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LOW-COST STRUCTURAL HEALTH MONITORING WITH ADVANCED DATA MANAGEMENT SYSTEM

By

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Synopsis: This paper presents an autonomous SHM system that was developed to detect and identify overload occurrence, and changes in structural behavior. The SHM system utilizes a new approach to identifying and extracting useful information from large data files. By reducing the large data files into smaller packets of the most relevant information, data processing is greatly relieved, reliable analytical results are quickly achieved, and the long-term structural performance of the bridge can be presented to bridge owners in a clear format that is more easily understood and utilized. Improved data mining and evaluation procedures allowed the amount of saved data to be significantly reduced to less than 0.1% of collected data. In addition, this system showcases application and testing of traditional strain gage sensors, installation of the system components, and wireless communication from the bridge site to the owner for monitoring updates. The installation of the strain gages and cabling required no training or special equipment other than safety and normal access equipment. Excluding the communication and power equipment and research and development costs, the system can be implemented at the cost of $10,000 to $15,000 depending on the number of sensors used.

Keywords: Data reduction – Field monitoring – Strain – Structural health monitoring

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INTRODUCTION

Rapid advances in sensing, computing and networking technologies within the recent past have allowed structural health monitoring (SHM) to become a more popular way to improve bridge management. In short, SHM is the process of evaluating the condition or change in behavior of a bridge over time using quantitatively measured response data complemented with advanced data analysis. When properly designed, a SHM system has a distinct advantage over conventional monitoring techniques in that, at any point during monitoring period, the overall condition of the bridge can be evaluated without subjectivity and without the need to physically be at the bridge. While some tools and technologies associated with SHM exist[1, 2], the bridge engineering community is still facing a need for convenient and effective SHM systems. For example, manually analyzing structures is very labor intensive and an error prone task. Although structural analyses may be performed with commercially available software, it typically takes considerable effort and, therefore, it appears that engineers frequently desire easier-to-use structural analysis tools. For a continuous monitoring system, it is important to be able to effectively process a massive amount of continuously collected data such that the output of a SHM system provides clear, usable benefits to bridge owners rather than inundating them with massive amounts of disjointed data. It is also important that a SHM system be capable of monitoring long-term phenomena as well as capturing short-term events. In addition, an SHM system must be low-cost, fully autonomous and highly reliable to be of true value to the end users. In order to address these issues, a low-cost, autonomous structural health monitoring system that can be used to continuously monitor typical girder bridges under ambient traffic loads was developed.

The developed system features two key uses. First, the system can be integrated into an active bridge management system by tracking usage and structural changes. Second, the system helps owners to identify overload occurrence, vehicle collisions, damage, and deterioration. These specific features were established to give owners tools to better manage bridge assets and were accomplished by completing three distinct work tasks: (1) Development of field data collection and analysis software that integrates with select data acquisition hardware, (2) Development of live load structural analysis software, and (3) Demonstration of the developed SHM system. The product of this work is a turnkey SHM system that consists of hardware and software components. 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 SHM system was developed such that, once started, it will operate autonomously with minimal user interaction.

FIELD DATA COLLECTION AND ANALYSIS SOFTWARE

The first major task involved developing the field data collection and analysis software (Fig. 1) that integrates with select data acquisition hardware. The software was designed to autonomously collect, process, reduce and evaluate the measured bridge response. Its use allows bridge owners to quantitatively monitor a bridge for overloads, vehicle collisions, as well as gradual changes in structural behavior. Significant effort has been given to develop data processing and evaluation algorithms that are based upon strong engineering principles while also taking full advantage of advanced data processing techniques.

The field monitoring software consists of three groups of programs: (1) a preliminary data acquisition and analysis component for identifying basic characteristics (2) a main data acquisition and processing component for data collection, reduction and evaluation processes, and (3) a report generation component for presenting monitoring 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 identifying events so that only the pertinent strain information is obtained. This process 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 the collected data 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 a 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 programs is used for immediate viewing of summarized information and for generating reports.

Monitoring approach and concept

Continuous monitoring produces massive amount of data. Analyzing every byte of data is impractical since not only does it require significant processing time and resources, but also not every byte of data is useful to end users. Thus, significant efforts have been given to simplify the data processing, which will be illustrated subsequently, such that the field monitoring software identifies, extracts, utilizes and saves only the most useful information contained within each strain record. With this approach, the field monitoring software allows faster processing time and better use of available hard drive space.

For simplified, yet efficient, data processing, some of the important terms were defined as the building blocks in the field monitoring software 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.

An '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 an 'overload', and an abnormal rapid change in strain, referred to as an 'impact'. 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. 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 the live load strain magnitude and the slope of the strain record that contains the event. If the identified event exceeds the 'overload event' threshold, which can be determined using structural analysis software or any other means, it will be recorded as an 'overload event'.

The idea used for identifying the 'impact event' is that if there is a vehicle collision to the structure, one may expect a sudden or abnormal change in strain, as shown in Fig. 2, in which case the slope of the strain record will be far greater than those induced by regular traffic. The 'impact event' is identified by examining the slope associated with the event, which involves examining three parameters: the start index, the peak index, and the event. As illustrated in Fig. 2, 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 magnitudes in strain. These three parameters are used to find the slope of the event strain record. Once the slope is determined, the software checks to see if the slope exceeds the predefined 'impact event' 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[3]. This may require collecting sample strain data from ambient traffic to establish an appropriate strain loading rate.

Data cleansing and processing

Measured strain data normally contains components that include both traffic induced strains and other unwanted elements such as noise, changes in strain induced by temperature variation, etc. The useful information for the developed system are those resulting from ambient traffic only. The approach for eliminating the temperature variations and minimizing noise is to remove unwanted elements from the measured strain data using engineering principals and data filtering, respectively. Thermal expansion and contraction are, in general, 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, the measured strain data are processed in small segments so that the temperature effects on any one set of measured strains can be ignored. To this end, the field monitoring software was designed to autonomously process measured strain segments every 10 minutes[3].

The minimization of noise requires blocking the source of the noise with filtering. Traffic induced strains, in general, have frequency contents that are lower than those of most other sources. Applying a low-pass digital filer, therefore, can modify the frequency content of strain records by only allowing frequencies that are lower than a specified cutoff frequency. Among the commonly used digital filtering techniques, the Chebyshev filter is known to effectively minimize peak detection error with a relatively fast processing speed[4]. Thus, the Chebyshev low-pass filter was used in the field monitoring software for minimizing noise.

Each sensor is configured using Fast Fourier Transform (FFT) and Power Spectrum Density (PSD) forms of analysis.

PSD plots are utilized to help identify noise and ambient traffic induced frequencies. After the PSD plots are generated for each sensor, comparisons can be made to determine a suitable cutoff frequency. Figures 3 and 4 are an example which shows the effectiveness of data cleaning. Presented in Fig. 3a and 3b are the example PSD plots that illustrated frequency contents within the measured strain recorded without and with traffic, respectively. From Fig. 3a, it can be seen that the noise induced frequencies are distributed throughout the displayed frequency range with a significant content detected at 4.8 Hz. As shown in Fig. 3b, it appears that the forced vibration frequencies are in the range of from 0 to 1 Hz. In addition, the fundamental frequency caused by free vibration (the first mode) of the ambient traffic was detected at approximately 2.7 Hz. Based upon the generated PSD plots, one may decide to set the cutoff frequency at 2.8 Hz. Note that, with this setting, although it does not eliminate all of the noise in the measured strain record, it allowed passage of the most dominant live load frequency content.

Figure 4 presents an example of a continuous 24-hour raw strain data and a 10-minute segment after data processing. The rolling fluctuation of baseline strain is a result of environmental temperature variations while the vertical ‘spikes’ extending from the baseline are strains from ambient traffic. For every 10-minute segmented strain data collected, this baseline strain is determined and adjusted to be zero so that the resulting segmented strain data becomes an absolute live load strain measurement. After such adjustment, each segmented data goes through the filtering process to minimize any noise. When the measured strain data are processed and filtered in segments that maintain an essentially constant strain baseline, they represent consistent and accurate information on bridge response to live load. Once processed, the software saves only the identified events obtained from the live loads crossing the bridge and discards the remaining data (note that only approximately 0.1% of collected data are saved after data processing).

Report generation

One of the main purposes of the field monitoring software is to deliver to users information that can be used to identify ‘alarm events’ and gradual changes in bridge performance. In order to meet this goal, two options were added. First, an option was included that allows users to receive a notification of any ‘alarm event.’ When this option is selected, the program will send a message, upon occurrence of an ‘alarm event’, via email that includes the date and time of each occurred event, sensor identification, cause of event (either ‘overload’ or ‘impact’) and the magnitude of the event. Furthermore, in order to allow users to access and review the archived and/or received data files, the software was developed such that it can present summarized information to users. These reports can be automatically generated in three formats: Microsoft Excel Worksheet, PDF, and hard copy. The formats of these reports are flexible and their contents can be modified to provide only the information desired. Regardless of the format, each report can contain information as follows:

- Monitoring period during which presented outputs are given
- Event history that presents each identified event
- Event histogram
- Statistical trends of events including absolute maximum and average
- Summary of messages regarding ‘alarm events’

With the approach developed and utilized in the field monitoring software, the identification of ‘alarm events’ and bridge performance change in the results only requires simple review of tables and graphs and does not require any further calculations. It was anticipated during the development phase that this visual format of the evaluation reports would allow for easier and more comfortable interpretation of monitoring results by bridge owners and managers.

LIVE LOAD STRUCTURAL ANALYSIS SOFTWARE

The second task involved developing the live load structural analysis software (Fig. 5), which was created to simplify the determination of some of the bridge specific parameters needed for the field monitoring software. The structural analysis software runs on a Windows platform personal computer and 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.

The analytical methods used in the structural analysis software are the same as the commonly used stiffness method except that the member stiffness matrix and the fixed-end moments have been modified to account for potential variations in member cross sections. If the cross section of the member varies along its entire length or along its segments, the section properties, such as area of the cross section and its moment of inertia, become variable and the analytical expressions for the coefficients of the unit displacement stiffness matrix and for the fixed end forces due to applied loads become more involved. Since the structural analysis software is intended to be used for analyzing bridges consisting of either (or both) prismatic or (and) non-prismatic members, it was developed so that each member (or span) can have up to five variable sections, each of which may contain a different moment of inertia.

The structural analysis software is capable of analyzing a bridge girder with various boundary conditions and member geometries under various moving load conditions. One unique feature of the structural analysis software is that it allows users to easily determine maximum results (e.g., maximum moment and/or strain) at any location. In addition, it contains many convenient features that are presented through a simple interface that integrates data entry and analysis with graphical representation. These features make creation and modifications of inputs and execution of analysis quick and easy, thereby, allowing the study of multiple 'what-if' scenarios more feasible. In general, one may use the structural analysis software for (1) analyzing 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.

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 (97.5 m x 9 m), three-span girder bridge in Story County, IA carrying US30 over the Skunk River near Ames, IA.

Hardware system

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 of 'alarm events'). The basic hardware components include sensors, the data acquisition hardware and a communication system. 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 1 to 4) were installed in the positive moment region of the girders in the center span and four sensors (sensors 5 to 8) were installed in the West end span.

The data acquisition, processing and communication system consists of a data acquisition, a 1 GHz desktop host PC, and a wireless router. These hardware components were installed in an environmentally controlled aluminum cabinet 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 basic temperature control.

The data acquisition instrument and the host PC were both connected to the router with Ethernet cables, creating a local area network that allows direct communication among the hardware components[3]. The network at the bridge site was then, due to fortunate proximity, connected to an existing network via wireless communication. For wireless communication between the bridge site and the network, an antenna was mounted on an overhead sign frame that is located at the west end of the bridge as shown in Fig. 6 (Note: connection to a network like this is not required). An overall schematic for the SHM system is illustrated in Fig. 7.

Field monitoring software demonstration

Prior to the running the field monitoring software, the 'overload event' thresholds for the sensors installed on the plate girders were determined using the structural analysis software. In each run, the bridge was subjected to various moving loads that include various legal trucks, H 20 truck, HS 20 truck and truck trains. After filter parameters were determined and all input settings were established, the main data acquisition and processing program was initialized, after which continuous data collecting and processing have been completely autonomous and have required no intervention except when reviewing and generating evaluation reports.

Each data point in the event history plot in Fig. 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 created like the one shown in Fig. 8b. In general, the trend line ('Daily Average Fit' in Fig. 8b) is an indication of a change in bridge behavior/condition over time. After reviewing the evaluation report, several observations and interpretations were made for overall bridge performance during the thirty days of monitoring:

- No ‘alarm event’ occurred during the monitored period. The field monitoring software was programmed to list those events, if any, that exceed the ‘overload event’ and ‘impact event’ thresholds for each sensor, and no identified events exceeded either threshold.
- The magnitudes of the daily maximum events fluctuate from day to day (see Fig. 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 due to a single ‘heavy’ traffic event (see Fig. 8b and Table 1). Therefore, a gradual performance change can be estimated or predicted by investigating the daily average and its change in slope over time. By reviewing the daily average of identified events, 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 of the daily average fit curve that is essentially zero for all sensors (see Fig. 8b and Table 2). If the condition of the bridge starts to change (due to damage or deterioration) 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 are created for Sensor 4. A typical example of this is presented in Fig. 9. After reviewing and comparing the histograms, several observations were made as follow:

- 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 the event histogram plots, there are dominant bins with high concentrations of identified events. It is expected that, when damage or deterioration starts to form, the dominant bins in the event histogram plot will slowly be distributed across several bins and/or shifted. If the damage gets worse, this shift would be faster.

CONCLUSIONS

- Convenient features included in the structural analysis software that are presented through a simple interface that integrates data entry and analysis with graphical representation allow the study of multiple scenarios more feasible.
- The field monitoring software was developed such that it can handle up to sixteen channels: one eight-channel data acquisition instrument plus one eight-channel expansion module. Although the expansion module was not included in the SHM system that was demonstrated, its usage was tested during development.
- During a little over thirty days of monitoring, the SHM system has performed as expected and has proven to be capable of continuously and autonomously monitoring the overall performance of the US30 bridge.
- Improved data mining and evaluation procedures utilized in the field monitoring software allowed the amount of saved data to be significantly reduced (only approximately 0.1% saved after data processing) and evaluation reports generated in a format that is clear and familiar to bridge owners.
- If properly implemented, it is believed that the developed system will allow owners to monitor its structural condition, detect overloads, and provide better access to valuable traffic information that can be used in planning, maintenance, and construction activities.
- Overall, the developed SHM system has been proven to be a stand-alone, autonomous system capable of processing and evaluating the continuously collected strain data and its use may provide bridge owners with the tools to better manage bridge assets.

IMPLEMENTATION AND DISCUSSION

Benefits of the developed system include its relative ease of implementation and relative low-cost. The installation of the strain gages and cabling required no training or special equipment other than safety and normal access equipment. Excluding the communication and power equipment and research and development (R&D) costs, the system can be implemented at the cost of $10,000 to $15,000 depending on the number of sensors used.

Bridge owners by nature are somewhat conservative and are often reluctant to use SHM systems until others have successfully completed a similar project. This is partially due to the significant effort required to develop a SHM system and also due to the lack of fundamental understanding of SHM system operation. One of the main objectives of this project was to develop a SHM system that can be used on any typical girder bridge. With the complete system developed in this project including two software packages, R&D efforts can be significantly eliminated and the system can be easily implemented on bridges. A step-by-step illustrative manual for system setup and software operations was also created and included in the project report[3] to assist owners and end users in instrumentation and operation of the system.

While the developed SHM system can be used on any typical girder bridge, its low-cost feature makes it suitable for implementation on secondary road bridges where traditional instrumentation systems are not often feasible due to time and cost constraints. Furthermore, if the data acquisition, processing and communication system is assembled as a mobile unit, its use can be expanded to monitor multiple bridges in succession.

REFERENCES

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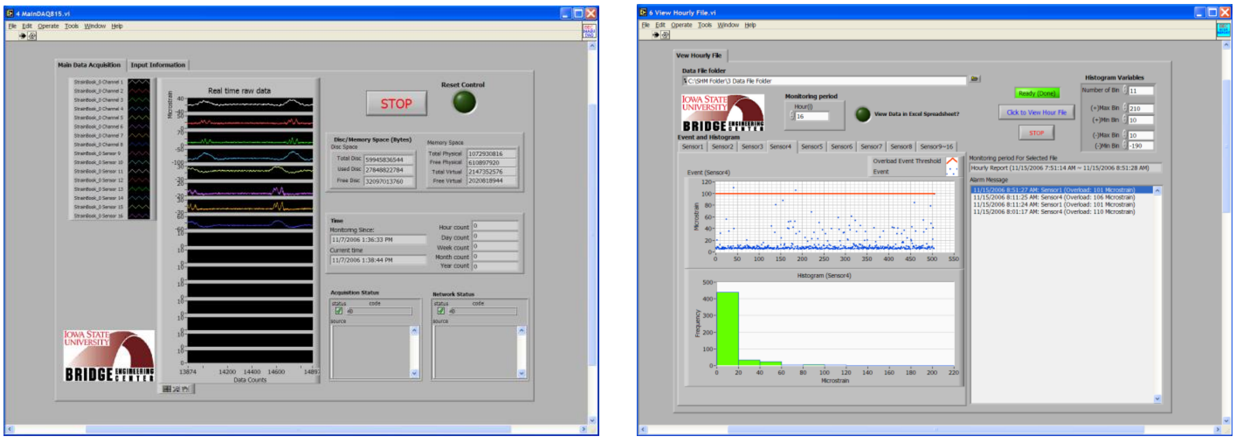
TABLE 1 – Statistical trends (daily maximum/average in microstrain, με).

	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 in microstrain (με) and percentage (%).

Sensor	Overload event threshold (με)	Maximum Event (με)	Average (με)	Daily Average 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



Disc/Memory Space (Bytes)
Disc Space
Total Disc: 59945836544
Used Disc: 27848822784
Free Disc: 32097013760
Memory Space
Total Physical: 1072930816
Free Physical: 610897920
Total Virtual: 2147352576
Free Virtual: 2020818944

Time
Monitoring Since: 11/7/2006 1:36:33 PM
Current time: 11/7/2006 1:38:44 PM
Hour count: 0
Day count: 0
Week count: 0
Month count: 0
Year count: 0

Acquisition Status
status ☑ code 0
source

Network Status
status ☑ code 0
source

Data File folder: C:\SHM Folder\3 Data File Folder
Monitoring period
Hour(I): 16
View Data in Excel Spreadsheet?

Histogram Variables
Number of Bin: 11
(+)Max Bin: 210
(+)Min Bin: 10
(-)Max Bin: 10
(-)Min Bin: -190

Monitoring period For Selected File
Hourly Report (11/15/2006 7:51:14 AM ~ 11/15/2006 8:51:28 AM)

Alarm Message
11/15/2006 8:51:27 AM: Sensor1 (Overload: 101 Microstrain)
11/15/2006 8:11:25 AM: Sensor4 (Overload: 106 Microstrain)
11/15/2006 8:11:24 AM: Sensor1 (Overload: 101 Microstrain)
11/15/2006 8:01:17 AM: Sensor4 (Overload: 110 Microstrain)

Figure 1 – Example screen shots of field monitoring software.

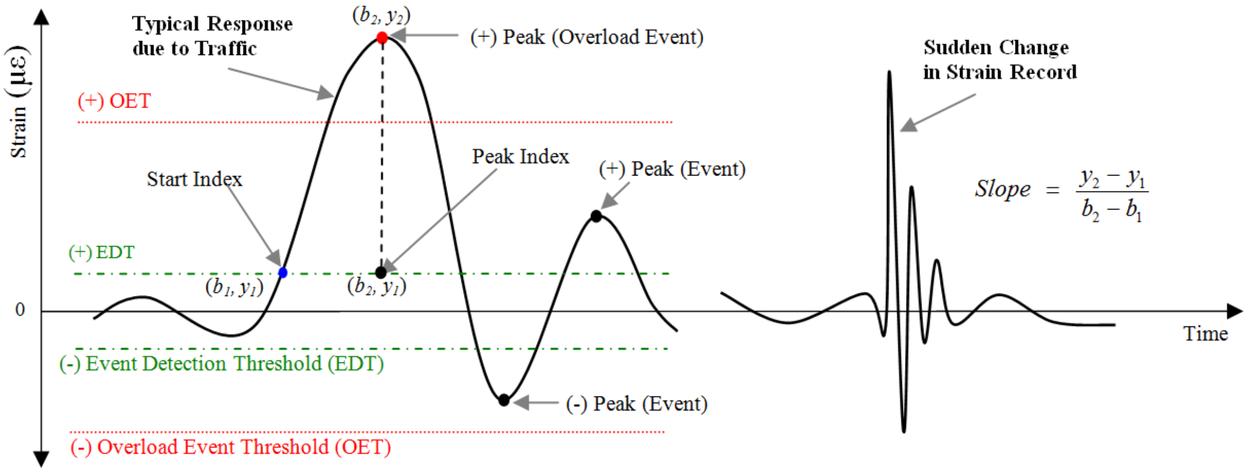
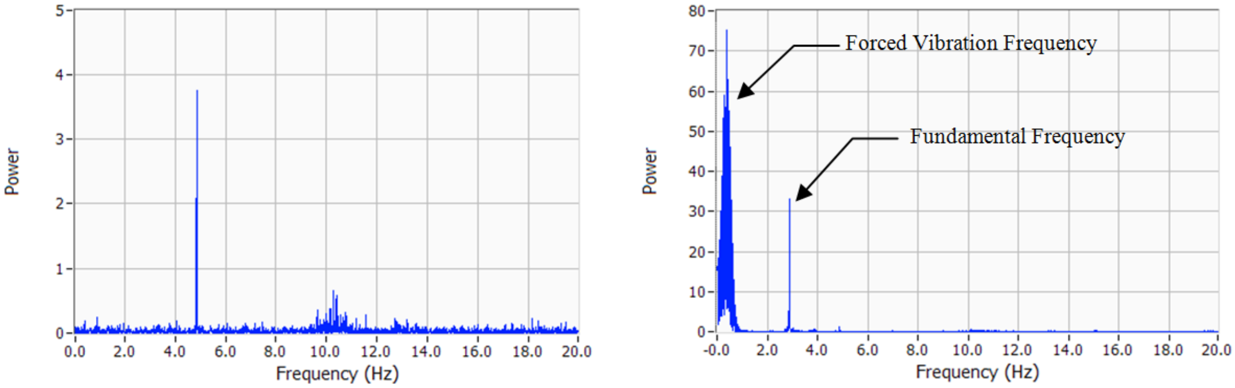


Figure 2 – Parameters used to determine events and alarm events



(a) Without traffic on the bridge (b) With traffic on the bridge

Figure 3 – Example PSD plots showing frequency contents of measured data

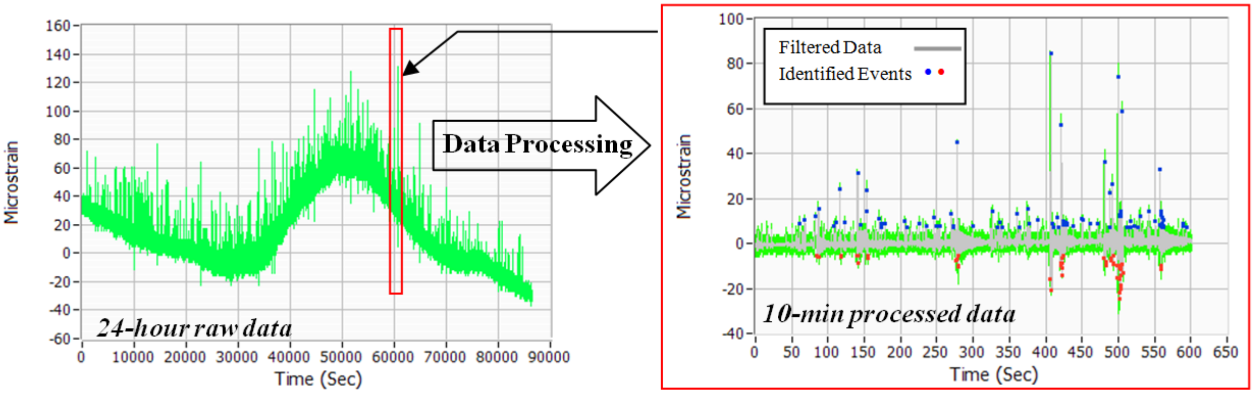
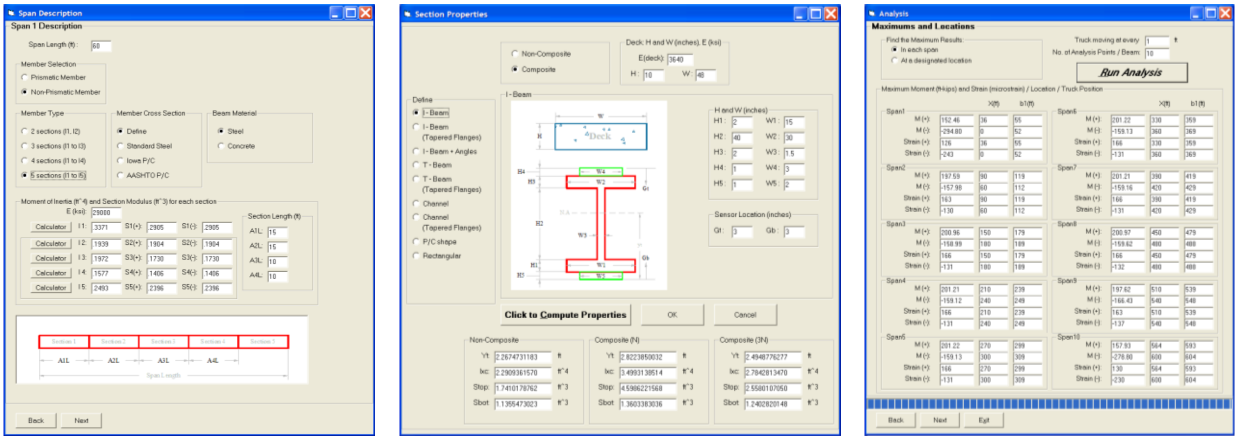


Figure 4 – Example of continuous 24-hour raw data and its 10-minute segment after data processing



Span Description

Span 1 Description

Span Length (ft): 60

Member Selection
○ Prismatic Member
● Non-Prismatic Member

Member Type
○ 2 sections (I1, I2)
○ 3 sections (I1 to I3)
○ 4 sections (I1 to I4)
● 5 sections (I1 to I5)

Member Cross Section
● Define
○ Standard Steel
○ Iowa P/C
○ AASHTO P/C

Beam Material
● Steel
○ Concrete

Moment of Inertia (ft^4) and Section Modulus (ft^3) for each section

E (ksi): 29000

Calculator	I1:	.3371	S1(+):	.2905	S1(-):	.2905
Calculator	I2:	.1939	S2(+):	.1904	S2(-):	.1904
Calculator	I3:	.1972	S3(+):	.1730	S3(-):	.1730
Calculator	I4:	.1577	S4(+):	.1406	S4(-):	.1406
Calculator	I5:	.2493	S5(+):	.2396	S5(-):	.2396

Section Length (ft)
A1L: 15
A2L: 15
A3L: 10
A4L: 10

Section Properties

○ Non-Composite
● Composite

Deck: H and W (inches), E (ksi)
E(deck): 3640
H: 10 W: 48

Define
● I - Beam
○ I - Beam (Tapered Flanges)
○ I - Beam + Angles
○ T - Beam
○ T - Beam (Tapered Flanges)
○ Channel
○ Channel (Tapered Flanges)
○ P/C shape
○ Rectangular

I - Beam

H and W (inches)
H1: 2 W1: 15
H2: 40 W2: 30
H3: 2 W3: 1.5
H4: 1 W4: 3
H5: 1 W5: 2

Sensor Location (inches)
Gt: 3 Gb: 3

	Non-Composite		Composite (N)		Composite (3N)	
Yt	2.2674731183	ft	2.8223850032	ft	2.4948776277	ft
Ixc	2.2909361570	ft^4	3.4993138514	ft^4	2.7842813470	ft^4
Stop	1.7410178762	ft^3	4.5986221568	ft^3	2.5580107050	ft^3
Sbot	1.1355473023	ft^3	1.3603383036	ft^3	1.2402820148	ft^3

Analysis

Maximums and Locations

Find the Maximum Results:
● In each span
○ At a designated location

Truck moving at every 1 ft
No. of Analysis Points / Beam: 10

Maximum Moment (ft-kips) and Strain (microstrain) / Location / Truck Position

		X(ft)	b1(ft)			X(ft)	b1(ft)
Span1				Span6			
M (+):	152.46	36	55	M (+):	201.22	330	359
M (-):	-294.80	0	52	M (-):	-159.13	360	369
Strain (+):	126	36	55	Strain (+):	166	330	359
Strain (-):	-243	0	52	Strain (-):	-131	360	369
Span2				Span7			
M (+):	197.59	90	119	M (+):	201.21	390	419
M (-):	-157.98	60	112	M (-):	-159.16	420	429
Strain (+):	163	90	119	Strain (+):	166	390	419
Strain (-):	-130	60	112	Strain (-):	-131	420	429
Span3				Span8			
M (+):	200.96	150	179	M (+):	200.97	450	479
M (-):	-158.99	180	189	M (-):	-159.62	480	488
Strain (+):	166	150	179	Strain (+):	166	450	479
Strain (-):	-131	180	189	Strain (-):	-132	480	488
Span4				Span9			
M (+):	201.21	210	239	M (+):	197.62	510	539
M (-):	-159.12	240	249	M (-):	-166.43	540	548
Strain (+):	166	210	239	Strain (+):	163	510	539
Strain (-):	-131	240	249	Strain (-):	-137	540	548
Span5				Span10			
M (+):	201.22	270	299	M (+):	157.93	564	593
M (-):	-159.13	300	309	M (-):	-278.80	600	604
Strain (+):	166	270	299	Strain (+):	130	564	593
Strain (-):	-131	300	309	Strain (-):	-230	600	604

Figure 5 – Example screen shots of structural analysis software.

Figure 6 – Wireless communication equipment installed at the west end of the bridge.

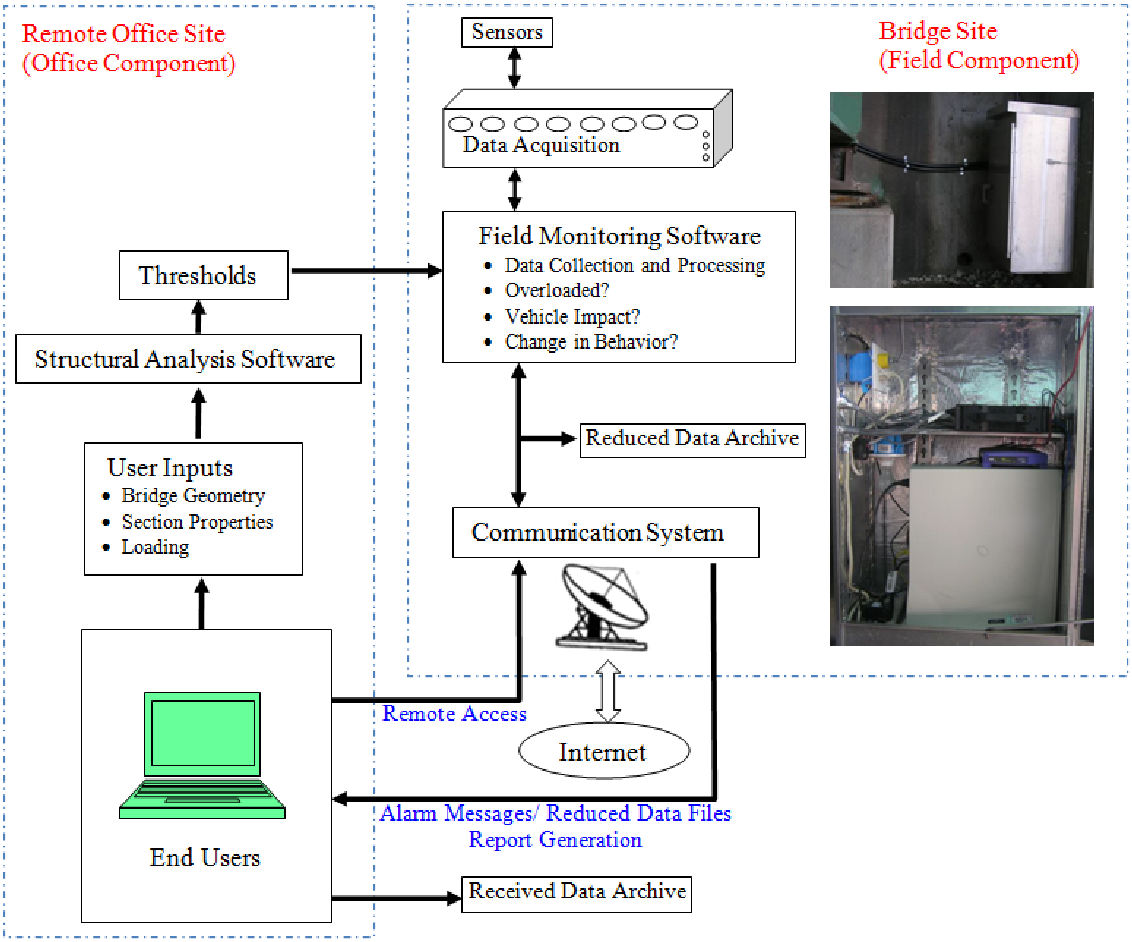
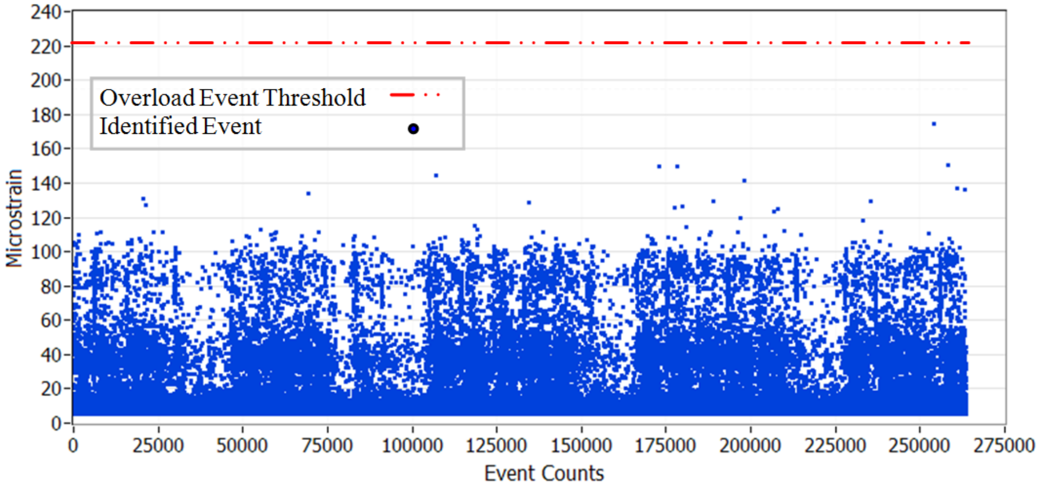
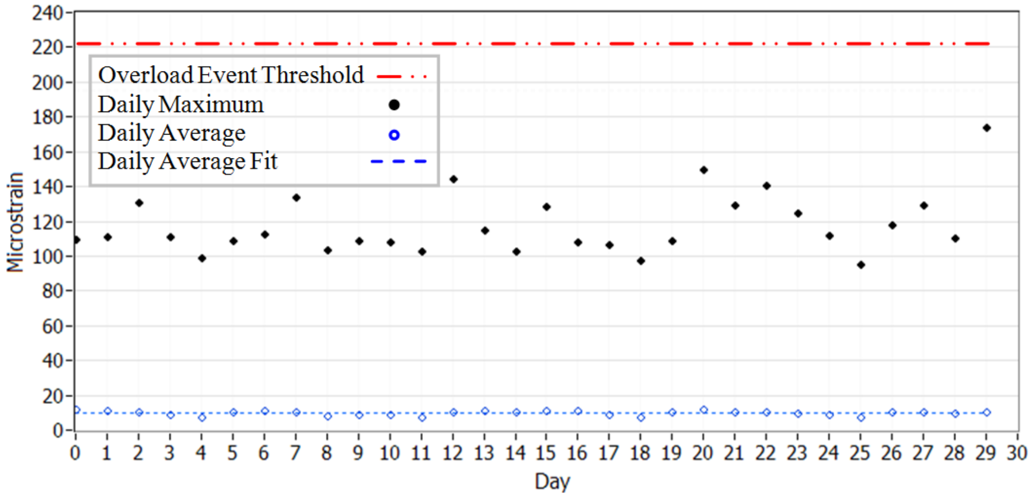


Figure 7 – Overall schematic of SHM system.

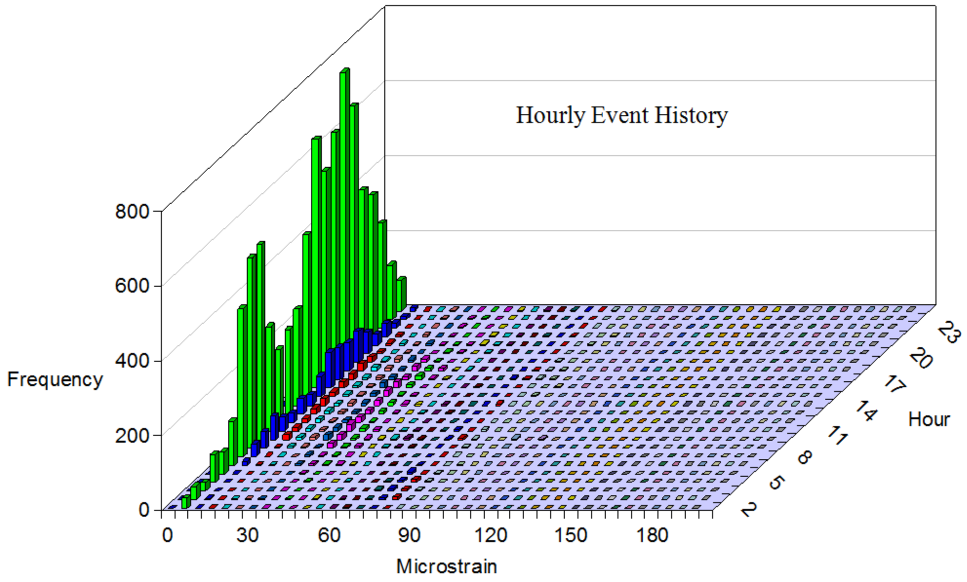


(a) 30-day event history for Sensor 4 (center span)



(b) 30-day daily statistical trends for Sensor 4 (center span)

Figure 8 – Example of monthly evaluation.



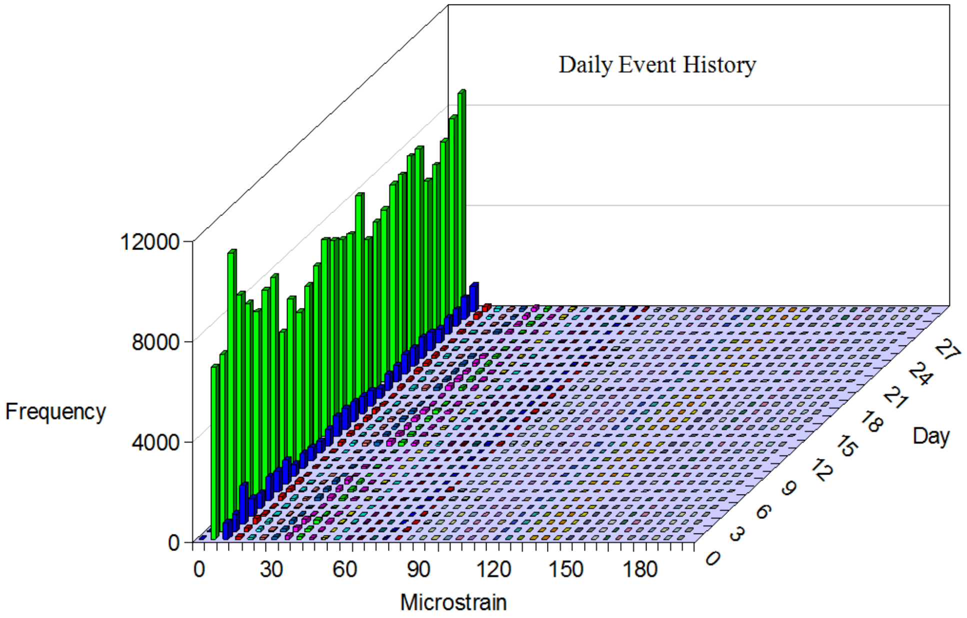


Figure 9 – Hourly and Daily Event Histograms for Sensor 4 – center span (bin width: 5 microstrain)