Development of a Low-Cost, Continuous Structural Health Monitoring System for Bridges and Components

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ABSTRACT

The Iowa State University Bridge Engineering Center developed a low-cost, continuous structural health monitoring system that can be used to monitor typical girder bridges. The developed structural health monitoring system can be grouped into two main categories: an office component and a field component. The office component is a structural analysis software program that can be used to generate thresholds which are used for identifying isolated events. The field component includes hardware and field monitoring software which performs data processing and evaluation. The hardware system consists of sensors, data acquisition equipment, and a communication system backbone. The field monitoring software has been developed such that, once started, it will operate autonomously with minimal user interaction. In general, the structural health monitoring 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.

Key words: bridge—evaluation—low-cost—overload—structural health monitoring

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INTRODUCTION

The ability to monitor the condition of a bridge to ensure its safe usage and to be able to effectively manage its operation is of significant interest to bridge owners. Over the decades, the most widely used condition monitoring methods rely on subjective, incremental visual assessments or localized testing techniques. However, these techniques often require traffic control to be implemented and may not be sensitive enough to identify damage and/or deterioration over time. In order to address this issue, the Iowa State University (ISU) Bridge Engineering Center developed an autonomous, continuous structural health monitoring (SHM) system that can be used to monitor typical girder bridges. The developed system features two key uses. First, the system can be integrated into an active bridge management system to track usage and structural changes. Second, the system helps owners to identify overload occurrence, vehicle collision to the structure, damage, and deterioration.

Numerous tools and technologies (currently available as well as emerging) associated with SHM applications have been well publicized (Aktan et al. 2003; Phares et al. 2003). The main issue now facing the bridge engineering community is not the lack of technologies that are available for SHM application, but rather how to accurately analyze a target bridge or its members and how to process continuously collected data such that the useful information can be extracted and used. It is also important that a SHM system be capable of monitoring long-term phenomena as well as capturing short-term events. In addition, the output of a SHM system must provide clear, usable benefits to bridge owners rather than inundating them with massive amounts of disjointed data. Such a need requires the development of a comprehensive approach to data management that also includes the development of high-performance localized data processing and evaluation algorithms. Significant effort has been given in the work summarized here to include data processing and evaluation algorithms that are based upon strong engineering principles while also taking full advantage of advanced data processing techniques.

OBJECTIVES

The primary objective of this research was to develop a low-cost, continuous SHM system that can be used to monitor typical girder bridges for detecting and identifying overload occurrence, vehicle collision to the structure, changes in structural behavior, identification of damage and deterioration, and for tracking usage. These specific needs were established to give owners tools to better manage bridge assets and were accomplished by completing three distinct work tasks as follows:

- Development of live load structural analysis software
- Development of field data collection and analysis software that integrates with select data acquisition hardware
- Demonstration of the developed SHM system

The product of this work is a turnkey SHM system that consists of hardware and software components. The hardware consists of off-the-shelf components that have been integrated to work together. Two software packages were also developed that allow for effective system use. First, a structural analysis package was developed that allows for bridge specific system configuration. Second, data collection/analysis/reporting package was developed that operates without user intervention to monitor for the above mentioned reasons.

STRUCTURAL HEALTH MONITORING SYSTEM

An overall schematic for the SHM system is illustrated in Figure 1. The SHM system can be principally grouped into two main components: an office component and a field component. The office component is basically a structural analysis software package that can be used to generate bridge-specific thresholds. The field component includes hardware and monitoring software which performs the data collection, processing, and evaluation. The hardware system consists of sensors, data acquisition equipment, and an optional communication system backbone. The field monitoring software was developed such that, once started, it will operate autonomously with minimal user interaction.

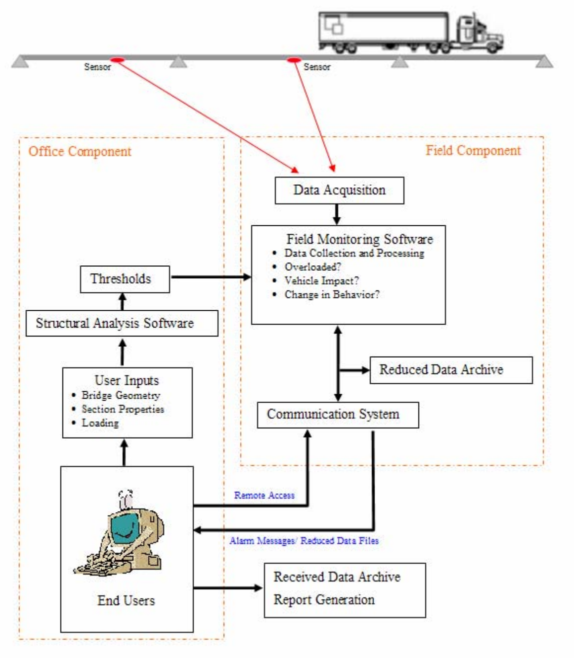


Figure 1. Overall schematic of SHM system

Structural Analysis Software

A Windows-based, two-dimensional, live load structural analysis program, BEC Analysis (see Figure 2), was created, using the Microsoft Visual Basic 6.0 programming language to simplify determination of some of the bridge specific SHM system parameters. BEC Analysis is capable of analyzing a bridge beam or girder with various boundary conditions and member geometries under various moving load conditions. One unique feature of BEC Analysis is that it allows users to easily determine maximum results (e.g., maximum moment and strain) at any location along the length of a bridge. In addition, it contains many convenient features which allow relatively quick analysis of a bridge. In general, one may use BEC Analysis for (1) analyzing beams or girders under moving loads, (2) computing absolute maximums in each span or at a desired location, and (3) generating envelopes of maximum moments and strains. The following summarizes some of the features that are included in BEC Analysis:

- Text fields and click-to-select options used to define bridge parameters
- Input defaults that will help novice users
- Library of various member cross section properties
- Calculator that computes section properties of virtually any member cross section
- Capable of analyzing up to ten spans

- Capable of modeling non-prismatic members
- Run multiple analyses without exiting the program
- Supports the American Association of State Highway and Transportation Officials (AASHTO) *Standard Specification for Highway Bridges*, Sixteenth Edition (AASHTO 1996)
- Supports various loading conditions
- Graphic diagrams
- Print/save results

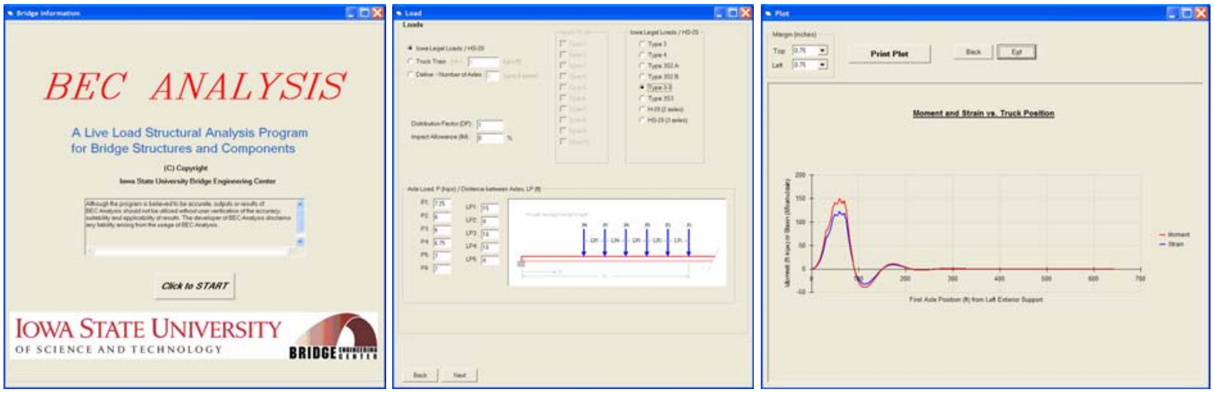


Figure 2. Example screen shots of BEC Analysis

BEC Analysis was designed to be used specifically for analyzing two-dimensional girder bridges subjected to moving loads. The commonly used two-dimensional stiffness matrix method was used as the computational backbone in BEC Analysis (Lee 2007). As a result, the program can determine the absolute maximum positive and negative moments and strains either in each span or at a designated location. In addition, envelopes can be generated. The envelopes contain the extreme values, both positive and negative, of moments and strains along the length of a model bridge. The results of the absolute maximums can be printed at the users' discretion. Moreover, users can review the analysis results graphically or save them for later review.

BEC Analysis consists of three modules: pre-processor, analysis, and post-processor. Each module was, respectively, developed to perform a certain task such as model generation, analysis, and result viewing. These three modules can be further categorized into six sub-groups: (1) Bridge Information windows (2) Span Description windows (3) Load window (4) Run Analysis window (5) Print/View/Plot windows. The pre-processor groups (1, 2 and 3) are used for data input, modeling, and on-screen graphic display. The analysis module (4) performs the analysis. The last module, postprocessor (5), was designed for reviewing the analysis results.

Field Monitoring Software

The field monitoring software (see Figure 3) was developed, in LabView 7.1, to function with IOtech instrumentation hardware (Lee 2007). The software was designed to collect, process, and evaluate the measured response of a bridge. Its use will allow bridge owners to quantitatively monitor a bridge for identifying overload occurrence, vehicle collision to the structure, damage, as well as gradual changes in behavior.

The field monitoring software consists of three groups of programs: (1) a preliminary data acquisition and analysis component intended for identifying basic characteristics, (2) a main data acquisition and processing component intended for data collection, reduction and evaluation processes, and (3) a report generation component intended for presenting results to the user. Each group of programs was designed to be accessed at any time. The preliminary data acquisition and analysis is a task that assists in reducing noise and detecting events so that only the pertinent strain information is obtained. It involves establishing the parameters that will be used during the data processing and evaluation processes that occur in other programs. The second group of programs controls the main data acquisition and the organization of the collected data and passes it to the processing components. During this process, collected data will be temporarily stored into designed segments and then internally passed through a series of data reduction programs in such a way as to allow the acquisition program to operate in real time while the processing programs operate in the background. These collected data are evaluated, reduced, written to a data file, and archived all within the local host PC. The results from the second group are a series of data files generated on a timely basis, each of which contains summarized information about the bridge performance. The third group of the field monitoring software is used for immediate viewing of summarized information and for generating reports.

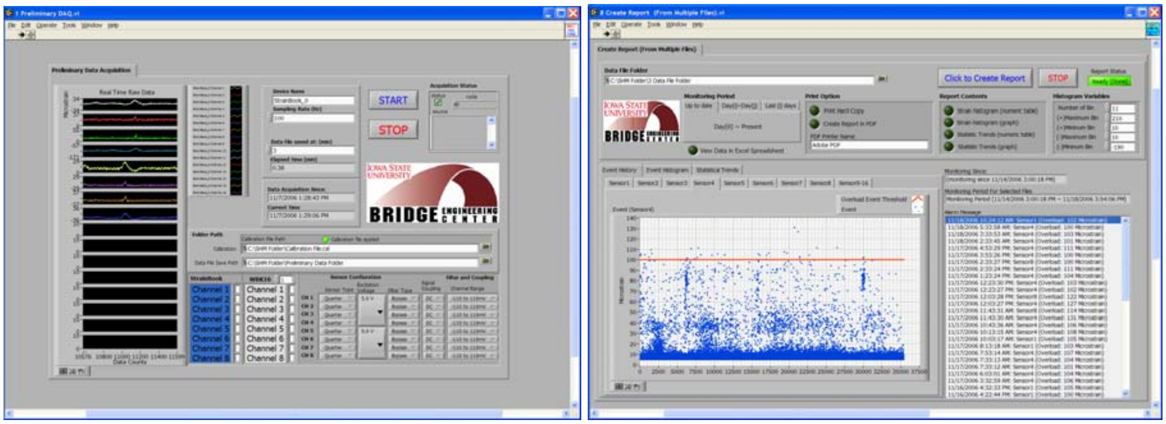


Figure 3. Example screen shots of field monitoring software

Monitoring Concept

An alarm event is determined by examining the peaks in a strain record. Alarm events can be generally thought of as either those caused by overloaded traffic, referred to as “overload,” and an abnormal rapid change in strain, referred to as “impact.” Some of the important terms that are used as the building blocks in the field monitoring software are defined as follows:

- Event: any peak in a strain record that exceeds a defined event detection threshold
- Alarm Event: overload event and/or impact event
- Overload event: event that exceeds the overload event threshold
- Impact event: event that that exceeds the impact event threshold.

In general, two steps are involved in the processing of the collected data: identification of events and examination of each event to see if it exceeds the predefined thresholds (Lee 2007). First, any peak in a measured strain record that exceeds the event detection threshold will be identified as an event. Once the event is detected, the software examines its magnitude in strain and the slope of the strain record that contains the event. If the event exceeds the overload event threshold, which can be determined using BEC Analysis or any other means, it will be recorded as an overload event. The impact event is identified by examining the slope associated with the event. If the slope exceeds the impact event threshold (possibly due to a vehicle collision to the structure), it will be recorded as an impact event. Identification of the impact event involves examining three parameters: the start index, the peak index, and the event. As illustrated in Figure 4, each parameter is expressed with b_i and y_i components, where b_i represents the time that the index or the event is recorded, while y_i represents their magnitude in strain. These three parameters are used to find the slope within the strain record that contains the event. The slope of an event can be defined as the ratio of the absolute difference between the magnitude of an event and that of an event detection threshold with respect to the time difference between a start index and a peak index. The slope can be determined as follows:

$$Slope = \frac{y_2 - y_1}{b_2 - b_1} \qquad (1)$$

Once the slope is determined, the software checks to see if the slope exceeds the predefined impact threshold. If exceeded, the software will recognize the event as an impact event. Note that the impact event threshold must be defined prior to running the field monitoring software (Lee 2007). This may require collecting sample strain data from ambient traffic to establish an appropriate strain rate.

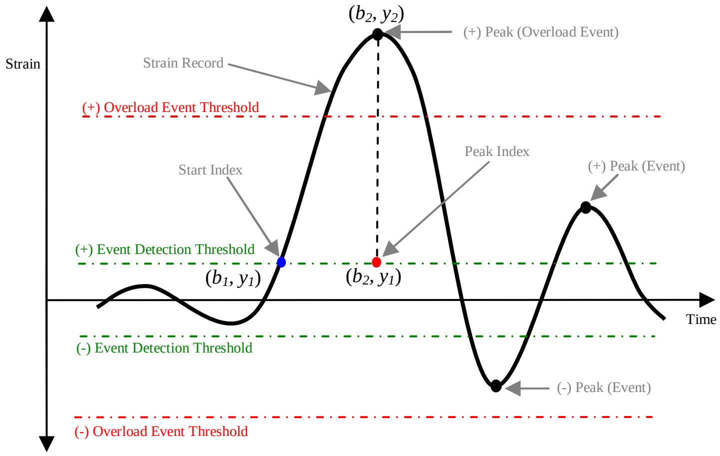


Figure 4. Parameters used to determine a slope in a strain record

The approach for compensating the temperature variations used here is based upon the idea that thermal expansion and contraction are very slow in comparison to changes associated with live loads. Therefore, one may assume that the change in strain due to temperature variations within a short period of time is insignificant. With this consideration in mind, it was decided that the strains be processed in small segments so that the temperature effects on each set of measured strains are minimal. To this end, the field monitoring software was developed to process measured strain segments every ten minutes (Lee 2007).

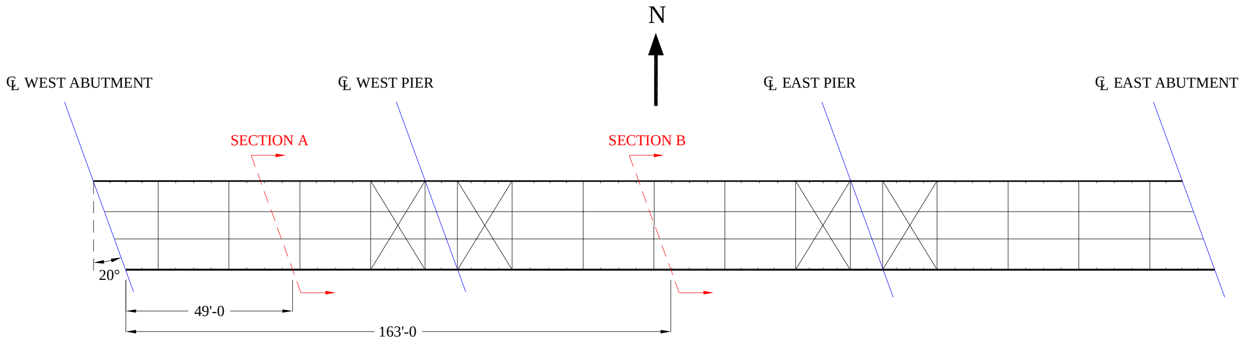
SYSTEM DEMONSTRATION

Once the development of the SHM system was completed, the system was tested and implemented on a highway bridge to demonstrate and verify its general usage. The bridge selected for demonstrating the use of the developed SHM system is the 320 ft. x 30 ft., three-span continuous, welded steel girder bridge shown in Figure 5. The bridge is located in central Iowa in Story County, Iowa, carrying US-30 over the

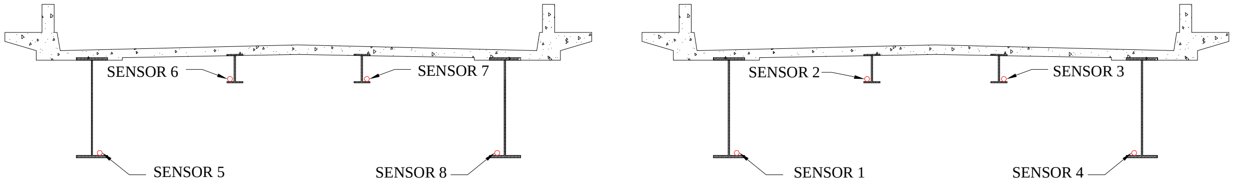
Skunk River near Ames, IA. The primary structural members are the two plate girders as the stringers are supported by floor beams which are then supported by the plate girders. The complete SHM system that was installed on the bridge uses an onsite computer to run the field monitoring software (i.e., process collected data and monitor for events and notify users any alarm events). The basic hardware components include sensors, the data acquisition hardware, and a communication system (Lee 2007). The selected quarter-bridge strain gages were installed at strategic points on the bridge. The locations of the strain gages were selected based primarily upon a preliminary engineering assessment but also with consideration of accessibility. To this end, four strain gages (Sensors 5 though 8) were installed in the positive moment region of the plate girders and stringers in the center span and four sensors (Sensors 1 though 4) in the west end span as shown in Figure 6. Note that all sensors were installed on the top of the respective member bottom flange.

(a) Side view (looking south east) **(b) Bottom view (looking east)**

Figure 5. Overall bridge photographs



(a) Plan view with sections A and B



(b) Section A in the west end span **(c) Section B in the center span**

Figure 6. Bridge strain gage location and reference sections

The data acquisition, processing, and communication system consists of the StrainBook/616 data acquisition instrument, a 1 GHz Dell desktop host PC, and a Linksys wireless router. These hardware components were installed in an environmentally controlled aluminum cabinet, shown in Figure 7, to protect them from weather and vandalism. The cabinet was mounted on the north corner of the west abutment wing wall and was supplied with electrical power through direct feed from an existing underground line (Note: power could also be supplied by solar power). The cabinet is equipped with a light bulb, a fan, and two thermostats to provide temperature control.

The StrainBook/616 data acquisition instrument and the host PC were both connected to the Linksys router with Ethernet cables, creating a local area network that allows direct communication among the hardware components (Lee 2007). The network at the bridge site was then, due to fortunate proximity, connected to the ISU network via wireless communication. For wireless communication between the bridge site and the ISU network, an antenna was mounted on an overhead sign frame that is located at the west end of the bridge (Note: connection to a network like this is not required). With an Internet connection available, users are able to:

- Access the host PC and operate the SHM system from anywhere in the world
- Receive processed and reduced data files and/or to be notified of any alarm events (e.g., overload occurrence and/or vehicle collision to the structure) via email.

Figure 7. Aluminum cabinet mounted on the north corner of the west abutment wing wall

Prior to the running the field monitoring software, the overload event thresholds for the sensors installed on the plate girders were determined using BEC Analysis. In each run, the bridge was subjected to various moving loads that include Iowa legal trucks: H 20 truck, HS 20 truck, and truck trains. After filter parameters were determined and all input settings were established (Lee 2007), the main program designed for data acquisition and processing was initialized at approximately 3 p.m. on November 14, 2006, after which continuous data collecting and processing have been completely autonomous and have required no intervention except when reviewing and generating evaluation reports. The contents in the evaluation report that was generated by one of the field monitoring software programs were reviewed.

Each data point in the event history plot in Figure 8a represents an event identified by the data processing algorithm. Along with the maximum daily event and average event, a linear best fit trend line for each sensor is given (see Figure 8b). In general, a sloping line with time is an indication in a change in bridge behavior/condition. After reviewing the evaluation report, several observations and interpretations were made for overall bridge performance during the 30 days of monitored period as follow:

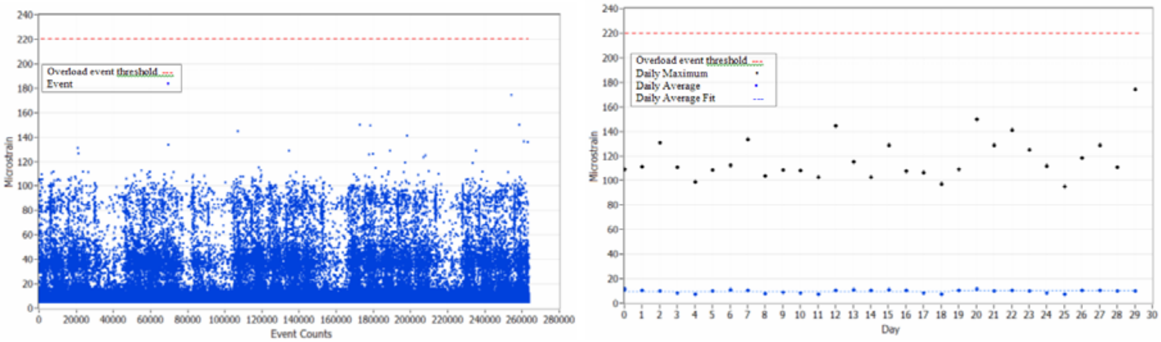
- No alarm event had occurred for the monitored period. The field monitoring software was programmed to list those events, if any, that exceed the overload event thresholds for each sensor, and no identified events exceeded the overload event thresholds that were set.
- The magnitudes of the daily maximum events fluctuate from day to day (see Figure 8b and Table

1). It should be noted, however, that the absolute maximums do not necessarily represent the gradual change in performance of the bridge. Rather, they simply represent individual events induced by “heavy” vehicles in different days.

- The daily average of identified event is less likely to show variability to single “heavy” traffic event (see Figure 8b and Table 1). Therefore, a gradual performance change can be estimated or predicted by investigating the daily average and the slope change over time. By reviewing the daily average of identified events for each sensor as illustrated in Figure 8b, it appears that the overall performance of the bridge was consistent for the monitored period (as would be expected). This observation was made by investigating the slope change (see Figure 8b and Table 2) of the daily average fit curve that is essentially zero for all sensors. If the condition of the bridge starts to change (due to deterioration, etc.) without a significant change in traffic pattern, the structural response of the bridge will also change and, therefore, the daily average is expected to change.

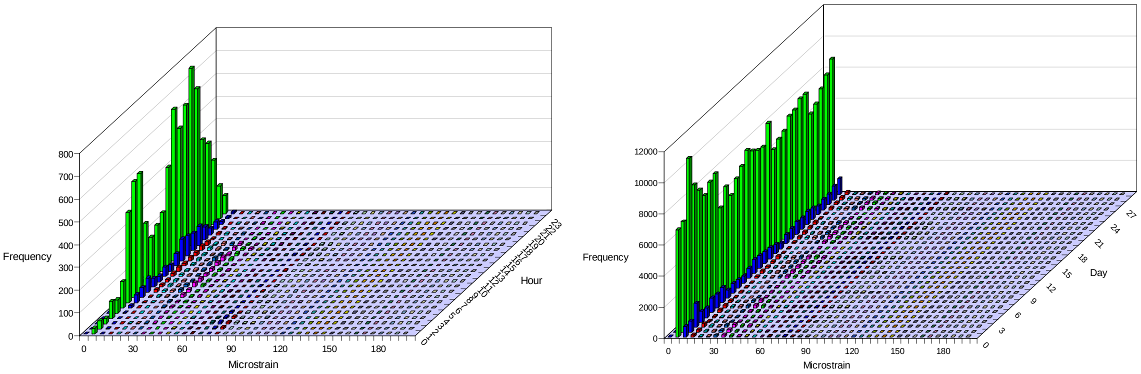
In order to provide hour-to-hour and day-to-day comparisons of the bridge response, 24-hour hourly event histograms and 30-day daily event histograms for Sensor 4 (typical of all sensors) were created and presented in Figure 9. After reviewing and comparing the histograms, several observations were made as follows:

- The numerical counts of identified events are different from hour-to-hour and day-to-day as expected. The variation in the number of identified events within the daily event histograms is less than that within the hourly event histogram. This was expected as hour-to-hour traffic patterns vary more than day-to-day traffic patterns.
- Although it does not represent exact traffic counts, the variation in the number of identified events within one chart is directly related to the traffic volume traversing the bridge in a given period.
- In all event histograms, there are dominant bins with high concentration of identified events.
- It is expected that, if the structural response of the bridge changes due to deterioration and/or damage with no significant change in traffic patterns, the dominant bins in the event histogram plot will be distributed across several bins and/or shifted.



(a) 30-day event history for Sensor 4 **(b) 30-day daily statistical trends for Sensor 4**

Figure 8. Monthly evaluation from Nov. 14th through Dec. 14th of 2006



(a) Hourly event histogram **(b) Daily event histograms**

Figure 9. Hourly and daily event histograms for Sensor 4 (bin width: 5 microstrain)

Table 1. Statistical trends (daily maximum/average in microstrain)

	Sensor1	Sensor2	Sensor3	Sensor4	Sensor5	Sensor6	Sensor7	Sensor8
Day 0	105/11	51/13	47/11	110/12	93/11	80/11	68/11	106/11
Day 1	102/11	41/12	46/13	111/11	99/11	76/11	71/11	105/10
Day 2	105/10	47/11	64/13	131/10	95/9	77/10	104/10	122/10
Day 3	102/9	41/12	47/13	111/9	91/9	74/9	68/8	93/9
Day 4	97/8	42/10	43/10	99/8	89/8	65/7	67/7	93/8
Day 5	105/10	37/11	47/13	109/10	88/10	68/11	73/10	106/10
Day 6	110/10	37/12	48/13	113/11	94/11	67/11	75/11	100/11
Day 7	137/10	51/11	53/12	134/11	112/10	80/10	101/10	110/10
Day 8	98/8	37/11	46/12	104/8	85/8	67/8	72/7	96/8
Day 9	165/10	41/12	45/13	109/9	156/10	84/10	74/8	103/9
Day 10	94/9	35/13	45/14	108/9	79/9	67/9	69/8	102/8
Day 11	82/8	34/10	39/11	103/8	75/8	54/7	62/7	91/7
Day 12	110/10	39/12	48/13	145/11	96/10	69/11	86/10	122/10
Day 13	119/10	38/12	52/14	115/11	124/10	71/11	86/11	103/11
Day 14	109/10	39/11	53/13	103/11	91/10	70/11	81/10	111/10
Day 15	130/11	78/12	91/14	129/12	114/11	69/11	82/11	100/11
Day 16	109/10	37/12	43/13	108/11	108/10	69/11	67/10	94/10
Day 17	101/9	38/13	46/14	106/9	87/9	66/9	69/8	99/8
Day 18	97/8	49/12	45/12	98/8	77/8	90/8	82/7	90/7
Day 19	104/10	35/11	45/12	109/11	90/11	65/11	71/10	104/10
Day 20	134/11	62/12	48/14	150/12	102/11	103/12	116/11	129/11
Day 21	107/10	40/11	41/13	129/10	96/10	69/11	74/10	134/10
Day 22	106/10	35/12	45/14	141/11	102/11	66/12	72/11	151/10
Day 23	126/10	50/11	54/13	125/10	99/10	92/10	90/10	131/10
Day 24	87/9	35/12	45/14	112/9	85/9	63/9	73/8	99/8
Day 25	86/8	36/11	39/12	96/8	79/8	57/7	62/7	84/7
Day 26	108/10	44/11	43/13	118/11	97/10	75/11	69/10	105/10
Day 27	109/10	40/12	46/14	129/11	98/10	68/11	70/11	109/10
Day 28	103/10	39/11	43/13	111/10	90/10	65/11	72/10	98/10
Day 29	141/10	48/12	58/13	174/11	120/10	96/11	97/10	167/10

Table 2. Overall summary of 30-day monitoring

Sensor	Overload event threshold (με)	Maximum event (με)	Average (με)	Daily average slope change
1	221	165	10	0
2	-	78	12	0
3	-	91	13	0
4	221	174	10	0
5	219	156	10	0
6	-	103	10	0
7	-	116	9	0
8	219	167	10	0

CONCLUSIONS

The following conclusions can be made regarding the cost, development, installation, and the overall performance of the SHM system:

- The developed low-cost SHM system is suitable for implementation of typical girder bridges. Excluding the communication and power equipments and research and development costs, the system can be implemented at the cost of $8,000 to $15,000 depending on the number of sensors used.
- The field monitoring software was developed such that it can handle up to 16 channels (one eight-channel StrainBook/616 plus one WBK16 eight-channel expansion module). Although the WBK16 was not included in the SHM system, its usage was tested during development.
- The installation of the strain gages and laying out the cables required no training or special equipment other than safety and normal access equipment. Although the time required for sensor installation was only around 30 minutes per gage including surface preparation, securing the sensor cable required more time and was relatively labor intensive. A two-man crew was used to install the strain gages and to secure the cables over a two-day period.
- Based upon comparisons with commercial analysis software, the live load structural analysis software, BEC Analysis, has been proven to be accurate.
- During a little over 30 days of monitoring period, the SHM system has performed as expected and has proven to be capable of continuously and autonomously monitoring the overall performance of the US-30 bridge.
- The SHM system has been proven to be a stand-alone, autonomous system capable of processing and evaluating the continuously collected strain data in the US-30 bridge.
- If properly implemented, the developed system will allow owners to monitor and control overloads and provide better access to valuable traffic information that can be used in planning, maintenance, and construction activities. Another benefit of the system is its relative ease of implementation and relative low cost. Overall, it is believed that the use of the SHM system developed herein will provide owners the tools to better manage bridge assets.

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