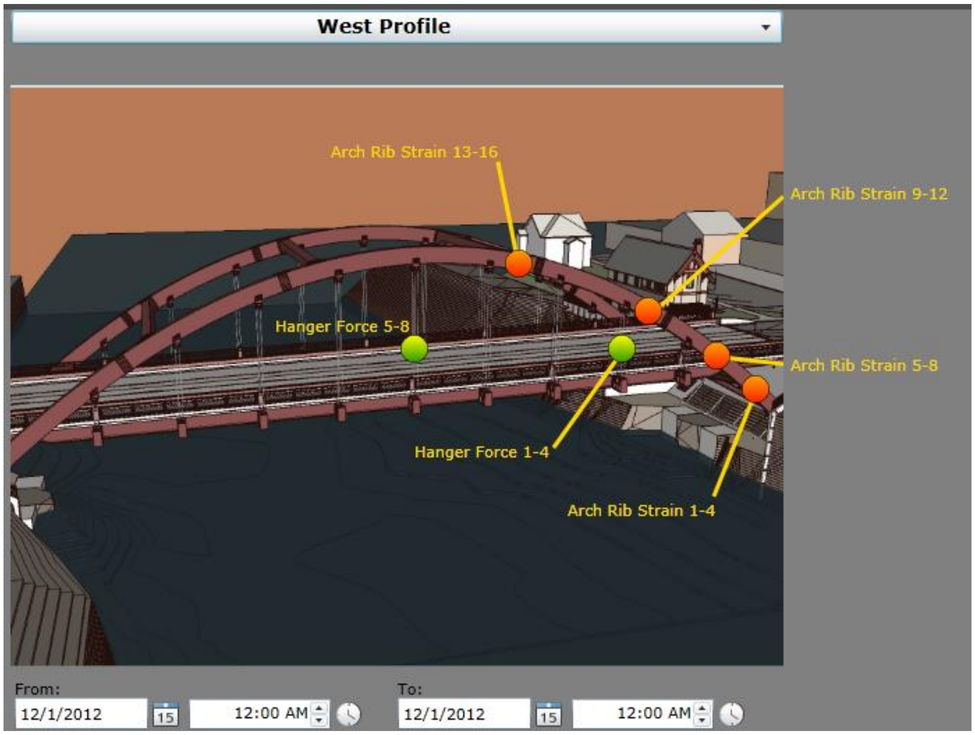


Figure 19. Locations of hanger members and the arch rib members on the bridge

Strain gauges on the lower portion of the bridge include those on the stiffening girder, floor beam, and stringers (Figure 20).

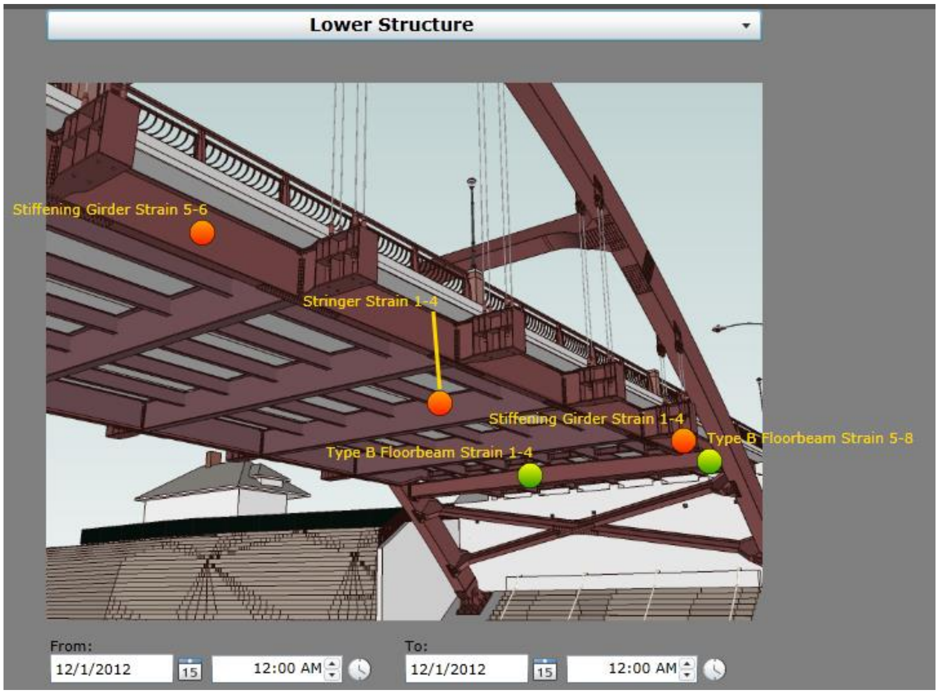


Figure 20 Strain sensor locations for the stiffening girder, floor beam, and stringer on the lower portion of the bridge superstructure

4. IMPLEMENTATION SITE RESULTS

Some representative SHM data for the I-80 Cherry Creek Bridge and the US 65 Iowa River Bridge are presented in this chapter. It is worth noting that there are three additional bridges coming on line in the near future that are part of Iowa DOT research and implementation projects. The bridges include the I-35 SB and I-35 NB bridges over the South Skunk River. Additionally, another bridge will come online in the near term on I-74 over the Mississippi River.

The SHM data provide significant information for assessing bridge condition in real time. A brief list of observations, as follows, are useful for bridge engineers and provides some general detail of how the data may be of use.

- Identify the percentage of truck events within a driving lane (e.g., the driving lane is typically very large compared to other lanes on a bridge).

- Identify the highest stressed location on a girder (which typically occurs in a driving lane). Inspections can be performed more effectively with these data.

- Identify bridge usage (based on one-minute maximum, minimum, and strain range). These data allow engineers to address fatigue in the bridge, particularly for fracture-critical bridges.

- Identify threshold exceedances, which can show that large strain events do occur with three or more trucks on a bridge at the same time. During construction activity, these can result in closing one of the normal traffic lanes.

- Identify load ratings with the collected data in real time, and the data can show changes in the load rating over time.

- Identify critical areas on the bridge using the long-term data. As an example, the strain data could alert the bridge engineer that a bearing is frozen or partially frozen. Over time, it is possible to create excessive stresses at the abutment.

4.1 I-80 near Newton, Iowa (Cherry Creek Bridge)

The Cherry Creek Bridge project provided further opportunities to fine-tune and expand the SHM system. This was the sixth bridge implemented using BECAS by the Iowa DOT. Identifying damage in the bridge was also an objective for monitoring this bridge. As the SHM system evolved, the intent was to improve the functionality of the system.

Selected Data

To demonstrate the type of data collected with the SHM system, several bridge girders were selected to show representative data plots. An arbitrary time-period of data collection was used to present data plots that began September 23, 2016. The data include 187,756 driving lane trucks detected, 12,643 passing lane trucks detected, and 137,000 load ratings calculated. A brief discussion of the results is presented below.

Figure 21 shows data that represent bridge usage or, more technically, helps bridge engineers to assess fatigue in the bridge.

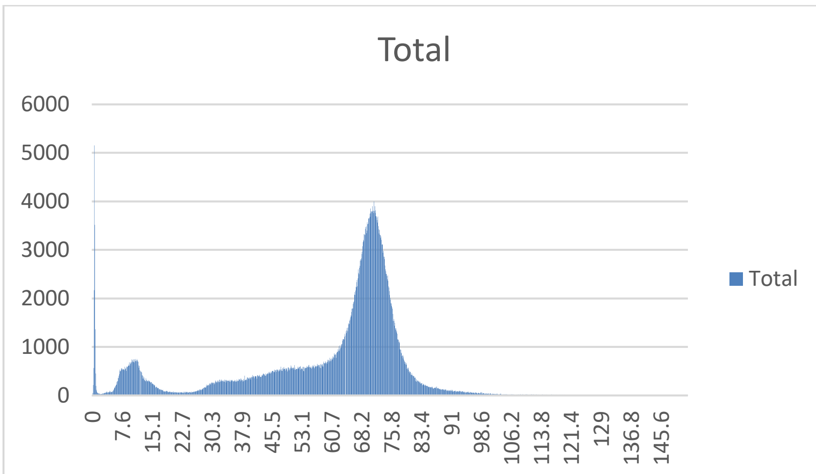
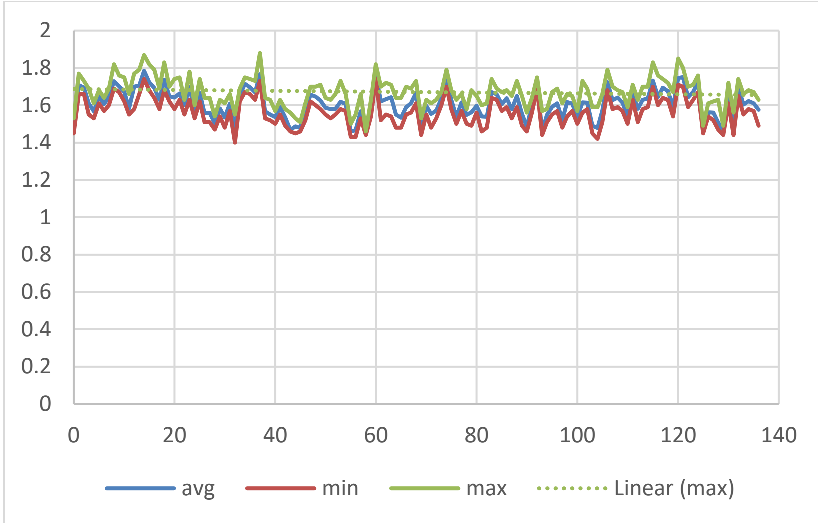


Figure 21. I-80 Cherry Creek Bridge usage (number) vs. microstrain

The plots are based on 1-minute maximum, minimum, and strain range, which are particularly useful for monitoring fracture-critical bridges.

The plot in Figure 22 shows the bridge load rating in real time.

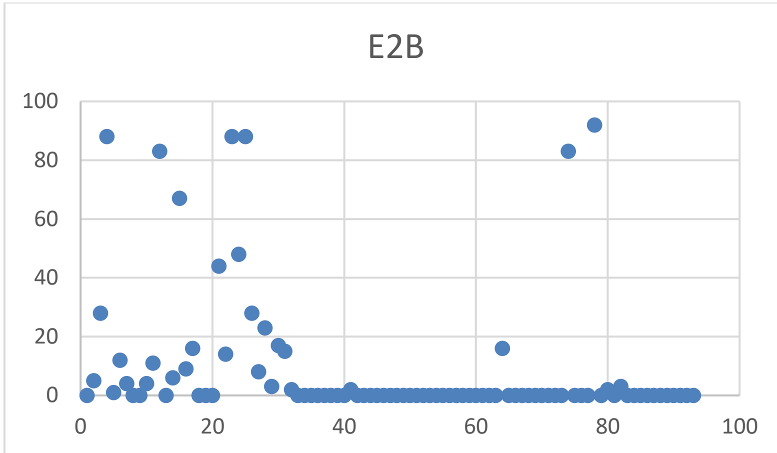


Relative date

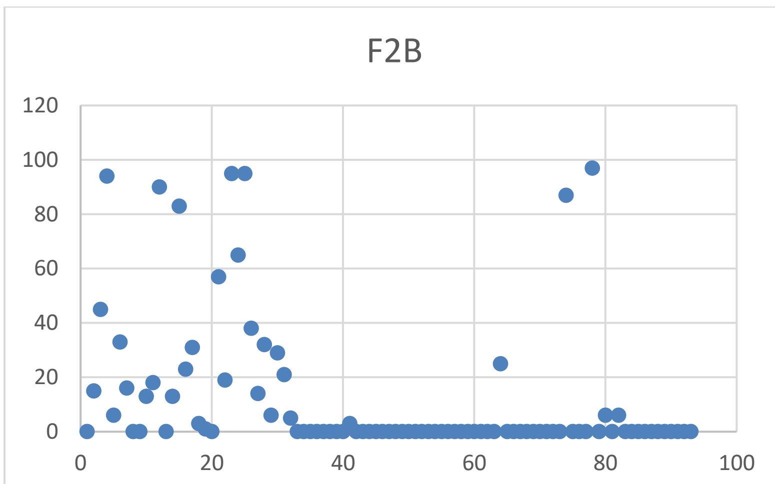
Figure 22. I-80 Cherry Creek Bridge load rating

The data are in the form of average, minimum, maximum, and linear maximum. The chart indicates that, over the time period associated with this plot, the load rating decreased (~0.01/year).

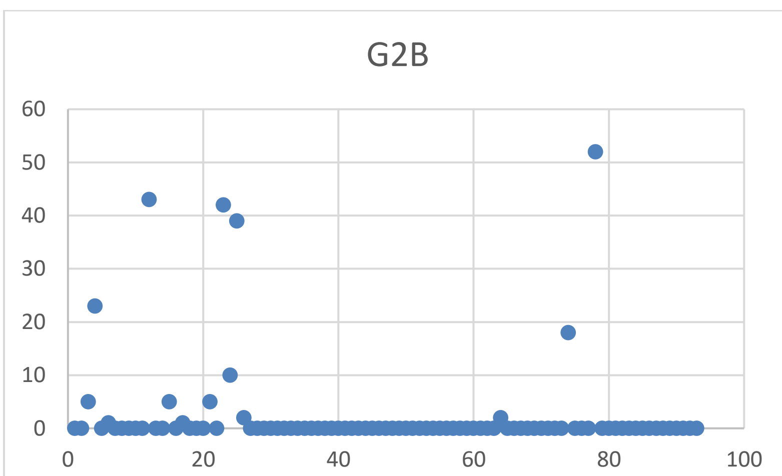
In general, the data plots below represent the stability, or lack thereof, of the bridge members' behavior over time. The locations on the bridge are in the first interior girder from the south and in the east end span of the bridge. Using probabilistic and statistical methods, the charts use strain data processed using a probabilistic method on a control chart. The three plots represent three separate locations on the bridge. The three data point locations on the bridge, E2B, F2B, and G2B, are shown in Figure 23, top to bottom.



Relative time



Relative time



Relative time

Figure 23. Behavior change – Beam 2, east end span, abutment bearing lock-up

Notice that, overall, the data show abnormal behavior because of the sporadic high number of test violations. The data points along the bottom of the plots at 0 represent the expected behavior.

The out-of-range data points suggest some potential structural issue. Oftentimes, a bridge bearing may be “frozen.”

4.2 US 65 over the Iowa River (Oak Street Bridge)

For this project, development and finalization of general hardware and software components for a bridge SHM system were implemented. The project was initially developed as a demonstration installation on the Iowa Falls Arch Bridge. The goal was to advance the SHM system to be ready for mainstream use by the Iowa DOT Office of Bridges and Structures.

The hardware system focused on using off-the-shelf sensors that could be read in either fast or slow modes, depending on the desired monitoring metric. As hoped, the installed system operated with very few problems.

In terms of communications—in part due to the anticipated installation of the SHM system on the I-74 bridge near the Quad Cities between Iowa and Illinois that was currently in progress—a hardline digital subscriber line (DSL) internet connection and grid power were used. During operation, this system transmits data to a central server location where the data are processed and then archived for future retrieval and used via the described database, visualization, and retrieval tools.

Through the US 65 (Oak Street) Bridge over the Iowa River demonstration project, it was observed that the biggest hurdle to widespread use of a system like this is storage of historical data. The data are being collected at relatively high-speed rates, and a very large volume of data are collected on a daily basis. Although, from an operational perspective, this is not an insurmountable problem, there are difficulties associated with physically storing this much information. As a result, for future installations, it is recommended that the Iowa DOT develop a policy regarding how long historical data should be retained.

Selected Data

To demonstrate the format and usefulness of the data collected with the SHM system, data are shown below. Figure 24 shows the real-time strain in the concrete bridge deck at one location (Deck Strain 2).

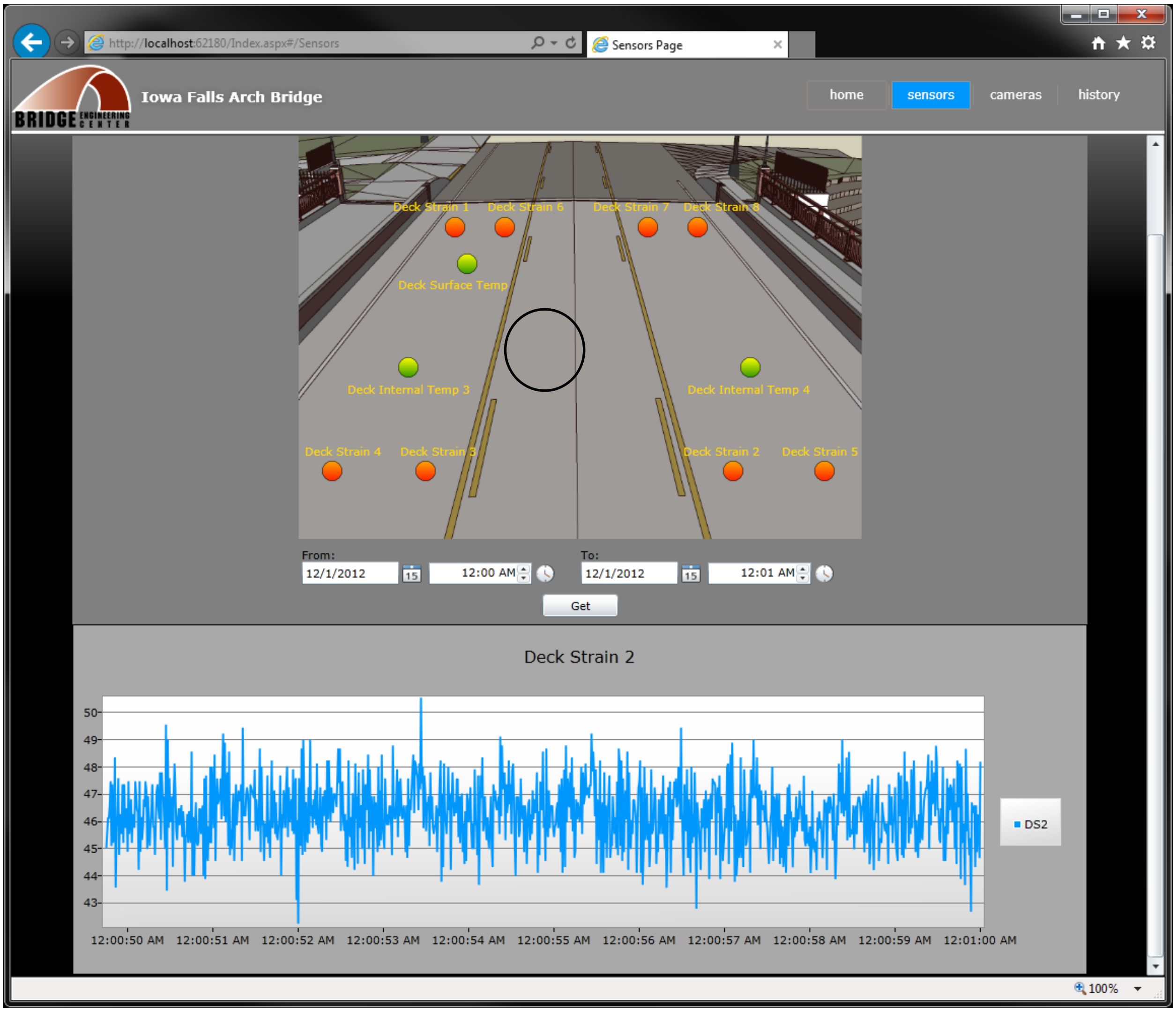


Figure 24. Iowa Falls Bridge data website sensor timespan results

Conversion of the strain data provides insight into the bridge deck performance. Figure 25 shows the south abutment camera live view underneath the bridge, which also houses the equipment cabinets that store the data collection system on-site, and the live traffic flow is viewed using the Roadside camera display located near the southbound lane.

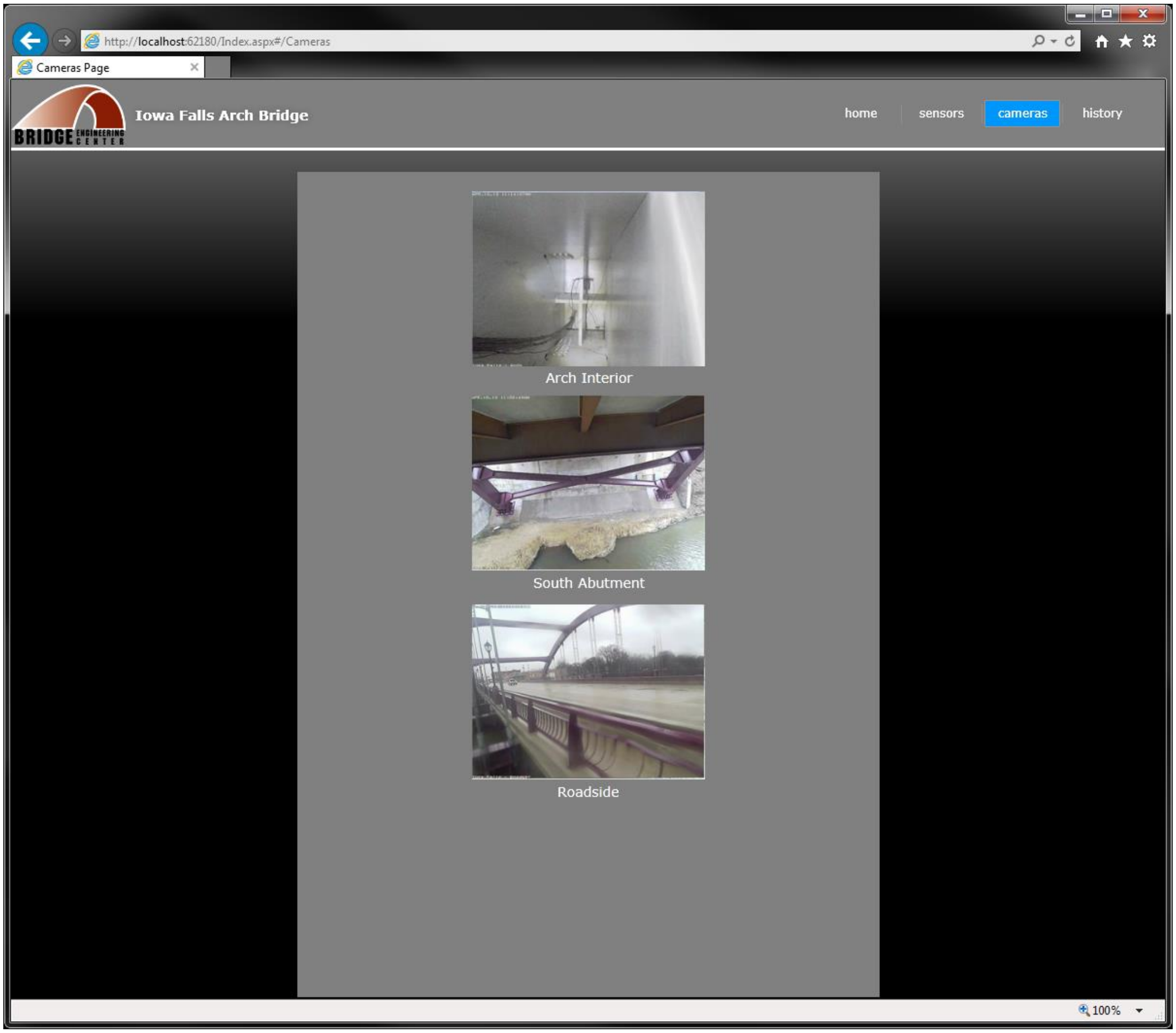


Figure 25. Iowa Falls Bridge data website camera selection

A third camera display, Arch Interior, is contained within the southwest base of the arch and is focused on the area of potential moisture build-up near the bottom of the arch. Real-time images provide a different type of important data to assess critical bridge elements.

5. RECOMMENDATIONS FOR LONG-TERM SHM IMPLEMENTATION

The Iowa DOT has already invested in implementing an SHM system for their bridges. There are multiple bridges in Iowa that have been "fitted" with the system, and there are considerable data collected to better identify bridge performance. Should the Iowa DOT have an interest in developing a more formal monitoring process than what has been developed to date, BEC would be interested in helping in any way.

Brief information about how the data may be useful to the Iowa DOT bridge inventory and some ideas are provided below.

5.1 Integration of SHM Data into a Holistic Bridge Preservation Plan

In general, it is already clear that bridge data collected from the SHM system has provided valuable information and insight. Bridge engineers will be able to develop ideas on how to use the data to understand bridge performance.

For example, the SHM system data could provide insights into the real-time data versus the actual design process used. Critical elements on a bridge could be evaluated using real-time data versus expected design behavior, thus gaining a better perspective. Furthermore, the real-time data can identify anomalies on the bridge (such as fatigue cracks or a bad bridge bearing), and alert bridge engineers that the bridge is not performing correctly.

Once a repair is made of an anomalous problem, subsequent real-time data can determine if the repair is effective. An important aspect of managing bridge performance (usually done by inspections of bridges every several years) is to develop a bridge rating to assure safety. Using the SHM system data, the bridge rating is continuously collected.

More specifically, it would be useful to refer to the bulleted list of observations at the beginning of Chapter 4. Implementation Site Results, as repeated here:

- Identify the percentage of truck events within a driving lane (e.g., the driving lane is typically very large compared to other lanes on a bridge).

- Identify the highest stressed location on a girder (which typically occurs in a driving lane). Inspections can be performed more effectively with these data.

- Identify bridge usage (based on one-minute maximum, minimum, and strain range). These data allow engineers to address fatigue in the bridge, particularly for fracture-critical bridges.

- Identify threshold exceedances, which can show that large strain events do occur with three or more trucks on a bridge at the same time. During construction activity, these can result in closing one of the normal traffic lanes.

- Identify load ratings with the collected data in real time, and the data can show changes in the load rating over time.

- Identify critical areas on the bridge using the long-term data. As an example, the strain data could alert the bridge engineer that a bearing is frozen or partially frozen. Over time, it is possible to create excessive stresses at the abutment.

This list could serve to help bridge engineers better understand the value of the data collected.

5.2 Establishment of a Bridge Monitoring "Command Center"

A focus on data interpretation and quick response to bridge issues is important for a successful program. One possible format might be to create a new focus area (or similar) within the Iowa DOT.

I. Review and use of data

1. Daily
2. Weekly
3. Monthly
4. Bi-annually

Establishing a regular and reliable process will be critical.

II. Process and procedure of reacting to issued alerts

1. Analytics and response
2. Communication

Given the availability of instantaneous data, there is an opportunity to respond appropriately to anomalous data events. The software should include a warning in such cases. Some assigned bridge personnel should be as follows.

Background

Over about the last 20 years, the BEC has developed a comprehensive bridge SHM system in collaboration with the Iowa DOT. The Iowa DOT is interested in implementing a sustainable process to reliably assess Iowa DOT bridge assets in a more effective and efficient manner. The BEC would be pleased to submit a formal research proposal to the Office of Bridges and Structures to continue this work.

Staffing Format and Needed Personnel

There will be some challenges in implementing the SHM System Plan, particularly with regard to staffing models and other resources. The following provides brief general comments on how the Iowa DOT might achieve their objectives.

1) Hire consultants
Consultants in this technical area are very limited, and given the complexity of the SHM system(s) and processes, this approach would likely only be able to handle some of tasks required to implement a system completely.

2) Hire additional Iowa DOT staff
The Iowa DOT may not likely have the appropriate staffing to implement the SHM system process that the BEC has developed. They would need to hire additional staff with appropriate background, but that would be challenging given the complexity of the SHM system and data processing. Additionally, an investment in hardware and software would be required.

3) Expand the scope of the current existing programmatic relationship between the Iowa DOT and ISU
ISU has already developed a programmatic bridge research program with the Iowa DOT, and ISU has already implemented SHM on multiple bridges for the Iowa DOT. ISU would be able to use some of their current bridge staff and add some additional staff as well, depending on feedback from the Iowa DOT. The experience gained already by the BEC and the Iowa DOT would allow a very efficient and effective SHM process.

APPENDIX A: SAMPLE SHM SYSTEM BRIDGE PERFORMANCE DATA

An example of representative data that may be produced by the SHM system for use by the Iowa DOT bridge engineers to better understand the bridge performance follows.

Office of Bridges and Structures
Bridge Maintenance and Inspection Unit

STRUCTURAL MONITORING SUMMARY DATA

General Information

Date: 2/23/2016
Monitoring period: 7/9/2015 to 2/23/2016
Maximum bridge temperature: 98.8 degrees Fahrenheit
Minimum bridge temperature: 1.7 degrees Fahrenheit
Number of single truck events: 68,158 (driving lane), 5,066 (passing lane)

General Behavior Information

Maximum strain: 268.4	Location: D2_BF	Usage: 33,667,224 ue/yr
Minimum strain: -229.0	Location: D2_BF	Usage: -9,524,644 ue/yr
Maximum strain range: 329.9	Location: D2_BF	Usage: 43,200,576 ue/yr

Threshold Exceedance Summary

Total number of threshold exceedances
- Maximum: 557
- Minimum: 190
- Range: 158

Location of highest number of exceedances
- Maximum: D4_BF
- Minimum: M2_BF
- Range: M1_BF

Load Rating Summary

Initial Average Load Rating: 1.602	Critical Section: Exterior Girder, positive M region
Final Average Load Rating: 1.608	Critical Section: Exterior Girder, positive M region

Average Load Rating Rate of Change: -0.003 per year

Maximum Load Rating: 1.79	Critical Section: Exterior Girder, positive M region
Minimum Load Rating: 1.60	Critical Section: Exterior Girder, positive M region

See additional details

Behavior Change Summary

F-Test Results
- Maximum Violations: 164 Location: A2_BF

Strain Range Results:
- Maximum Violations: 2 Location: E3_BF

Behavior at Select Locations:

Location	Observed Behavior
A2_BF	High strains when temperatures are below freezing
E3_BF	Higher ranges of behaviors when temperature exceed freezing
A4_BF	Abutment bearing appears to lock-up at lower temperatures
A5_BF	Abutment bearing appears to lock-up at lower temperatures

See additional details

SUMMARY OF MONITORING OBSERVATIONS

During the monitoring period over 70,000 single lane events were identified with approximately 93% of the events occurring in the driving lane. It appears that the highest stressed location is girder number 2 (mostly under the driving lanes) and that the maximum stresses occur in the positive moment region. Maximum measured stresses in the highest stress region were measured to be just under 8 ksi. Maximum stress range at the maximum stress range location were measured to be just greater than 9.5 ksi. Maximum negative stress at this location (note that this a commonly positive bending location) were measured to be approximately -6.6ksi.

As a general measure of bridge usage, the 1-minute maximum, minimum, and strain range were collected throughout the monitoring period. These have been summed and then normalized to a yearly value. At the maximum strain locations, the normalized usage was Maximum=33,667,224 ue/yr, Minimum=9,524,644 ue/year, and Range=43,200,576 ue/year. As this is the first monitoring period no basis for comparison can be made. During subsequent monitoring periods these values will be reported to track changes in bridge usage.

During the monitoring period there were almost 900 threshold exceedances observed. The majority of these were due to the initial settings being too low. However video corroboration indicates that at times large strain events do occur with three or more trucks are on the bridge at a time. At various times during the monitoring period atypically configured trucks were observed to have crossed the bridge. These atypical trucks were common sources of threshold exceedances. For a period of time during the monitoring period there was construction activity just “downstream” of the bridge. These activities sometimes resulted in the closing of one of the normal traffic lanes.

The initial and final load ratings are essentially the same (approximately 1.61). Over the monitoring period the load rating was estimated to be between 1.60 and 1.79. In all cases, the load rating was controlled by the exterior girder positive moment capacity. The exterior girder is likely carrying a higher than anticipated load due to the presence of the relatively large barrier rail which increases the total stiffness at the bridge edges. This behavior is not one commonly assumed during design. The fact that the highest stress region (mentioned above) is not an exterior girder, indicates that the location of the normal travel lane is not inducing large loads in the exterior girders. Should the traffic pattern change, this behavior will certainly change. Over the monitoring period, the load rating tended to decrease slightly – reducing at a rate of 0.008 per year. However, during the monitoring period no reduction in capacity (due to loss of section, etc.) was taken into account.

The behavior of the bridge was generally consistent throughout the monitoring period with one exception – the west abutment. It has been consistently observed that the west bearings transitions from a “free” condition to a more “fixed” condition as the temperature drops. Even more, once the temperature drops below freezing the bearings tend to display a marked increase in lock-up. While this is not likely causing any significant problems, this behavior is not as intended and if allowed to continue or worsen, may result in excessive stresses at the abutment.

Expert Opinion Factor: 1.25

APPENDIX B: SHM IMPLEMENTATION PUBLICATIONS FROM BEC TO DATE

A list of Bridge Engineering Center SHM Implementation publications to date is included in this appendix. These are listed newest to oldest, with the publication years in boldfaced type, for each of the categories below.

Reports

Phares, B., S. Jayathilaka, Y.-J. Deng, L. Greimann, and T. Wipf. **2020.** *Development of a Structural Health Monitoring System to Evaluate Structural Capacity and Estimate Remaining Service Life for Bridges*. Bridge Engineering Center, Iowa State University, Ames, IA. https://bec.iastate.edu/research/in-progress/development-of-a-structural-health-monitoring-system-to-evaluate-structural-capacity-and-estimate-remaining-service-life-for-bridges/.

Lu, P. and B. Phares. **2018**. *Integration of Structural Health Monitoring into Multilayer Statewide Bridge Maintenance and Management Practices – SHM-Facilitated Condition-Based Maintenance (SHM-CBM) Prioritization System*. Midwest Transportation Center and Bridge Engineering Center, Iowa State University, Ames, IA. https://intrans.iastate.edu/app/uploads/2019/02/SHM_multilayer_statewide_bridge_mtc_and_mgmt_w_cvr.pdf.

Phares, B. M., J. Dahlberg, and N. Burdine. **2015**. *Implementation of a Pilot Continuous Monitoring System: Iowa Falls Arch Bridge*. Bridge Engineering Center, Iowa State University, Ames, IA. https://intrans.iastate.edu/app/uploads/2018/03/Iowa_Falls_Arch_Bridge_w_cvr1.pdf.

Phares, B. M., T. J. Wipf, P. Lu, L. F. Greimann, and M. Pohlkamp. **2010**. *An Experimental Validation of a Statistical-Based Damage Detection Approach*. Bridge Engineering Center, Iowa State University, Ames, IA. https://intrans.iastate.edu/app/uploads/2018/03/shm_validation_report_w_cvr.pdf.

Wipf, T. J., B. M. Phares, J. D. Doornink, L. F. Greimann, and D. L.Wood. **2007**. *Evaluation of Steel Bridges (Volume I): Monitoring the Structural Condition of Fracture-Critical Bridges using Fiber Optic Technology*. Bridge Engineering Center, Iowa State University, Ames, IA. https://intrans.iastate.edu/app/uploads/2018/03/steel-bridge-vol1.pdf.

Phares, B. M., T. J. Wipf, Y-S. Lee, and J. D. Doornink. **2007**. *Evaluation of Steel Bridges (Volume II): Structural Health Monitoring System for Secondary Road Bridges*. Bridge Engineering Center, Iowa State University, Ames, IA. https://intrans.iastate.edu/app/uploads/2018/03/steel-bridge-vol2.pdf.

Phares, B. M., T. J. Wipf, L. F. Greimann, and Y. S. Lee. **2005**. *Health Monitoring of Bridge Structures and Components Using Smart-Structure Technology: Volume 1*. Wisconsin Highway Research Program, Madison, WI. https://minds.wisconsin.edu/bitstream/handle/1793/6915/WHRP05-03_Final_Report_Volume_I.pdf?sequence=1&isAllowed=y.

Phares, B. M., T. J. Wipf, L. F. Greimann, and Y. S. Lee. **2005**. *Health Monitoring of Bridge Structures and Components Using Smart-Structure Technology: Volume 2*. Wisconsin Highway Research Program, Madison, WI. https://minds.wisconsin.edu/bitstream/handle/1793/6915/WHRP05-03_Final_Report_Volume_II.pdf?sequence=2&isAllowed=y.

Journal Papers

Seo, J., B. Phares, P. Lu, T. Wipf, and J. Dahlberg. **2013**. Bridge Rating Protocol Using Ambient Trucks through Structural Health Monitoring System. *Engineering Structures*, Vol. 46, pp. 569–580. https://www.sciencedirect.com/science/article/pii/S0141029612004488.

Lee, Y-S., B. Phares, T. Wipf, and F. Malhas. **2013**. Structural Health Monitoring with an Active Data Management System for Secondary Road Bridges. *ACI Structural Journal Special Publication SP-292*: *Structural Health Monitoring Technologies*. Vol. 292, pp. 6.1–6.14. https://www.concrete.org/publications/internationalconcreteabstractsportal.aspx?m=results&Publication=Special+Publication&volume=292.

Phares, B., P. Lu, T. Wipf, L. Greimann, and J. Seo. **2013**. Evolution of a Bridge Damage-Detection Algorithm. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2331, pp. 71–80. https://journals.sagepub.com/doi/10.3141/2331-07.

Phares, B., P. Lu, T. Wipf, L. Greimann, and J. Seo. **2013**. Field Validation of a Statistical-Based Bridge Damage-Detection Algorithm. *ASCE Journal of Bridge Engineering*, Vol. 18, No. 11, pp. 1227–1238. https://ascelibrary.org/doi/10.1061/%28ASCE%29BE.1943-5592.0000467.

Lu, P., B. M. Phares, L. Greimann, and T. J. Wipf. **2010**. Bridge Structural Health-Monitoring System Using Statistical Control Chart Analysis. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2172, pp. 123–131. https://journals.sagepub.com/doi/abs/10.3141/2172-14.

Non-Refereed Papers

Lee, Y-S., B. M. Phares, and T. J. Wipf. **2007**. Development of a Low-Cost, Continuous Structural Health Monitoring System for Bridges and Components. Proceedings of the 2007 Mid-Continent Transportation Research Symposium, August 16–17, Ames, IA.

Lu, P., B. M. Phares, T. J. Wipf, and J. D. Doornink. **2007**. A Bridge Structural Health Monitoring and Data Mining System. Mid-Continent Transportation Research Symposium, August 16, Ames, IA.

Lu, P., B. M. Phares, T. J. Wipf, and J. D. Doornink. **2007**. A Strain-Based Fiber Optic Bridge Structural Health Monitoring System. Proceedings of the Second International Conference on Structural Condition Assessment, Monitoring, and Improvement (SCAMI-2), November 19–21, Changsha, China.

Doornink, J. D., B. M. Phares, T. J. Wipf, and D. L. Wood. **2006**. Damage Detection in Bridges through Fiber Optic Structural Health Monitoring. SPIE Symposium on Optics East, The International Society for Optical Engineering, Photonic Sensing Technologies, October, Boston, MA, Vol. 6371.

Doornink, J. D., B. M. Phares, and T. J. Wipf. **2006**. Fiber Optic Structural Health Monitoring of Fracture-Critical Bridges. Paper published on the Symposium CD for the International Bridge Conference, June 12–14, Pittsburgh, PA.

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