

Evaluation of Steel Bridges (Volume II): Structural Health Monitoring System for Secondary Road Bridges



Final Report
December 2007

Sponsored by
the Iowa Department of Transportation (Project 03-135)
and
the Iowa Highway Research Board (Project TR-493)



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Technical Report Documentation Page

1. Report No. IHRB Project TR-493 CTRE Project 03-135	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Evaluation of Steel Bridges (Volume II): Structural Health Monitoring System for Secondary Road Bridges		5. Report Date December 2007	
		6. Performing Organization Code	
7. Author(s) Brent M. Phares, Terry J. Wipf, Yoon-Si Lee, and Justin D. Doornink		8. Performing Organization Report No.	
9. Performing Organization Name and Address Center for Transportation Research and Education Iowa State University 2711 South Loop Drive, Suite 4700 Ames, IA 50010-8664		10. Work Unit No. (TRAIS)	
		11. Contract or Grant No.	
12. Sponsoring Organization Name and Address Iowa Highway Research Board Iowa Department of Transportation 800 Lincoln Way Ames, IA 50010		13. Type of Report and Period Covered Final Report	
		14. Sponsoring Agency Code	
15. Supplementary Notes			
16. Abstract <p>This report is divided into two volumes. Volume I summarizes a structural health monitoring (SHM) system that was developed for the Iowa DOT to remotely and continuously monitor fatigue critical bridges (FCB) to aid in the detection of crack formation. The developed FCB SHM system enables bridge owners to remotely monitor FCB for gradual or sudden damage formation. The SHM system utilizes fiber bragg grating (FBG) fiber optic sensors (FOSs) to measure strains at critical locations. The strain-based SHM system is 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 the bridge owner for interpretation and decision making.</p> <p>This volume (Volume II) summarizes the development and demonstration of an autonomous, continuous SHM system that can be used to monitor typical girder bridges. The developed SHM 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 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 damage and deterioration.</p>			
17. Key Words analysis—bridge—evaluation—overload—structural health monitoring		18. Distribution Statement No restrictions.	
19. Security Classification (of this report) Unclassified.	20. Security Classification (of this page) Unclassified.	21. No. of Pages 219	22. Price NA

EVALUATION OF STEEL BRIDGES – VOLUME II: STRUCTURAL HEALTH MONITORING SYSTEM FOR SECONDARY ROAD BRIDGES

**Final Report
December 2007**

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Sponsored by
the Iowa Highway Research Board
(IHRB Project TR-493)

Preparation of this report was financed in part
through funds provided by the Iowa Department of Transportation
through its research management agreement with the
Center for Transportation Research and Education,
CTRE Project 03-135.

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ACKNOWLEDGMENTS

The investigation presented in this report was conducted by the Bridge Engineering Center at Iowa State University. The research was sponsored by the Iowa Department of Transportation, Highway Division, and the Iowa Highway Research Board. Bruce Brakke of the Iowa Department of Transportation is acknowledged for his support of the project and for his technical input. Several other Office of Bridges and Structures personnel at the Iowa Department of Transportation provided input and support during the project and are also acknowledged, particularly Ahmad Abu-Hawash and Norm McDonald.

EXECUTIVE SUMMARY

This report is divided into two volumes. Volume I summarizes a structural health monitoring (SHM) system that was developed for the Iowa DOT to remotely and continuously monitor fatigue critical bridges (FCB) to aid in the detection of crack formation. The developed FCB SHM system enables bridge owners to remotely monitor FCB for gradual or sudden damage formation. The SHM system utilizes fiber bragg grating (FBG) fiber optic sensors (FOSs) to measure strains at critical locations. The strain-based SHM system is 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 the bridge owner for interpretation and decision making.

This volume (Volume II) summarizes the development and demonstration of an autonomous, continuous SHM system that can be used to monitor typical girder bridges. The developed SHM 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 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.

1. INTRODUCTION

1.1. Background

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.

In the recent past, there have been rapid advances in the development of the technologies needed for effective SHM. SHM is a relatively new but fast growing field within the bridge engineering community. 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.

Numerous tools and technologies (currently available as well as emerging) associated with SHM applications have been well publicized [1, 2]. 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.

1.2. Objective and Product

The primary objective of this research was to develop a 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.

1.3. Report Content

This report is divided into four chapters. A detailed description of the system development and its components are given in Chapter 2. Chapter 3 presents the demonstration of the SHM system and the associated performance evaluation. General summary and conclusive discussions are provided in Chapter 4. In addition, significant “user manual” materials are provided in the report appendices.

2. STRUCTURAL HEALTH MONITORING SYSTEM

The system developed in this work and presented herein was developed to be an open and flexible SHM system that can be used to monitor, under normal operating conditions, typical girder bridges for overloading and changes in behavior (e.g., from deterioration, sudden events, etc.). A reliable system of this type requires accurate analysis, structural modeling and consideration of typical scenarios.

An overall schematic for the SHM system is illustrated in Figure 2-1. 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.

Detailed descriptions of each of the components and their implementation are presented in the following sections. Section 2.1 describes various features included in the structural analysis software and highlights some of the theoretical methodologies used to develop it. In Section 2.2, various elements of the field monitoring software are discussed along with a general background and summary of the methodologies employed in the development. Finally, Section 2.3 discusses the hardware components that include sensors, data acquisition, and communication.

2.1. Structural Analysis Software

A Windows-based, two-dimensional, live-load structural analysis program, *BEC Analysis*, was created 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 (maximum moment and strain) at any location along the length of a model 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 modeling non-prismatic members

- Run multiple analyses without exiting the program
- Supports the AASHTO Standard Specification for Highway Bridges, Sixteenth Edition [3]
- Supports various loading conditions
- Graphic diagrams
- Print/Save results

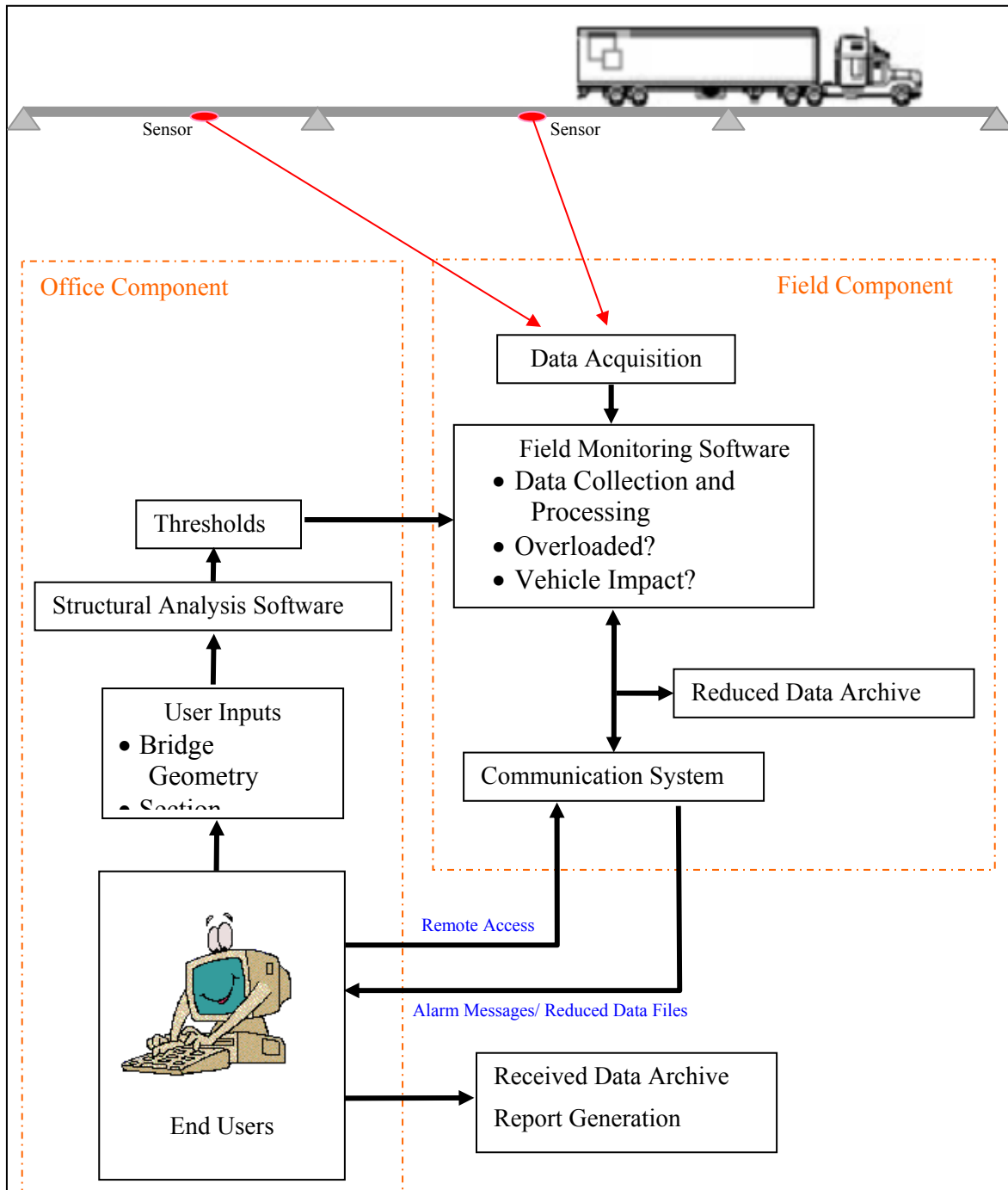


Figure 2-1. Overall schematic of SHM system

BEC Analysis was designed to be used specifically for analyzing two dimensional girder bridges subjected to moving loads. The structure to be analyzed is idealized to a mathematical model that consists of a member or a series of members. In this software, member ends are referred to as nodes or joints. Properties are assigned to each joint and member to simulate the real structure. Member simulations are accomplished by inputting material properties, section properties, and member definitions within each span. Boundary conditions are simulated by assigning restraint conditions to nodes. Loads are simulated by combinations of concentrated loads that represent vehicle axles and by uniformly distributed loads plus concentrated load(s) that represents truck train loadings. The commonly used two-dimensional stiffness matrix method was used as the computational backbone in *BEC Analysis*. 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.

2.1.1. General Methodology

As the accessibility of powerful computers has become more common, the use of matrix algebra has become more commonplace. Thus, the analysis algorithm used in *BEC Analysis* is based on classic beam theory and the direct stiffness method of matrix structural analysis. The stiffness method is one of the most popular methods used in computer structural analysis programs and its formation is well published. Thus, it will be only briefly outlined here. Inherent assumptions used in developing the analytical methods are as follows:

- All materials are assumed to behave elastically.
- Plane cross sections remain plane.
- All elastic deformations are relatively small.
- A fixed support is defined as an end condition capable of resisting end moment without rotation, while a pinned/roller support is one in which there is no resistance to angular rotation and, thereby, no end moment.
- For a composite sections, the moment of inertia of the entire transposed section is used.
- Non-prismatic spans may be approximated with stepped prismatic members.

The analytical methods used in *BEC Analysis* are the same as the routine stiffness method except that the member stiffness matrix and the fixed-end moments have been modified to account for the potential variation in member cross sections. The general matrix formulation for the member end forces can, therefore, be expressed as below:

$$\{MA\} = \{MF\} + [KS]\{D\} \quad (2.1)$$

where,

- $\{MA\}$ = Member end force vector
- $\{MF\}$ = Fixed end moment vector
- $[KS]$ = Unit displacement stiffness matrix
- $\{D\}$ = Nodal displacement vector ($\{D\} = -[S]^{-1}\{Z\}$)

$$\begin{aligned}\{Z\} &= \text{Nodal force vector} \\ [S] &= \text{Stiffness matrix}\end{aligned}$$

The general theories and methodologies briefly outlined in this section have been incorporated into a computer program, *BEC Analysis*, which makes time-consuming analyses relatively simple. All that is required to complete an analysis is to define the important bridge parameters. The following section presents a summary of *BEC Analysis*.

2.1.2. Features and Components of *BEC Analysis*

BEC Analysis runs on a Windows platform personal computer (PC) 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. 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. Figure 2-2 schematically depicts the organization and hierarchy of each window within *BEC Analysis*. Screen shots of each window are presented in Figures 2-3 through 2-11 with the various windows, text box controls, frames, command buttons and other indicators numerically labeled in each figure. The features included in each window and the general procedures for running *BEC Analysis* are discussed in the subsequent sections. In addition, descriptions of each of the controls, indicators and command buttons, and the principle procedures required to run *BEC Analysis* are provided in Appendix A.

2.1.2.1. Bridge Information Window

BEC Analysis can be started by double clicking the program icon. Once the program has loaded, the *BEC Analysis* title screen shown in Figure 2-3 will appear. By clicking the 'Click to START' command button on the title screen, the program will be initialized and move to the next window that contains the 'General Information' frame shown in Figure 2-4. In this frame, the number of spans (#2) and boundary conditions (#3) can be specified. The number entered in the 'Number of Spans' text box control (#2) will dictate how many 'Span Description' windows (#5) in which information for each span will be entered will be needed. The 'Boundary Condition' (#3) frame contains controls which allow the user to specify the boundary conditions for the exterior supports. Three options are available: fixed, pin/roller and rotational spring.

- A fixed support is a support that has all degrees of freedom restrained.
- A pinned/roller support restrains only one or two degrees of freedom. If a model bridge is built with more than two spans, interior supports will be modeled as pin/roller with full continuity between the adjacent spans.
- A rotational spring support can be defined by inserting the appropriate corresponding rotational spring constants. The spring constant must be between zero and infinity.

2.1.2.2. Span Description Window

The next step involves entering information about each span in the ‘Span Description’ window (#5) shown in Figure 2-5; in this window, geometry, member type, material and section properties for each span are specified. Up to ten ‘Span Description’ windows will appear, one by one, depending upon the number of spans specified in #2. The input required for each ‘Span Description’ window involves specifying the length of the span (#6) followed by selection of member types and materials. Two options are available in the ‘Member Selection’ frame (#7):

- Prismatic member: member size and section properties are constant along the span. If selected, controls #8 and #12 through #16 will be disabled.
- Non-prismatic member: member size and section properties are not constant along the span. Up to five different sections with different properties can be defined using controls #8 through #16.

• The ‘Member Cross Section’ frame (#9) allows the user to define or select sections for a member with the material properties defined in the ‘Beam Material’ frame (#10). One of the convenient features in *BEC Analysis* is a section property ‘Calculator’ (#12) with which users can either directly input section properties of a member or have the program automatically compute the section properties of virtually any cross section. Allowable shapes include user-definable geometries, common standard steel shapes, Iowa P/C shapes and AASHTO P/C shapes. Detailed description on these options will be discussed in Section 2.1.2.3.

The text boxes in #13, 14 and 15 display the moment of inertia (#13), the section modulus (#14) at the lower sensor location and the section modulus (#15) at the upper sensor location for each segment in a member. These values can be either manually entered by the user or computed with the ‘Calculator’ (#12). Note that the default sensor locations are set to be at the bottom of the beam (lower sensor) and the top of the beam (upper sensor). Note that these sensor locations can be changed in the ‘Sensor Location’ frame (#25) which can be found in the ‘Section Properties’ window (#19).

The length of each segment in a member is defined in the ‘Section Distance’ frame (#16). Note that this frame will only be enabled if the ‘Non-Prismatic Member’ option is selected in #7. Also note that the graphic display in #17 will display how a member is segmented in each span. A different graphic will be displayed according to the options selected in #7 and #8.

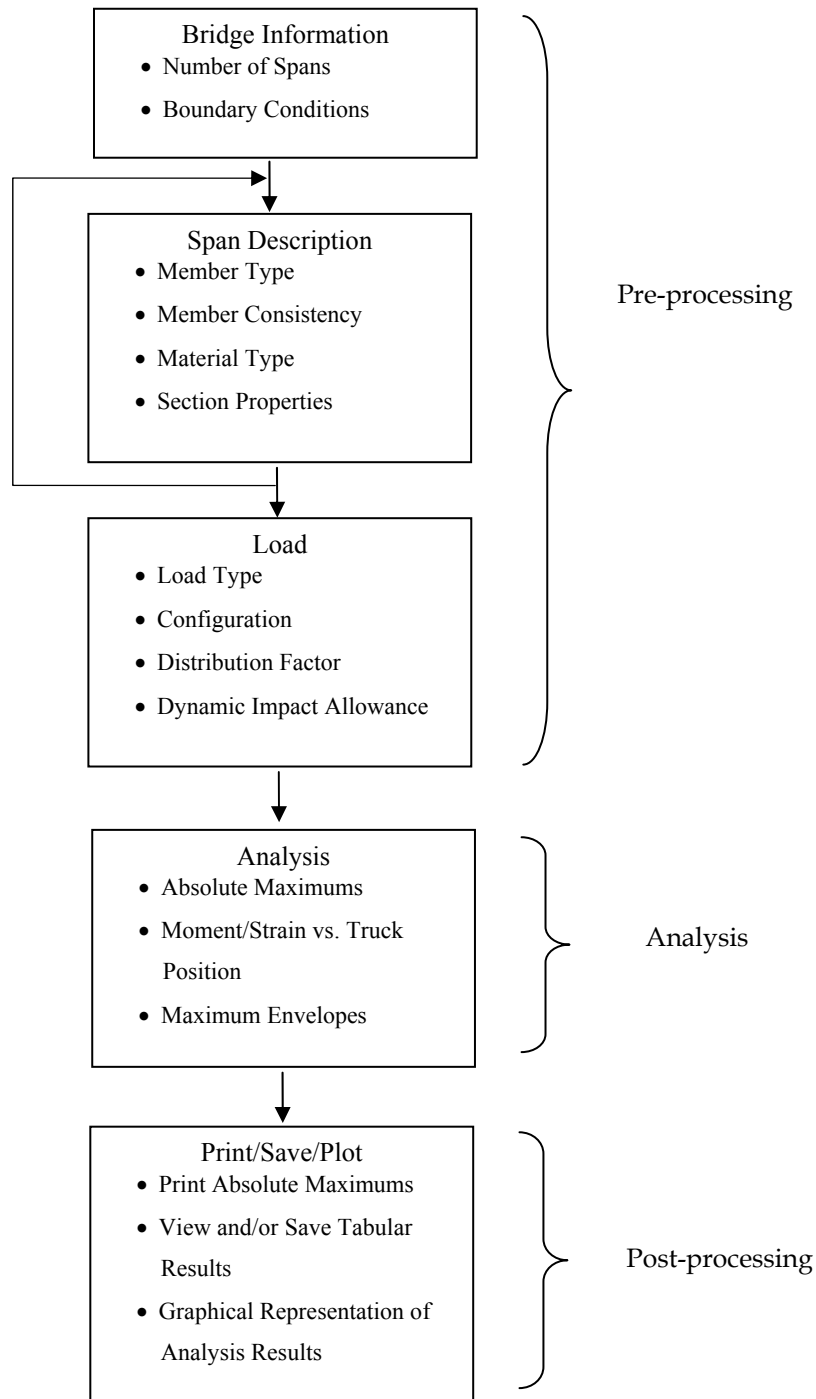


Figure 2-2. General flowchart illustrating the overall operation of *BEC Analysis*

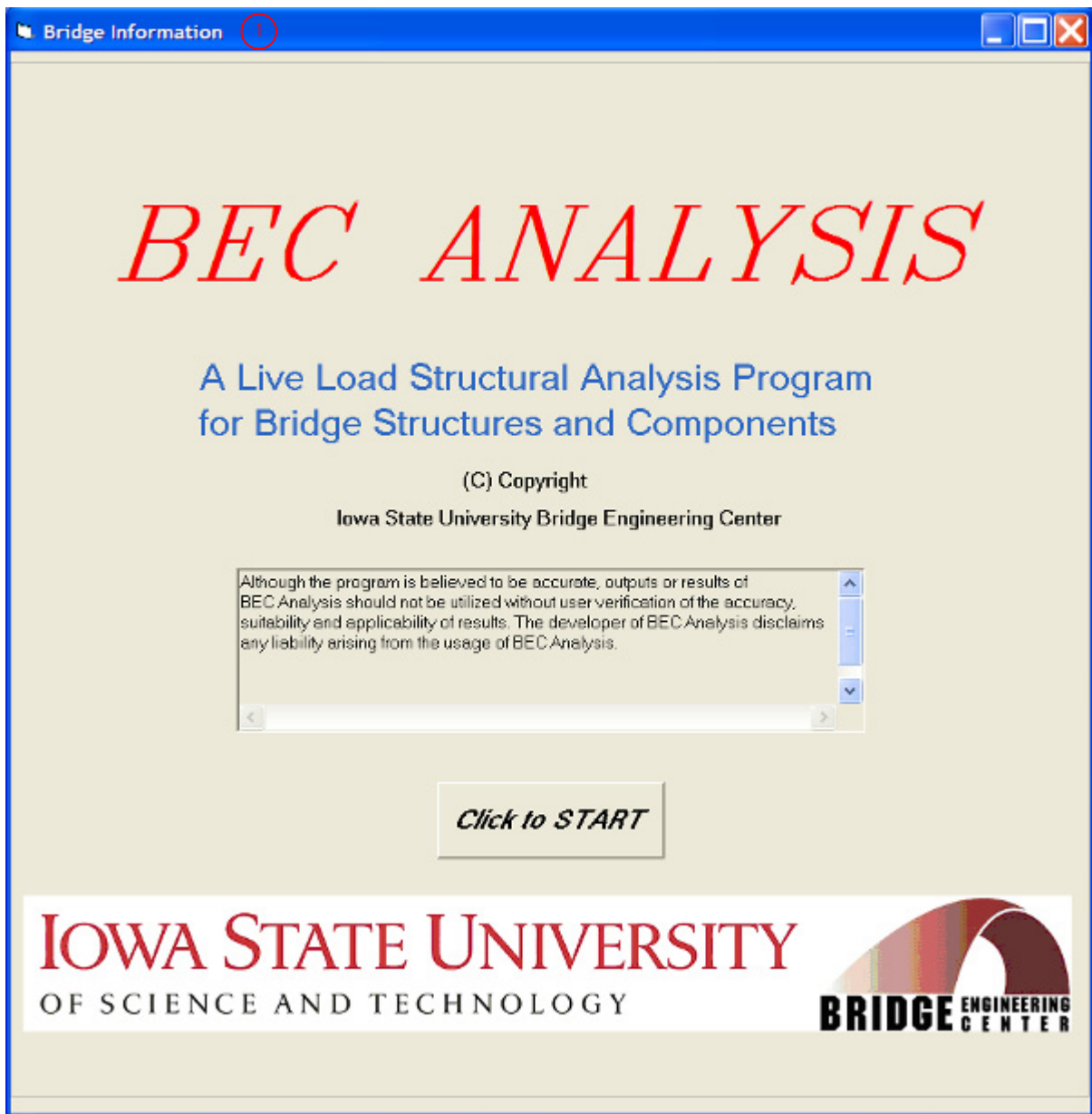


Figure 2-3. *BEC Analysis* title screen

Bridge Information 1

General Information

Number of Spans : 10 2 (upto 10 spans)

Boundary Condition 3

Left Exterior Support	Interior Support	Right Exterior Support
<input checked="" type="radio"/> Fixed	<input checked="" type="radio"/> Pinned/Roller	<input checked="" type="radio"/> Fixed
<input type="radio"/> Pinned/Roller		<input type="radio"/> Pinned/Roller
Rotational Spring Constant (ft-kips/radian)		Rotational Spring Constant (ft-kips/radian)
0		0

Next 4

Figure 2-4. General information options

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 (ft⁴) and Section Modulus (ft³) 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 1

Section 2

Section 3

Section 4

Section 5

A1L

A2L

A3L

A4L

Span Length

Back

Next

Figure 2-5. Span Description window

Section Properties (19)

☐ Non-Composite (20)
☒ Composite

Deck H and W (inches), E (ksi)
 E(deck): 3640 (21)
 H: 10 W: 48

Define (22)

- ☒ I-Beam (23)
- ☐ I-Beam (Tapered Flanges)
- ☐ I-Beam + Angles
- ☐ T-Beam
- ☐ T-Beam (Tapered Flanges)
- ☐ Channel
- ☐ Channel (Tapered Flanges)
- ☐ P/C shape
- ☐ Rectangular

I-Beam (23)

H and W (inches) (24)

H1:	2	W1:	15
H2:	40	W2:	30
H3:	2	W3:	1.5
H4:	1	W4:	3
H5:	1	W5:	2

Sensor Location (inches) (25)

Gt:	3	Gb:	3
-----	---	-----	---

(26) Click to Compute Properties

OK (27) Cancel (28)

Non-Composite		Composite (N)		Composite (3N)	
Yt:	2.2674731183 ft (29)	Yt:	2.8223850032 ft (30)	Yt:	2.4948776277 ft (31)
Ixc:	2.2909361570 ft ⁴	Ixc:	3.4993138514 ft ⁴	Ixc:	2.7842813470 ft ⁴
Stop:	1.7410178762 ft ³	Stop:	4.5986221568 ft ³	Stop:	2.5580107050 ft ³
Sbot:	1.1355473023 ft ³	Sbot:	1.3603383036 ft ³	Sbot:	1.2402820148 ft ³

(a) Section properties for 'Define' option

Figure 2-6. Section Properties window

Section Properties

☐ Non-Composite ☒ Composite

Deck
 E(deck): 3640
 H: 10 W: 48
 E: elastic modulus (ksi)
 H: height (inches)
 W: width (inches)

Standard Steel
☒ W Shape
☐ M Shape
☐ S Shape
☐ HP Shape
☐ Channel
☐ MC Channel

W44x335
 W44x290
 W44x262
 W44x230
 W40x593
 W40x503
 W40x431
 W40x372
W40x321
 W40x297
 W40x277
 W40x249
 W40x215
 W40x199
 W40x174
 W40x466
 W40x392
 W40x331
 W40x278
 W40x264
 W40x235
 W40x211

Beam Information
 Area: 94.1 in²
 Depth: 40.08 in
 Y bottom: 20.04 in
 Ixc: 25100 in⁴

Sensor Location (inches)
 Gt: 3 Gb: 3
 Gt: distance from top of beam
 Gb: distance from bottom of beam

Click to Compute Properties OK Cancel

Non-Composite		Composite (N)		Composite (3N)	
Yt:	1.6700000000 ft	Yt:	2.4845090592 ft	Yt:	2.0370083250 ft
Ixc:	1.2104552469 ft ⁴	Ixc:	2.3453148849 ft ⁴	Ixc:	1.7189707933 ft ⁴
Stop:	0.8524332725 ft ³	Stop:	3.8734103633 ft ³	Stop:	1.6324638021 ft ³
Sbot:	0.8524332725 ft ³	Sbot:	1.0495884432 ft ³	Sbot:	0.9619265726 ft ³

(b) Section properties for 'Standard Steel' option

Figure 2-6. (continued)

Section Properties (19)

☐ Non-Composite (20)
☒ Composite

Deck

E(deck): 3640 (21) E: elastic modulus (ksi)
 H: 10 W: 48 H: height (inches)
 W: width (inches)

Iowa P/C

☒ LX (35)
☐ Bulb-Tees

LXA30 - LXA46 (36)
 LXA50 - LXA55
 LXB34 - LXB50
 LXB55 - LXB59
 LXB63 - LXB67
 LXC30 - LXC46
 LXC71 - LXC80
 LXD45 - LXD60

Beam Information

Area: 382.5 in² (34)
 Depth: 39 in
 Y bottom: 17.06 in
 Ixc: 62000 in⁴

Sensor Location (inches)

Gt: 3 (25) Gb: 3
 Gt: distance from top of beam
 Gb: distance from bottom of beam

Click to Compute Properties (26) OK (27) Cancel (28)

Non-Composite		Composite (N)		Composite (3N)	
Yt:	1.421666667 ft (29)	Yt:	2.6710579710 ft (30)	Yt:	2.0837864823 ft (31)
Ixc:	2.9899691358 ft ⁴	Ixc:	10.6333421095 ft ⁴	Ixc:	7.0026762294 ft ⁴
Stop:	1.8943838242 ft ³	Stop:	32.3258847229 ft ³	Stop:	7.6430614637 ft ³
Sbot:	2.5518939993 ft ³	Sbot:	4.3920229242 ft ³	Sbot:	3.8186977038 ft ³

(c) Section properties for 'Iowa P/C' option

Figure 2-6. (continued)

Section Properties (19)

☐ Non-Composite (20)
☒ Composite

Deck

E(deck): 3640 (21) E: elastic modulus (ksi)
 H: 10 W: 48 H: height (inches)
 W: width (inches)

AASHTO P/C

☒ Slab Beams (37)
☐ Box Beams
☒ I-Beams
☐ Bulb-Tees

I
 II
 III
 IV (38)
 V
 VI

Beam Information

Area: 789 in² (34)
 Depth: 54 in
 Y bottom: 24.73 in
 Ixc: 260730 in⁴

Sensor Location (inches)

Gt: 3 (25) Gb: 3
 Gt: distance from top of beam
 Gb: distance from bottom of beam

(26) **Click to Compute Properties** (27) OK (28) Cancel

Non-Composite		Composite (N)		Composite (3N)	
Yt:	2.0608333333 ft (29)	Yt:	3.1410539795 ft (30)	Yt:	2.5423226203 ft (31)
Ixc:	12.5737847222 ft ⁴	Ixc:	29.6695322870 ft ⁴	Ixc:	20.1722305475 ft ⁴
Stop:	5.7436397665 ft ³	Stop:	26.7547127983 ft ³	Stop:	11.8126706996 ft ³
Sbot:	6.9436454978 ft ³	Sbot:	10.2625314149 ft ³	Sbot:	8.7999090394 ft ³

(d) Section properties for 'AASHTO P/C' option

Figure 2-6. (continued)

Figure 2-7. Load window

Analysis (53)

Maximums and Locations

Find the Maximum Results: (53)

☐ In each span

☒ At a designated location (54)

X = 30 (55) ft (from the left exterior support)

Truck moving at every 1 (56) ft

Run Analysis (57)

Maximum Moment (ft-kips) and Strain (microstrain) / Truck Position (62)

M (+):	150.64 (58)	when P1 is at	59 (62)	ft
M (-):	-39.50 (59)	when P1 is at	112	ft
Strain (+):	124 (60)	when P1 is at	59	ft
Strain (-):	-33 (61)	when P1 is at	112	ft

Back (18) Next (4) Exit (64) (63)

(a) 'At a designated location' option

Figure 2-8. Analysis window

Analysis 52

Maximums and Locations

Find the Maximum Results:

53 ☒ In each span

54 ☐ At a designated location

Truck moving at every 1 56 ft

No. of Analysis Points / Beam: 10 65

Run Analysis 57

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

		66	67 X(ft)	68 b1(ft)
Span1				
M (+):	152.46	36	55	
M (-):	-294.80	0	52	
Strain (+):	126	36	55	
Strain (-):	-243	0	52	
Span2				
M (+):	197.59	90	119	
M (-):	-157.98	60	112	
Strain (+):	163	90	119	
Strain (-):	-130	60	112	
Span3				
M (+):	200.96	150	179	
M (-):	-158.99	180	189	
Strain (+):	166	150	179	
Strain (-):	-131	180	189	
Span4				
M (+):	201.21	210	239	
M (-):	-159.12	240	249	
Strain (+):	166	210	239	
Strain (-):	-131	240	249	
Span5				
M (+):	201.22	270	299	
M (-):	-159.13	300	309	
Strain (+):	166	270	299	
Strain (-):	-131	300	309	
Span6				
M (+):	201.22	330	359	
M (-):	-159.13	360	369	
Strain (+):	166	330	359	
Strain (-):	-131	360	369	
Span7				
M (+):	201.21	390	419	
M (-):	-159.16	420	429	
Strain (+):	166	390	419	
Strain (-):	-131	420	429	
Span8				
M (+):	200.97	450	479	
M (-):	-159.62	480	488	
Strain (+):	166	450	479	
Strain (-):	-132	480	488	
Span9				
M (+):	197.62	510	539	
M (-):	-166.43	540	548	
Strain (+):	163	510	539	
Strain (-):	-137	540	548	
Span10				
M (+):	157.93	564	593	
M (-):	-278.80	600	604	
Strain (+):	130	564	593	
Strain (-):	-230	600	604	

63

Back 18 Next 4 Exit 64

(b) 'In each span' option

Figure 2-8. (continued)

Print Maximums (70)

Margin (inches) (70)

Top: 0.75

Left: 0.75

Print (71)

View Data (72)

Back (18)

Exit (64)

Analysis

Maximums and Locations (73)

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 (kips) and Strain (microstrain) / Location / Truck Position

		X(ft)	b1(ft)
Span1	M (+):	152.46	36
	M (-):	-294.80	0
	Strain (+):	126	36
	Strain (-):	-243	0
Span2	M (+):	197.59	90
	M (-):	-157.96	60
	Strain (+):	163	90
	Strain (-):	-130	60
Span3	M (+):	200.96	150
	M (-):	-158.99	180
	Strain (+):	166	150
	Strain (-):	-131	180
Span4	M (+):	201.21	210
	M (-):	-159.12	240
	Strain (+):	166	210
	Strain (-):	-131	240
Span5	M (+):	201.22	270
	M (-):	-159.13	300
	Strain (+):	166	270
	Strain (-):	-131	300
Span6	M (+):	201.22	330
	M (-):	-159.13	360
	Strain (+):	166	330
	Strain (-):	-131	360
Span7	M (+):	201.21	390
	M (-):	-159.16	420
	Strain (+):	166	390
	Strain (-):	-131	420
Span8	M (+):	200.97	450
	M (-):	-159.62	480
	Strain (+):	166	450
	Strain (-):	-132	480
Span9	M (+):	197.62	510
	M (-):	-166.43	540
	Strain (+):	163	510
	Strain (-):	-137	540
Span10	M (+):	157.93	564
	M (-):	-276.83	600
	Strain (+):	130	564
	Strain (-):	-230	600

(a) When 'In each span' option is selected

Figure 2-9. Print Maximums Window

Print Maximums (69)

Margin (inches) (70)

Top: 0.75

Left: 0.75

Print (71)

View Data (72)

Back (18)

Edit (64)

Analysis

Maximums and Locations

Find the Maximum Results:

☐ In each span

☒ At a designated location

X = 0.0 ft (from the left exterior support) (73)

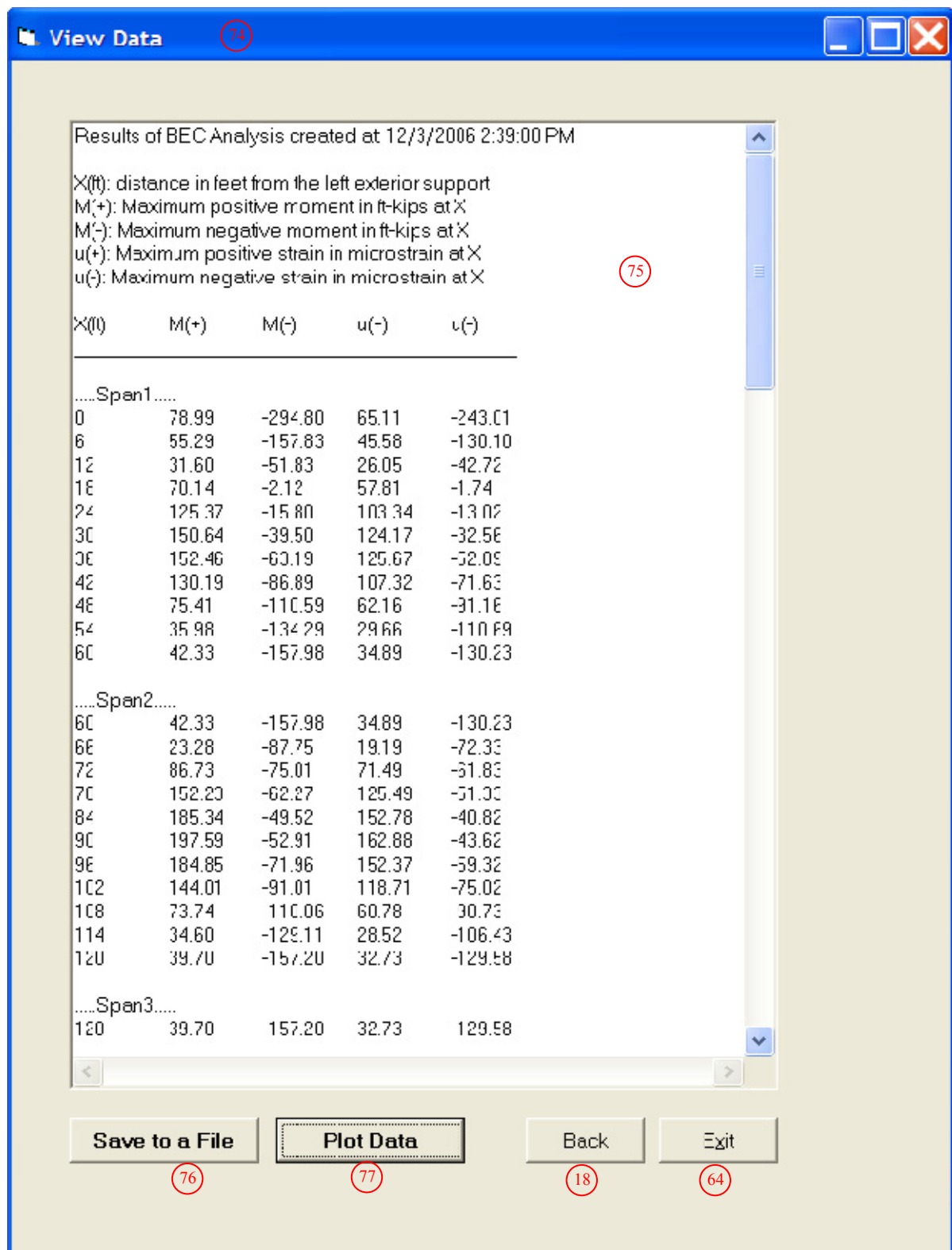
Track moving at every 1 ft

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

M (+):	150.64	when P1 is at	59	ft
M (-):	-39.50	when P1 is at	112	ft
Strain (+):	124	when P1 is at	59	ft
Strain (-):	-33	when P1 is at	112	ft

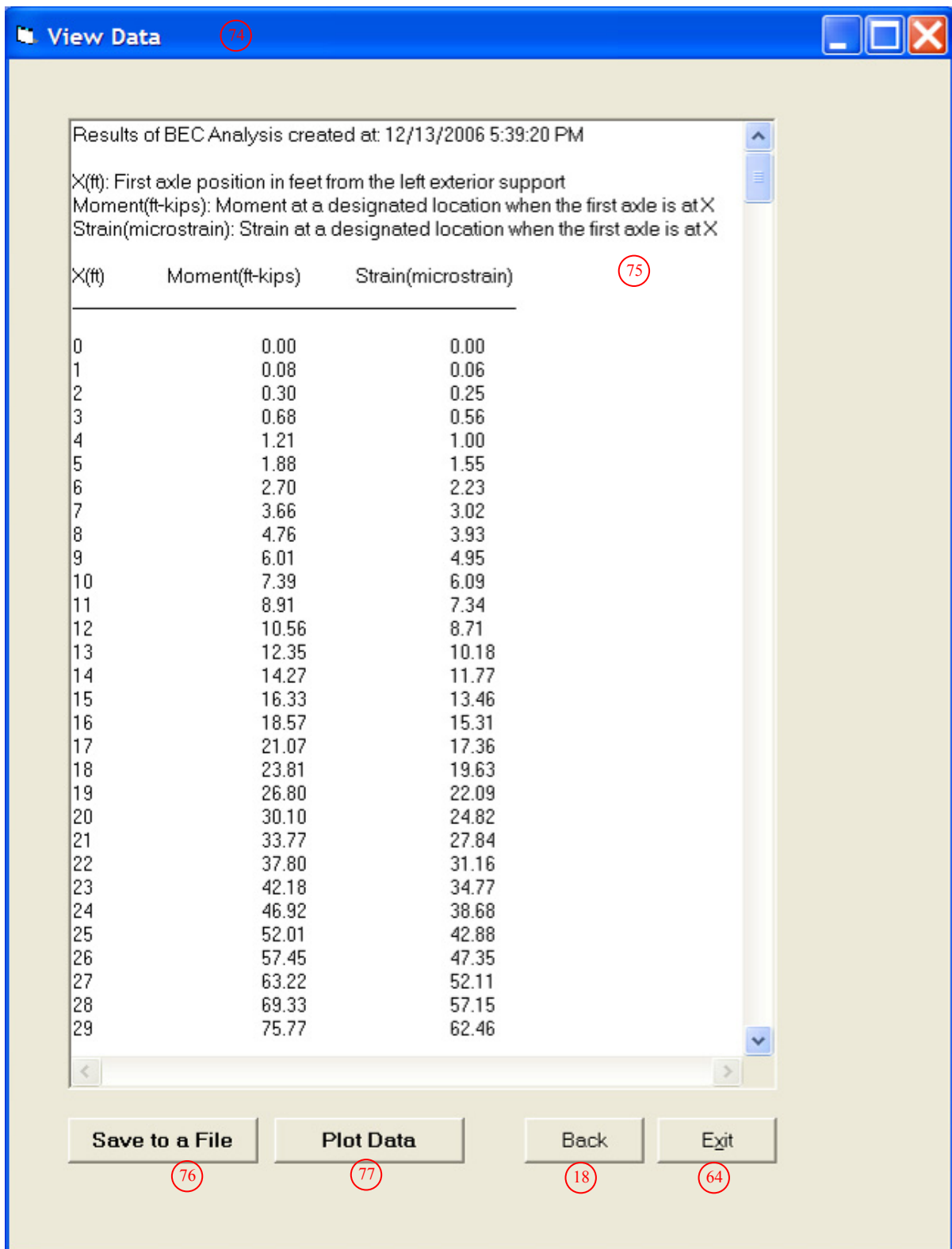
(b) When 'At a designated location' option is selected

Figure 2-9. (continued)



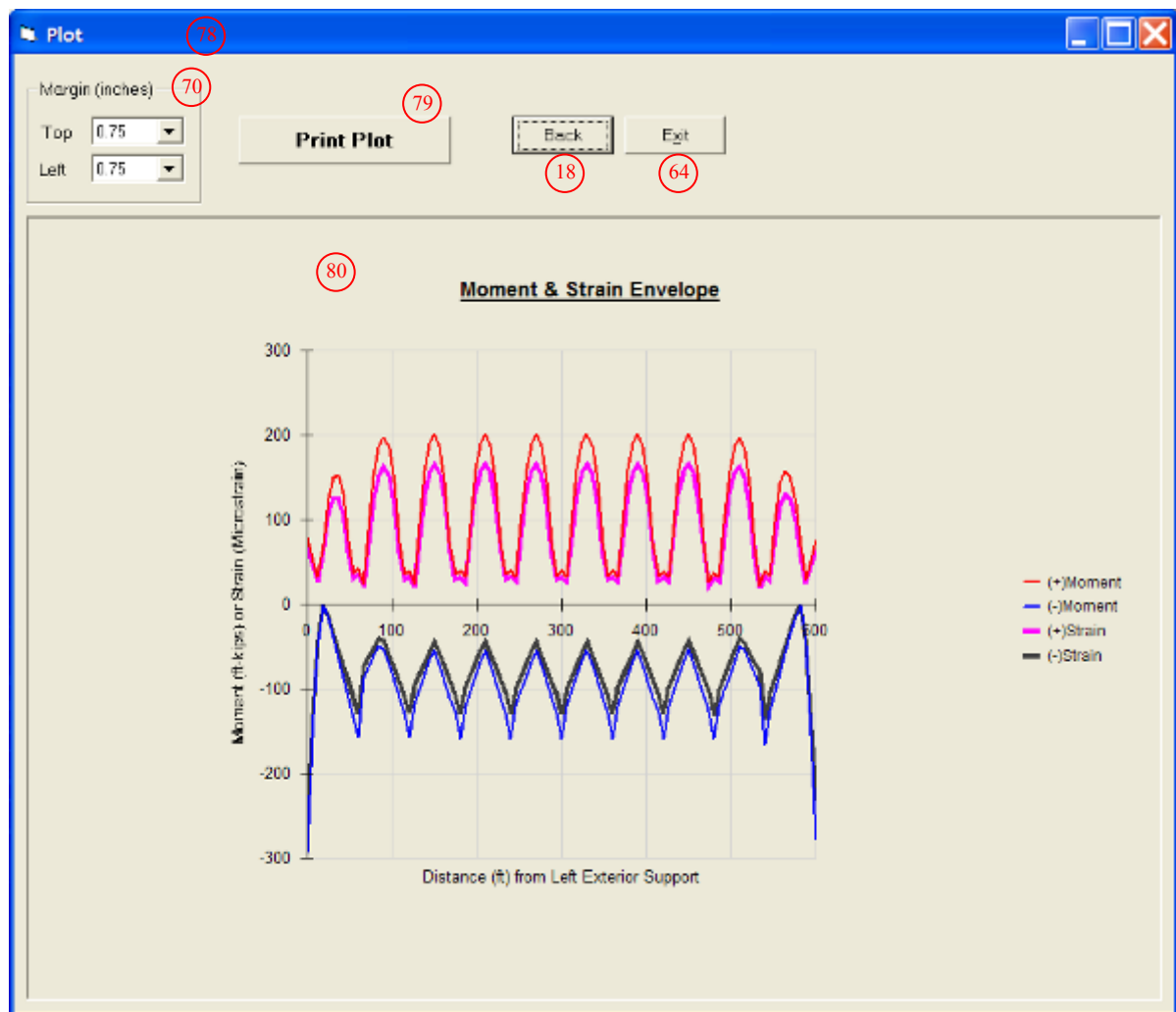
(a) When 'In each span' option is selected

Figure 2-10. View Data Window



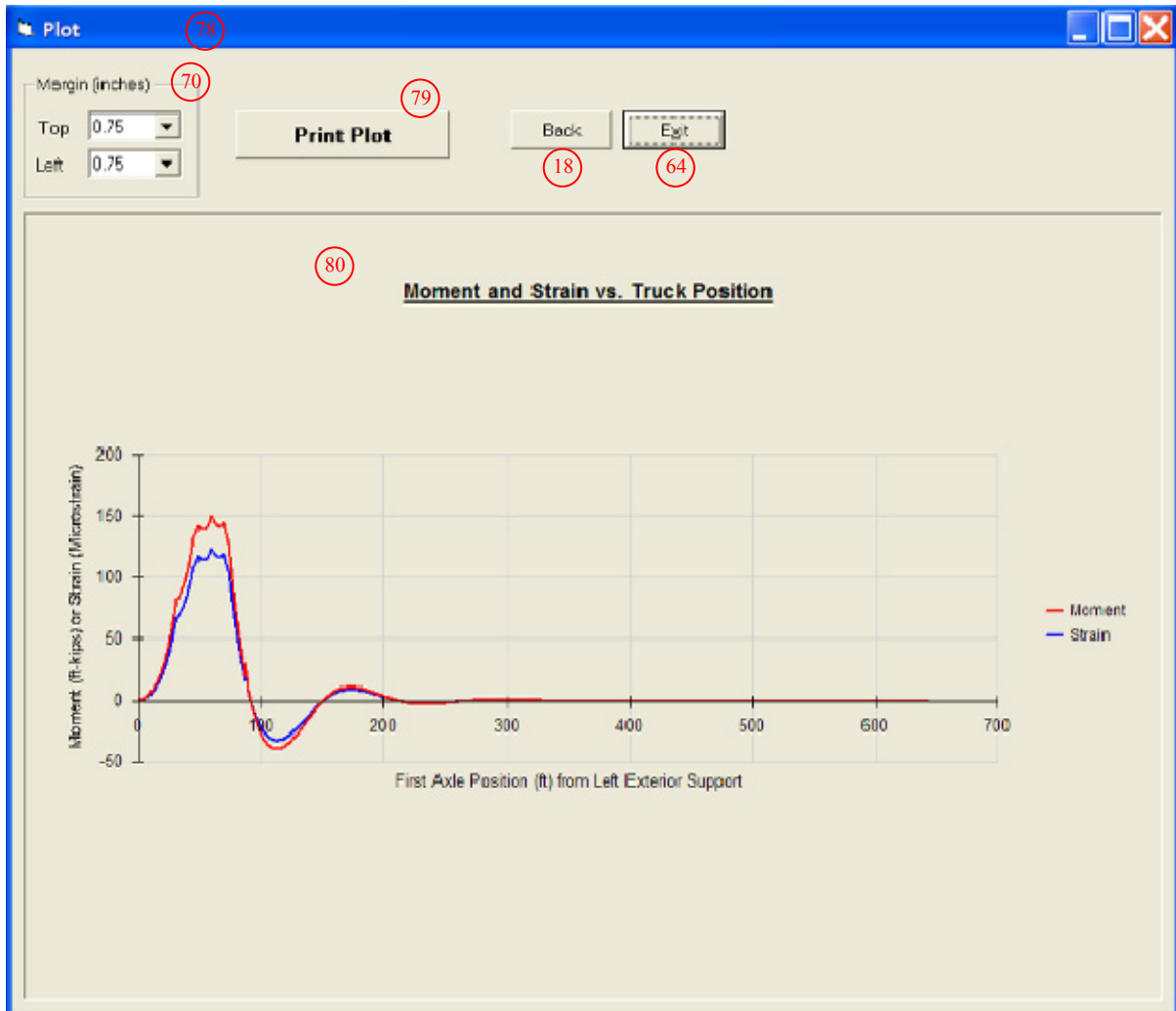
(b) When 'At a designated location' option is selected

Figure 2-10. (continued)



(a) When 'In each span' option is selected

Figure 2-11. Plot window



(b) When 'At a designated location' option is selected

Figure 2-11. (continued)

2.1.2.3. Section Properties Window

The 'Section Properties' window (#19) illustrated in Figure 2-6 will only be called when the 'Calculator' command (#12) is pressed. In this window, geometric section properties for general section types (user-defined), standard steel, Iowa P/C and AASHTO P/C can be computed. Frames #20 and #21 allow the user to generate section properties for either composite or non-composite sections. Composite action calculations are engaged when the 'Composite' option is selected in #20. The material properties and dimensions of the tributary deck are defined in the 'Deck' frame (#21). Note that frame #21 will only be enabled if the 'Composite' option is selected.

The program will compute section properties when the 'Click to Compute Properties' command button (#26) is pressed. The results are automatically copied, when the 'OK' command button (#27) is pressed, into #13, #14 and #15. The section modulus for each segment will be computed at the locations specified in the 'Sensor Location' frame (#25).

Section Properties window for user definable cross sections

The window shown in Figure 2-6a will be called when the 'Define' option in the 'Member Cross Section' frame (#9) is selected. It allows users to compute section properties for general section types. Options for nine general section types are provided as follows:

- I – Beam
- I – Beam (Tapered flanges)
- I – Beam + Angles
- T – Beam
- T – Beam (Tapered flanges)
- Channel
- Channel (Tapered flanges)
- P/C shape
- Rectangular shape

Depending upon the option selected in the 'Define' frame (#22), a corresponding graphic representation will be displayed in the graphic display indicator #23. Dimensions for each shape can be defined with the text box controls provided in the 'H and W' frame (#24) where the letter 'H' represents vertical dimensions and 'W' represents horizontal dimensions.

Section Properties window for standard steel cross sections

Section properties for standard steel can be computed in the window illustrated in Figure 2-6b. This window is called when the 'Standard Steel' option is selected in the 'Member Cross Section' frame (#9). In this window, information on six classes of standard steel sections can be found. A member can be selected with a mouse click. Upon selected, the member label will be highlighted in blue and the corresponding section properties will be displayed in the 'Beam Information' frame (#34).

Section Properties window for Iowa P/C cross sections

The Section Properties window presented in Figure 2-6c appears if the ‘Iowa P/C’ option is selected in the ‘Member Cross Section’ frame (#9). Information on two types of Iowa P/C sections can be found. Upon selection, the list box indicator #36 will display the members that are available and their basic properties will be displayed in the ‘Beam Information’ frame (#34).

Section Properties window for AASHTO P/C cross sections

Section properties for AASHTO P/C section can be computed in the window illustrated in Figure 2-6d. This window is called if the ‘AASHTO P/C’ option is selected in the ‘Member Cross Section’ frame (#9). Information on four types of AASHTO P/C sections can be found.

Upon selection of an option in the ‘AASHTO P/C’ frame (#37), the list box indicator #38 will display the corresponding members that are available. A member can be selected with a mouse click. If selected, its label will be highlighted in blue and the corresponding section properties for the selected member will be displayed in #34.

2.1.2.4. Load Window

Once a model bridge has been constructed using the above described windows, loads can be defined in the form of either a series of point loads that simulate trucks or uniformly distributed loads with one or two point loads that simulate lane loads. The ‘Load’ window (#39) shown in Figure 2-7 allows the user to configure live loads that will be applied to the bridge. The software provides options for Iowa legal loads, H-20 and HS-20 trucks, truck train as well as user-definable live loads. In addition, a distribution factor (DF) and impact allowance (IM) can be defined.

When the user chooses the ‘Iowa Legal Loads/HS-20’ option (#40), the ‘Iowa Legal Loads/HS-20’ frame (#46) will be enabled which allows the user to select one of the listed trucks. When an option is selected in #46, the information of the selected truck – axle weight (wheel line load), distance between each axle and its graphic representation – will be displayed in #49, #50 and #51, respectively.

A truck train loading will be applied if the ‘Truck Train’ option (#41) is selected. Selecting this option will enable a text box control, where a default magnitude for a uniformly distributed load will be displayed (#43), and the ‘Apply W on’ frame (#45), which allows the user to choose the span(s) upon which the uniformly distributed load will be applied.

If users wish to apply a live load that is not available in the above, a manual load generation can be performed. This can be accomplished by selecting the ‘Define’ option (#42), which allows users to configure a truck with up to eight axles. After defining the desired number of axles in the ‘Number of Axles’ text box (#48), a corresponding number of text boxes will appear in #49 and #50 where the specific configuration is entered.

2.1.2.5. Analysis Window

The analysis is performed in the ‘Analysis’ window shown in Figure 2-8. This portion of the software allows the user to run the analysis and to view absolute maximum results. The analysis is performed when the ‘Run Analysis’ command button (#57) is pressed. Upon completion, a prompt dialog box will appear indicating that the analysis was successfully completed.

The specific results generated by the software depend upon the options selected and the inputs entered. For example, the program will generate absolute maximum moments and strains at a location, X, which would have been specified in text box #55 as illustrated in Figure 2-8a if the ‘At a designated location’ option (#53) is selected. By selecting the ‘In each span’ option (#53), the program will generate the magnitudes (#66) and locations (#67) of the absolute maximum moments and strains in each span as illustrated in Figure 2-8b. Note that the location, X, at which the maximum is generated, and the first axle position, b1, are symbolically displayed in the graphic indicator #51 in the ‘Load’ window (#39).

In addition to the absolute maximum results discussed above, *BEC Analysis* can also generate moments and strains with respect to truck position (‘moment and strain vs. truck position’) or envelopes of maximums. The results of ‘moment and strain vs. truck position’ analysis or envelopes can be accessed in the ‘View Data’ window (#74) and also in the ‘Plot’ window (#78), which will be discussed subsequently.

2.1.2.6. Print Maximums Window

The Print Maximums window shown in Figure 2-9 allows the users to print a hard copy of the absolute maximum results displayed in the ‘Analysis’ window. The specific results displayed will be based upon the options selected in the ‘Find the Maximum Results’ frame in the ‘Analysis’ window (#53).

2.1.2.7. View Data Window

As mentioned in Section 2.1.2.5, ‘moment and strain vs. truck position’ analysis results can also be generated during the analysis. The ‘View Data’ window (#74) allows the user to access the specific numerical results. As illustrated in Figure 2-10, the data display box shows the maximum moments and strains in each span. Note that the left column, X (ft.), represents the distance along the bridge for “envelopes of maximums” as shown in Figure 2-10a; while it represents the first axle positions in the ‘moment and strain vs. truck position’ analysis results as shown in Figure 2-10b. Also note that in Figure 2-10a, the maximum results are displayed separately for each span. These numerical data can also be saved to a text file. This can be accomplished by pressing the ‘Save to a File’ command button (#76). When pressed, the user will be prompted to designate a file path to which the displayed data will be written and saved.

2.1.2.8. Plot Window

Options are available which allow the user to obtain plots of the ‘moment and strain vs. truck position’ diagrams. After reviewing and/or saving the data, a plot can then be generated. When the ‘Plot Data’ command button (#77) is pressed, the program will move to the ‘Plot’ window (#78) where the ‘moment and strain vs. truck position’ diagrams will be graphically displayed in the plot display box (#80) as illustrated in Figure 2-11.

2.2. Field Monitoring Software

The field monitoring software was developed to function with IOtech instrumentation hardware, which will be discussed subsequently. The software was designed to collect, process, and evaluate the measured bridge response. Its use will allow bridge owners to quantitatively monitor a bridge for potential cause of damage as well as gradual changes in behavior. The following gives general background information and briefly describes the methodology followed during portions of the development of the field monitoring software. Specific components of the field monitoring software and the required initial setup procedures are then described. In addition, the general procedures involved in running each component of the field monitoring software are also described.

2.2.1. General Background and Methodology

2.2.1.1. Identifying “Alarm Events”

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 will be 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. 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, 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 2-12, 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. 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. This may require collecting sample strain data from ambient traffic to establish an appropriate strain rate.

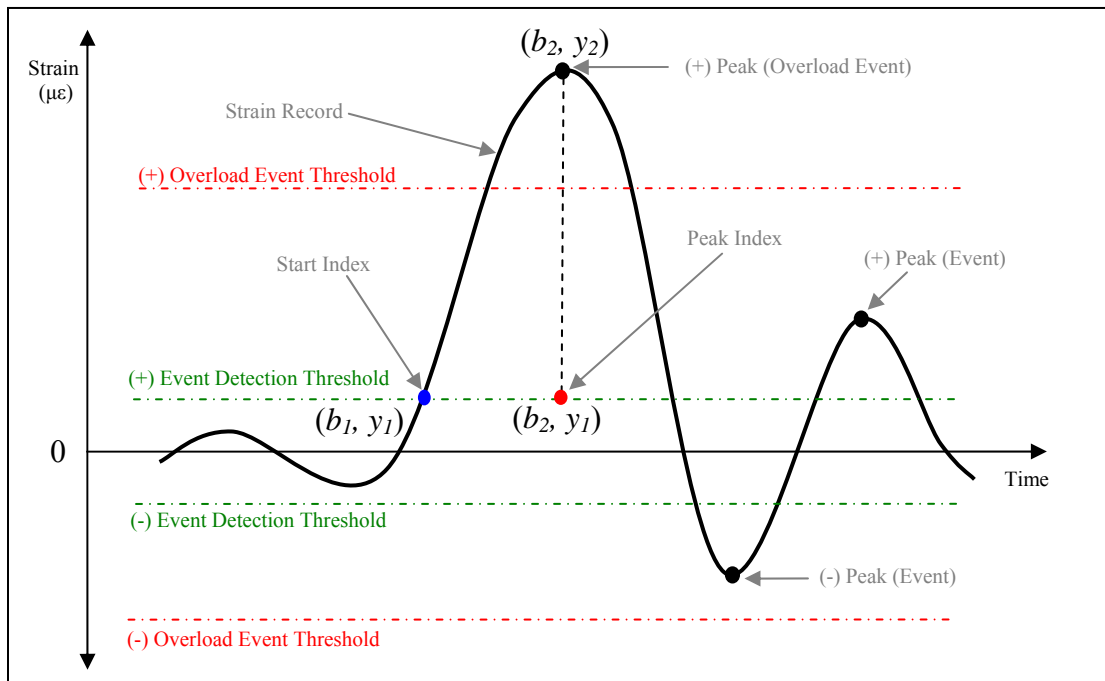


Figure 2-12. Parameters used to determine a slope in a strain record

2.2.1.2. Compensation of Temperature Effects and Noise Minimization

Collecting reliable strain data requires attention to the unique characteristics of bridges and the surrounding environment. Typically, measured strain data from bridges contains components that can be categorized into two general parts: traffic induced strains and other unwanted elements such as changes in strain induced by temperature variations and noise. The useful information for the methodology used here are those collected data resulting from ambient traffic only. Therefore, eliminating or minimizing the unwanted elements is imperative.

It is widely known that temperature related effects are one of the most common “issues” with measured strain data. Various attempts have been made by manufacturers to minimize the sensitivity to temperature through selection of strain gauge materials. Although adjusted strain gauges are known to reduce ‘some’ level of thermal issues, they do not totally

eliminate the effect. 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 10 minutes.

Minimizing noise in measurement systems is important as it can present a serious problem. The typical environment surrounding a bridge may contain abundant sources of noise. In general, high frequency noise is normally induced by radio signals while electronic equipment generates noise in almost all frequency ranges. Although completely preventing the occurrence of noise would be the ideal situation, it is seldom practical. Fortunately, the use of simple techniques such as appropriate grounding techniques, shielded and twisted wires, etc. can control some level of noise. However, they do not eliminate noise completely. One solution to further minimize noise is to identify and block the source of noise by use of filtering. The use of filtering allows users to remove specific components that are not of interest. Measured live load strains may have content across the entire frequency spectrum. However, the most important elements are contained in a relatively well defined frequency range. In order to define where the desired strain data falls and /or where the noise falls, a Fast Fourier Transform (FFT.) analysis can be utilized. A FFT. analysis allows users to view the frequency content of measured strain data. Then, one can choose an appropriate filter technique to extract the data of interest.

Traffic induced strains, in general, have frequency contents that are lower than those of most other sources. Applying a low-pass digital filter, therefore, can modify frequency contents of strain records by only allowing frequencies that are lower than a specified cutoff frequency. Previous work by the research team has shown that the Chebyshev filter effectively minimizes peak detection error with a relatively fast processing speed. Thus, the Chebyshev low-pass filter was utilized for minimizing noise in the field monitoring software.

2.2.1.3. Data Acquisition and Storage

While a slow speed monitoring strategy may be suitable for monitoring displacements and deformations, a high speed data acquisition is needed for capturing events that occur in a short time window, such as maximum traffic induced strains, large amplitude vibrations, and behavior caused by a vehicle collision. Therefore, it was decided that the data sampling rate should be user selectable to provide more flexibility in the use of the software. With this option available, it is thought that the software can be used to monitor bridges built for high speed (e.g., highway bridges) as well as low speed traffic (e.g., local bridges).

For a long term SHM system, data sets that are collected over extended periods of time can cause problems as the size of the generated files can be quite large. Managing a large data volume can be problematic since significant effort can be required to identify and extract the desired characteristics. Storage of a large volume of collected data can also cause problems since it may require significant disc space. To address these issues, significant attention was

given to incorporate data reduction and processing algorithms so that only the useful information is used and retained.

2.2.1.4. Results Presentation

In addition to efforts related to data processing and storage, significant attention was given to ensuring that the system presents useful evaluation results to the user. As will be illustrated subsequently, the field monitoring software was developed to provide users with following information:

- Identifying and notifying alarming events
- Traffic event history
- Statistical trends

One of the main purposes of the field monitoring software is to deliver users information that can be used to identify potential damage 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. To this end, algorithms were added so that reports can be automatically generated in three formats: Microsoft Excel Worksheet, PDF, and hard copy. 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 recorded event
- Event histogram
- Statistical trends of events including absolute maximum and average
- Summary of messages regarding “alarm events”

2.2.2. *Components of the Field Monitoring Software and Required Initial Setup*

2.2.2.1. Components of the Field Monitoring Software

There are three groups of programs included in the field monitoring software: (1) a preliminary data acquisition and analysis component that is 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 is designed to be accessed at any time. The preliminary data acquisition and analysis tools assist in reducing noise and detecting events. 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 tools controls the main data acquisition and the organization of the collected data. During this process, collected data are 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, each of which contains summarized information about the bridge performance. The third group of the field monitoring software is used for generating and viewing summarized reports.

During software development, significant effort was taken to ease and minimize user interaction. This was accomplished by utilizing a series of GUI for each of operation. Each program was designed to provide users with immediate feedback. A total of eight programs were created as are listed below:

- | | | |
|--|---|---|
| • 1 Preliminary DAQ.VI | } | (1) Preliminary Data Acquisition and Analysis |
| • 2 FFT.-PSD Analysis.VI | | |
| • 3 Input.VI | } | (2) Main Data Acquisition and Processing |
| • 4 MainDAQ815.VI | | |
| • | | |
| • 5 View Strain History.VI | } | (3) Report Generation |
| • 6 View Hourly File.VI | | |
| • 7 Create Report (from single file).VI | | |
| • 8 Create Report (from multiple files).VI | | |

The first two programs (*1 Preliminary DAQ.VI* and *2 FFT.-PSD Analysis.VI*) are designed for preliminary data acquisition and analysis while *3 Input.VI* and *4 MainDAQ815.VI* are intended for use during main data acquisition and processing. The remaining programs are used for viewing and/or generating reports. Included in the title of the first four programs (1, 2, 3 and 4) is a number that indicates the order in which they should be executed. The other four programs (5, 6, 7 and 8) can be executed only when needed and in any order. Each program features a user interface and visualization command controls that are facilitated by tools contained in the program's graphical environment.

Presented in Figure 2-13 is a general flowchart that illustrates the overall procedures undertaken by the field monitoring software. Screen shots of each program are shown in Figures 2-14 through 2-21. Note that the front panels of each program contain two different types of displays: controls and indicators. Controls are devices that provide input and supply data to the programs. Indicators are devices that display output and/or data generated by the programs. Brief descriptions on select controls and indicators of each program are presented in Appendix B.

2.2.2.2. Required Initial Setup

The field monitoring software can be used only after (a) completing the IOtech software installation, hardware system setup and sensor calibration, and (b) creating a main directory, ‘SHM Folder’, that will contain input files and four sub directories for data transfer and storage. System requirements and necessary procedures on IOtech software installation and hardware system setup, as well as the sensor calibration process are provided in Appendix C. The user must create a directory entitled “SHM Folder” that contains the following four folders: “1 Raw Data”, “2 Data Process”, “3 Data File Folder”, and “Preliminary Data Folder”. In the following sections, overall procedures involved in running each program are described. In addition, step-by-step instructions on how to run each component are provided in Appendix B.

2.2.3. *Preliminary Data Acquisition and Analysis*

The first applications of the field monitoring software suite, preliminary data acquisition and analysis, are used to collect and establish information needed by other programs. Specifically, this process is intended to establish parameters that will be used in data processing, for reducing noise, and detecting events.

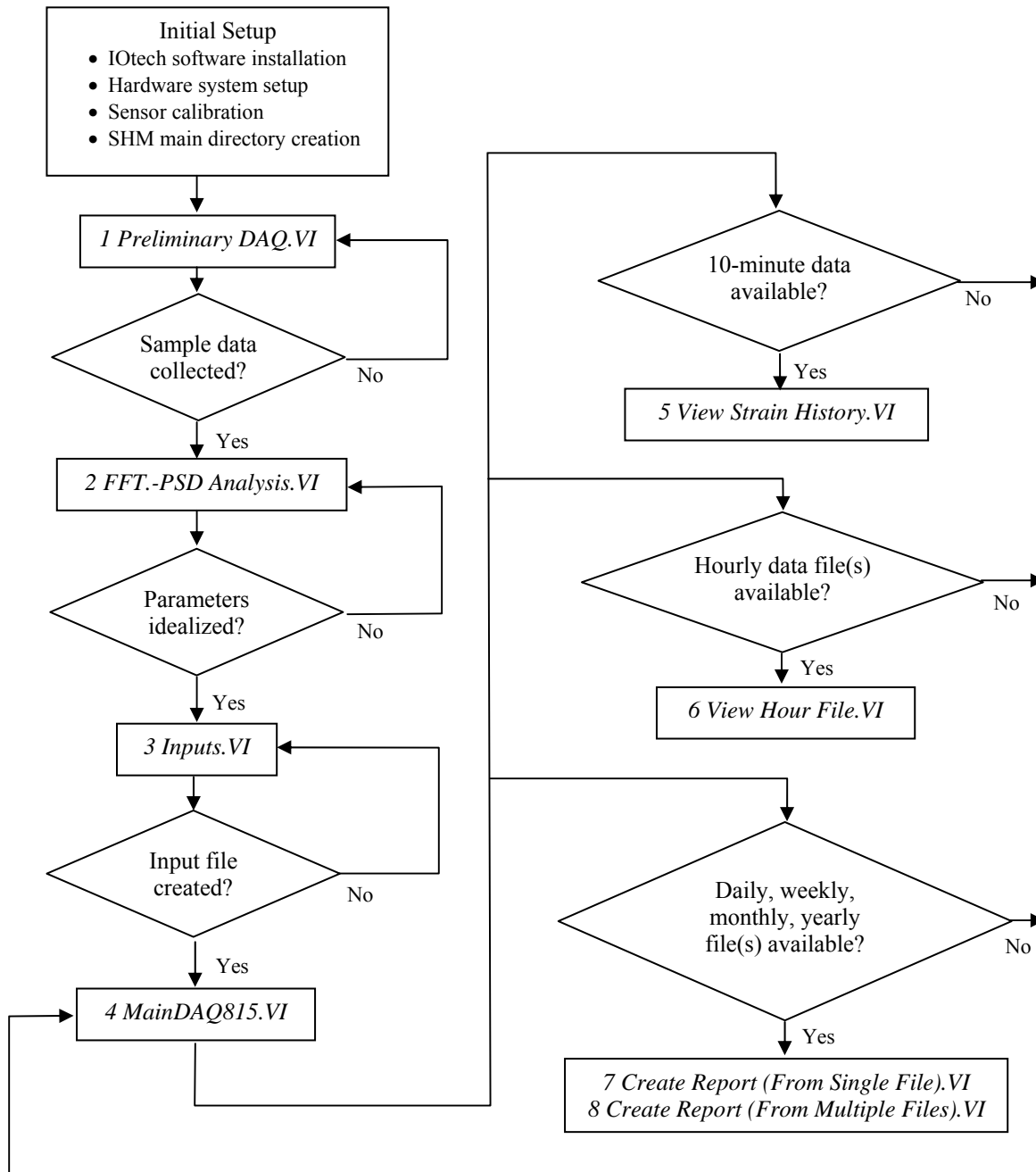


Figure 2-13. Illustration of overall procedures involved in the field monitoring software

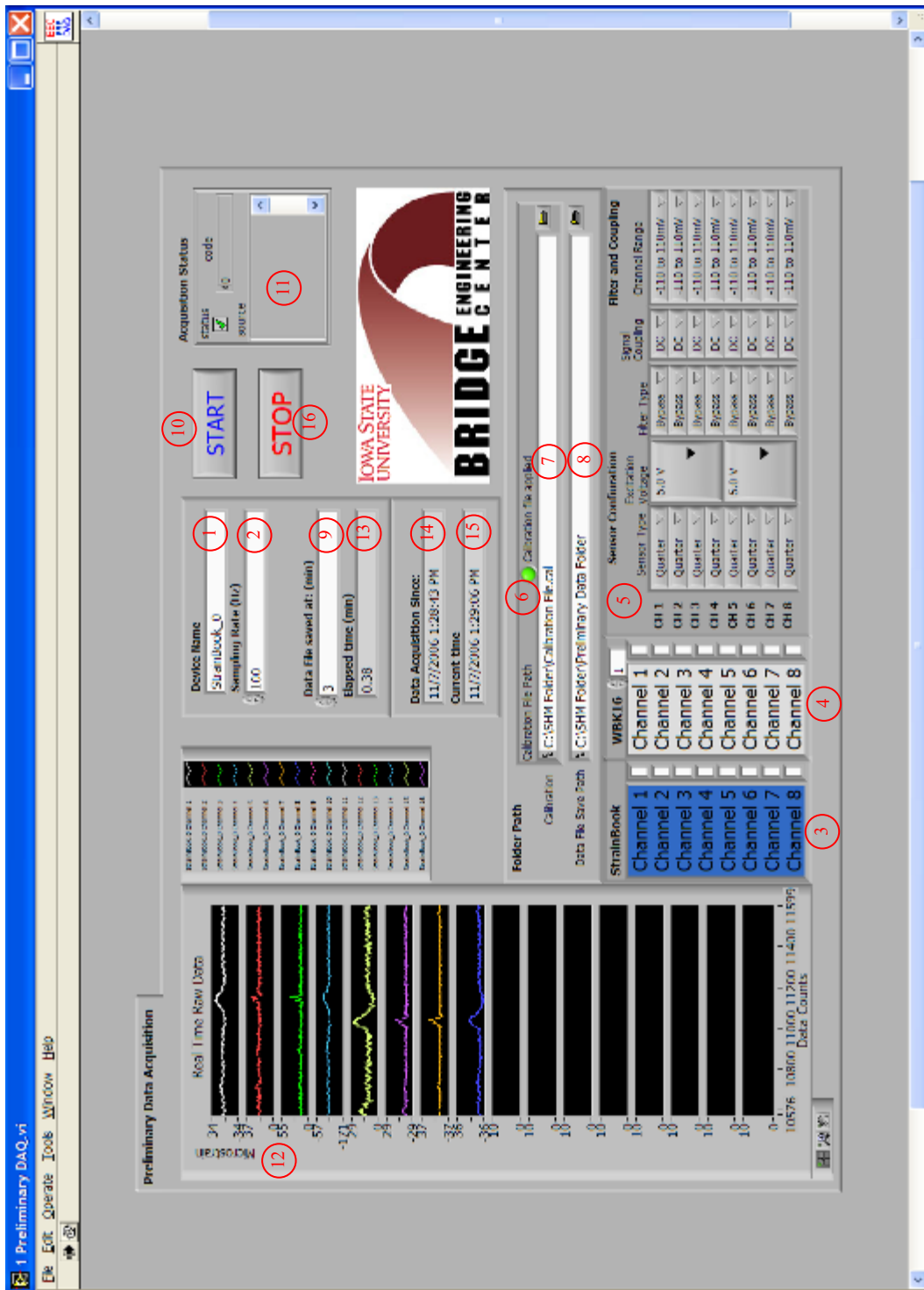
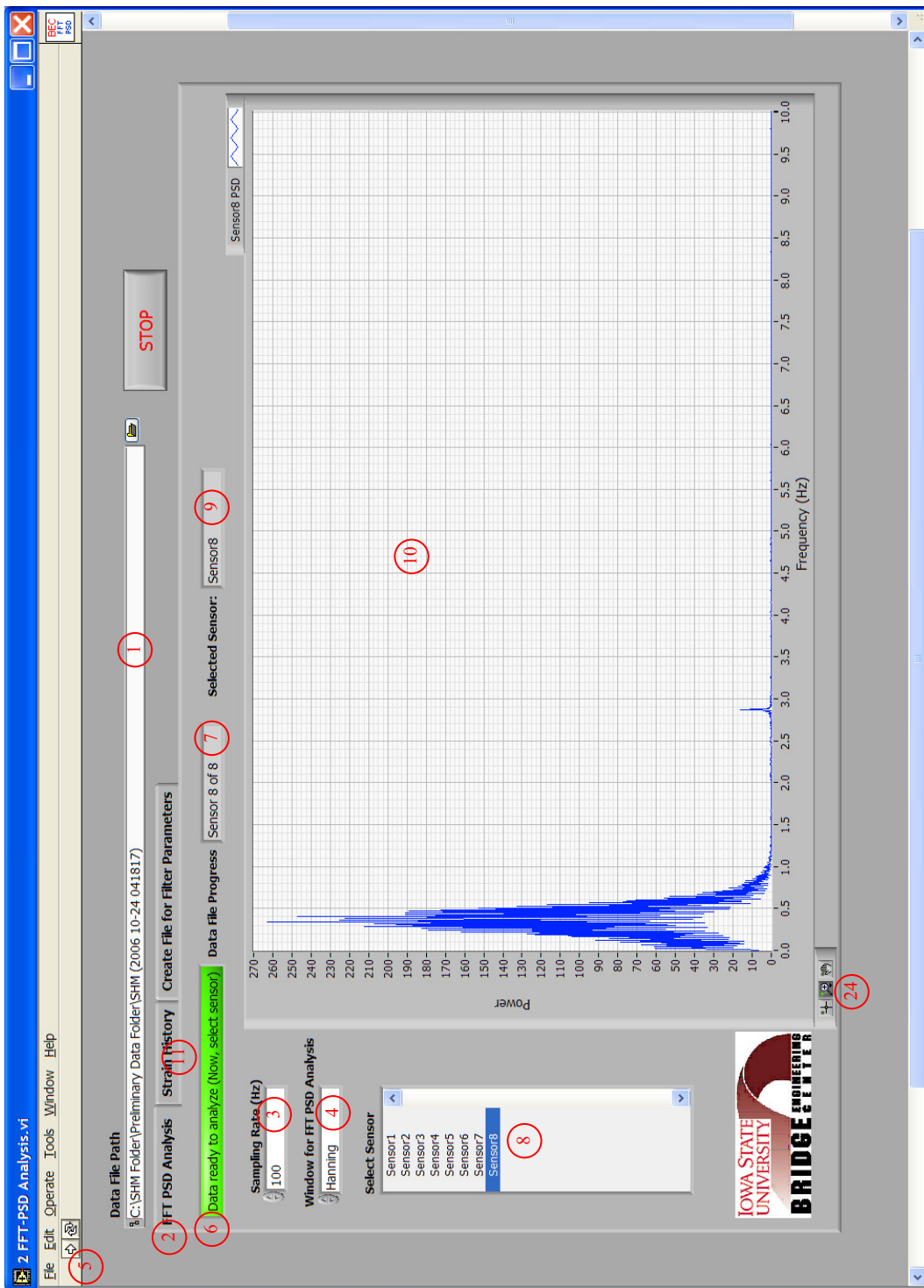
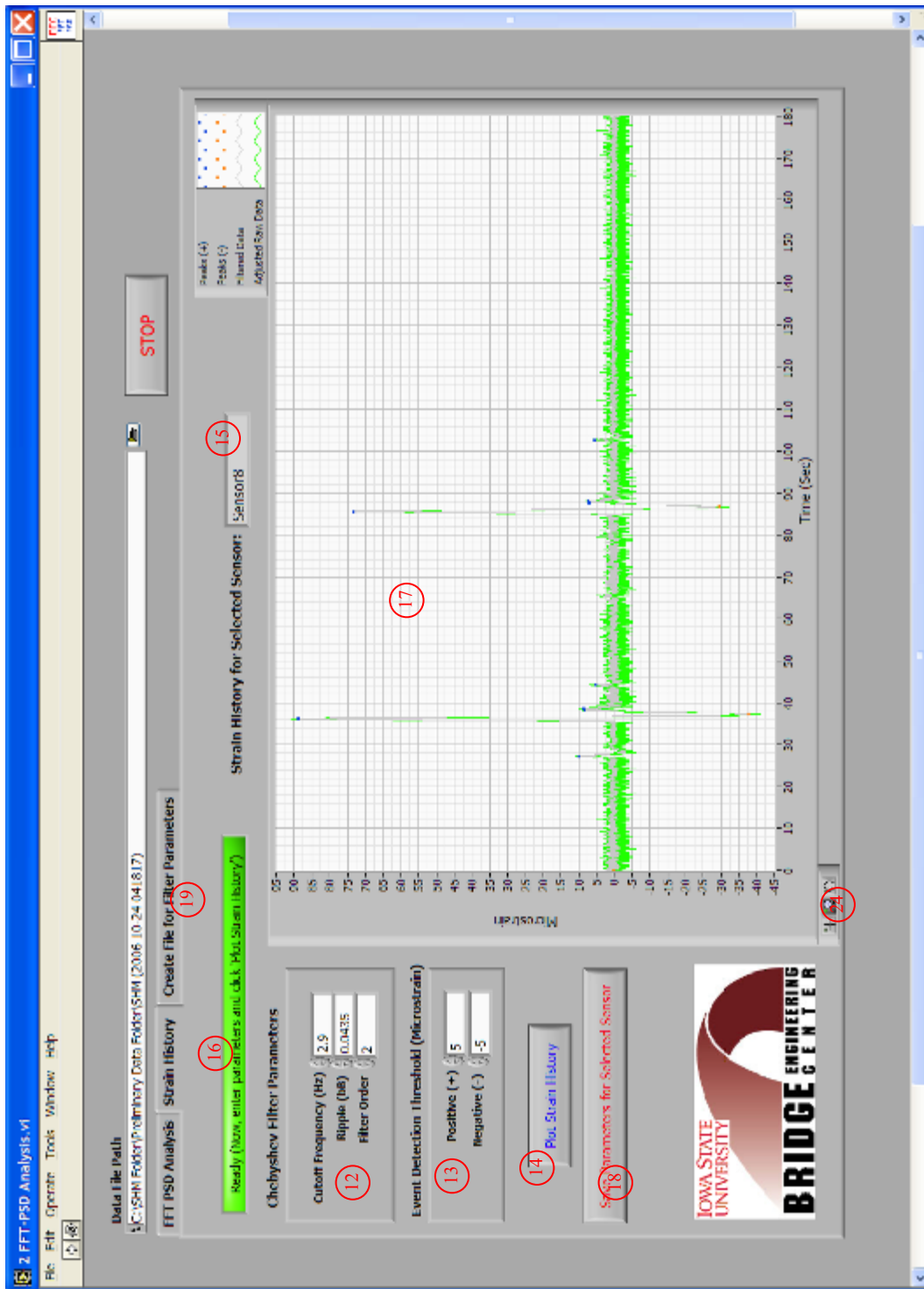


Figure 2-14. Screen shot of *1 Preliminary DAQ.VI* front panel



(a) FFT.-PSD plot display for the selected sensor

Figure 2-15. Screen shot of 2 FFT.-PSD Analysis. VI front panel



(b) Strain record display for the selected sensor

Figure 2-15. (continued)

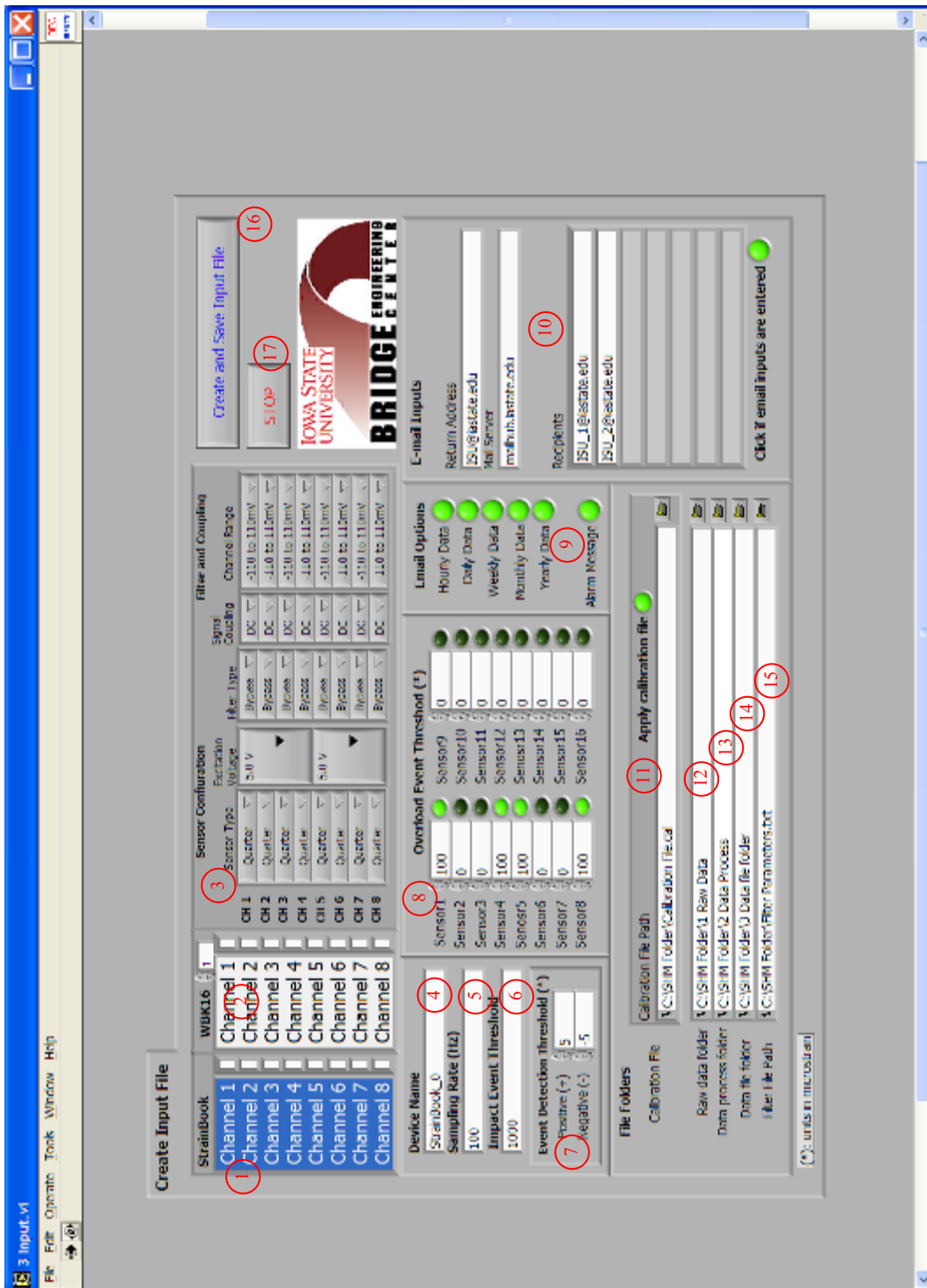
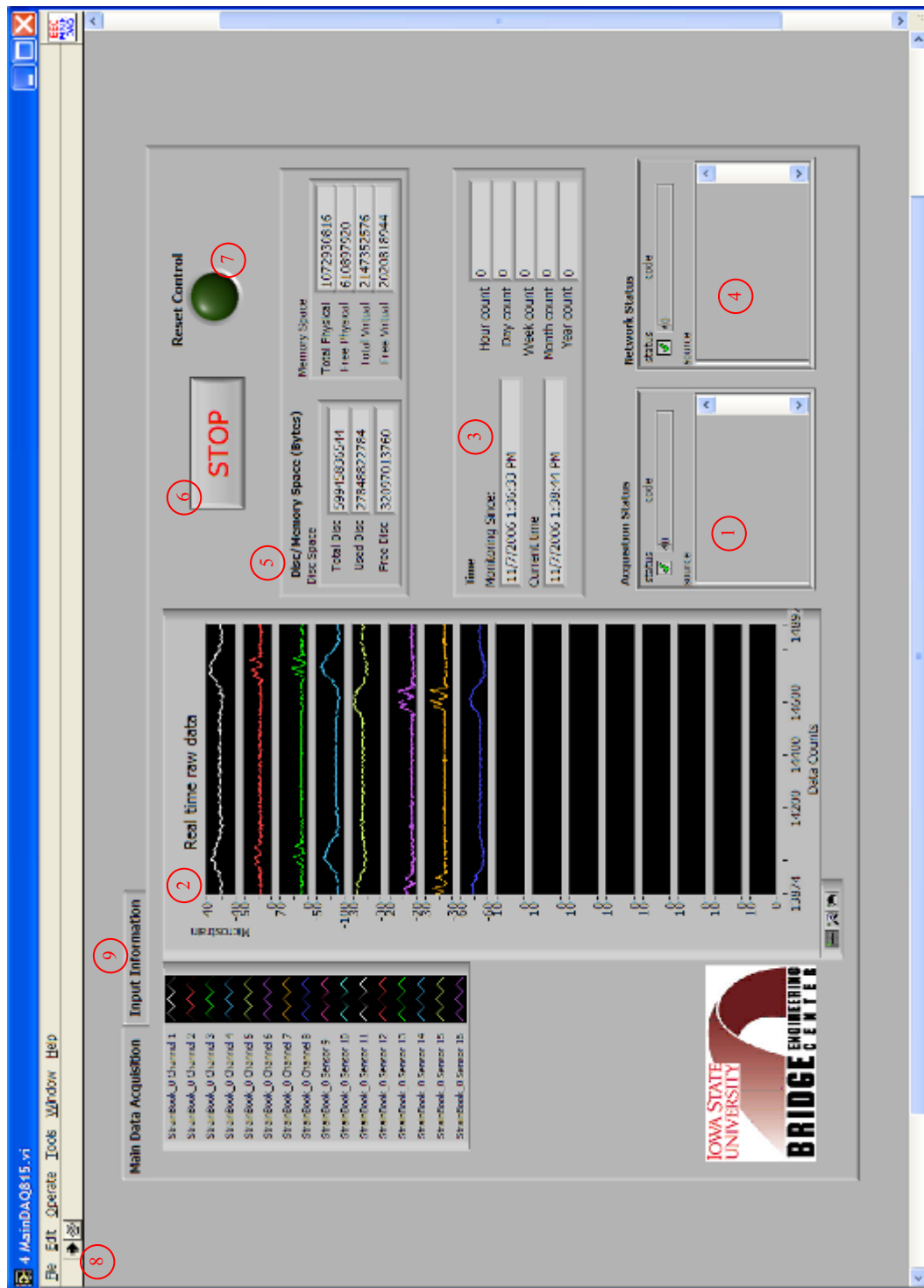
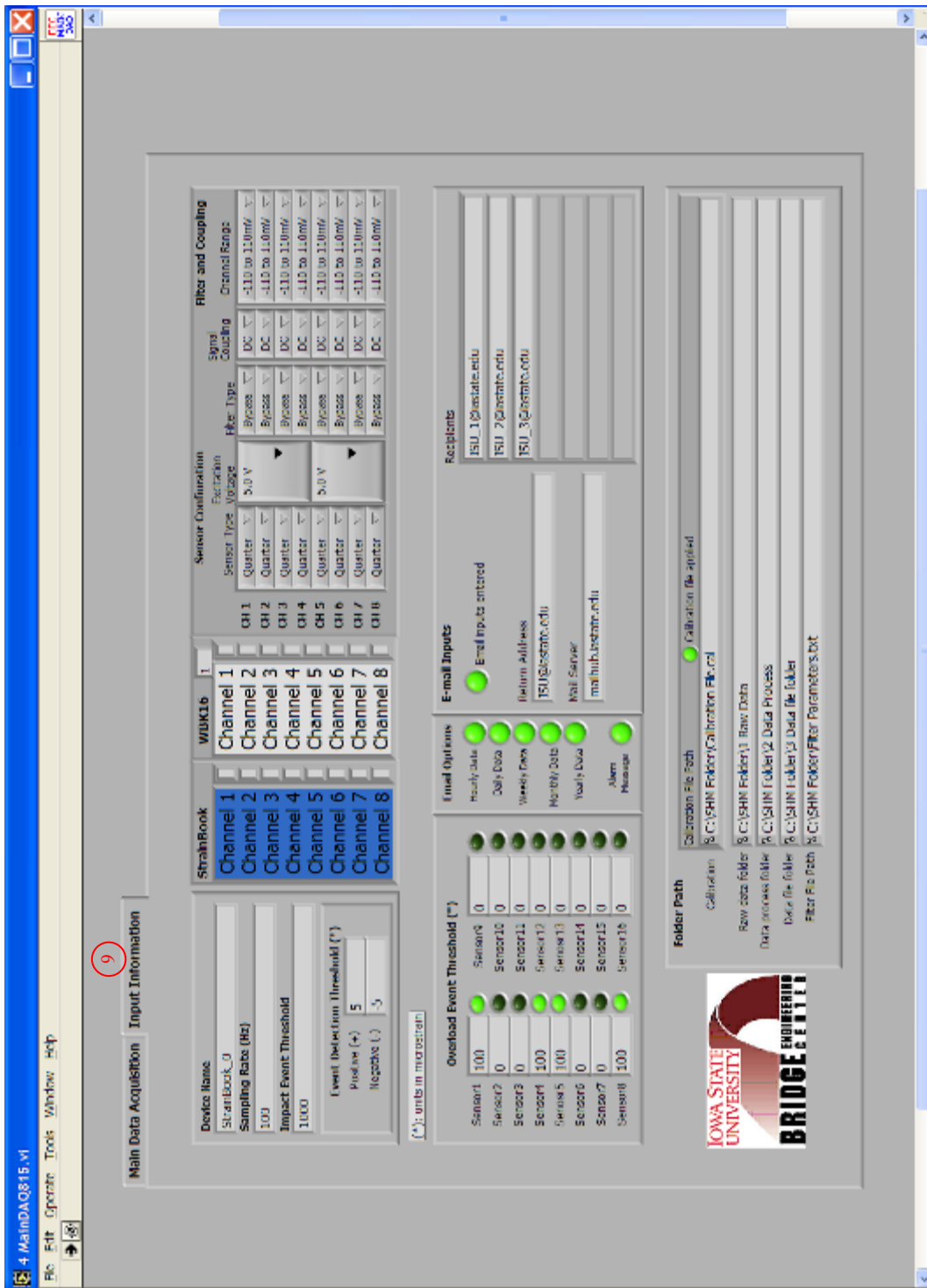


Figure 2-16. Screen shot of 3 Input.VI front panel



(a) Illustration of Main Data Acquisition tab

Figure 2-17. Screen shots of 4 *MainDAQ815.VI* front panel



(b) Illustration of Input Information tab

Figure 2-17. (continued)

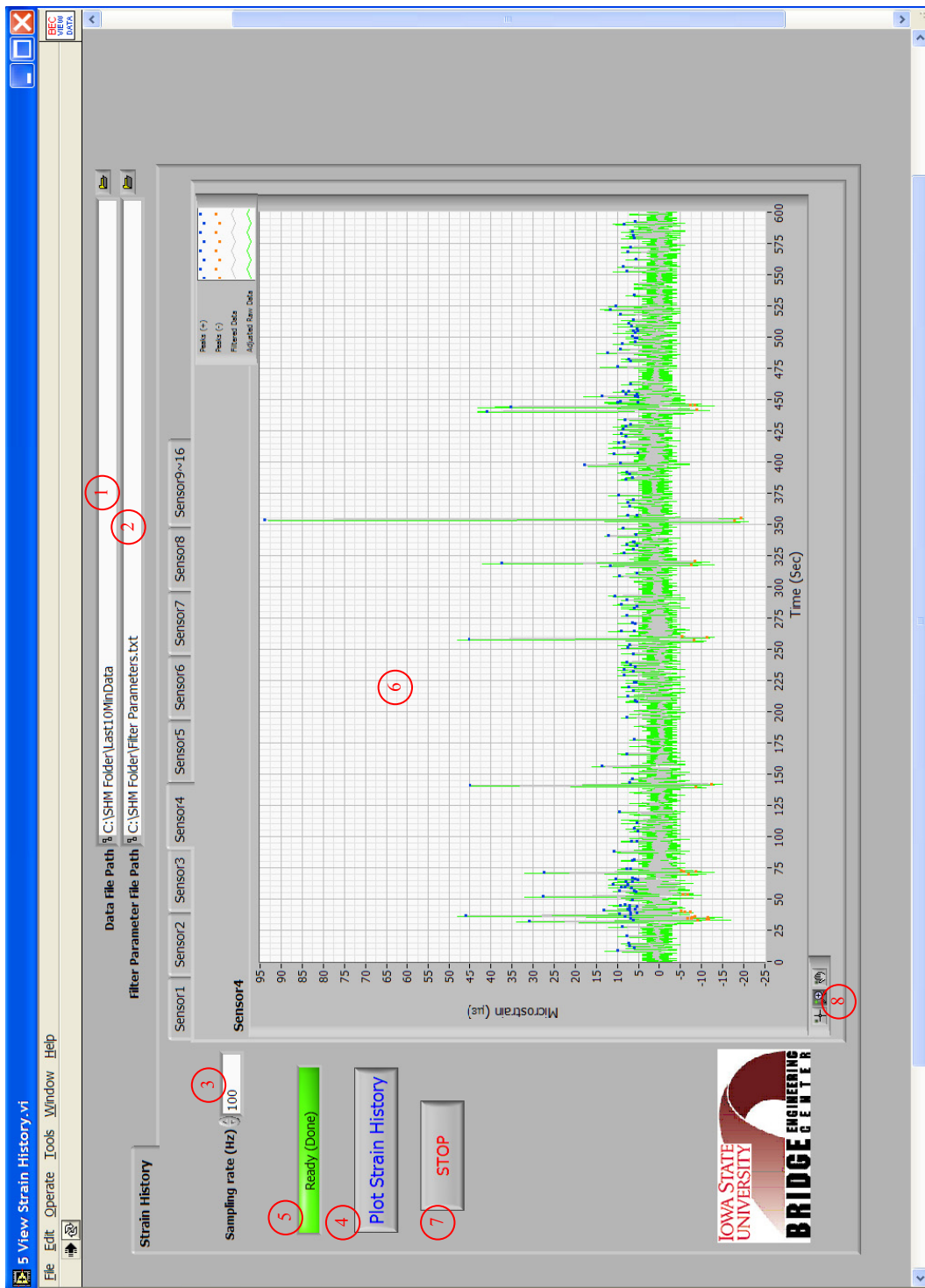
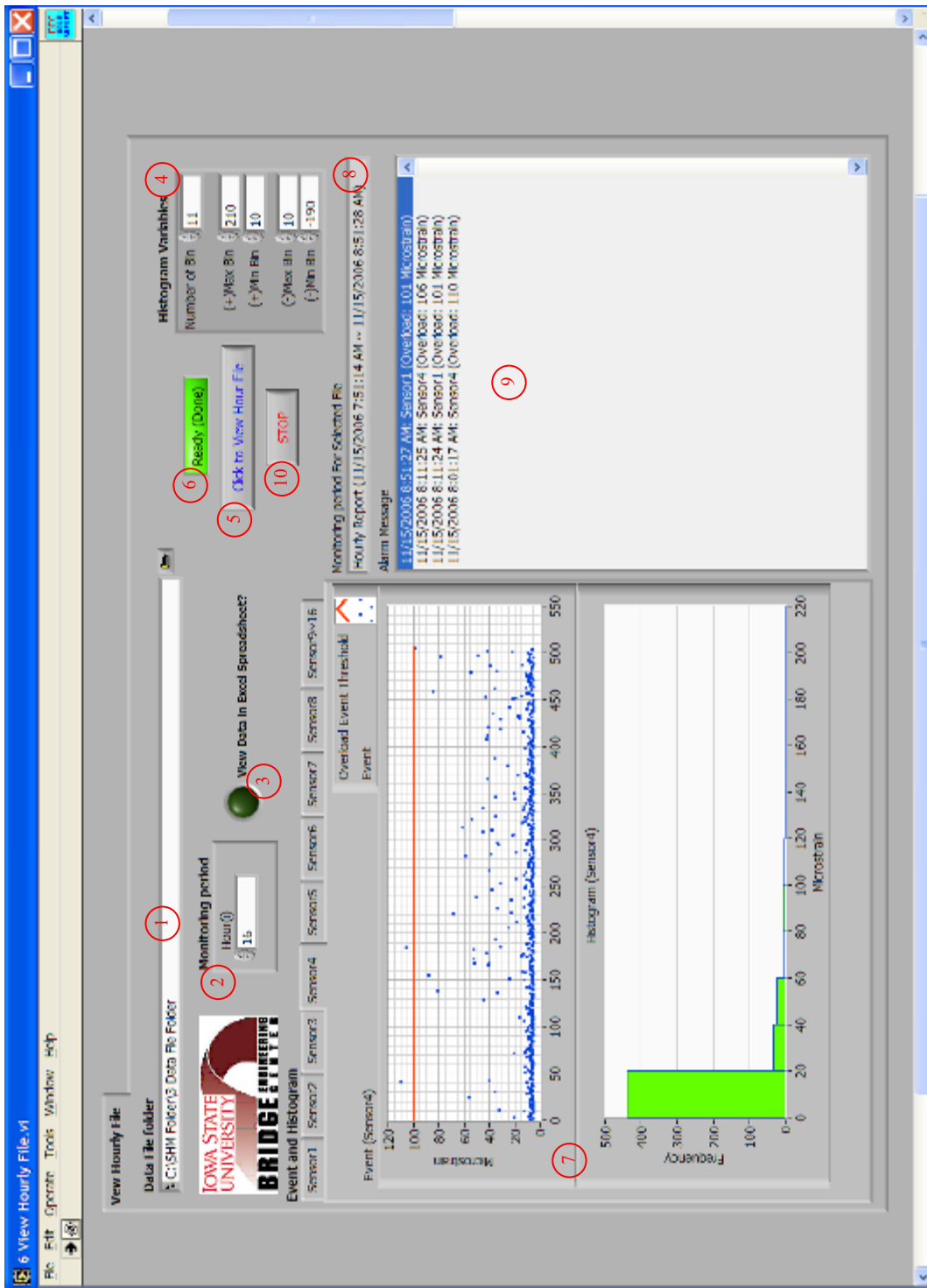


Figure 2-18. Screen shot of 5 View Strain History.VI front panel



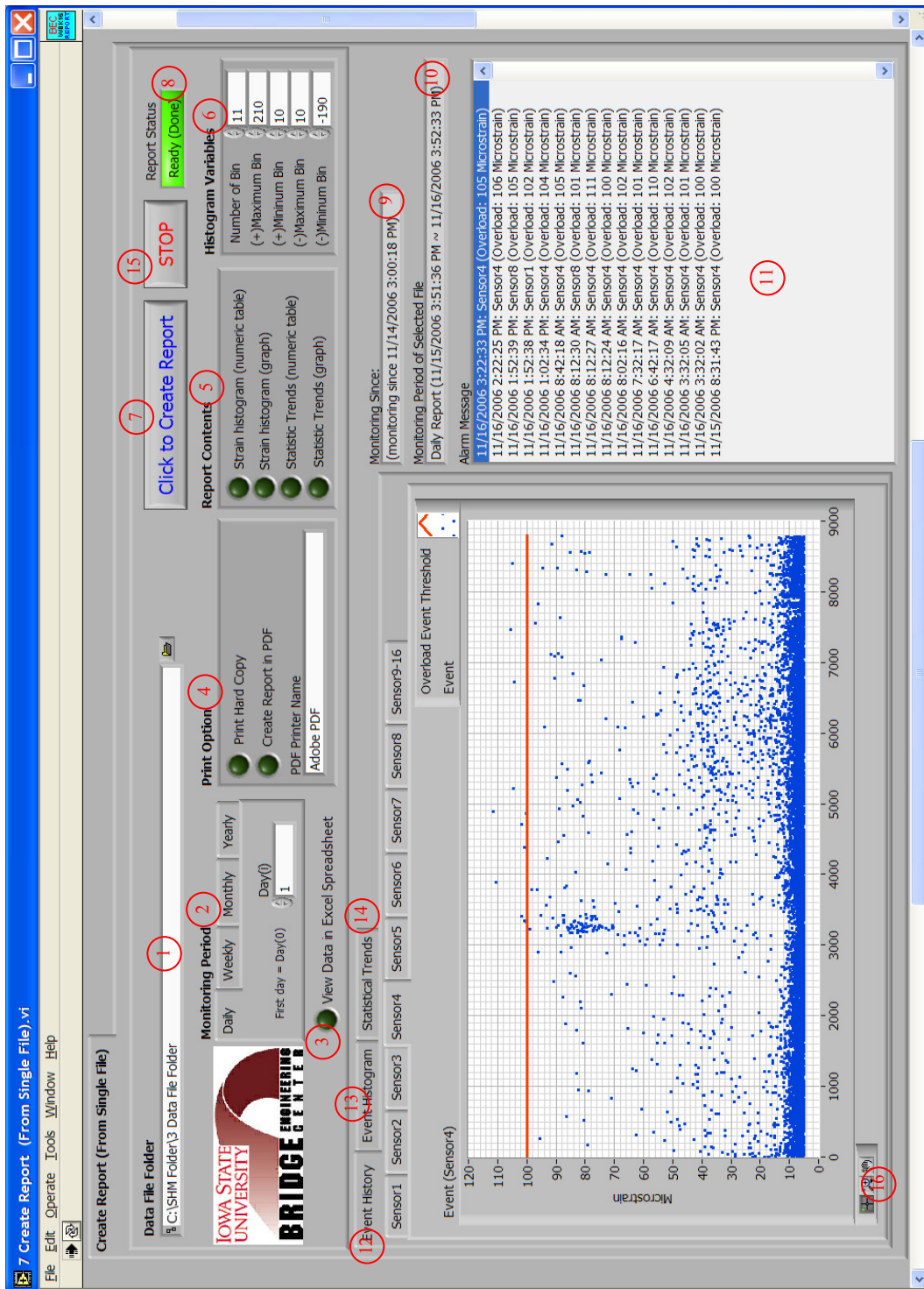


Figure 2-20. Screen shot of 7 Create Report (From Single File).VI front panel

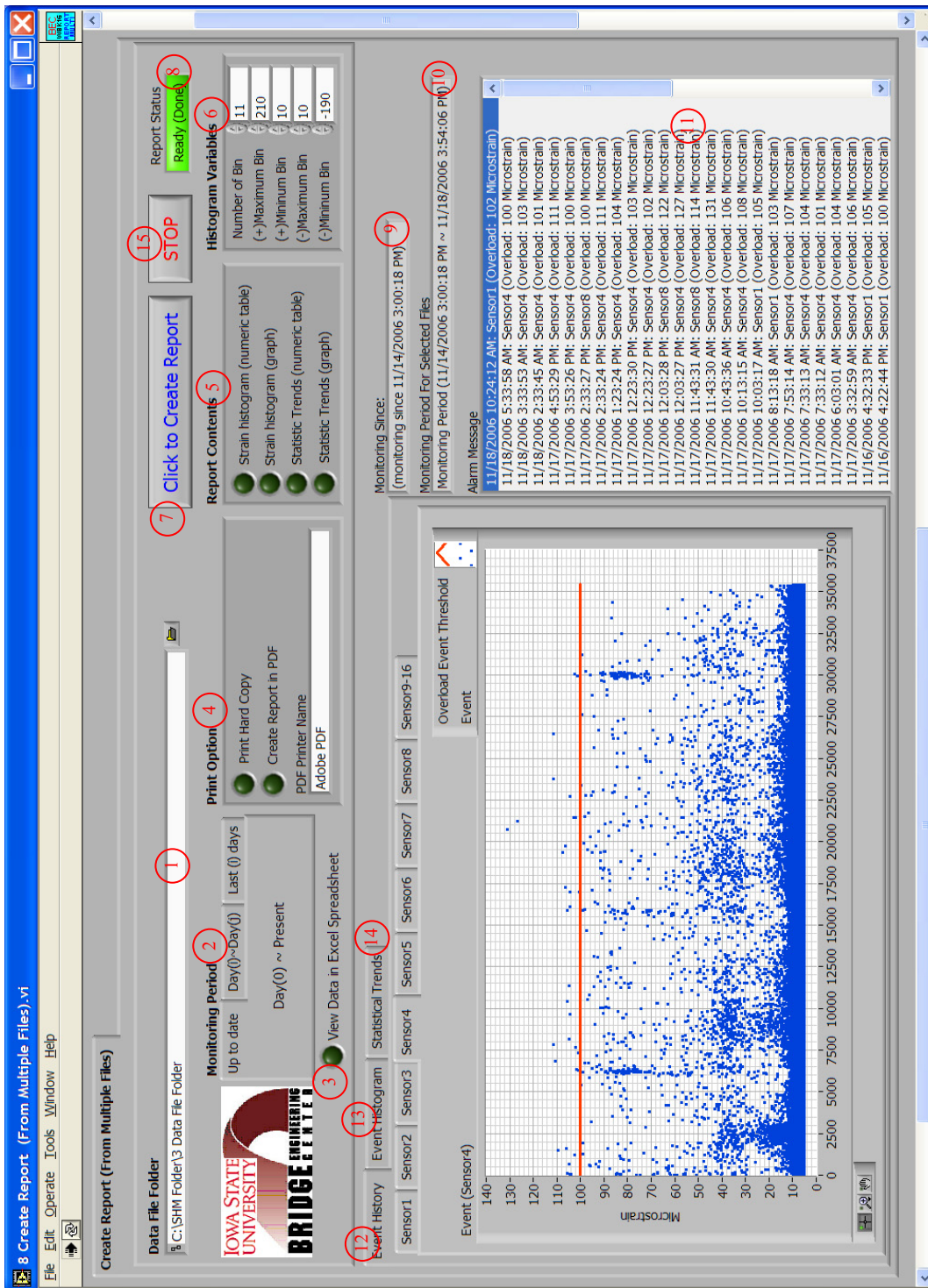


Figure 2-21. Screen shot of 8 Create Report (From Multiple Files). VI front panel

2.2.3.1. Preliminary Data Collection and Storage

1 Preliminary DAQ.VI allows users to acquire a small amount data for immediate viewing, storage to the hard disk, and for use within *2 FFT.-PSD Analysis.VI* to configure filter parameters. Illustrated in Figure 2-14 is a typical setup for *1 Preliminary DAQ.VI*. Three steps—(a) basic setup on input parameters (b) program execution, and (c) results verification—are involved in using this program. The first step requires users to input parameters in controls #1 through #9 that are shown in Figure 2-14 as follows:

- Enter a device name in control #1. The device name used here must match what was used during the hardware system setup.
- Enter a sample rate (#2) at which the data acquisition is to be performed (number of samples per second).
- Select the channels of a connected StrainBook/616 and, if applicable, a WBK16 expansion module to be activated (#3 & #4). More than one channel can be selected by ‘Ctrl + Mouse click’.
- Configure each channel (#5) based upon the specific type of strain sensor being used.
- Apply and select a calibration file, which was created during the sensor calibration process, by setting the LED (#6) to true (bright green) and by assigning a calibration file path in control #7.
- Designate a folder directory (#8) in which the data will be saved. The recommended directory name is ‘C:\SHM Folder\Preliminary Data Folder’ as is shown in control #8 in Figure 2-14. Users can use the ‘Browse’ button to display a tree of all directories available on the host PC.
- Enter the time duration in control #9 for which each data file will be saved.

Once the above setup is completed, data collection can be initiated. This step involves two controls and five indicators—#10 through #16 shown in Figure 2-14—as follows:

- Start data collection by clicking on the ‘START’ control (#10).
- Check the acquisition status in indicator #11. When the ‘START’ control is pressed, it searches the data acquisition instrument specified in control #1. One of the following situations will occur:
 - The check mark on the status check box stays green and indicators #12, #13, #14 and #15 will display real time data, elapsed time, beginning time at which data acquisition is initialized and current time of data acquisition, respectively. This indicates that the data acquisition instrument was found and that all input parameters are correctly defined.
 - The check mark on the status check box turns red and a message appears on the message box along with an error code. This indicates that either the data acquisition instrument was not found, or one or more input parameters are missing. In order to resolve this error, users must check either (or both) the hardware and IOtech software installation setup or (and) the input parameters before running the program again.
- Once the data acquisition is completed, click the ‘STOP’ button (#16). This will

terminate the program.

Each saved data file is named with letters and numeric numbers. The notation starts with “SHM” followed by numeric numbers representing the time at which each data file was saved. The naming conventions adopted are described as follows:

SHM (YYYY MM-DD hhmmss)

where,

- SHM: Structural Health Monitoring
- YYYY: year
- MM: month
- DD: day
- hh: hour of the day
- mm: minute of the hour
- ss: seconds within the minute

When the elapsed time (#13) exceeds the time specified in control #9, the data file will be closed and saved to the directory designated in control #8. Meanwhile, new data will be written to a new file. This process will be repeated until the program is terminated. Contained in each file are columns of tab delimited data with each column representing the strain record for one sensor. For example, if eight sensors are used, the data file will contain eight columns of tab delimited data.

The main goal of acquiring these sample data sets is to collect data to be used for noise reduction by separating traffic induced frequencies from noise induced frequencies. To do this properly, two steps are required. The first step requires the collection of strain data sets (a) when ambient traffic crosses the bridge and (b) when no traffic is present on the bridge. The second step is described in the following section.

2.2.3.2. Investigation of Frequency Contents and Determination of Filter Parameters

Identification of strain due to noise involves comparing noise induced frequency contents with those induced by traffic. The data sets obtained from running *1 Preliminary DAQ.VI* are used to perform a FFT. analysis that results in a power spectral density (PSD) plot for each strain record. The FFT.-PSD analysis allows users to view different frequencies that make up the measured strain. By investigating the PSD plots, dominant frequencies from ambient traffic and noise can be identified. As previously mentioned, traffic induced strains in a typical bridge normally have frequency contents that are lower than those of noise. With this frequency characteristic, therefore, one may minimize noise by applying a low-pass digital filter with an appropriate cutoff frequency. At the end of the process, a text file containing filter parameters and event detection thresholds for each channel is created. The followings describe each step involved in running *2 FFT.-PSD Analysis.VI*.

Three primary tasks are performed within *2 FFT.-PSD Analysis.VI*: (a) identification of dominant frequencies through a FFT.-PSD analysis (b) idealization of filter parameters and

plotting the resultant strain history and (c) creating a filter parameter file. As illustrated in Figure 2-15, each task is performed in three different program “tabs”. The first task involves opening a data file acquired with *1 Preliminary DAQ.VI* and then running the FFT.-PSD analysis. The following steps are required to perform this task:

1. Select a data file from those that were saved in the ‘Preliminary Data Folder’ by using the browsing tool in control #1.
2. Under the ‘FFT.-PSD Analysis’ tab control (#2), enter a sample rate in Hertz (#3). Note that the sample rate used here must be the same as the one used while acquiring the data.
3. Choose a time-domain window (#4) to be used in the FFT. analysis and PSD development. The recommended option is ‘Hanning’ and is set as the default.
4. Run the program by clicking the run button (#5). As soon as the run button is pressed, the status indicator (#6) will turn red indicating that the FFT.-PSD analysis is running. Indicator #7 will display the data file read progress. When the data file reading is completed, the total number of sensors used during the preliminary data acquisition will be displayed.
5. Upon completion of the FFT.-PSD analysis, the status indicator (#6) will turn bright green indicating that PSD plots for each sensor are ready to be viewed.
6. Select a sensor with a mouse click within control #8. Then, the indicator #9 will display the selected sensor and a PSD plot for the selected sensor will be displayed in indicator #10.
7. Identify the dominant frequencies from ambient traffic plus noise or noise alone (depending upon a sample file selected) and determine the desired cutoff frequency for the filter (note: more detail on how to determine the desired cutoff frequency will be discussed in Chapter 3).
8. Move to the ‘Strain History’ tab control (#11) and enter the cutoff frequency determined in step *vii*.
9. Click the “Plot Strain History” control (#14) to see the effect of filtering for the selected sensor. Indicator #17 will display the strain history.
10. Go back to the ‘FFT.-PSD Analysis’ tab control (#2) and repeat “step *vi*” through “step *ix*” to see the effect of filtering for all sensors.
11. Repeat the “step *i*” through “step *x*” until an appropriate cutoff frequency is determined. This may require examining several data files, one at a time. By comparing the dominant frequencies of traffic plus noise induced and noise alone induced, an appropriate cutoff frequency can be determined.

12.

Once the FFT.-PSD analysis is completed and the desired cutoff frequency has been determined, the second task can be performed to establish the appropriate filter parameters and to see if events (peaks) are properly identified. The following steps are required to perform this task:

13. Perform the “step *i*” through “step *v*”, but this time, select a data file that contains traffic plus noise induced strain.
 14. Select a sensor with a mouse click within control #8 and move to the ‘Strain History’ tab (#11).
 15. Enter three filter parameters (#12) that will be applied to the selected strain data: cutoff frequency (Hz), ripple (dB), and filter order.
- 16.
- a. The cutoff frequency is determined by investigating dominant frequencies of traffic plus and noise induced and noise alone induced.
 - b. A ripple of 0.0435 dB, which is equivalent to 0.5% passband allowable error, is set as a default as it is often a good choice for digital filters [4]. The 0.5% passband allowable error was converted to 0.0435 ripple in dB as follows:

$$0.0435 \text{ dB} = \left| 20 \log \left(\frac{100\% - 0.5\%}{100\%} \right) \right|$$
 - c. The order of a Chebyshev filter is equal to the number of poles in the transfer function of the filter. In general, a filter is considered to work better with more poles. However, this may not be always true. Therefore, several attempts (trial and error) may be necessary to determine the appropriate filter order. The default is set as 2nd order and the order must be an even number.
17. Enter event detection thresholds (#13) that will be applied to the selected strain data. The event detection thresholds should be determined such that peaks are not identified from the free vibration response of the bridge (more detail will be discussed in Chapter 3). Once set, only those events that exceed the event detection thresholds will be recognized by the program and displayed in indicator #17.
 18. Press the ‘Plot Strain History’ control (#14) to plot strain history and view the effects of filtering the selected strain data. When pressed, indicator #15 will display the selected sensor and the status indicator (#16) will turn red indicating that plotting strain history is in progress.
 19. Upon completion, the status indicator will turn bright green and a strain history plot for the selected sensor is displayed on the graph indicator #17.
 20. At this point, the user needs to decide if the filter parameters used are adequate to minimize noise while identifying proper peaks or events. If the user desires to alter the filter parameter settings, new parameters need to be defined in #12 and the ‘Plot Strain History’ control (#14) needs to be pressed again. Otherwise, save the filter parameter settings for the selected sensor by pressing the ‘Save Parameters for Selected Sensor’ control (#18).

The next task requires the user to check if the parameter settings are stored for each selected sensor, one-by-one, and create a text file that will contain the filter parameters and event detection thresholds for all sensors. The following tasks must be performed:

21. Move to the 'Create File for Filter Parameter' tab control (#19) and check if the filter parameters and event detection thresholds for the selected sensor are stored in the table indicator (#20) where each row represents the settings for the sensor specified in the first column named 'Sensor'.
22. Repeat "steps *xiii*" through "step *xix*" until the filter parameters and the event detection thresholds have been established for all sensors.
23. Set the path (#21) to which the filter parameters and event detection thresholds will be saved. The default file name and directory is 'C:\SHM Folder\Filter Parameters.txt'.
24. Click the 'Create File for Filter Parameters' control (#22) to create a text file that contains the filter parameters and event detection thresholds for all sensors.
25. Click the 'STOP' control (#23) to stop the program.

2.2.4. Main Data Acquisition and Processing

Once the preliminary data collection and analysis have been completed, the second group of the field monitoring software – the SHM main data acquisition and processing – can be initiated. In general, this involves two steps – (1) input information settings and (2) main data acquisition, processing and reduction – that require running two programs: *3 Input.VI* and *4 MainDAQ815.VI*. The outcome of *3 Input.VI* is a binary file that contains input settings that are needed for operation of *4 MainDAQ815.VI*. It should be noted that *4 MainDAQ815.VI* must be installed as a "service program" on the field PC. Operating the program as a service allows autonomously resuming when the power comes back on in case of power outage. During this installation process, the time for which the program is forced to wait until the acquisition instrument is initialized must be defined. The recommended "pause" time is 60 seconds. Detailed procedures on installing *4 MainDAQ815.VI* as a service program are provided in Appendix D. The information presented in the following sections describes the detailed procedures pertaining to how *3 Input.VI* and *4 MainDAQ815.VI* are operated.

2.2.4.1. Input Information Settings for Main Data Acquisition and Processing

Before *4 MainDAQ815.VI* can be activated for the main data acquisition and processing, an input file that contains required information must be created with *3 Input.VI*. In general, three steps need to be completed: (1) input entry (2) program execution and (3) verification. First, the user needs to enter the input settings. Note that some procedures are the same as those used in running *1 Preliminary DAQ.VI*. The required input information is as follows:

- Select the channels of a connected StrainBook/616 and, if applicable, a WBK16 expansion module to be activated (#1 & #2). More than one channel can be selected by 'Ctrl + Mouse click'.
- Configure each channel (#3) based on the type of strain sensor and its setting used.
- Enter the device name in control #4. The device name used here must match

what was used during the hardware system setup.

- Provide the sample rate (#5) at which the data acquisition is to be performed (number of samples per second).
- Enter the impact event threshold in control #6. The impact event threshold is a ratio of the absolute difference between the magnitude of the event and that of the event detection threshold with respect to the time difference between a start index and a peak index in a strain record (a single event or traffic response). The impact event threshold is used to determine if the identified event is an impact event.
- Enter the plus and minus event detection thresholds (#7) that will be applied to the collected strain data.
- In the 'Overload event threshold' control (#8), enter the overload event threshold for each sensor that was determined from the structural analysis software (*BEC Analysis*) or other means. Also, with a mouse click, select LED options for each sensor to which the overload event threshold will be applied. If set to true (bright green), any overload event (an event that exceeds the specified overload event threshold) for the selected sensor will be recorded and temporarily stored within 4 *MainDAQ.VI*.
- Select the type of data files, with a mouse click (#9), to be sent via email (LED options). Given that the internet connection is available, if users desire to receive daily data files only, for example, the LED option for 'Daily Data' must be selected (bright green) with a mouse click and other options must remain unselected (dark green). Six options are available as follows:
 - - a. Hourly Data: allows users to receive hourly-generated reduced data files, each of which contains event history in the preceding hour
 - b. Daily Data: allows users to receive daily-generated data files, each of which contains event history in a day
 - c. Weekly Data: allows users to receive weekly-generated data files, each of which contains event history in the preceding week
 - d. Monthly Data: allows users to receive monthly-generated data files, each of which contains event history in the preceding month
 - e. Yearly Data: allows users to receive yearly-generated data files, each of which contains event history in the preceding year
 - f. Alarm Message: allows users to receive a text message of an alarm event upon occurrence.
- Enter email information that the reduced data files are sent from/to (#10) and set 'Check if email inputs are entered' (LED option) to true (bright green) with a mouse click. Three pieces of information are required:
 - - a. Return address: email address of the file and/or message sender
 - b. Mail server: the name or IP address of an SMTP server
 - c. Recipients: email addresses of the file and/or message recipients. Each address can be a separate array element
- Apply the calibration file (#11), which was created during the sensor calibration

process, by setting the LED option to true (bright green) and by assigning the calibration file path.

- Designate the folder directory in which raw strain data file are to be written and saved (#12). The default is 'C:\SHM Folder\1 Raw Data'. This is one of the sub-directories created during the initial setup (see Section 2.2.2.2).
- Designate the folder directory to which the raw data are moved for data reduction and evaluation (#13). The default is 'C:\SHM Folder\2 Data Process'. This is one of the sub-directories created during the initial setup (see Section 2.2.2.2).
- Designate the folder directory in which all the reduced data files (Hourly, Daily, Weekly, Monthly and Yearly Data files) will be saved. The default is 'C:\SHM Folder\3 Data File Folder'. This is one of the sub-directories created during the initial setup (see Section 2.2.2.2).
- Set the path (#15) for the filter parameters file that contains the event detection thresholds and filter parameters.

Once the input settings are entered, users can execute the program by pressing the 'Create and Save Input File' control (#16). This will result in the creation of a 'DAQ Inputs' file in the main directory (C:\SHM Folder\DAQ Inputs). The last step is to stop the program by pressing the 'STOP' control (#17).

2.2.4.2. Main Data Acquisition, Reduction and Evaluation

After a 'DAQ Inputs' file that contains the input information is created, the main data acquisition and processing can be initiated by running *4 MainDAQ.VI*. As soon as *4 MainDAQ.VI* program is run, it checks the data acquisition instrument.

Given that the data acquisition was successfully initialized, as depicted in Figure 2-17, the Acquisition Status control (#1) will display a green check mark in the 'status' check box and no error message will appear in the 'source' dialog box. While the program is running, the following information will be displayed on the control panel of the program shown in Figure 2-17:

- Real time raw data for each sensor in the graph indicator (#2).
- The 'Time' indicator (#3) displays information on
 - time at which data acquisition was initialized,
 - current time, and
 - count of elapsed hour, day, week, month and year, which also indicates the number of data files created and available for report generation.
- Network status (#4). One of the following situations will occur:
 - The check mark on the status check box is green and no error message appears on the message box. This indicates that the network connection is established and alarm messages and data files created by the program can be sent via email to the recipients specified during input information setting. It should be noted that even when the status indicates no error, information may not be sent to the recipients due to a security settings. Typically used virus scan software is designed to block access from any unknown programs.

Therefore, users need to make appropriate changes on the security settings so that the execution program *4 MainDAQ815.VI* is unblocked. Since the security settings may vary depending on Windows types (2000, XP, NT, etc.) and virus scan software used, users may need to consult with a system analyst to resolve this.

- The check mark on the status check box turns red and a message appears on the message box along with an error code. This indicates that the network connection is either unavailable (or not established). It should be noted that this error will not cause the program to stall or stop. All other functions except the email will still be functioning. The program is programmed such that when an error related to network connection occurs, the program will skip that step and carry on other tasks. Also note that since all data files created by the program will be saved in '3 Data File Folder' in the main directory, users can always retrieve the data files manually.
- Available disc and memory space on the field PC. The total, used and free (available) disc and physical memory space of the field PC will be displayed in Bytes in the 'Disc/Memory Space' indicator (#5).

Raw data collection with *4 MainDAQ.VI* is similar to data collection with *1 Preliminary DAQ.VI*. The only significant difference is that while *1 Preliminary DAQ.VI* writes and saves data files to the 'Sample Data File' folder in the main directory, *4 MainDAQ815.VI* uses three folders within the main directory: '1 Raw Data', '2 Data Process', and '3 Data File Folder'.

Raw strain records for each sensor are collected and written to a data file in the '1 Raw Data' folder directory with the same format discussed in Section 2.2.3.1. Every 10 minutes, this data file will be closed, saved and moved to the '2 Data Process' folder for data processing. At that point, the strain records are filtered and processed. Following the data reduction process, only the extracted strain records (events) will be passed on to the next phase of data evaluation. Before all other raw strain records are discarded, a data file, 'Last10MinData' that contains the raw strain record for 10 minutes, will be created in the main directory to allow the user to access the last 10 minutes of data. Note that while the information within the file is updated every time a sub-program, *Data Process.VI*, is called and new strain records for 10 minutes are saved, the name of the file will not change. Accessing this 'Last10MinData' will be discussed subsequently.

During the data reduction and evaluation processes, each peak or event will be detected and alarm messages will be recorded. Upon an occurrence of an "alarm event," a sub-program, *SMTP Email Send Message.VI*, will be called and a warning message will be sent to the recipients whose addresses are specified in the DAQ Inputs file (note: it requires an internet connection). Each alarm message will be sent in the form of a text message that includes the date and time of the event, sensor identification, cause of event (either 'overload' or 'impact') and the magnitude of the event in microstrain. The information generated by *Data Process.VI* will be temporarily stored within the sub-program before it is written to a file. Meanwhile, raw strain records will be written to a new data file and the procedures within *Data Process.VI*, will be repeated every 10 minutes. When the *Data Process.VI* is notified six times (6 x 10 minutes = 1 hour), a notification will be sent from the *Data Process.VI* to a

sub-program, *Hour.VI*, within which hourly data files will be created and saved in the ‘3 Data File Folder’. The procedures performed within sub-programs – *Week.VI*, *Month.VI*, and *Year.VI* – are very similar to the *Day.VI* except that the number of times each sub-program is notified is different and that the notifications to *Week.VI*, *Month.VI* and *Year.VI* are all sent from *Day.VI*.

Once the *MainDAQ815.VI* is successfully started, the data acquisition, reduction, evaluation and archiving processes will be completely autonomous and require no further user intervention unless the user desires to change input settings or restart the program. To do this, a user must stop the program by pressing the ‘STOP’ control (#6), set the ‘Reset’ control (LED option in #7) to true (bright green) and re-run the program by pressing the ‘Run’ control (#9). These actions will result in autonomously creating an ‘Old Data File Folder’ to which previously archived data files will be moved. This will allow the user to keep the old data files saved in a different directory so that they can be retrieved if necessary. When an ‘Old Data File Folder’ is created, the time at which the folder is created will be included in the folder name. The naming convention used here is similar to those discussed in Section 2.2.3.1 except that, in this case, the letters ‘SHM’ is replaced with ‘Old Data File Folder’.

As described, the outcome of 4 *MainDAQ815.VI* is data files created on a timely basis (hourly, daily, weekly, monthly and yearly) that are archived in the ‘3 Data File Folder’ in the main directory. In writing and creating each data file, the binary format was utilized as it takes less memory and does not require slow sequential searching of data content. The data files created here will be used for the application of viewing and generating reports, which are described in Section 2.2.5.

2.2.4.3. Accessing Last 10-Minute Data

As mentioned previously, strain records stored in the ‘Last10MinData’ file will be updated every 10 minutes to allow a user to view what has recently been collected. 5 *View Strain History.VI* as shown in Figure 2-18 was developed to allow a user to easily view these data. The following procedures are involved in running the program:

- Select the data file (#1) that contains collected strain records.
- Set the path (#2) to the filter parameters file that contains the event detection thresholds and filter parameters that were previously established.
- Enter the sample rate (#3) that was used during data acquisition.
- Press the ‘Plot Strain History’ control button (#4) to execute the program. When this button is pressed, the status indicator (#5) will turn red indicating that the operation is in progress. Upon completion, the indicator will turn bright green and the strain history for each sensor will be displayed on the graph indicator (#6). The strain history for each sensor can be accessed by selecting the tabs designated for each sensor.
- Stop the program by pressing STOP button control (#7).

2.2.5. Report Generation

Once the data files are created and archived in the '3 Data File Folder' directory and/or sent to users via email, these data files can be accessed and reports generated by executing *6 View Hourly File.VI*, *7 Create Report (From Single File).VI* and *8 Create Report (From Multiple Files).VI*. When the SHM system is operated for a long time, numerous data files will be archived in the '3 Data File Folder' directory. Although the naming convention utilized would ease identifying each data file, it may still take some effort to find a particular data file. In order to address this issue, these programs were programmed to find the correct file or files specified by user inputs. The procedures involved in executing each of these programs are described in the following sections.

2.2.5.1. Accessing Hourly Created Data Files

6 View Hourly File.VI allows users to view event history, event histogram, and alarm messages from hourly created data files either within the front panel or in an Excel Worksheet. Illustrated in Figure 2-19 is an example setting for *6 View Hourly File.VI*. The following procedures are involved in running the program:

- Select the directory (#1) in which the hourly data files are archived. The default is set as 'C:\SHM Folder\3 Data File Folder'. If users want to access an hour file received via email, the path to the folder that contains the received file must be selected.
- Select a monitoring period (#2). The number in the text box indicates the hour since monitoring began (starting with zero). For example, if the user wants to open an hour file that contains the event history obtained during the first hour of monitoring, '0' must be entered; if the user wants to access a hour file occurring 56 days, 3 hours later, the user would enter '1346'.
- To view the data file in an Excel Worksheet, set the LED option (#3) to true (bright green).
- Configure the histogram setting (#4). This option allows users to change five variables: number of bins, and maximum and minimum bins for both positive and negative events.
- Press the 'Click to View Hour File' control (#5) to execute the program. The event history and histogram, monitoring period and alarm messages will be displayed in the indicators #6, #7 and #8, respectively. The event history and histogram for each sensor can be accessed by selecting the tabs designated for each sensor.
- Stop the program by pressing STOP control (#9).

2.2.5.2. Creating Reports (Accessing Daily, Weekly, Monthly or Yearly Created Data Files)

Three sets of information are generated for each sensor in a performance report: event history, event histogram and statistical trends. The event history graph presents the numerical count of identified events along the x-axis with their magnitudes in microstrain on

the y-axis. The histogram presents the count of events in each bin, whose size can be defined by users. The statistical trends graph displays the absolute maximum event, the average event, and a trend line for the averages over the monitoring period.

The following procedures are involved in running *7 Create Report (From Single File).VI* and *8 Create Report (From Multiple Files).VI*. Note that the numberings for the controls and indicators used on the front panels of these two programs are the same as shown in Figures 2-20 and 2-21. Therefore, they are treated together in the following description:

- Select the directory (#1) in which the data files are archived. The default is set to 'C:\SHM Folder\3 Data File Folder.'
- In the 'Monitoring Period' control (#2), select data file(s) to be plotted and processed for the report generation. See Note-1 below for detailed description.
- To view the data file in an Excel Worksheet, set the LED option (#3) to true (bright green).
- Select the print options (#4). This allows the user to print the report either (or both) in a paper copy or (and) in PDF format given that corresponding option(s) are selected (bright green).
- Select the report content options (#5). This allows the user to choose the contents that will be included in the report. Four options are available:
 - a. Strain histogram (numeric table): numerical count of events in each bin where the bin size is specified by users
 - b. Strain histogram (graph): graphical representation of numerical count of events
 - c. Statistic Trends (numeric table): numerical values of absolute maximum events, average events (hourly or daily depending upon the data file selected), and average trend line over the selected monitoring period.
 - d. Statistic Trends (graph): graphical representation of events over the selected monitoring period.
- Configure the event histogram variables (#6). This option allows users to change five variables: number of bins, and maximum and minimum bins for positive and negative events.
- Press the 'Click to Create Report' control (#7) to execute the program. As soon as the program is executed, the status indicator (#8) will turn red indicating that the program is in progress. Upon completion, the indicator will turn bright green and the following results will be generated:
 - results displayed on the front panel for immediate view
 - the time at which the data acquisition was initialized: #9
 - the monitoring period: #10
 - alarm messages recorded during the monitoring period: #11
 - event history, event histogram, and statistical trends for each sensor: #12, #13 and #14, respectively (see Note-2 below for more detail).
 - an Excel Worksheet, hard copy, and/or PDF file depending upon the selected options (#3, #4, and #5).
- Stop the program by pressing STOP control (#15).

Note-1: As can be seen in Figures 2-20 and 2-21, controls and indicators used on the front panels of each program are exactly the same with the exception of the ‘Monitoring Period’ control (#2). *7 Create Report (From Single File).VI* is designed to access one data file at a time while *8 Create Report (From Multiple Files).VI* allows users to open multiple files at once. Consequently, different options in control #2 for selecting data files were utilized. For *7 Create Report (From Single File).VI*, users can choose a different type (daily, weekly, monthly and yearly) of data file from provided tabs where the title of each tab represents a time duration for which one file is created and archived as shown in Figure 2-22. For example, if the user wants to access information obtained during the second week of monitoring, the user must select ‘Weekly’ tab and enter a number ‘1’ in the text box. Note that the index ‘i’ starts from zero. For *8 Create Report (From Multiple Files).VI*, the user can access multiple data files given that those data files are already created and archived. Three options are available as listed below:

- a. Up to date: allows the user to access all daily data files created (Figure 2-23a)
- b. Day (i) ~ Day (j): allows to access multiple daily data files created during user specified time period (Figure 2-23b)
- c. Last (i) days: allows to access multiple daily files created during the last user specified days (Figure 2-23c)

Note that, except in the ‘Up to date’ tab shown in Figure 2-23a, the user can select a monitoring period by using the up and down arrows to increase or decrease number in the text box, or simply type in the desired number.

Note-2: Plots of event history, event histogram and statistical trends are displayed on separate tabs to avoid clutter on the front panel. The appearance (scale and format) of any graphic display can be modified (pan or zoom) while the program is running or stopped through the use of the graphic palette located on the left bottom corner of each graph (or by right clicking the graph and selecting Visible Items>>>Graph Palette from the shortcut menu). An example of the graphical indicator that displays history event can be found in Figures 2-20 and 2-21 while examples of graphical representation of an event histogram and statistical trends are presented in Figure 2-24. The formats used to display event history and event histogram are the same for both programs. Also, the format used to display statistical trends in *8 Create Report (From Multiple Files).VI* is the same. However, the format of the graph indicator for displaying statistical trends in *7 Create Report (From Single File).VI* can change depending on the tabs (or pages) selected in the Monitoring Period control (#2) in Figure 2-20. If users select a monitoring period in the ‘Daily’ tab, the graph indicator will display statistical trends of each hour for 24 hours as shown in Figure 2-24b. On the other hand, if users choose a monitoring period in ‘Weekly’, ‘Monthly’ or ‘Yearly’ tabs, it will display statistical trends of each day for user specified monitoring periods. For example, if a monitoring period is selected in the ‘Weekly’ tab on the front panel of *7 Create Report (From Single File).VI*, it will access one of the weekly created data files, each of which contains collected information for seven days. Therefore, it will display statistical trends of each day for 7 days as shown in Figure 2-24c.

Interface for selecting a daily data file. It features four tabs: Daily, Weekly, Monthly, and Yearly. The 'Daily' tab is selected. Below the tabs, there is a label 'First day = Day(0)' and a numeric input field with the value '0'.

(a) Daily data file

Interface for selecting a weekly data file. It features four tabs: Daily, Weekly, Monthly, and Yearly. The 'Weekly' tab is selected. Below the tabs, there is a label 'First week = Week(0)' and a numeric input field with the value '1'.

(b) Weekly data file

Interface for selecting a monthly data file. It features four tabs: Daily, Weekly, Monthly, and Yearly. The 'Monthly' tab is selected. Below the tabs, there is a label 'First month = Month(0)' and a numeric input field with the value '2'.

(c) Monthly data file

Interface for selecting a yearly data file. It features four tabs: Daily, Weekly, Monthly, and Yearly. The 'Yearly' tab is selected. Below the tabs, there is a label 'First year = Year(0)' and a numeric input field with the value '0'.

(d) Yearly data file

Figure 2-22. Data file selection option for 7 *Create Report (From Single File).VI*

Interface for selecting 'Up to date' data. It features three tabs: Up to date, Day(i)~Day(j), and Last (i) days. The 'Up to date' tab is selected. Below the tabs, the text 'Day(0) ~ Present' is displayed.

(a) Up to date

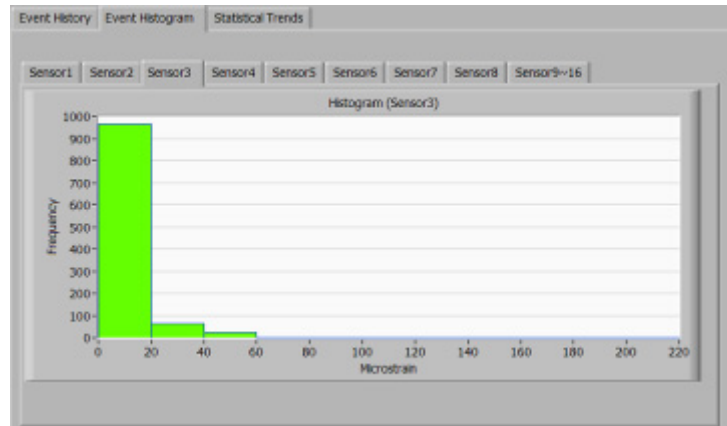
Interface for selecting data from Day (i) to Day (j). It features three tabs: Up to date, Day(i)~Day(j), and Last (i) days. The 'Day(i)~Day(j)' tab is selected. Below the tabs, there is a label 'First Day = Day(0)' and two numeric input fields: 'Day(i)' with the value '1' and 'Day(j)' with the value '3'.

(b) Day (i) to Day (j)

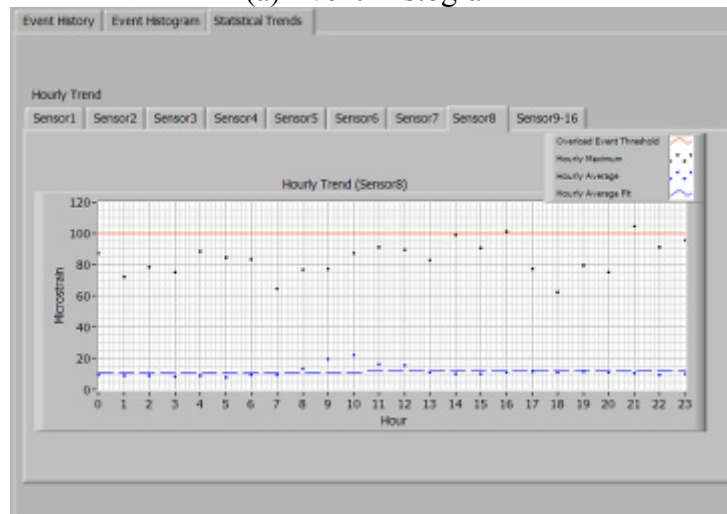
Interface for selecting the last (i) days to present. It features three tabs: Up to date, Day(i)~Day(j), and Last (i) days. The 'Last (i) days' tab is selected. Below the tabs, there is a label 'Last' followed by a numeric input field with the value '2' and the text 'days to Present'.

(c) Last (i) days to present

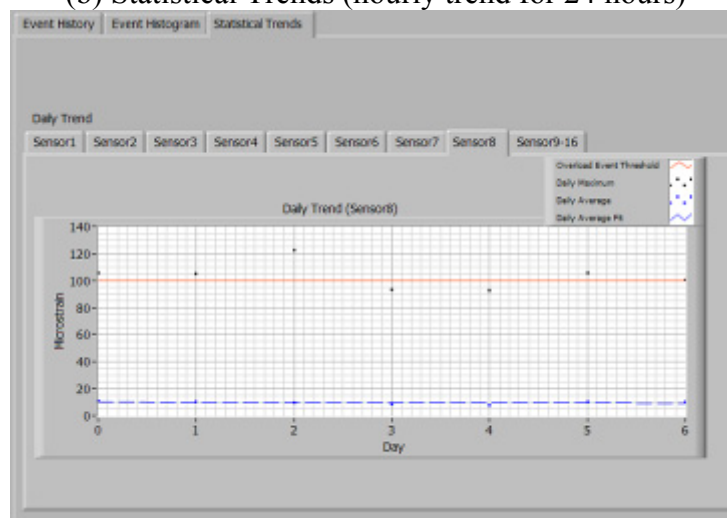
Figure 2-23. Data file selection option for 8 *Create Report (From Multiple Files).VI*



(a) Event Histogram



(b) Statistical Trends (hourly trend for 24 hours)



(c) Statistical Trends (daily trend for 7 days)

Figure 2-24. Examples of event histogram and statistical trends

2.3. Hardware System

This section describes the hardware components of relevance to the developed system. The hardware system generally consists of sensors, the data acquisition instrument and, optionally, a communication system.

2.3.1. Sensor

Among the numerous types of sensors that can be used in SHM, strain sensors offer a convenient and well understood method to instrument a bridge. Strain sensors measure expansion and contraction in the substrate material induced by mechanical stress or thermal effects. Three types of conventional strain sensors are commonly used: strain transducers, weldable strain gages, and bondable foil strain gages. The selection of strain sensor typically depends on a number of factors: cost, durability and temperature sensitivity.

Although virtually any strain sensor could be used with the developed system, weldable strain gages from Hitec Products, Inc. were selected to be the recommended sensor. Hitec Products manufactures weldable strain gages that are precision foil gages bonded to a stainless steel shim, prewired and waterproofed. These strain gages are hermetically sealed and are designed to withstand years of exposure to the elements. The installation requires less skill than bondable strain gages and can be done in virtually any environment. The gages can be attached to a steel member with the use of a low-power capacitive discharge spot welder. The time required for sensor installation depends on the accessibility but, in typical situations, would take less than 30 minutes per gage.

The cost of the Hitec Products weldable strain gage varies depending on the type (e.g., $\frac{1}{4}$, half, full bridge, etc.) but typically ranges between \$50~\$100 per gage plus the cost of lead wire (approximately \$0.25 per foot).

2.3.2. Data Acquisition Equipment

As mentioned in Section 2.2, the field monitoring software was designed to function with IOtech instrument hardware, StrainBook/616 and its expansion module, WBK16 that are shown in Figure 2-25. StrainBook/616 is a portable strain gage measurement system that connects to a PC's Ethernet port. Each unit comes with eight built-in strain channels. The StrainBook/616 contains a 1 MHz A/D converter that is capable of scanning all selected channels at 1 micro second and continuously transmitting collected data to a host PC. The maximum sample rate per channel is 1 MHz divided by the number of channels selected. For example, if all 8 channels are configured, the maximum sampling rate is 125 kHz. The StrainBook/616 is capable of accepting input from strain gages configured for full, half or quarter bridge configurations. The prices (in 2006) of the StrainBook/616 and the WBK16 expansion module are \$6,000 and \$4,000 per unit, respectively.



Courtesy of IOTech

(a) StrainBook/616 with 8 built-in strain channels



Courtesy of IOTech

(b) WBK16 8-channel expansion module

Figure 2-25. IOTech instrument hardware

2.3.3. Communication System

As with any typical SHM system that involves data acquisition and processing, acquired data need to be transferred to a host PC for data processing and evaluation. For data storage and delivery to users, two scenarios may be considered; once the acquired data are processed and evaluated, necessary information regarding bridge performance can be either (1) stored in the host PC that is connected to the data acquisition instrument for later retrieval or (2) sent to users at other location. Illustrated in Figures 2-26a and 2-26b are the two possible communication schematics. The StrainBook/616 is capable of connecting both directly to an Ethernet port on the host PC or to a network hub or router via its built-in 10/100BaseT Ethernet interface. Note that either a straight-through or a cross-over cable can be used to connect between instruments. For the first case, the communication between the data acquisition instrument and the host PC can be accomplished by simply using Ethernet cable alone. The later case requires a network or Internet connection. In this case, the

StrainBook/616 is connected to the Ethernet through a network device. Some network devices such as a wireless access point (WAP) or a router may be used as a connector. Note that the field monitoring software was programmed to work for both situations.

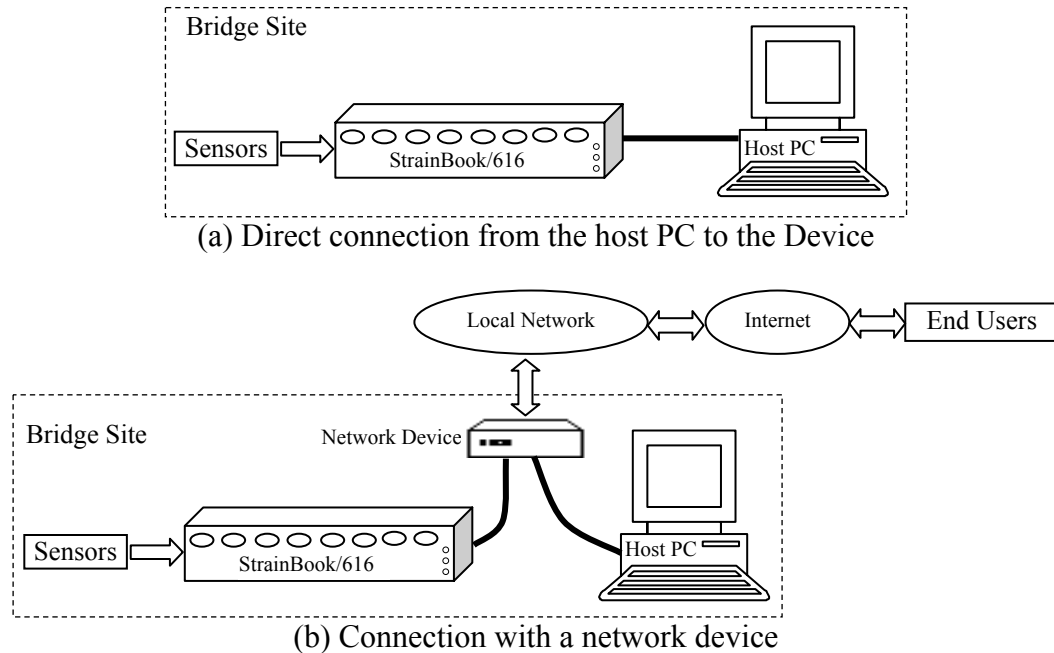


Figure 2-26. Communication schematics

3. SYSTEM DEMONSTRATION

The developed SHM system was tested and implemented on a US 30 highway bridge in order to demonstrate and verify its general usage. The following sections summarize this demonstration.

3.1. Bridge Description

The bridge selected for demonstrating the use of the SHM system is the 320 ft. x 30 ft., three-span continuous, welded steel girder bridge shown in Figure 3-1. The bridge is located in central Iowa in Story County, IA carrying US Highway 30 (US 30) over the Skunk River near Ames, IA.

The bridge consists of two 97.5-ft. end spans and a 125-ft. center span. The bridge girders are spliced at locations 30 ft. from the two piers in all spans. The roadway width is 30 ft. allowing two traffic lanes and a narrow shoulder on each side. The bridge has moderate curbs that are integral with the deck and concrete guardrails connected to the curbs. The bridge deck is a nominal 7 1/4-in. thick cast-in-place, reinforced concrete slab. The bridge deck is supported by two exterior plate girders and two WF 18x45 interior stringers. 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 spacing between the exterior plate girder and the interior stringer is 9 ft. while the interior stringers are spaced at 8 ft. as shown in Figure 3-2. The sizes of the plate girder flanges are variable as shown in Figure 3-3. The abutments are stub reinforced concrete and the piers consist of concrete columns. Both the abutments and the piers that support the plate girders have rocker-type bearings and the bridge is skewed 20 degrees.



(a) End view (looking east)



(b) Side view (looking south east)



(c) Bottom view (looking east)

Figure 3-1. Overall bridge photographs



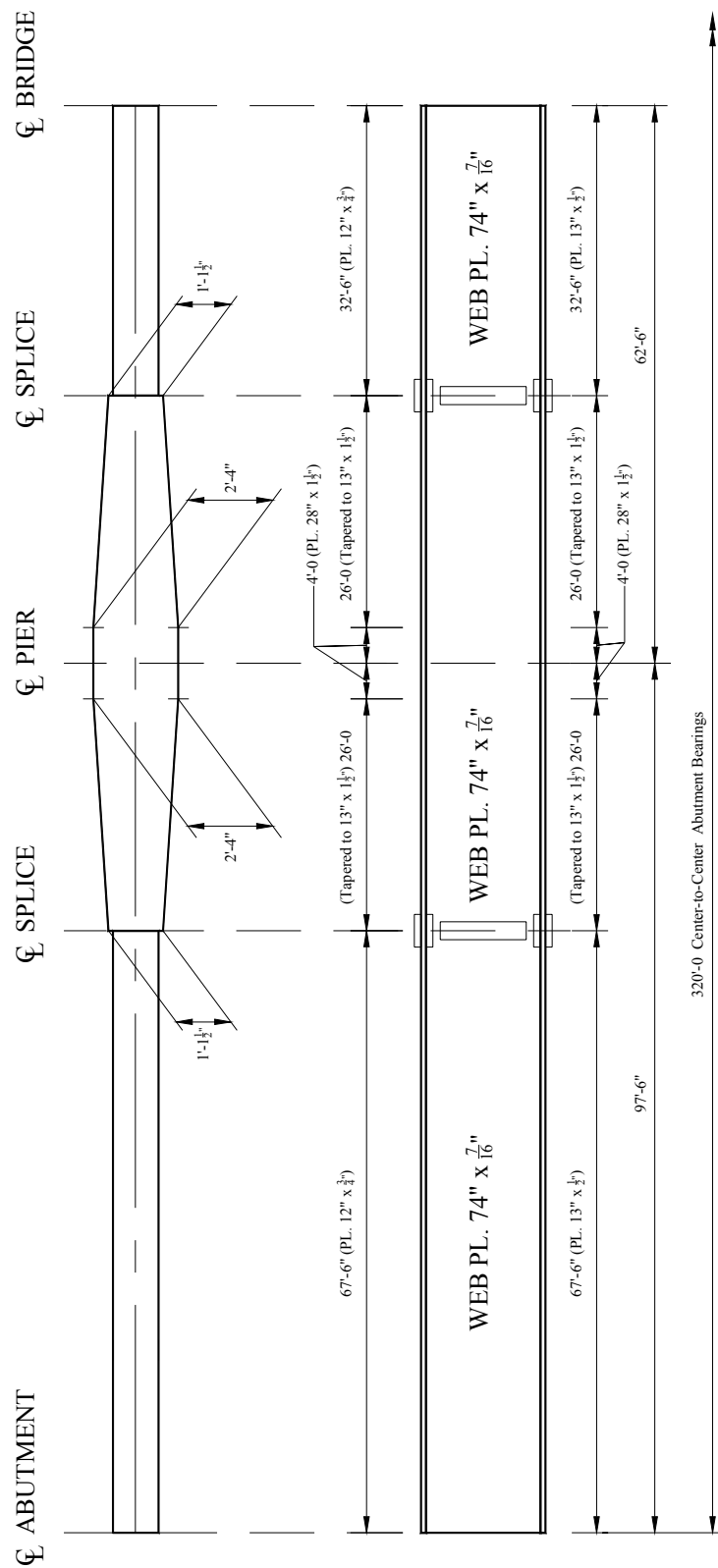


Figure 3-3. Plate girder detail

3.2. Hardware Components Installation

As described previously, the basic hardware components include sensors, the data acquisition hardware and a communication system. The complete SHM system that was installed on the US 30 bridge uses an onsite computer to run the field monitoring software. The selected sensors, data acquisition hardware and computer equipment were installed at the bridge site during the fall of 2006. A brief description on the installation and connection of these components are provided in the following.

3.2.1. Sensor Installation

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 through 8) were installed in the positive moment region of the plate girders and stringers in the center span and four sensors (Sensors 1 through 4) in the West end span as shown in Figure 3-4. Note that all sensors were installed on the top of the respective member bottom flange.

Installation of the strain gage began with surface preparation. A hand-held grinder was used to remove the paint from the steel beams. The strain gages were then attached to the steel surface using a portable, battery-operated low capacity discharge spot welder.

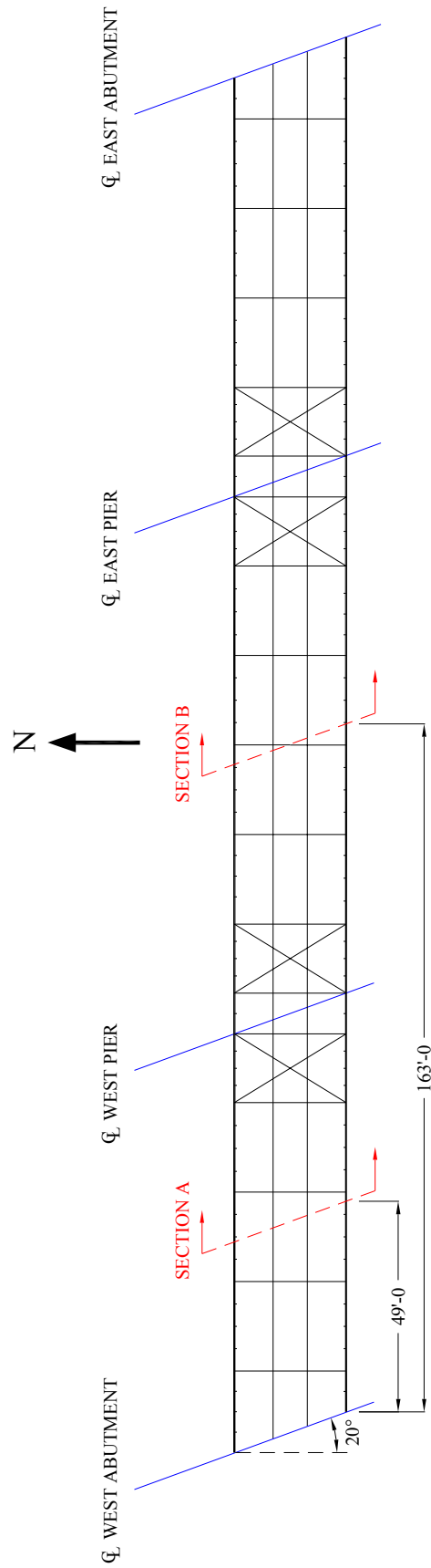
Since the SHM system is intended for a long-term monitoring, additional measures were performed to ensure longevity of the strain gages. After welding, each strain gage was covered with butyl rubber and aluminum foil tape to protect them from surrounding moisture.

The installation of the strain gages cables required no training or special equipment other than safety and normal access equipment such as harness, ladder, etc. Although the time required for sensor installation was only around 30 minutes per gage including surface preparation, securing the sensor cable required notable 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.

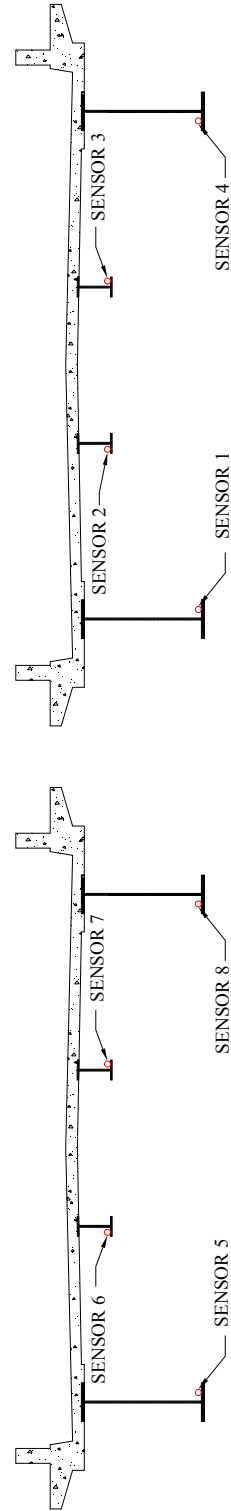
3.2.2. Data Acquisition, Processing and Communication System

The data acquisition, processing and communication system consists of the StrainBook/616 data acquisition instrument, a 1 GHz Dell desktop host PC, and a wireless router. These hardware components were installed in an environmentally controlled aluminum cabinet, shown in Figure 3-5, 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 connection between the sensor wires and the StrainBook/616 and between the StrainBook/616 and the router were made in accordance with the product manual provided in Appendix C. The StrainBook/616 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. The network at the bridge site was, due to fortunate proximity, then connected to Iowa State University (ISU) network via wireless communication.



(a) Plan view with sections A and B



(b) Section A in the West end span

(c) Section B in the center span

Figure 3-4. Bridge strain gage location and reference sections



(a) Aluminum cabinet mounted on the north corner of the west abutment wing wall



(b) Hardware components inside the cabinet

Figure 3-5. Environmentally controlled cabinet containing the monitoring equipments

3.3. Determination of Overload Event Threshold

As previously mentioned, the primary structural members are the two plate girders as the stringers are supported by the floor beams which are then supported by the plate girders. Thus, it was decided to only monitor the plate girders for identification of alarm events while both the plate girders and stringers are monitored for changes in behavior.

This section demonstrates how alarm events for the plate girders at the sensor locations were determined using *BEC Analysis*. The plate girders in each span were divided into sections as they contain different section properties along the members. To this end, the west and east end spans were divided into three sections while the center span was divided into five sections as illustrated in Figure 3-6. Note that the cross section dimensions for the sections with variable size flanges (tapered regions) were assumed to be at the middle point in each region. Based upon the detailed plan information, the following input parameters were established:

- Number of spans: 3
- Boundary conditions: pinned/roller – pinned/roller – pinned/roller
- Span length
 - West end span (Span 1): 97.5 ft.
 - Center span (Span 2): 125 ft.
 - East end span (Span 3): 97.5 ft.
- Concrete slab cross section dimensions and material property
 - Modulus of elasticity (E_{Deck}) = 3640 ksi
 - Thickness = 7.25 in.
 - Effective Width = 87 in.
- Plate girder material property
 - Modulus of elasticity (E) = 29000 ksi
- Plate girder cross section dimensions in the west end span (Span 1)

Section	Top Flange (inches)	Web (inches)	Bottom Flange (inches)
1	12 x 0.75	74 x 0.4375	13 x 1.5
2	20.5 x 1.5	74 x 0.4375	20.5 x 1.5
3	28 x 01.5	74 x 0.4375	28 x 1.5

- Plate girder cross section dimensions in the center span (Span 2)

Section	Top Flange (inches)	Web (inches)	Bottom Flange (inches)
1	28 x 1.5	74 x 0.4375	28 x 1.5
2	20 x 1.5	74 x 0.4375	20.5 x 1.5
3	12 x 0.75	74 x 0.4375	13 x 1.5
4	20 x 1.5	74 x 0.4375	20.5 x 1.5
5	28 x 1.5	74 x 0.4375	28 x 1.5

- Plate girder cross section dimensions in the east end span (Span 3)

Section	Top Flange (inches)	Web (inches)	Bottom Flange (inches)
1	28 x 1.5	74 x 0.4375	28 x 1.5
2	20 x 1.5	74 x 0.4375	20.5 x 1.5
3	12 x 0.75	74 x 0.4375	13 x 1.5

- Distribution factor (DF) and impact allowance (IM) were determined in accordance with the AASHTO Standard Specifications for Highway Bridges, 16th edition [3] to be
 - DF = 2.769
 - IM = 22% for the west end span and 20% for the center span

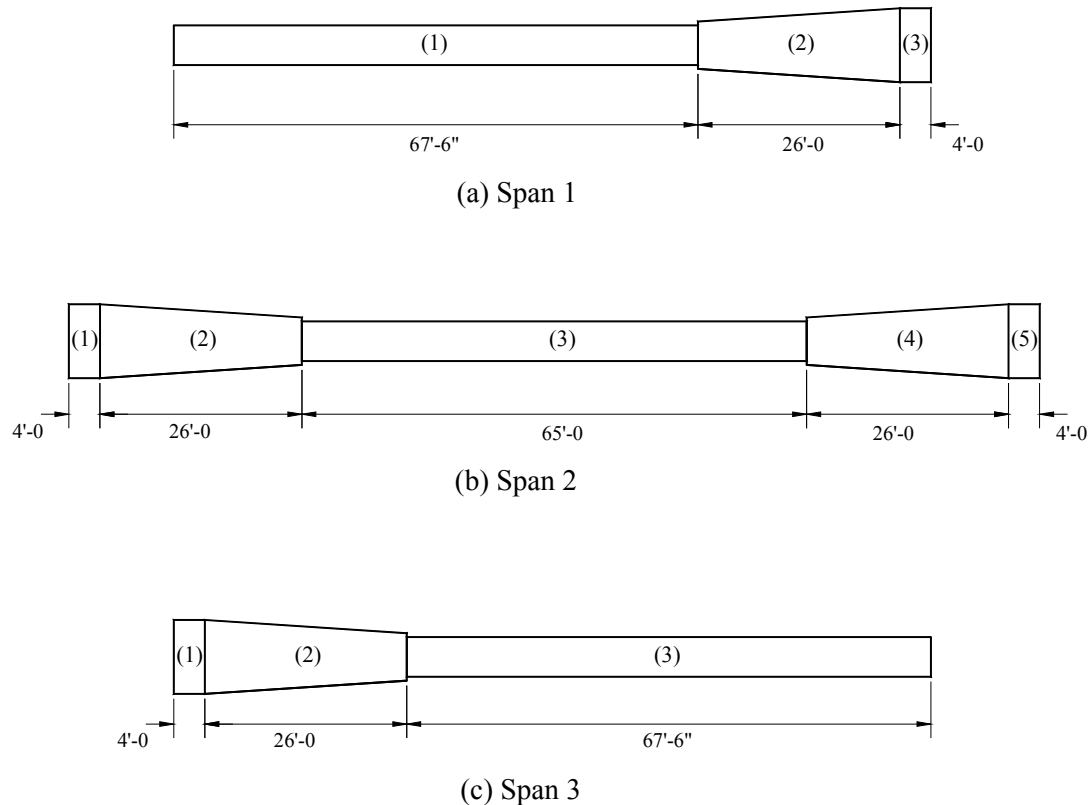


Figure 3-6. Plate girders divided into sections

Once all the input parameters were established, *BEC Analysis* was run following the steps described previously and the overload event thresholds at each sensor location were determined. In addition, the bridge was analyzed with other commercially available software

to verify the results generated by *BEC Analysis*. The results generated by *BEC Analysis* and their verification checks are presented in the subsequent sections.

3.3.1. Live Load Analysis with BEC Analysis

In this section, the live load analysis results generated from running *BEC Analysis* for the US 30 bridge are presented. In each run, the bridge was subjected to a moving load that traversed the bridge. Various loadings including Iowa legal trucks, H-20, HS-20 trucks and truck trains (or lane loads) were considered and each loading type was analyzed individually. The Iowa legal trucks, H-20 and HS-20 trucks were simulated with series of concentrated loads while concentrated load(s) and uniformly distributed loads were used to simulate the truck train (or lane) loading. For the HS 20 truck with 3 axles, although the distance between the first two axles remains the same, one needs to consider different spacing for the last two axles (rear axles spacing) as it can vary from 14 to 30 ft. as specified in the AASHTO Specification [3]. Thus, several load cases with different rear axle spacing were considered. For analyzing the model bridge subjected to the truck train loadings, several cases were considered in terms of a span or spans loaded with the uniformly distributed load of 0.64 kips/ft.. For example, when analyzing the model bridge at the sensor locations in the west end span), the uniformly distributed load was applied in the west and east end spans as it generates larger maximum results than when one or all spans are loaded. Similarly, for analyzing the model bridge at the sensor locations in the center span, only the center span was loaded with the uniformly distributed load. Note that besides the uniformly distributed load, a concentrated load of 18 kips was applied to the model bridge as a moving load.

The absolute maximum positive moments and strains at the sensor locations as well as the corresponding first axle positions for each loading case are presented in Tables 3-1 and 3-2. The plots of the theoretical moments and strain due to each load are presented in Appendix E.

Once the analysis of the bridge was completed and the absolute maximums due to each loading case are determined, the overload event thresholds for the plate girders were determined. For this demonstration, the threshold was set as the least absolute maximum strain among those resulting from running all the design truck loads. As can be determined from the information in Tables 3-1 and 3-2, the least absolute maximum strains were resulted from the H-20 truck for both spans and, therefore, 219 microstrain and 221 microstrain were selected as the overload event thresholds for the plate girders in the west end span and in the center span, respectively.

Table 3-1. Summary of maximum moments (ft.-kips) and strains (microstrain) and corresponding first axle positions, b1 (ft.) for Sensors 5 and 8

Load Type	Moment	b1 (ft.)	Strain	b1 (ft.)
Iowa Legal Truck (Type3)	1384	64	250	64
Iowa Legal Truck (Type4)	1538	60	277	60
Iowa Legal Truck (Type3S2A)	1674	63	302	63
Iowa Legal Truck (Type3S2B)	1596	63	288	63
Iowa Legal Truck (Type3-3)	1806	68	326	68
Iowa Legal Truck (Type3S3)	1724	84	311	84
H 20 Truck (2 axles)	1216	63	219	63
HS 20 Truck (3 axles – 14 ft.)	1929	63	348	63
HS 20 Truck (3 axles – 15 ft.)	1907	63	344	63
HS 20 Truck (3 axles – 20 ft.)	1798	63	324	63
HS 20 Truck (3 axles – 25 ft.)	1692	63	305	63
HS 20 Truck (3 axles – 30 ft.)	1589	63	287	63
Truck train (or Lane) loading	1637	49	295	49

Table 3-2. Summary of maximum moments (ft.-kips) and strains (microstrain) and corresponding first axle positions, b1 (ft.) for Sensors 1 and 4

Load Type	Moment	b1 (ft.)	Strain	b1 (ft.)
Iowa Legal Truck (Type3)	1404	178	253	178
Iowa Legal Truck (Type4)	1556	178	281	178
Iowa Legal Truck (Type3S2A)	1716	177	310	177
Iowa Legal Truck (Type3S2B)	1688	177	305	177
Iowa Legal Truck (Type3-3)	1859	192	335	192
Iowa Legal Truck (Type3S3)	1800	198	325	198
H 20 Truck (2 axles)	1228	177	221	177
HS 20 Truck (3 axles – 14 ft.)	1947	177	351	177
HS 20 Truck (3 axles – 15 ft.)	1926	177	348	177
HS 20 Truck (3 axles – 20 ft.)	1825	177	329	177
HS 20 Truck (3 axles – 25 ft.)	1731	318	312	177
HS 20 Truck (3 axles – 30 ft.)	1646	177	297	177
Truck train (or Lane) loading	1670	163	301	163

3.3.2. BEC Analysis Validation

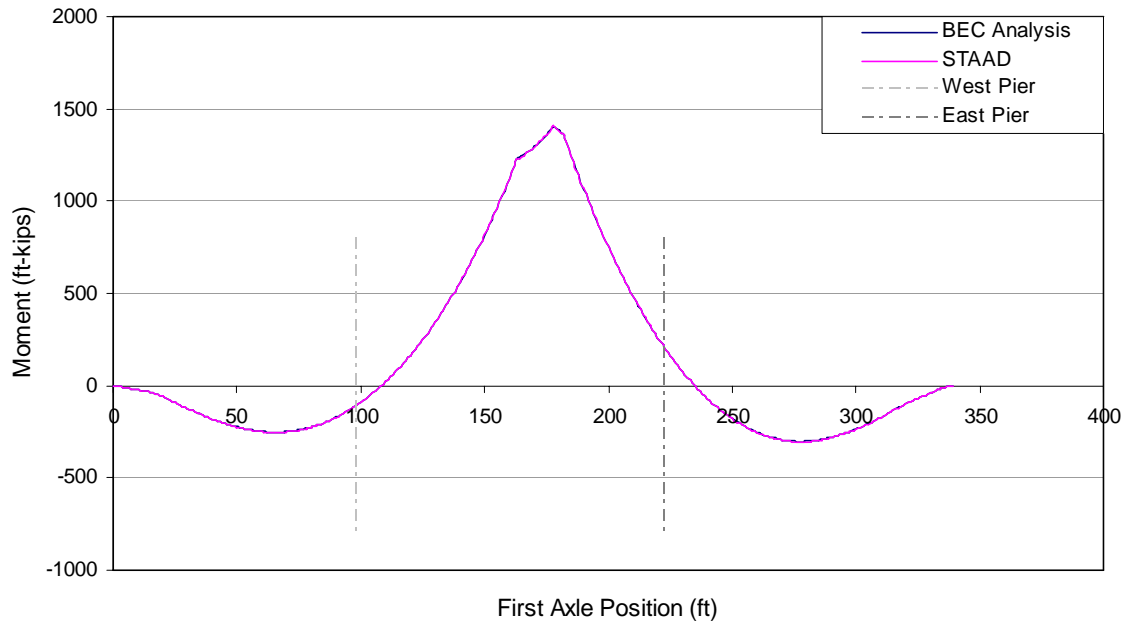
In order to validate the accuracy of *BEC Analysis*, numerous structures were analyzed with *BEC Analysis* and their results were compared to those generated by hand computations as well as other structural analysis software such as QConBridge and STAAD.Pro. Only the validation checks performed with STAAD.Pro, in which the US 30 bridge was used as a model bridge, are presented here.

Using STAAD.Pro, an analytical model representing the plate girders was constructed with two dimensional beam elements and a pinned support boundary condition assigned at the

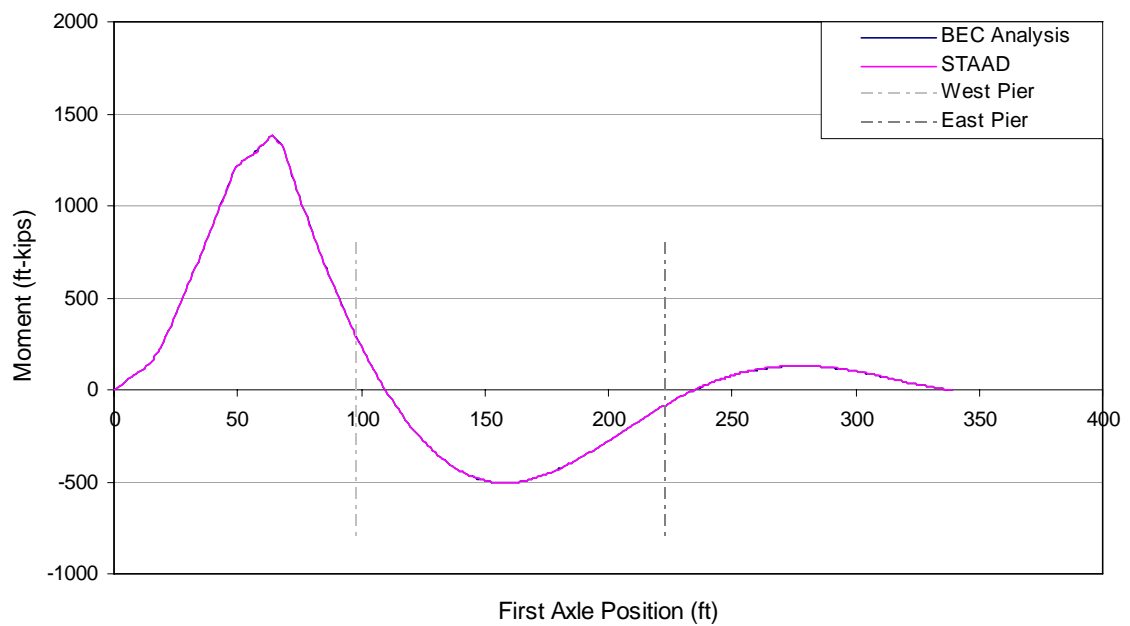
west pier and roller supports assigned at the east pier and at the both abutments. Each span was divided into sections in a manner that was used in *BEC Analysis* as shown in Figure 3-6.

After modeling the bridge, moving loads that represent the Iowa legal trucks (Types 3, 4, 3S2 A, 3S2 B, 3-3 and 3S3) were created and the model bridge was analyzed for each of the Iowa legal trucks. An increment of 1 ft. was used to dictate the total number of load cases simulating the moving trucks. The DF and IM that were used in *BEC Analysis* were also included in the analyses with STAAD.Pro. Once the model bridge was constructed with the required input parameters specified, the analyses were performed for each Iowa legal truck and results were compared with those generated by *BEC Analysis*.

Typical results obtained by running *BEC Analysis* and those by STAAD.Pro are shown in Figure 3-7. In general, both analyses produced results with an excellent agreement. In all cases, the discrepancies in the results generated by *BEC Analysis* and STAAD.Pro were less than 1%, thereby validating the accuracy of *BEC Analysis*.



(a) Sensors 1 and 4 in the center span



(b) Sensors 5 and 8 in the west end span

Figure 3-7. Analytical moments due to Iowa legal truck (Type 3) at the sensor locations with respect to the first axle position

3.4. Field Monitoring Software Demonstration

This section summarizes how the field monitoring software was specifically set up and used for the US 30 bridge. Additionally, sample evaluation reports for the US 30 bridge are also presented. The information regarding functions of each VI and its procedures were explained in Chapter 2. Therefore, only brief descriptions are presented in the subsequent sections.

3.4.1. Sample Data Collection and Noise Minimization

As mentioned in Chapter 2, measured strain data contains various components that include traffic induced strains and other unwanted elements such as changes in strain induced by drift and noise. The useful information for the system developed herein is that resulting from ambient traffic only. The effect of drift is eliminated by the data processing algorithm. The minimization of noise requires blocking the source of the noise with filtering. This is accomplished by running *2 FFT.-PSD Analysis.VI* with data collected with *1 Preliminary DAQ.VI*.

Following the general procedures provided previously, numerous data sets, including those with no traffic and those with ambient traffic traversing the bridge were collected. After data collection, each data set was investigated for the identification of noise and traffic induced frequencies. After the PSD plots were generated, comparisons were made to determine a suitable cutoff frequency. Presented in Figures 3-8 and 3-9 are the resulting PSD plots that illustrated frequency contents within the measured strain recorded with and without traffic, respectively.

From Figure 3-8, 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 that appears in all PSD plots. As shown in Figure 3-9, 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 2.8 Hz in all sensors. Also, it can be seen that there is a notable frequency at 4.8 Hz which is the same as was observed without any traffic present.

Once the PSD plots were generated and the noise induced and traffic induced frequency contents were investigated, three filter parameters for the lowpass frequency filter (i.e., cutoff frequency, filter order and ripple) and peak detection thresholds described in Chapter 2 were determined for each sensor. The purpose in determining the filter parameters is to eliminate or minimize the noise. Based upon the generated PSD data, it was decided to set the cutoff frequency at 2.8 Hz. With this setting, although it did not eliminate all of the noise in the measured strain record, it allowed passage of the most dominant live load frequencies. The ripple and filter order for each sensor was determined based on the explanations and recommendations discussed in *The Scientist and Engineer's Guide to Digital Signal Filter Processing* [4] and *LabVIEW Analysis Concepts* [5]. The peak detection thresholds were set at ± 5 microstrain for all sensors. This value was determined so that it would not affect the identification of traffic events (peaks) while eliminating those events induced by free

vibration of the bridge. Examples of strain history plots that illustrate the effect of setting the filter parameters and the peak detection thresholds are presented in Figure 3-10.

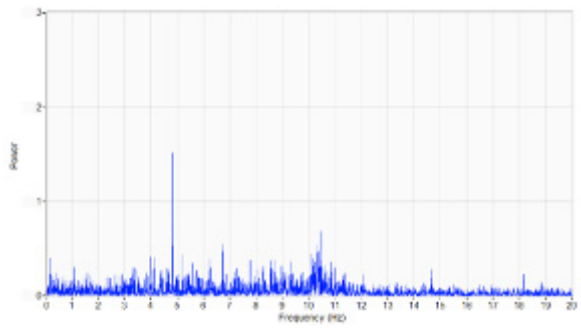
Figures 3-10a and 3-10b illustrate the noise induced strain history plots generated from a 3-minute sample data (Note: strain history before filtering is in green and after filtering is in gray). By comparing these two plots, it is obvious that the use of the cutoff frequency at 2.8 Hz minimizes most of the noise.

Examples of the strain history plots that illustrate the effect of using different peak detection thresholds are presented in Figures 3-10c through 10e. As shown in Figures 3-10c through 3-10e, the use of ± 2 microstrain resulted in numerous peaks being detected during free vibration. However, setting the threshold to ± 5 microstrain minimized detection of the free vibration portion of the record.

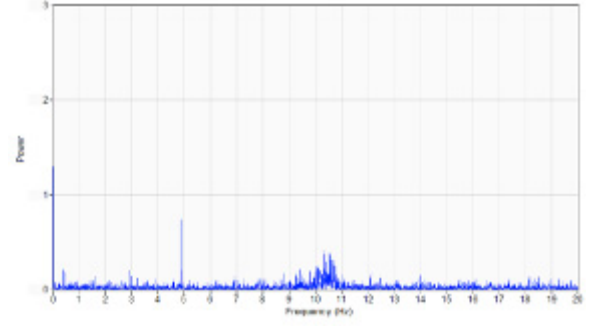
After the filter parameters and peak detection thresholds were determined, they were saved to a text file in the SHM main directory so that it can be used during normal monitoring. The finalized filter parameters and peak detection thresholds for each sensor are presented in Table 3-3.

Table 3-3. Filter parameters and peak detection thresholds

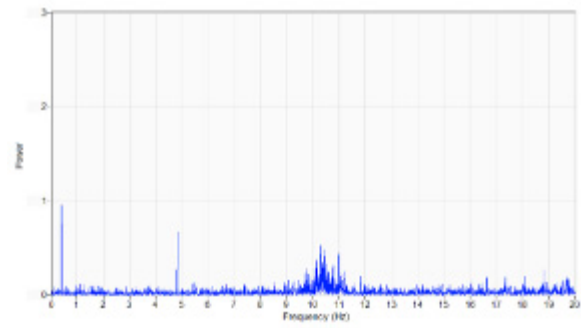
Sensor	Cutoff Frequency (Hz)	Filter Order	Ripple (dB)	Peak Detection Thresholds (microstrain)	
				Positive	Negative
1	2.8	8	0.0435	5	-5
2	2.8	4	0.0435	5	-5
3	2.8	6	0.0435	5	-5
4	2.8	12	0.0435	5	-5
5	2.8	6	0.0435	5	-5
6	2.8	4	0.0435	5	-5
7	2.8	10	0.0435	5	-5
8	2.8	8	0.0435	5	-5



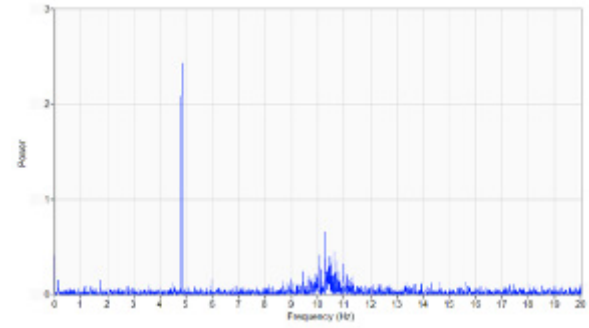
(a) Sensor 1



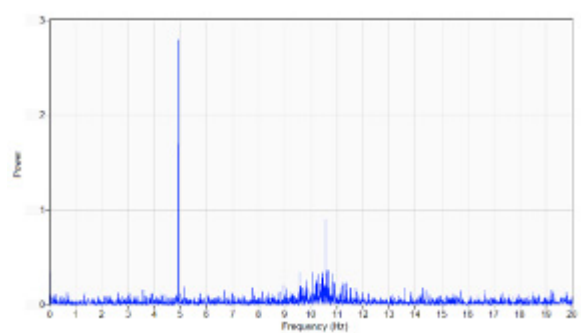
(b) Sensor 2



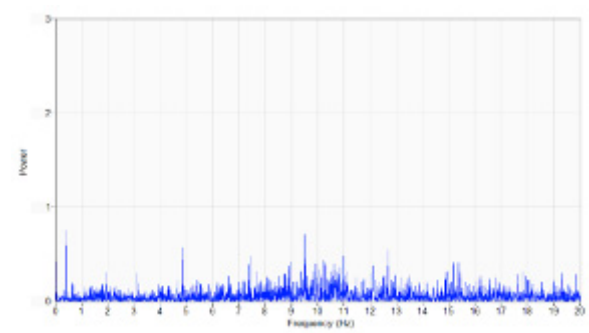
(c) Sensor 3



(d) Sensor 4



(e) Sensor 5



(f) Sensor 6

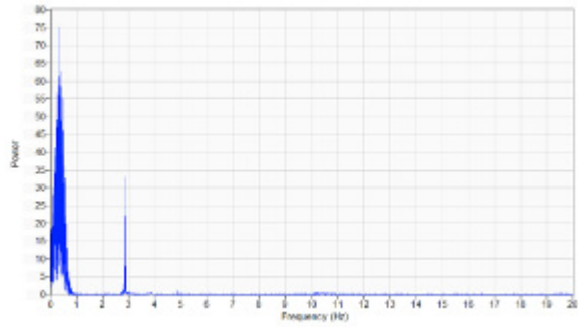


(g) Sensor 7

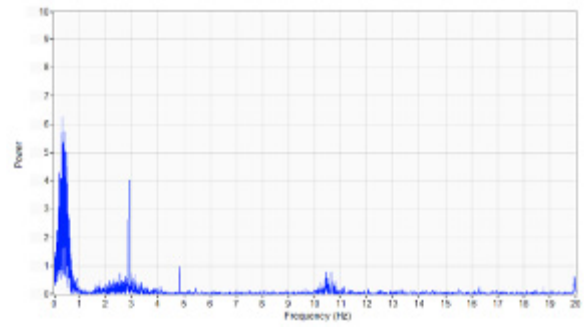


(h) Sensor 8

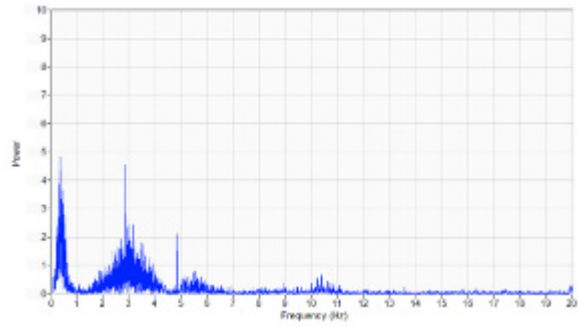
Figure 3-8. PSD plot from sample data with no traffic on the bridge



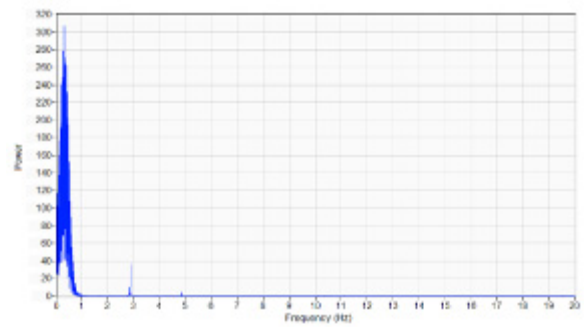
(a) Sensor 1



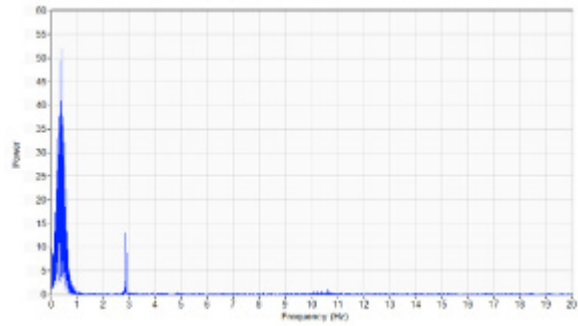
(b) Sensor 2



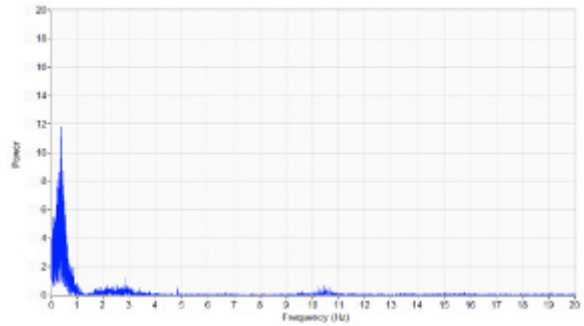
(c) Sensor 3



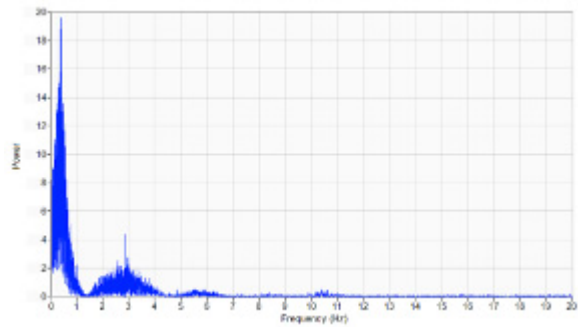
(d) Sensor 4



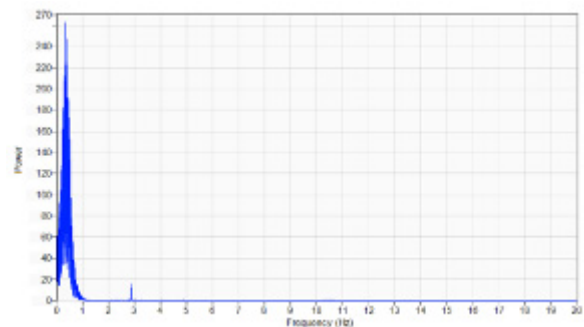
(e) Sensor 5



(f) Sensor 6

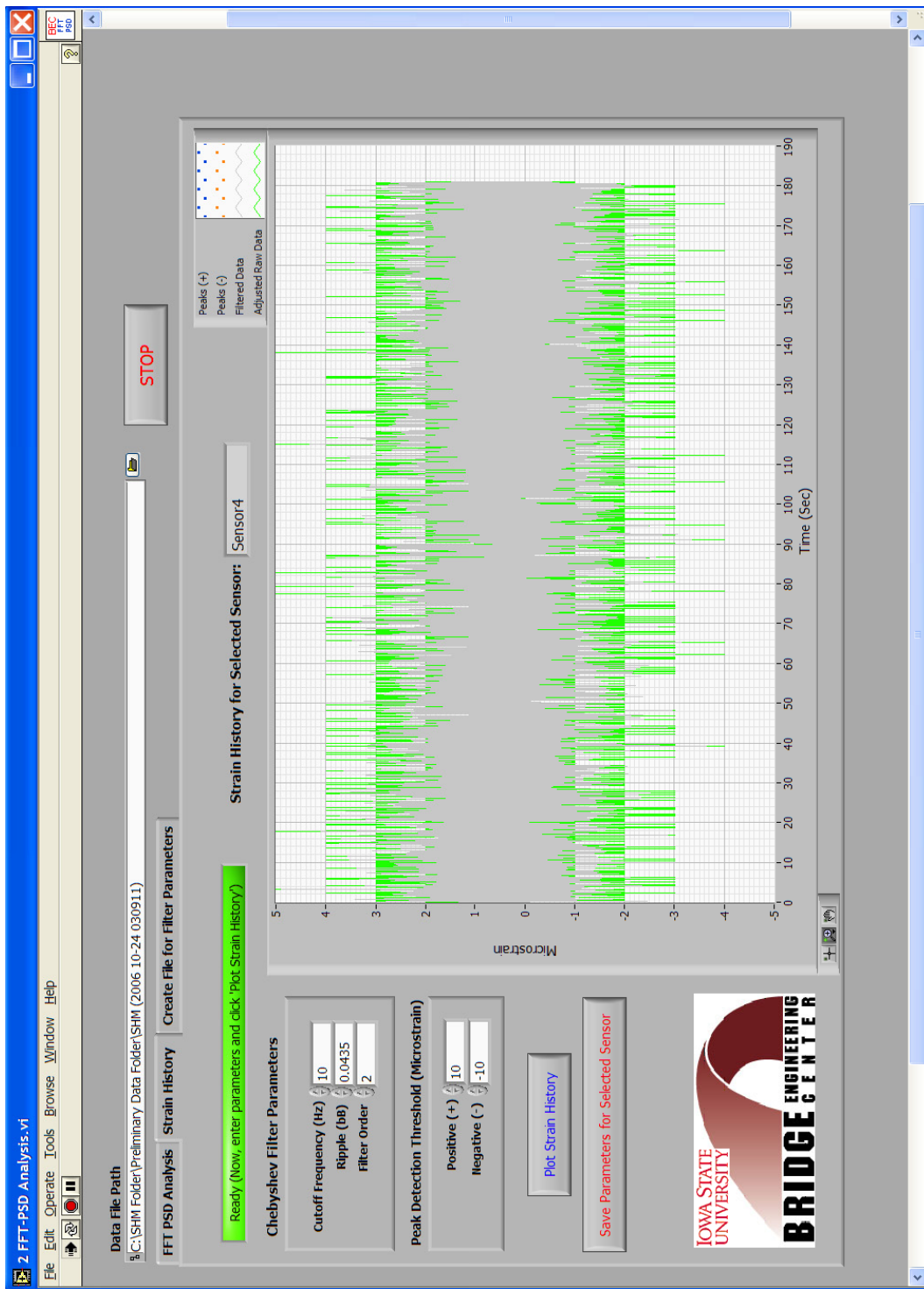


(g) Sensor 7



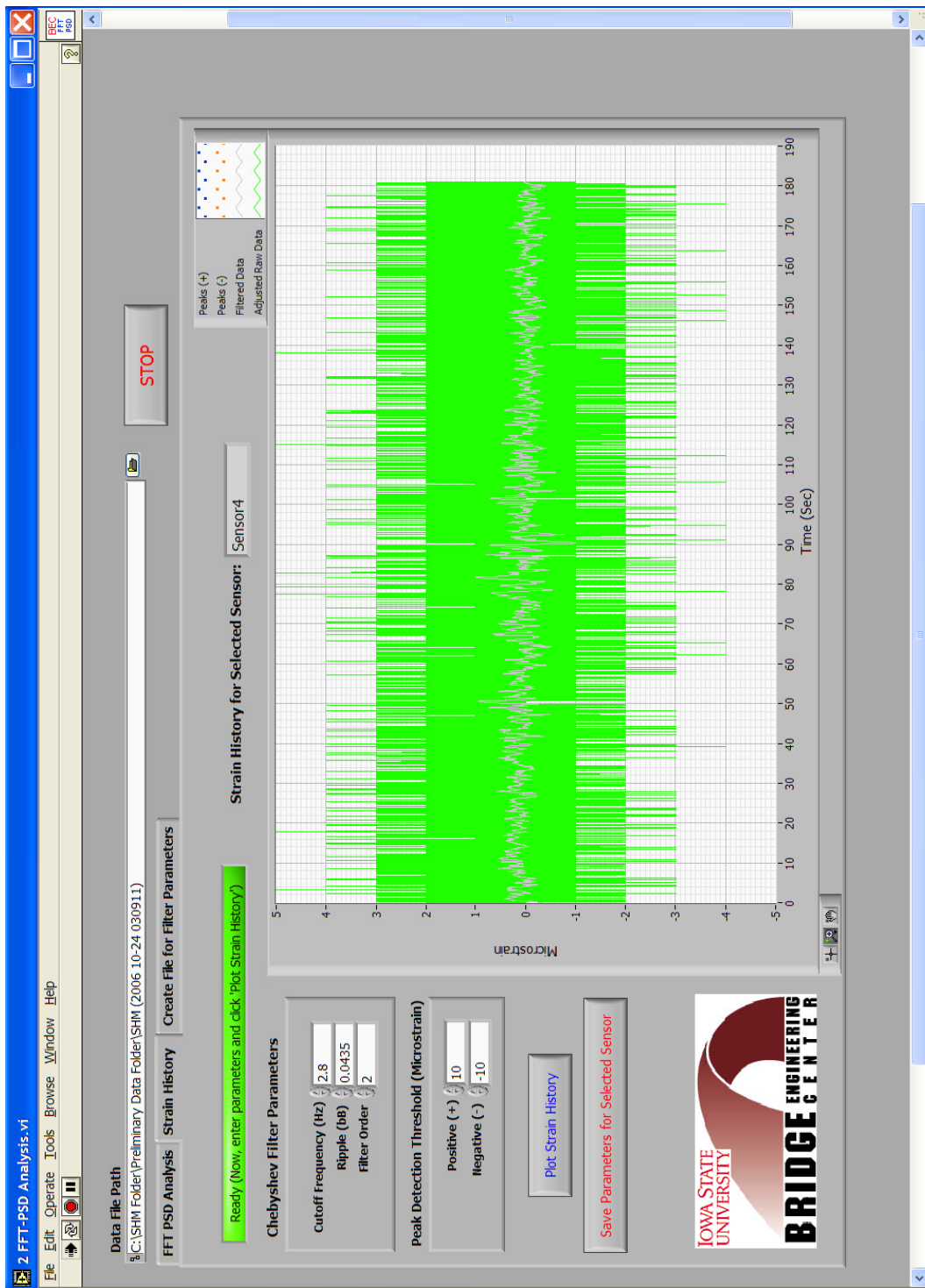
(h) Sensor 8

Figure 3-9. PSD plot from sample data with traffic on the bridge



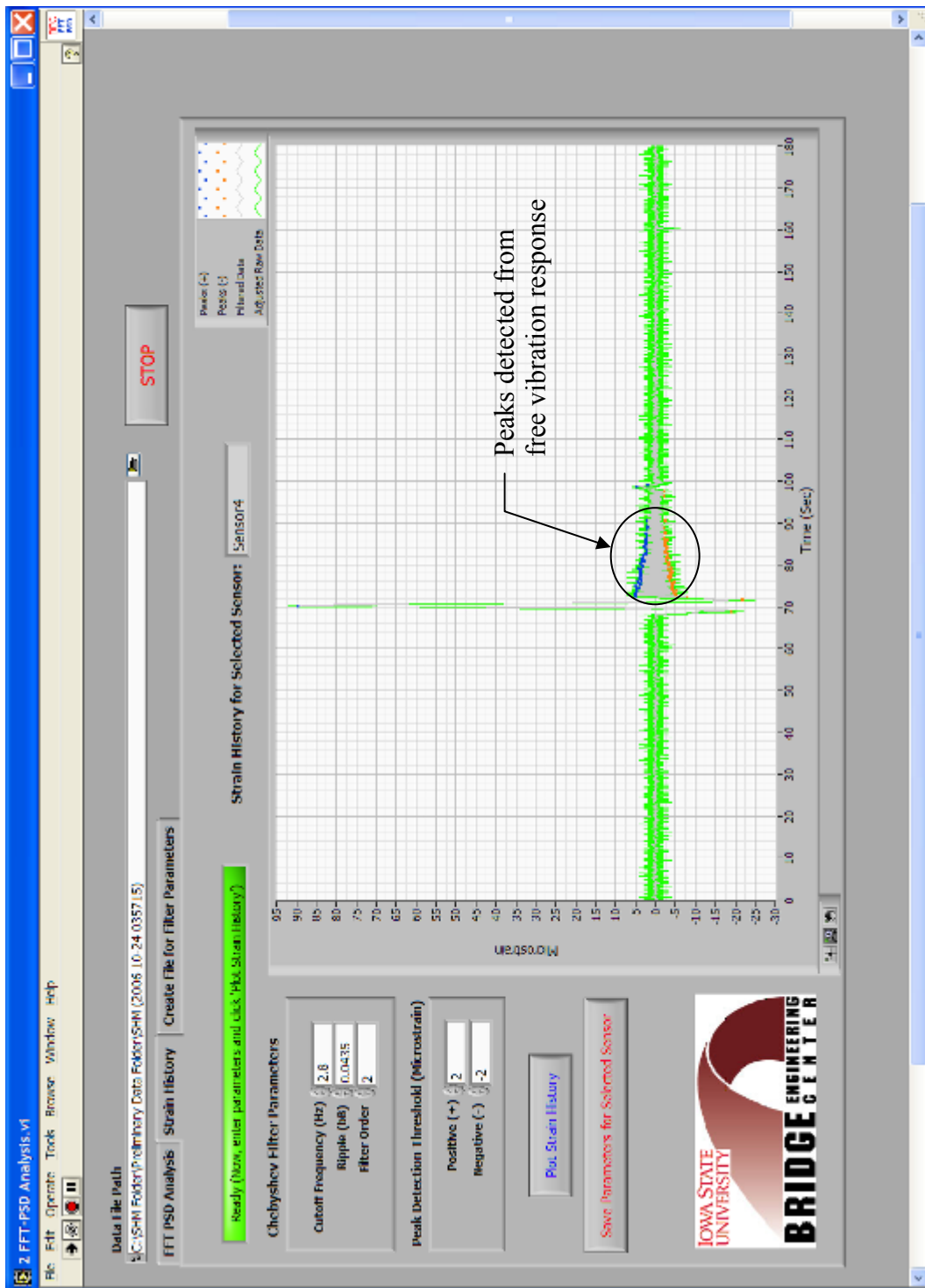
(a) Noise induced strain history with cutoff frequency set at 10 Hz (3-minute sample data)

Figure 3-10. Illustration of effect on filter parameters and peak detection thresholds



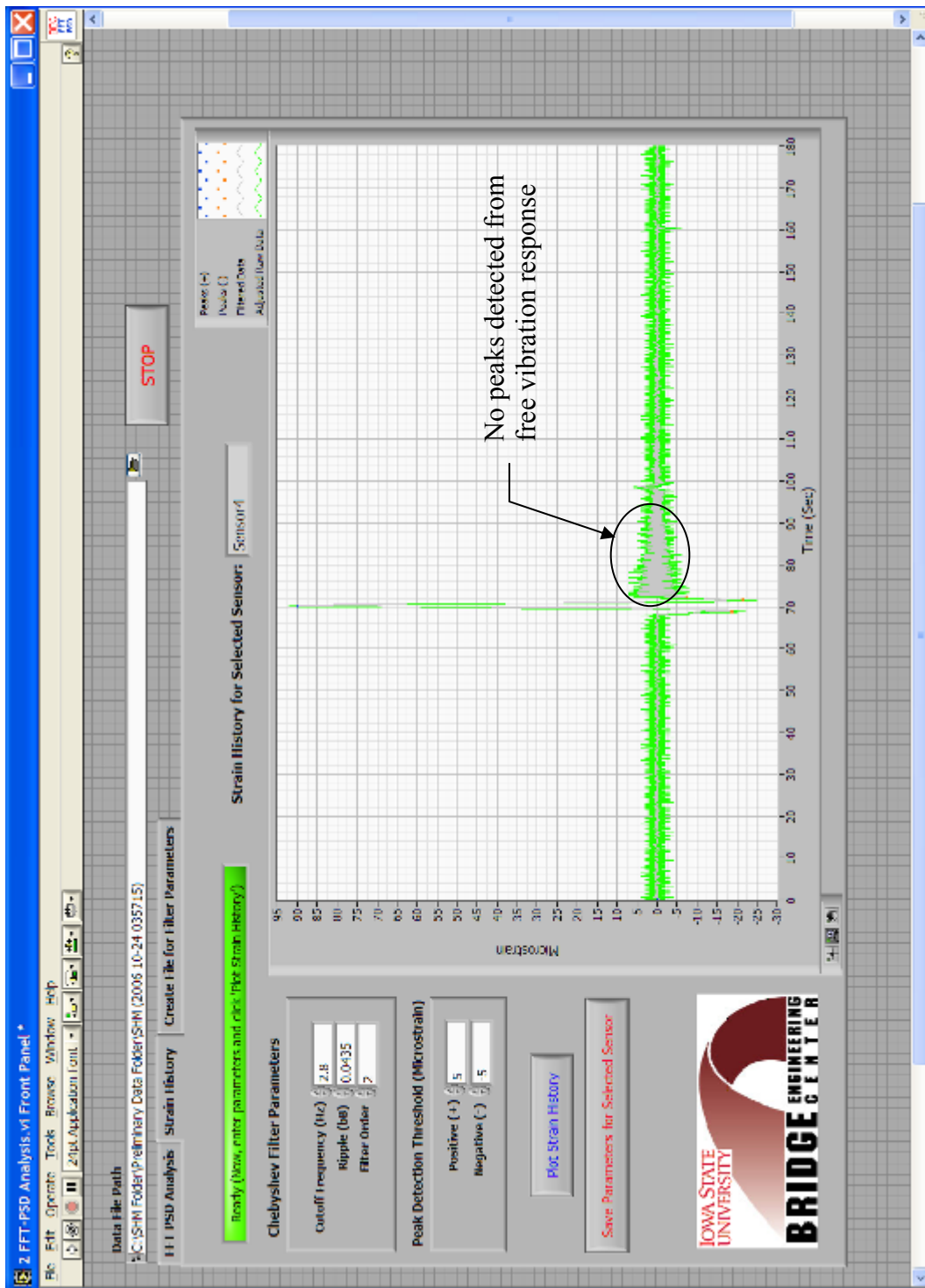
(b) Noise induced strain history with cutoff frequency set at 2.8 Hz (3-minute sample data)

Figure 3-10. (continued)



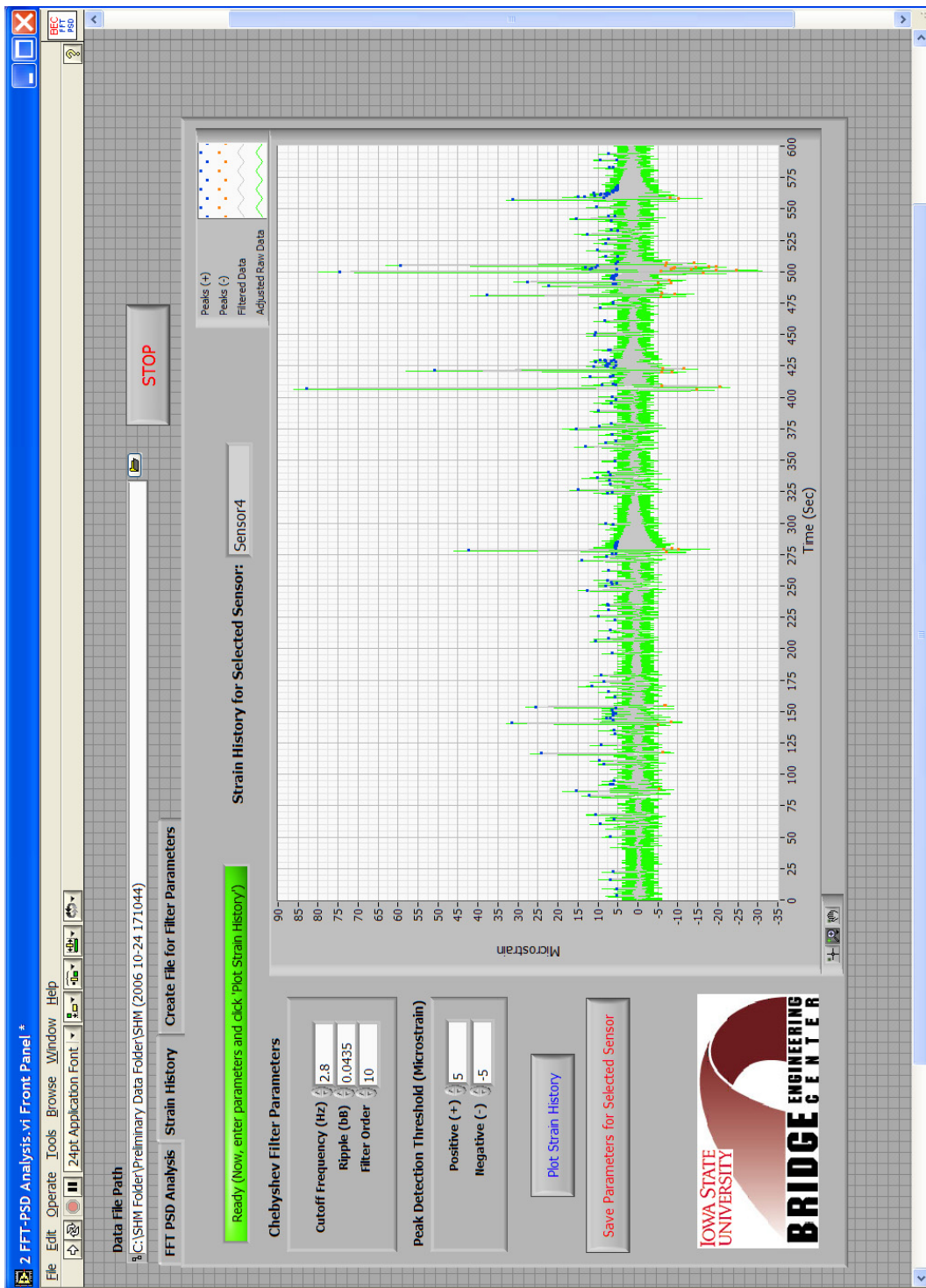
(c) Semi-truck induced strain history with peak detection thresholds set at ± 2 microstrain (3-minute sample data)

Figure 3-10. (continued)



(d) Semi-truck induced strain history with peak detection thresholds set at ± 5 microstrain (3-minute sample data)

Figure 3-10. (continued)

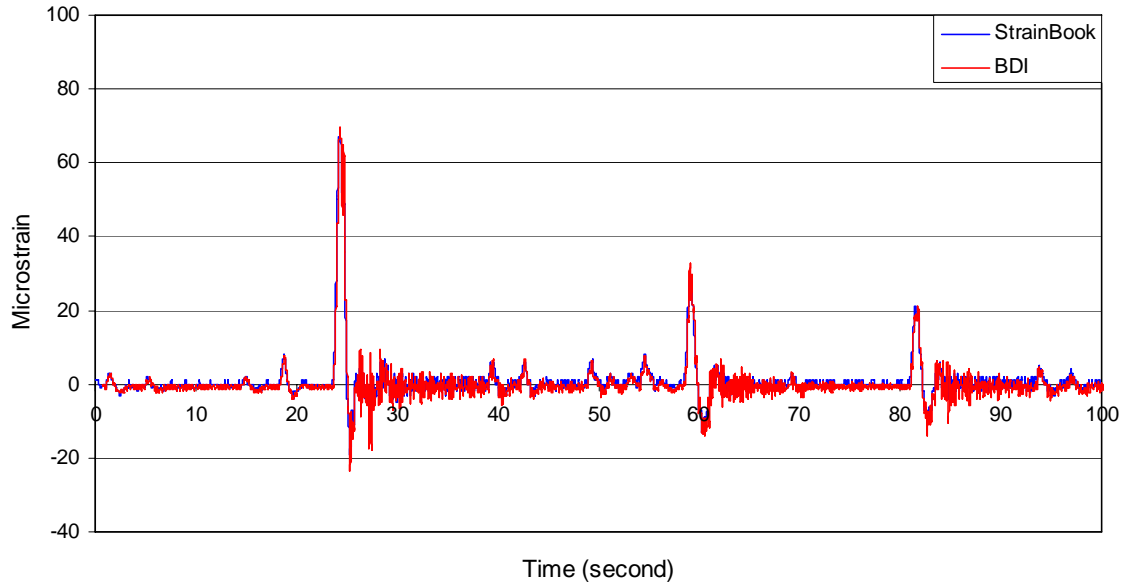


(e) Strain history with peak detection thresholds set at ± 5 microstrain (10-minute sample data)

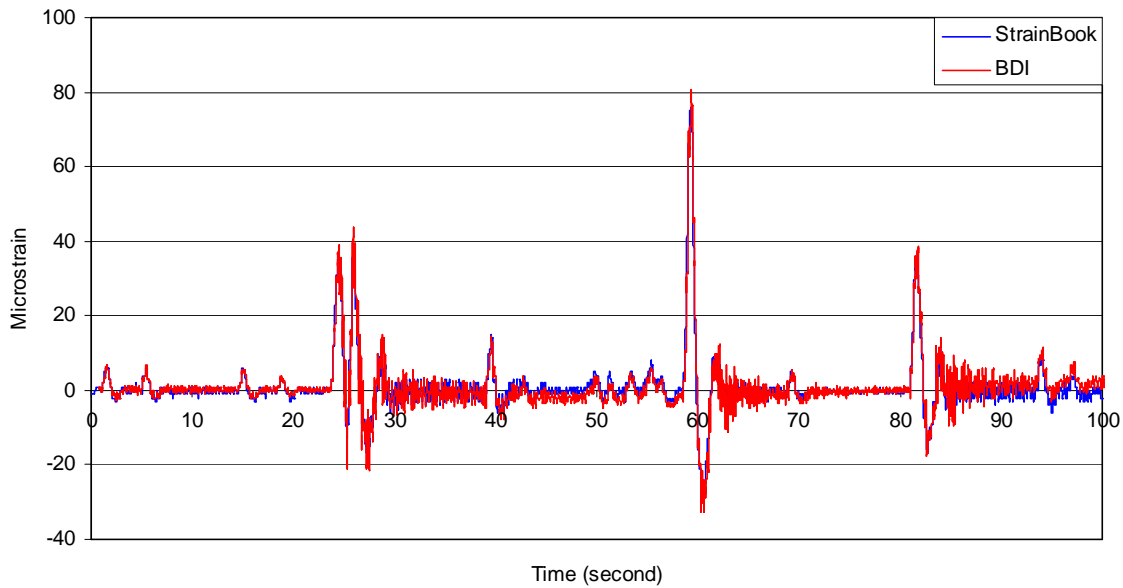
Figure 3-10. (continued)

3.4.2. System Validation

In order to validate the accuracy of strain measurement from the SHM system, an in-service field test was conducted. For this testing, a strain measurement system from Bridge Diagnostics, Inc. (BDI) and two BDI strain transducers were utilized with each strain transducer installed next to the weldable strain gages (approximately 6 in. apart) in the west end span (i.e., Sensor 5 and Sensor 8). Once the BDI system was setup, strains of randomly selected segments of ambient traffic were simultaneously collected by the SHM system and the BDI system and the measured strains from both systems were compared. Figure 3-11 presents a representative example of the comparison between the measured strains obtained by both systems. By comparing the strains obtained by both systems, it was observed that both systems produced fairly consistent strains. In general, the overall discrepancies in measured strains were less than 5 $\mu\epsilon$ and, therefore, the SHM system was thought to be performing accurately.



(a) Sensor 5



(b) Sensor 8

Figure 3-11. Examples of in-service validation testing (comparison of measured strains collected by the BDI system and the SHM system)

3.4.3. Input Settings and Main Data Acquisition/Processing

After the hardware components had been installed and the filter parameters and peak detection thresholds determined, *3 Input.VI* was run following the procedures described previously and a binary file (DAQ Inputs) that contains input settings was created and saved in the main directory as was previously shown. The input settings that were used in *3 Input.VI* were exactly the same

as the example depicted in Figure 2-16 except the magnitude of the overload event thresholds for the select sensors and the email address information.

After the DAQ Inputs file was created and saved in the main directory, the main program designed for data acquisition and processing, *4 MainDAQ815.VI*, was initialized at approximately 3 pm on November 14th, 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 following section presents a 30-day evaluation report obtained during the monitored period from 3:00 pm on November 14th, 2006 to 4:47 pm on December 14th, 2006. During this monitoring period, a total of 755 data files including 720 hour files, 30 day files, 4 week files and a single month file were created and archived.

3.4.4. Bridge Performance Evaluation Report

As previously mentioned, the three main purposes of the SHM system are to identify alarm events, to investigate gradual changes in structural response of the bridge that would provide users with information regarding damage, and to provide information on overall bridge usage. Such information can be obtained directly from reviewing the evaluation report. The evaluation report presented in this section was generated by accessing thirty daily files with *8 Create Report (From Multiple Files).VI*.

Only some portions contained in the evaluation reports are summarized and displayed in Tables 3-4 through 3-6 and Figure 3-12 while an example of a complete evaluation report generated by *8 Create Report (From Multiple Files).VI* is provided in Appendix F.

Each data point in any of the event history plot in Figure 3-12 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. 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 monitored period, as follows:

- 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 as can be seen in Tables 3-4 and 3-5 as well as in Figure 3-12, no identified events exceeded the overload event thresholds that were set. Therefore, no alarm event is listed in the evaluation report (see Appendix F).
- The magnitudes of the daily maximum events, as presented in Table 3-5 and Figure 3-12, fluctuates from day to day. 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. 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 3-12, 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 (Table 3-4) 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.

- Comparing the numerical counts of events identified in the north plate girders with those in the south plate girders (Sensor 1 vs. Sensor 4 in the center span and Sensor 5 vs. Sensor 8 in the west end span), more events were identified in the south plate girder than in the north plate girder. This was originally expected as more traffic is expected to travel in the driving lane (south lane) than in the passing lane (north lane). Similar results can be observed from comparing the numerical counts of events identified in the stringers (Sensor 2 vs. Sensor 3 and Sensor 6 vs. Sensor 7).
- From reviewing the number of identified events in Table 3-6 and Figure 3-12, relatively fewer events were identified from the sensors installed on the stringers than on the plate girders. One possible reason could be the peak detection thresholds that were used in the data processing. Typically, the magnitudes of the measured strains in the stringers are smaller than those in the plate girders.

In order to provide hour-to-hour, day-to-day and week-to-week comparisons of the bridge response, 24-hour hourly event histograms and 30-day daily as well as weekly event histograms for Sensor 4 (typical of all sensors) were created and presented in Figures 3-13 and 3-14. After reviewing and comparing the histograms, several observations were made as follows:

- The numerical counts of identified events are different from hour-to-hour, day-to-day and week-to-week as expected. The variation in the number of identified events within the daily and weekly 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 or week-to-week 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.
- Examining the hourly event histograms for a typical weekday and weekend day, it is obvious that the traffic volume is consistently higher during the daytime than nighttime.
 - The weekday hourly event histogram shows high traffic volume during the evening commute time (5 to 7 PM).
 - The weekend day hourly event histogram shows a bell-shaped distribution where the traffic volume is the highest in the afternoon.
- The traffic volume in a typical weekday is higher than that of a weekend day.
- 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.

Table 3-4. Overall summary of 30-day monitoring

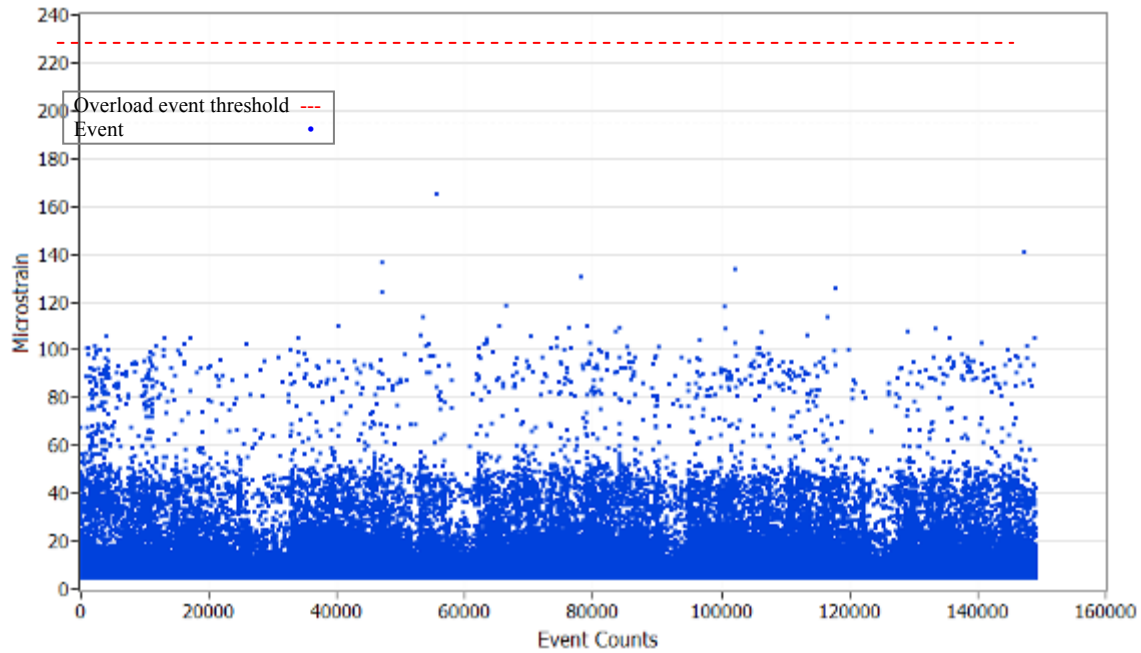
Sensor	Overload event threshold ($\mu\epsilon$)	Maximum Event ($\mu\epsilon$)	Average ($\mu\epsilon$)	Slope Change
1	221	165	10	0
2	-	78	12	0
3	-	91	13	0
4	221	174	10	0
5	219	156	10	0
6	-	103	10	0
7	-	116	9	0
8	219	167	10	0

Table 3-5. Statistical Trends (daily maximum/average in microstrain)

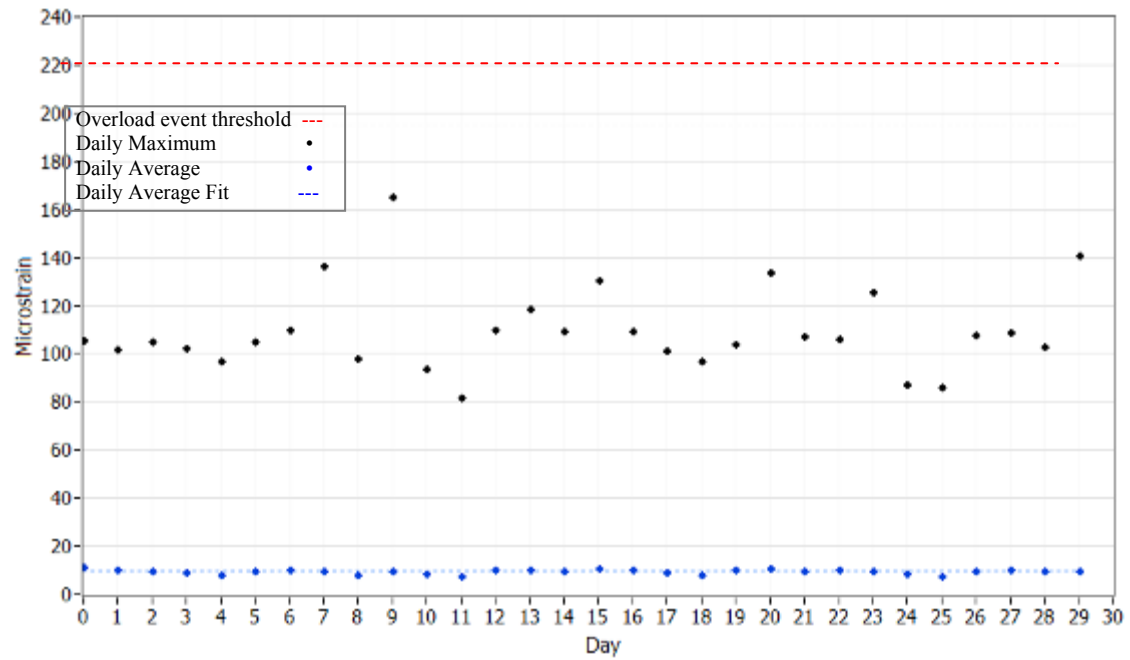
	Sensor1	Sensor2	Sensor3	Sensor4	Sensor5	Sensor6	Sensor7	Sensor8
Day 0	105/11	51/13	47/11	110/12	93/11	80/11	68/11	106/11
Day 1	102/11	41/12	46/13	111/11	99/11	76/11	71/11	105/10
Day 2	105/10	47/11	64/13	131/10	95/9	77/10	104/10	122/10
Day 3	102/9	41/12	47/13	111/9	91/9	74/9	68/8	93/9
Day 4	97/8	42/10	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 3-6. Number of identified events (bin width – 20 microstrain)

Sensor\ Min. bin	0	20	40	60	80	100	120	140	160	180	20 0	Total
1	1378 49	809 3	245 6	271	452	56	5	1	1	0	0	1491 84
2	3283 6	597 1	34	2	0	0	0	0	0	0	0	3884 3
3	3896 7	877 3	223	3	1	0	0	0	0	0	0	4796 7
4	2459 01	846 9	489 9	201 8	213 3	199	12	5	1	0	0	2636 37
5	9552 1	736 9	630	500	163	7	2	1	0	0	0	1041 93
6	9261 0	917 0	133 1	296	5	2	0	0	0	0	0	1034 14
7	1915 47	101 98	576 9	594	13	4	0	0	0	0	0	2081 25
8	2561 14	101 87	360 3	260 0	919	22	9	2	1	0	0	2734 57

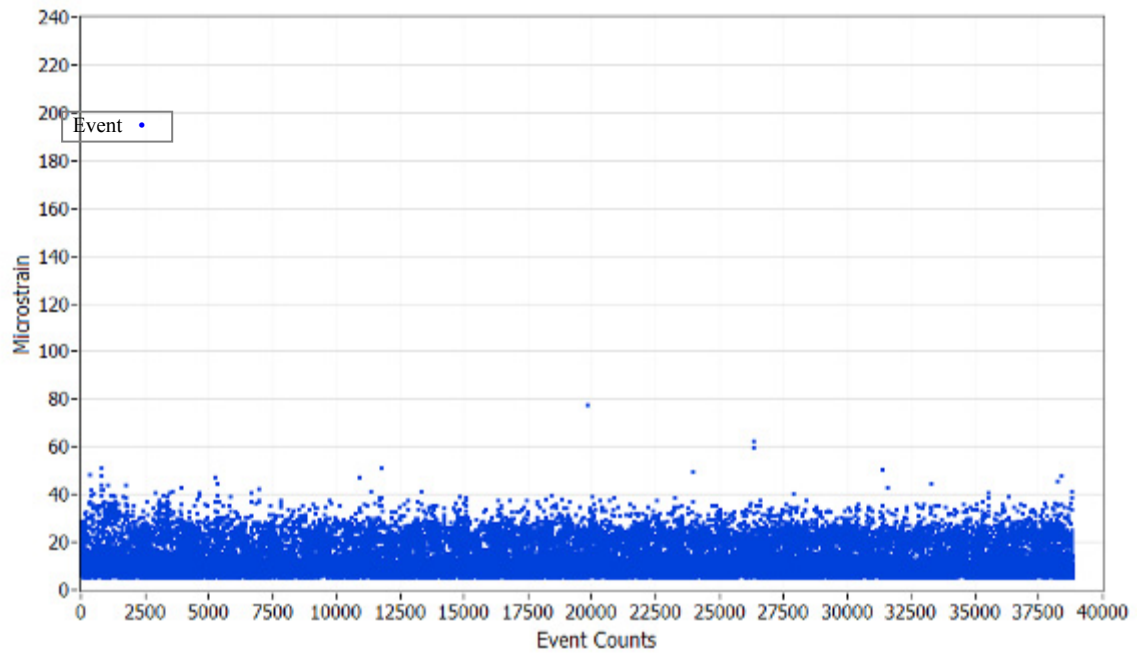


(a) 30-day event history for Sensor 1

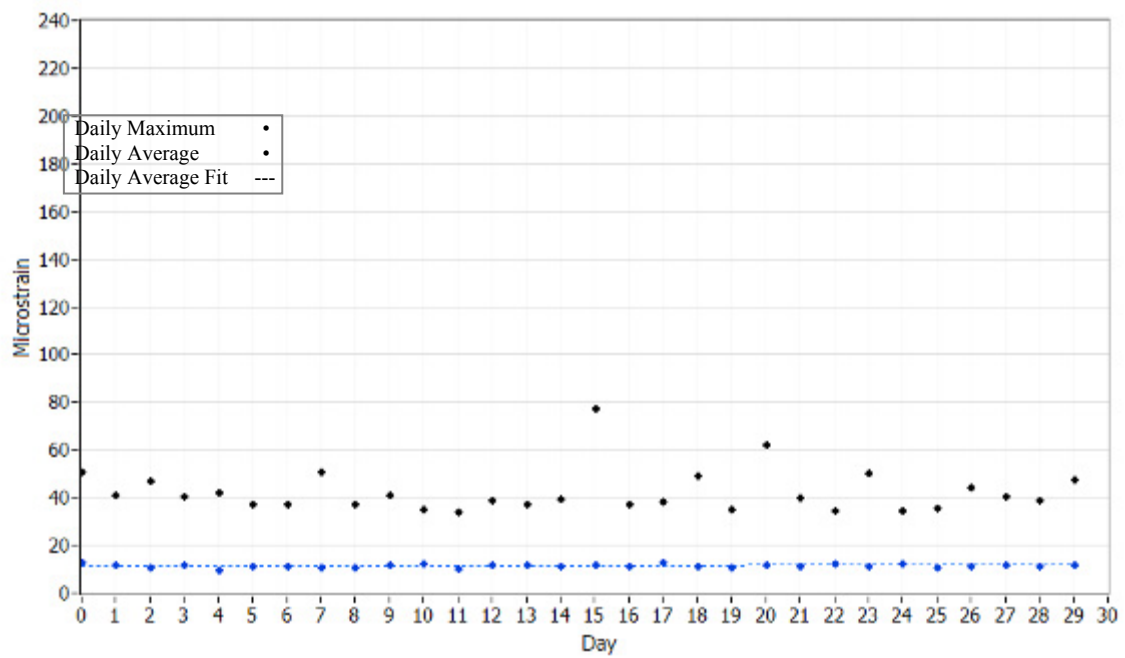


(b) 30-day daily statistical trends for Sensor 1

Figure 3-12. Monthly evaluation from on Nov. 14th through Dec. 14th of 2006

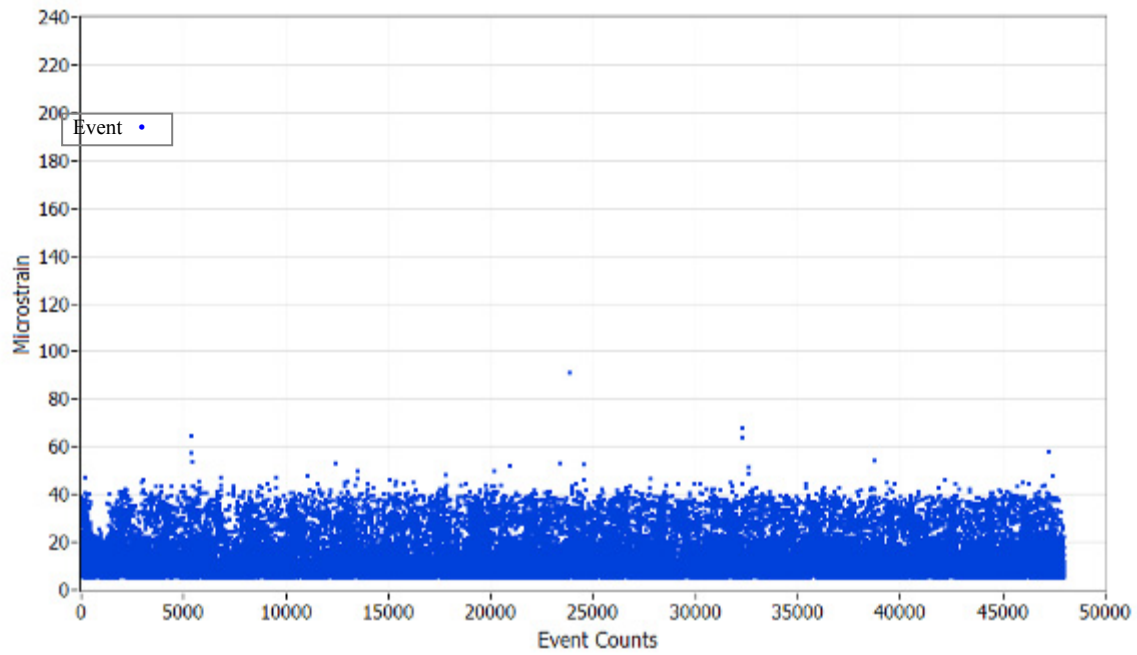


(c) 30-day event history for Sensor 2

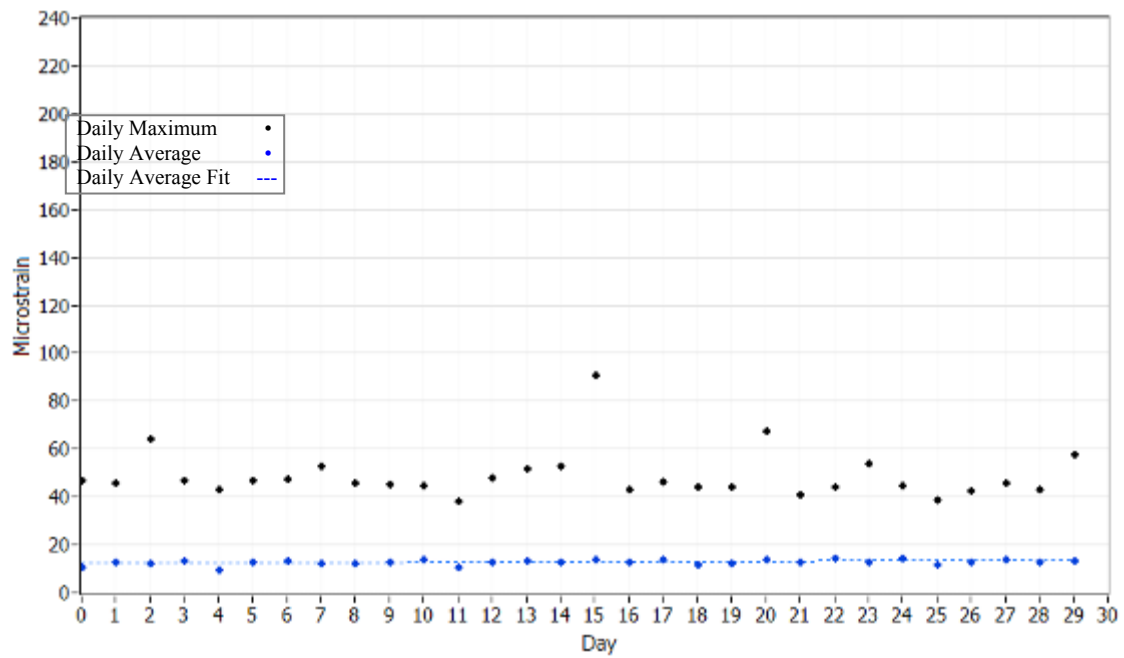


(d) 30-day daily statistical trends for Sensor 2

Figure 3-12. (continued)

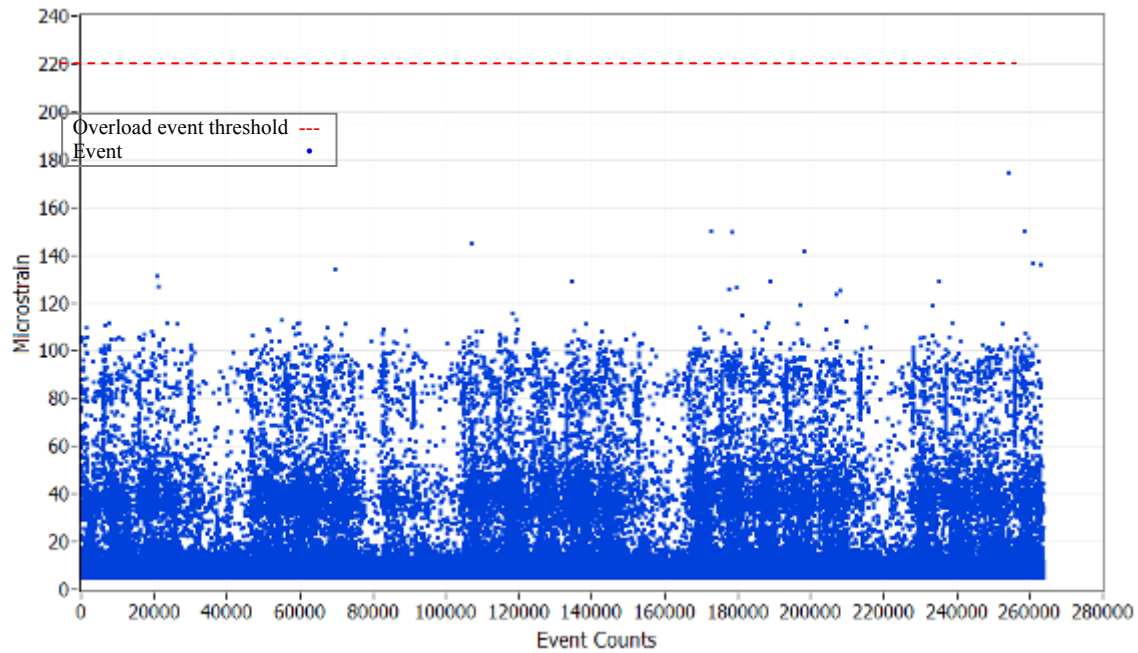


(e) 30-day event history for Sensor 3

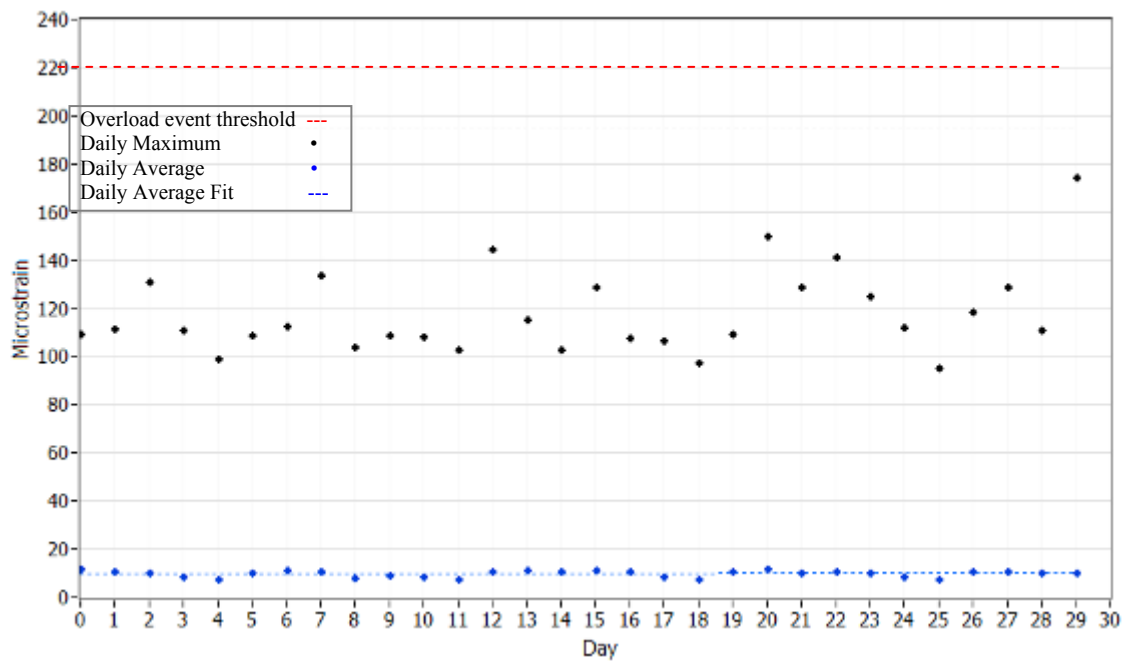


(f) 30-day daily statistical trends for Sensor 3

Figure 3-12. (continued)

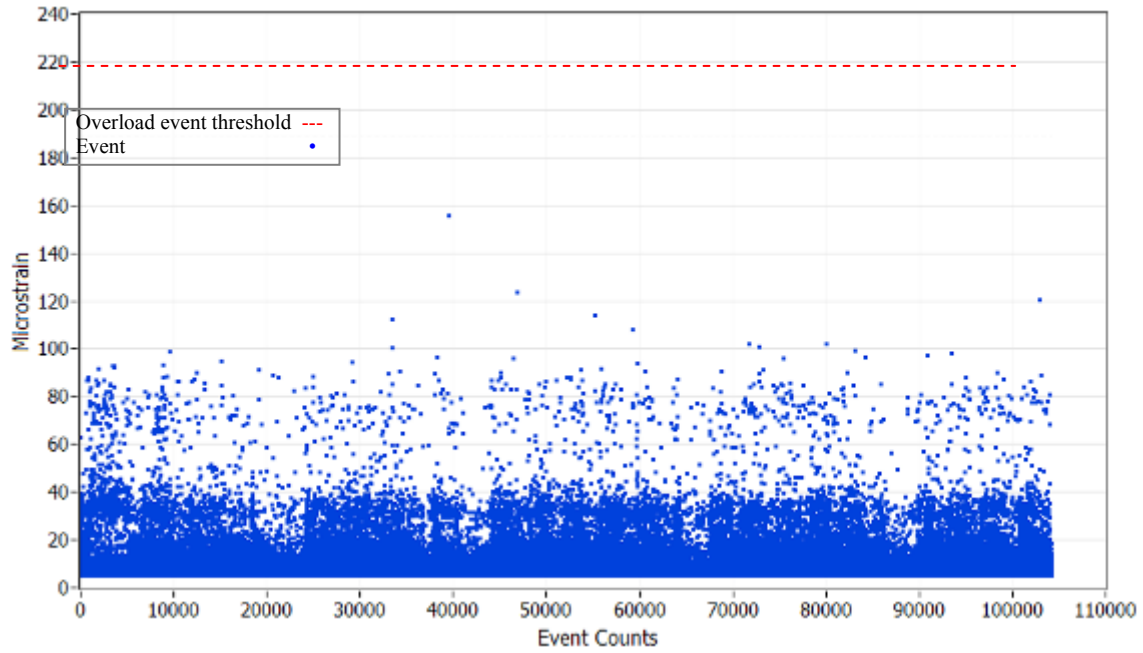


(g) 30-day event history for Sensor 4

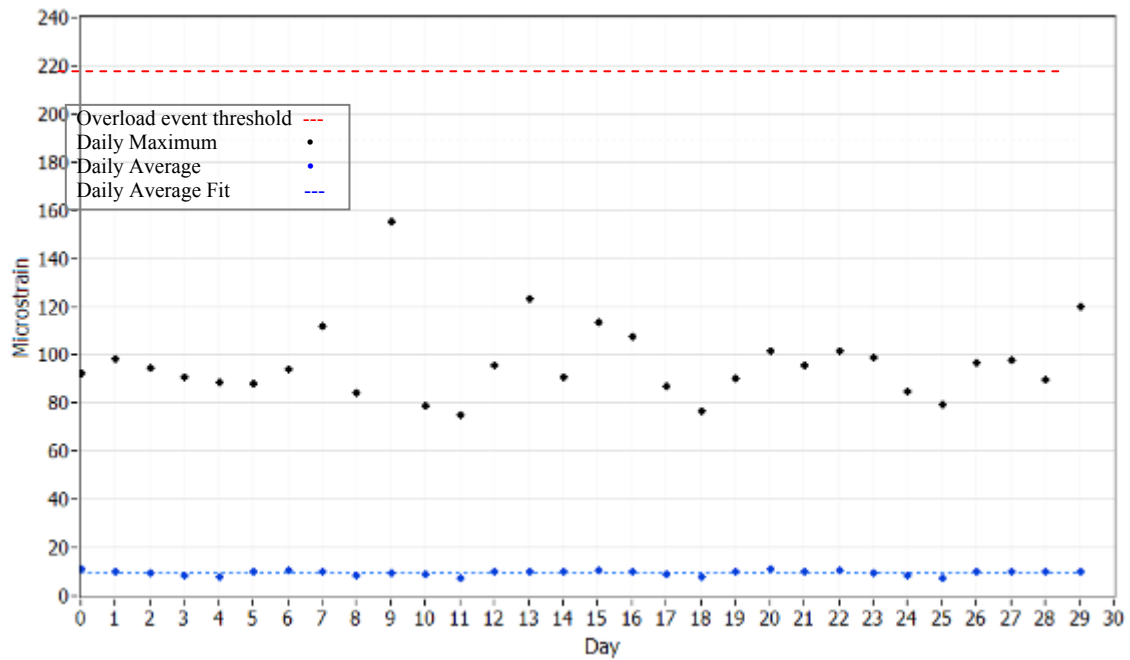


(h) 30-day daily statistical trends for Sensor 4

Figure 3-12. (continued)

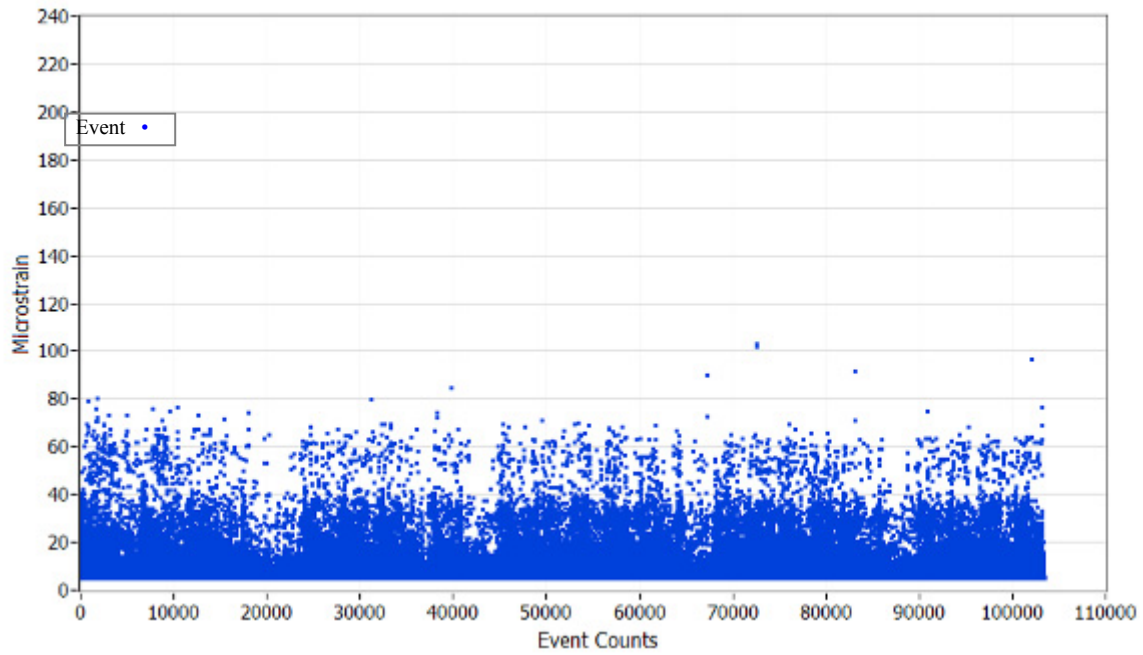


(i) 30-day event history for Sensor 5

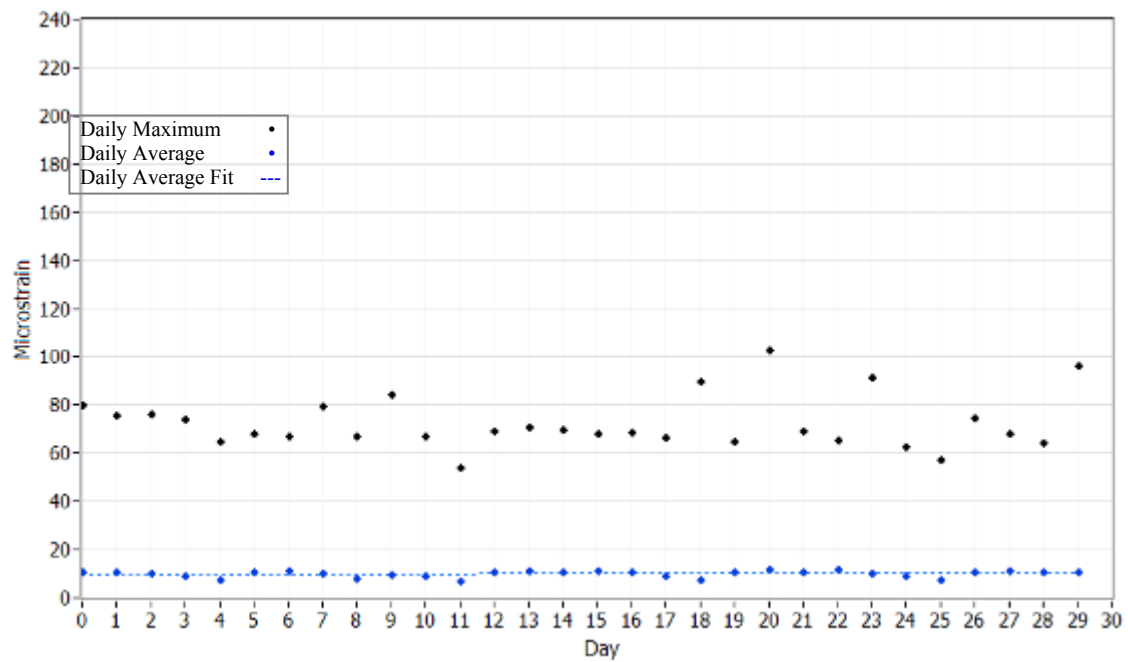


(j) 30-day daily statistical trends for Sensor 5

Figure 3-12. (continued)

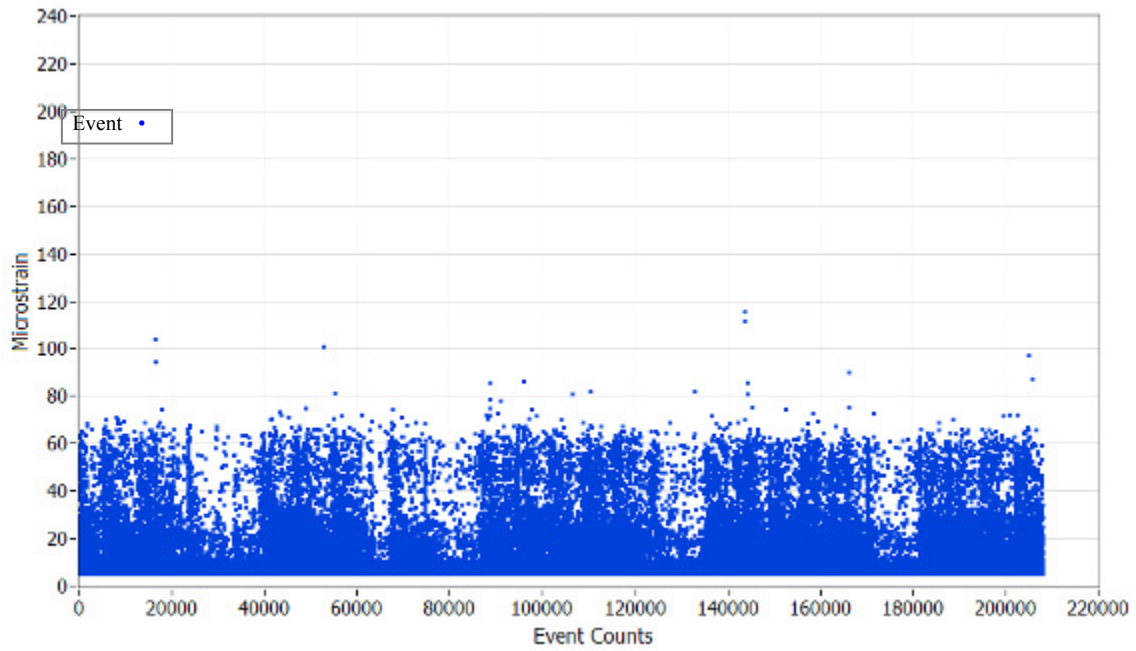


(k) 30-day event history for Sensor 6

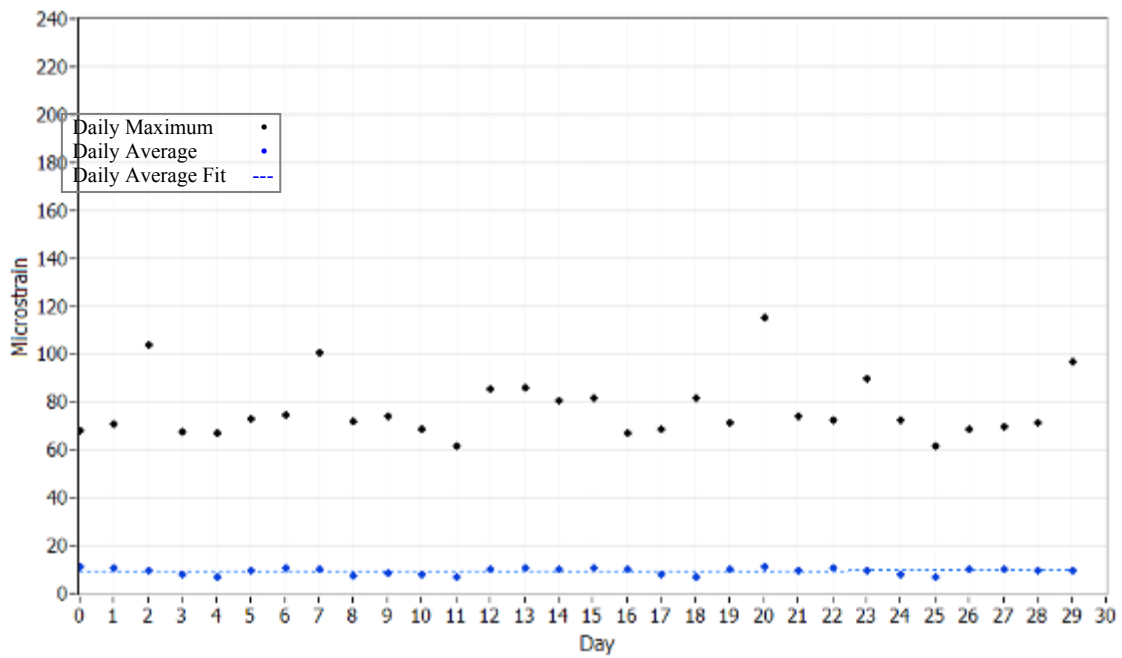


(l) Daily 30-day daily statistical trends for Sensor 6

Figure 3-12. (continued)

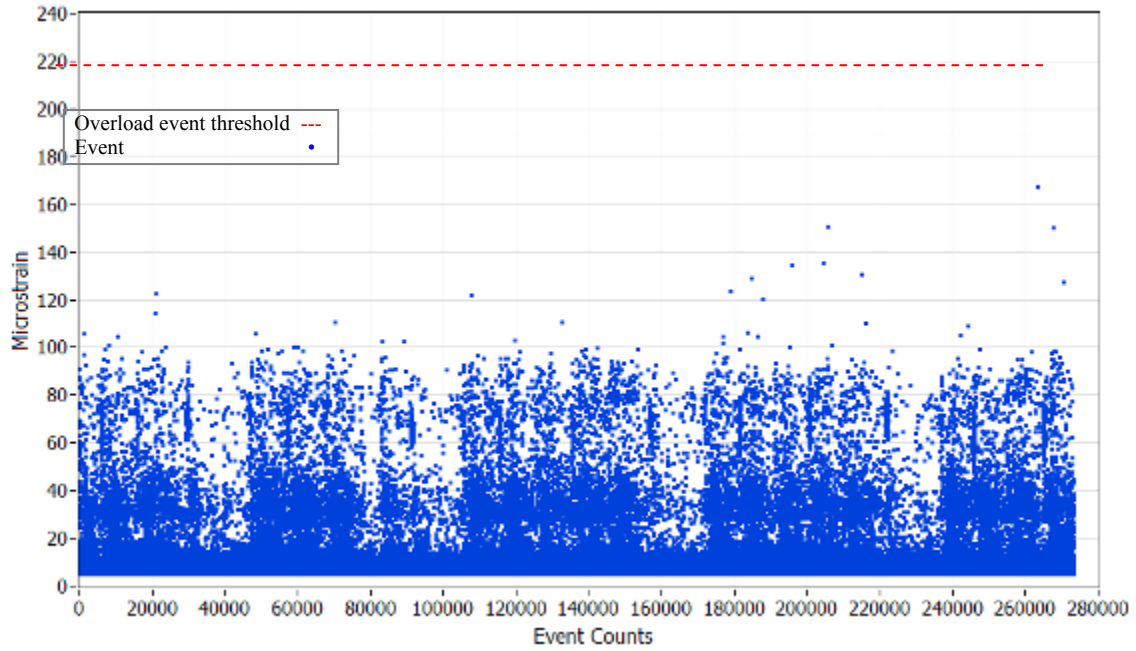


(m) 30-day event history for Sensor 7

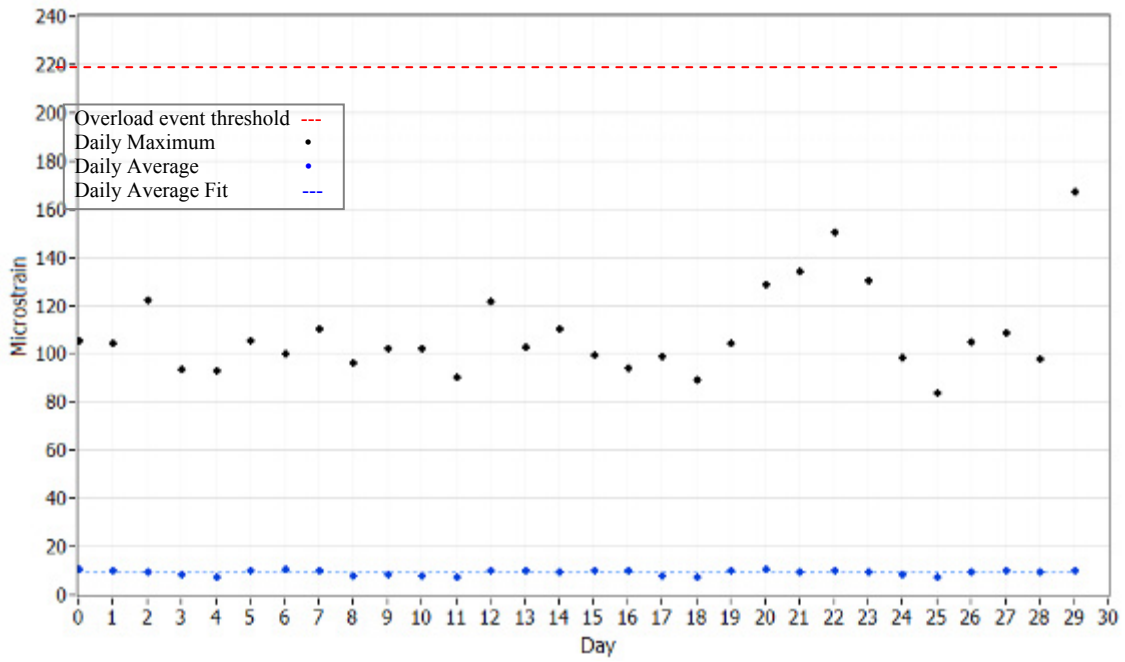


(n) 30-day daily statistical trends for Sensor 7

Figure 3-12. (continued)

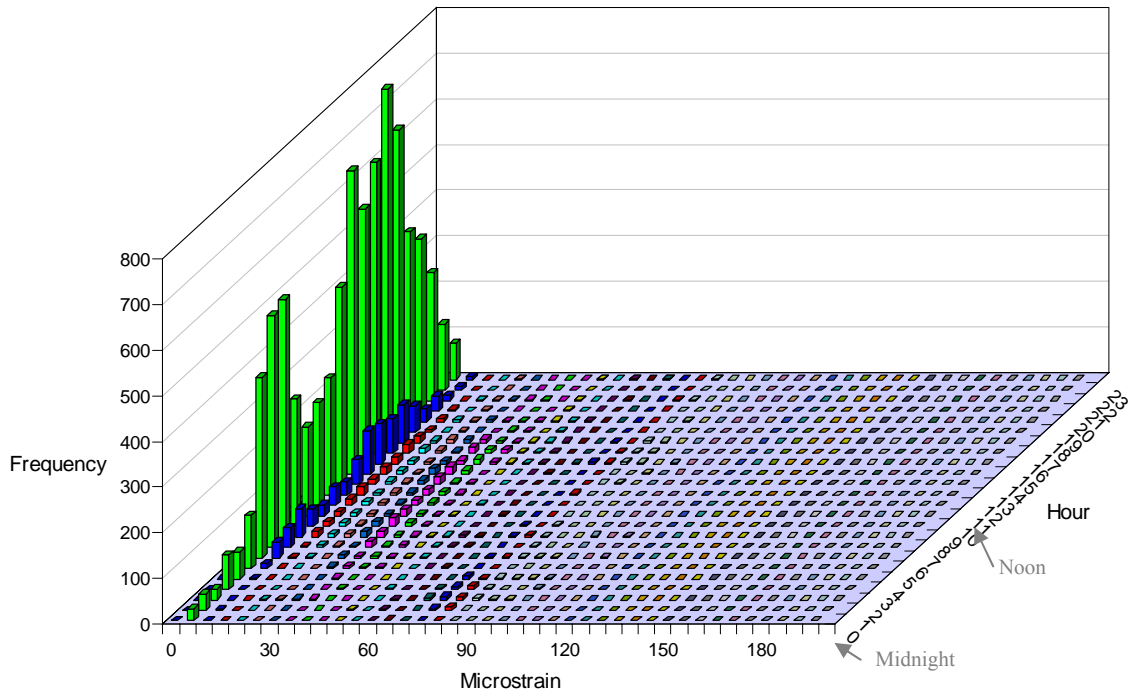


(o) 30-day event history for Sensor 8

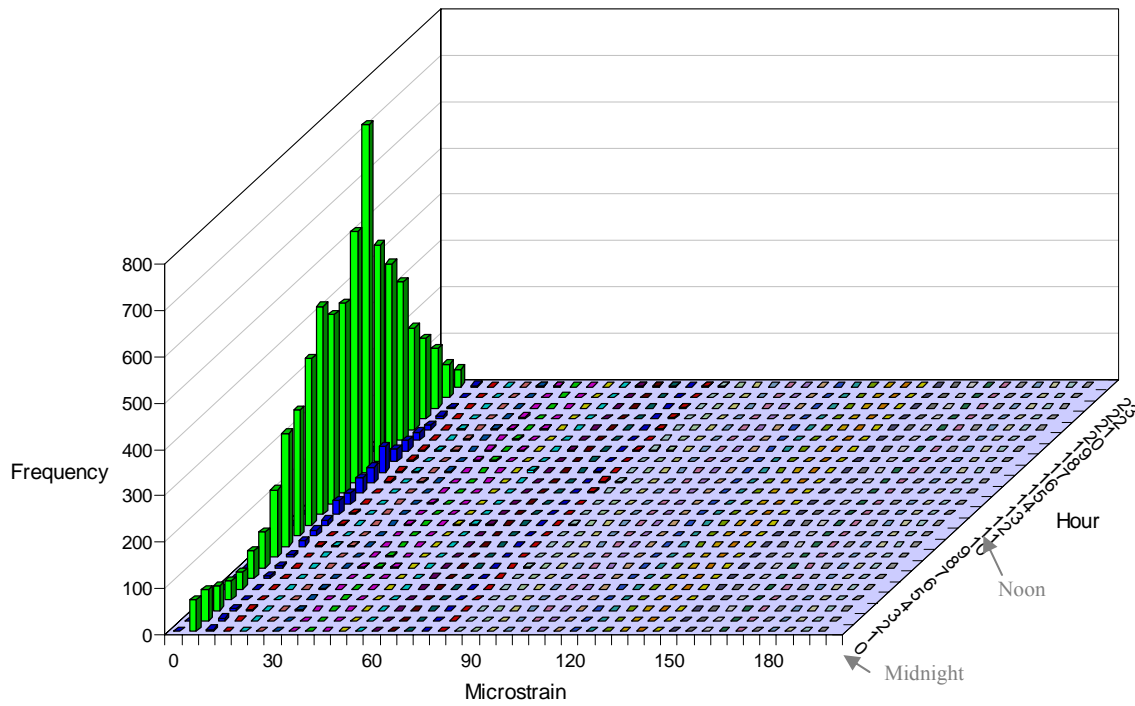


(p) 30-day daily statistical trends for Sensor 8

Figure 3-12. (continued)

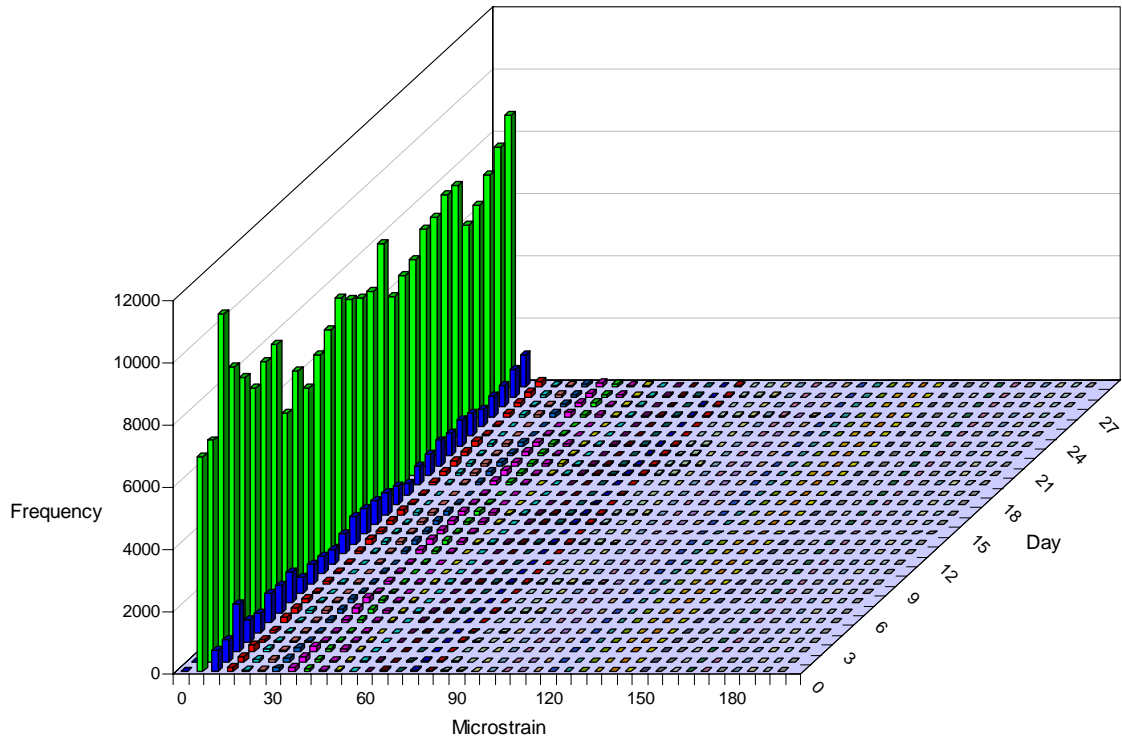


(a) Hourly event histogram for Nov. 16th (Thursday), 2006

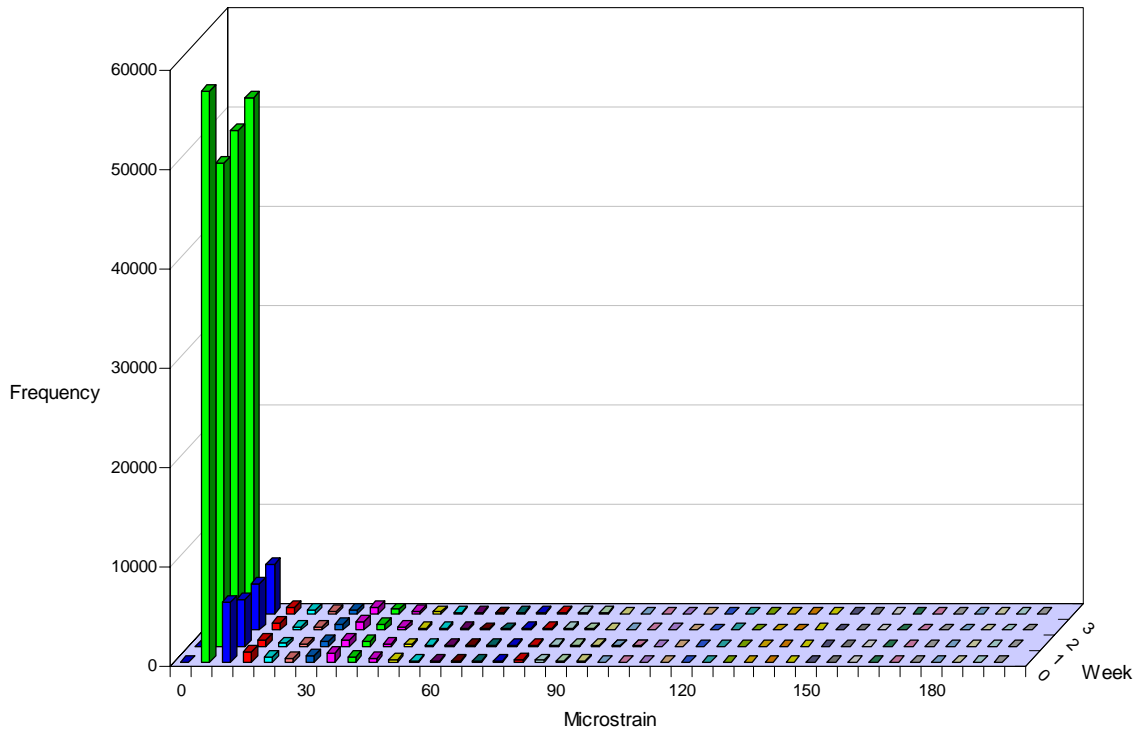


(b) Hourly event histogram for Dec. 3rd (Sunday), 2006

Figure 3-13. Hourly event histograms of typical weekday and weekend day for Sensor 4 (bin width: 5 microstrain)



(a) Daily event histograms (Nov. 14th 3 pm through Dec. 14th 3 pm, 2006)



(b) Weekly event histogram (Nov. 14th 3 pm through Dec. 12th 3 pm, 2006)

Figure 3-14. Daily and weekly event histograms for Sensor 4 (bin width: 5 microstrain)

4. SUMMARY AND CONCLUSIONS

4.1. Summary

The primary objective of this project was to develop a continuous SHM system that can provide bridge owners with tools to better manage their bridge assets. The SHM system can be principally grouped into two main categories: an office component and a field component. The office component is basically a structural analysis software program that can be used to generate thresholds which will be used for identifying isolated events. The field component includes hardware and the 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 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 damage and deterioration. This report has documented three distinct work tasks performed to accomplish the objective. The first two tasks involved developing the SHM system while the last task was to demonstrate the system. A brief summary of the individual tasks follows.

The first task involved developing the live load structural analysis software, *BEC Analysis*. In Section 2.1, the general effort given in the development and the components and features of *BEC Analysis* were described. The algorithm was based upon classical beam theory and the direct stiffness method of matrix structural analysis. The analytical methods used in *BEC Analysis* are the same to the routine stiffness method except that the member stiffness matrix and the fixed-end moments are specific functions of the variation in the member cross section. *BEC Analysis* 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. These three modules can be further categorized into six 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. All of the data input and editing is completed with the aid of windows screens, each of which contains controls and indicators. The analysis module (4) performs a live load analysis of a model bridge and is activated when the program is executed. The last module, postprocessor (5) was designed for reviewing analysis results. Overall, *BEC Analysis* is capable of analyzing a bridge beam or girder with various boundary conditions and member geometries. It also allows the structural response to be analyzed under various loading conditions. One unique feature of *BEC Analysis* is that it allows users to easily determine maximum results (maximum moment and strain) at any location along the length of a model bridge subjected to moving loads. 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 on a model bridge, and (3) generating envelopes of maximum moments and strains.

The second task involved developing the field data collection and analysis software that integrates with select data acquisition hardware. The general background information and the methodology used during the development and the components and features of the field

monitoring software were described in Section 2.2. In addition, the descriptions on the hardware system within the SHM system were presented in Section 2.3. The field monitoring software was developed to specifically function with IOtech instrumentation hardware. 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 potential 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 that is 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.

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. The bridge is located in central Iowa in Story County, IA carrying US30 over the Skunk River near Ames, IA. 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 selected sensors, data acquisition hardware and computer equipment were installed at the bridge site during the fall of 2006.

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, the main program designed for data acquisition and processing, *4 MainDAQ815.VI*, was initialized at approximately 3 pm on November 14th, 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 were reviewed and several observations and interpretations were made for overall bridge performance during the thirty days of monitored period.

4.2. Conclusions

The following conclusions can be made regarding the 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 R & D 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 sixteen 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 thirty 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 US30 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 US30 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, the objective of the project was successfully accomplished and 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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APPENDIX A

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A1. Descriptions on controls and indicators used in *BEC Analysis*

- #1. **Bridge Information Window** – Contains the *BEC Analysis* title screen and General Information frame.
- #2. **Number of Spans Control** – Total number of bridge spans. The number entered here will dictate the number of ‘Span Description’ windows (#5) into which information for each span will be entered.
- #3. **Boundary Condition Frame** – Describes how a model bridge is supported. Three options are available for exterior supports: fixed, pin/roller and rotational spring. Note that interior supports are assigned to be rollers with 100% continuity over the support.
- #4. **Next Command** – Moves to the next window.
- #5. **Span Description Window** – Allows geometry, member type, and material and section properties for each member to be defined. Up to ten ‘Span Description’ windows will appear one by one depending upon the input given in #2.
- #6. **Span Length Control** – Span length.
- #7. **Member Selection Frame** – Two options are available:
 - Prismatic member: member size and section properties are constant along the span. If selected, controls #8 and #16 will be disabled.
 - Non-prismatic member: member size and section properties are not constant along the span. Up to 5 different sections can be defined within a span by using controls #8 through #16.
- #8. **Member Type Frame** – Allows modeling a non-prismatic span with a stepwise approximation by dividing into up to 5 prismatic segments. Although using more segments will result more accurate analysis, processing time will be longer.
- #9. **Member Cross Section Frame** – Allows users to define or select sections for a member from a database included in the program. Four options are available:
 - Define: see #22
 - Standard Steel: see #32
 - Iowa P/C: see #35
 - AASHTO P/C: see #37
- #10. **Beam Material Frame** – Type of member material in each span. Upon selection (either steel or concrete), corresponding elastic modulus will be assigned in #11.
- #11. **E (ksi) Control** – Modulus of elasticity of either 29000 ksi or 3640 ksi will be automatically assigned depending on the material type selected in #10. A different value can be assigned by simply typing in a desired value.
- #12. **Calculator Command** – Used to calculate section properties in each member segment. When pressed, a ‘Section Properties’ window will appear.
- #13. **Ii Control** – Moment of inertia for each segment either to be entered or computed by the ‘Calculator’ (#12).
- #14. **Si(+) Control** – Section modulus for each segment at a sensor location specified in #25. If a sensor location is not specified, the default will be the bottom of the beam. This section

- modulus is either manually entered by users or computed by the ‘Calculator’ (#12).
- #15. **Si(-) Control** – Section modulus for each segment at a sensor location specified in #25. If a sensor location is not specified, the default will be the top of the beam. This section modulus is either manually entered by users or computed by the ‘Calculator’ (#12).
- #16. **Section Length Frame** – Length of each segment. This will only be enabled if ‘Non-Prismatic’ option was selected in #7.
- #17. **Section Display** – General graphic representation of how a member will be segmented in each span. A different graphic will be displayed according to options selected in #7 and #8.
- #18. **Back Command** – Moves to the previous window.
- #19. **Section Properties Window** – Called when ‘Calculator’ (#12) is pressed. A different window will be activated depending upon the options selected in #9. A ‘Section Properties’ window calculates geometric section properties for general section types (user-defined) and also provides section properties for standard steel, Iowa P/C and AASHTO P/C sections. When completed, moment of inertia and sections modulus values will be automatically copied into #13, #14 and #15 in the ‘Span Description’ window.
- #20. **Composite Option Frame** – Allows generating section properties for a beam that is either composite or non-composite with the deck.
- #21. **Deck Frame** – Allows users to specify modulus of elasticity and dimension of the deck.
- #22. **Define Frame** – Allows users to select among nine general section types: I-beam, I-beam (tapered flanges), I-beam with angles, T-beam, T-beam (tapered flanges), channel, channel (tapered flanges), P/C shape and rectangular shape.
- #23. **Cross Section Display** – Graphic representation of a cross section selected in #22. It displays general information about the dimensions of the deck and beam components.
- #24. **Beam Dimension Frame** – Allows users to configure beam components.
- #25. **Sensor Location Frame** – Vertical locations at which section modulus will be computed for a composite or non-composite member.
- #26. **Click to Compute Properties Command** – When pressed, section properties will be computed and the results listed below will be displayed in #29, #30 and #31 for non-composite, composite (N) and composite (3N) sections, respectively. Note that section properties for a long-term composite (3N) section are computed and displayed in #31 for comparison purposes only and are not used in the analysis.
- #27. **OK Command** – When pressed,
- The results displayed in #29 or #30 will be copied into #13, #14 and #15 depending upon the option selected in #20.
 - The program will close the Section Properties window and move back to a previous window (‘Span Description’ window, #19).
- #28. **Cancel Command** – When pressed, the program will cancel the actions performed within the ‘Section Properties’ window and move back to a previous window (‘Span Description’ window, #19).
- #29. **Non-Composite Frame** – Displays results for a non-composite section.
- #30. **Composite (N) Frame** – Displays results for a short-term composite section.
- #31. **Composite (3N) Frame** – Displays results for a long-term composite section.
- #32. **Standard Steel Option** – Provides 6 options of standard steel section types: W shape, S shape, HP shape, channel, and MC channel.
- #33. **Standard Steel List Box** – Lists standard steel section types depending upon the option selected in #32 and allows the user to select a member with a mouse click. If selected, its label will be highlighted in blue and corresponding section properties for the selected

- member will be displayed in #34.
- #34. **Beam Information Frame** – Displays section properties of a selected member.
 - #35. **Iowa P/C Option** – Provides 2 options of Iowa P/C types: LX and Bulb-Tees.
 - #36. **Iowa P/C List Box** – Lists Iowa P/C section types depending on the option selected in #35 and allows the user to select a member with a mouse click. If selected, its label will be highlighted in blue and corresponding section properties for the selected member will be displayed in #34.
 - #37. **AASHTO P/C Option** - Provides four options of AASHTO P/C section types: Slab Beams, Box Beams, I-Beams and Bulb-Tees.
 - #38. **AASHTO P/C List Box** – Lists AASHTO P/C section types depending on the option selected in #37 and allows the user to select a member with a mouse click. If selected, its label will be highlighted in blue and corresponding section properties for the selected member will be displayed in #34.
 - #39. **Load Window** – Allows users to configure live loads that will be applied as moving live loads to a model bridge. The Load window provides options for Iowa legal loads, HS-20 trucks, truck train, as well as user-defined live loads. In addition, distribution factor (DF) and impact allowance (IM) are input here.
 - #40. **Iowa Legal Loads/HS-20 Option** – Option for applying either pre-defined Iowa legal loads, the H-20 or the HS-20 trucks to a model bridge. Selecting this option will enable the Iowa Legal Loads/HS-20 frame (#46) that lists available types of trucks.
 - #41. **Truck Train Option** – Option for applying truck train to a model bridge. Selecting this option will enable the ‘W’ control (#43) and the ‘Apply W on’ frame (#45).
 - #42. **Define-Number of Axles Option** – Option for applying a series of point loads (up to eight) that represent axles of a truck.
 - #43. **W Control** – Magnitude of uniformly distributed load in kips/ft that will be applied on selected span(s) of a model bridge if the Truck Train option (#41) is selected.
 - #44. **Number of Axles Control** – Number of axles that will be applied as moving live loads to the model bridge. Up to eight axles can be specified.
 - #45. **Apply W on Frame** – Lists span(s) in which a uniformly distributed load will be applied. The uniformly distributed load whose magnitude is specified in #43 will be applied only to checked spans(s). This frame will be enabled when the ‘Truck Train’ option (#41) is selected.
 - #46. **Iowa Legal Loads/HS-20 Frame** – Lists types of Iowa legal trucks and HS-20 trucks. This frame will be enabled only when the ‘Iowa Legal Loads/HS-20’ option (#40) is selected. Upon selection, information on axle configuration and weight of each axle (wheel line load) for a selected load will be automatically assigned to #49 and #50.
 - #47. **Distribution Factor Control** – Distribution factor that will be used in the analysis.
 - #48. **Impact Allowance Control** – Dynamic load allowance (or impact allowance) that will be used in the analysis.
 - #49. **Axle Load Control** – Weight of each axle (wheel line load) to be entered manually or assigned by #46. Number of controls that will appear on the screen will be dictated by #44.
 - #50. **Distance Between Axles Control** – Distance between each axle to be entered manually or assigned by #46. Number of controls that will appear on the screen will be dictated by #44.
 - #51. **Axle Configuration Display** – General graphic representation of defined axle configuration on a model bridge. Axle configuration display will change according to the options (#44 or #46) selected.
 - #52. **Analysis Window** – Allows users to run analysis and view absolute maximum results

either at a designated location or in each span.

- #53. **In Each Span Option** – Option for viewing locations and magnitudes of maximum moments and strains in each span.
- #54. **At a Designated Location Option** – Option for viewing magnitudes of maximum moments and strains at a specified location.
- #55. **X Control** – Location at which the maximum moments and strains will be generated upon completion of analysis. This control will be enabled when option #54 is selected.
- #56. **Truck Moving At Every Control** – Incremental distance that each axle will move along the model bridge starting from the left exterior support. The smaller the increment, the longer the processing time will be (i.e., inversely proportional to the increment used) but the greater the accuracy.
- #57. **Run Analysis Command** – When pressed, the analysis will be initialized and the progress can be seen on the progress bar #63. When the analysis is successfully completed, a prompt dialog box with ‘Analysis Complete’ will appear.
- #58. **M(+) Indicator** – Maximum positive moment in ft-kips at the location specified in #55 or #67.
- #59. **M(-) Indicator** – Maximum negative moment in ft-kips at the location specified in #55 or #67.
- #60. **Strain(+) Indicator** – Maximum positive strain in microstrain at the location specified in #55 or #67.
- #61. **Strain (-) Indicator** – Maximum negative strain in microstrain at the location specified in #55 or #67.
- #62. **Truck Position Indicator** – Location of P1 (first axle) on a model bridge when corresponding results are generated. The location of P1 is measured from the left exterior support. It is illustrated as ‘b1’ in Axle Configuration display (#51) and in #68.
- #63. **Progress Bar Indicator** – Shows the analysis progress.
- #64. **Exit Command** – When pressed, the program will be terminated.
- #65. **Number of Analysis Points/Beam Control** – Number of analysis points for each span that will be used during the analysis. While more analysis points will generate more accurate analysis, the processing time will be longer.
- #66. **Maximum Results Indicators** – Displays the maximum positive and negative moments and strains in each span.
- #67. **Location of Maximum Results Indicators** – Displays locations at which maximum results are generated in each span.
- #68. **First Axle Position Indicators** – Displays locations of P1 (first axle) that generated the maximum results in each span.
- #69. **Print Maximums Window** – Allows user to print the absolute maximums generated during the analysis.
- #70. **Margin Frame** – Allows users to set margins (top and left) on a standard paper size.
- #71. **Print Command** – When pressed, the absolute maximum will be printed out.
- #72. **View Data Command** – Allows users to retrieve and view the maximums generated according to the option selected (either #53 or #54) and input specified in #65.
- #73. **Output Image Display Box** – Displays an output image to be printed.
- #74. **View Data Window** – Allows users to view and/or save data of the maximum envelopes or ‘moment and strain vs. truck position’ analysis results generated during the analysis depending on the option selected (either #53 or #54).
- #75. **Output Data Display Box** – Displays output data to be saved in a text file.

- #76. **Save to a File Command** – When pressed, data displayed in #75 will be saved to a text file.
- #77. **Plot Data Command** – Allows users to plot envelopes or ‘moment and strain vs. truck position’ diagrams generated during the analysis.
- #78. **Plot Window** – Allows users to view and print a plot of envelopes or ‘moment and strain vs. truck position’ diagrams generated during the analysis.
- #79. **Print Plot Command** – When pressed, a plot of envelopes or ‘moment and strain vs. truck position’ diagrams will be printed.
- #80. **Plot Display Box** – Displays a plot of envelopes or ‘moment and strain vs. truck position’ diagrams generated during the analysis.

A2. Principle Procedures in Running *BEC Analysis*

- i. Press 'Click to START' (Fig. A-1) on the *BEC Analysis* title screen to initialize the *BEC Analysis*. This will open the 'General Information' frame.
- ii. Enter the number of spans by entering the desired number in #2 (Fig. A-2)
- iii. Set the boundary conditions for each span in #3.
- iv. Click 'Next' (#4) to move to the 'Span Description' window (#5) as shown in Fig. A-3.
- v. Enter the span length in #6.
- vi. Select the member type (#7). If the 'Prismatic Member' option is selected in #7, skip step vii. If the 'Non-Prismatic Member' option is selected, continue on the next step.
- vii. Select the number of discrete segments (sections) to be used to describe the member (#8).
- viii. Select a type of member cross sections that will be used in 'Calculator' (#12). If section properties of a member are already known and will be entered manually, this step can be skipped.
- ix. Select a member material. Upon selection, corresponding values will be specified to #11.
- x. Check to see if the desired modulus of elasticity is displayed in #11. A different value can manually be entered if needed.
- xi. This step can be skipped if section properties for each segment are manually entered. Otherwise, click 'Calculator' (#12). A Section Properties window will appear based upon the option (#9) selected in step viii.

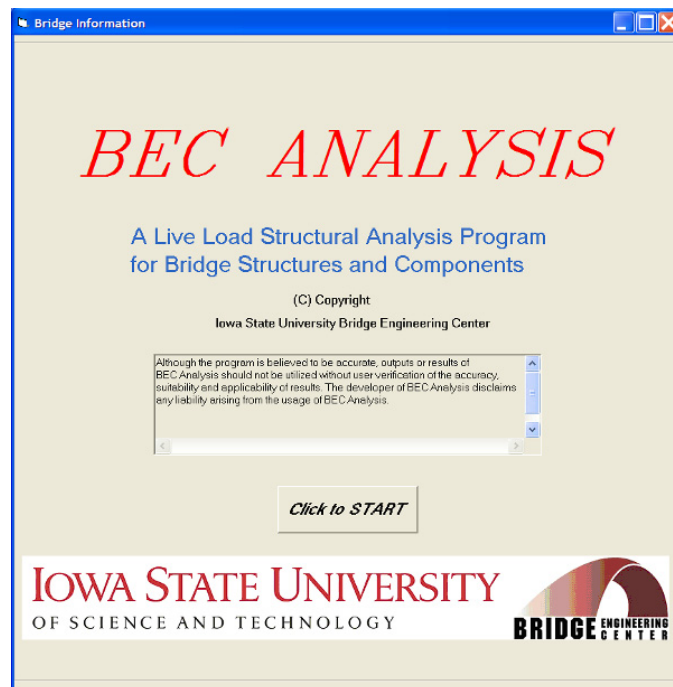


Figure A-1. *BEC Analysis* title screen on Bridge Information window

Bridge Information

General Information

Number of Spans: (also 11 spans)

Boundary Condition

Left Exterior Support: ☒ Fixed ☐ Pinned/Roller

Interior Support: ☒ Fixed ☐ Pinned/Roller

Right Exterior Support: ☒ Fixed ☐ Pinned/Roller

Rotational Spring Constant (K kips/inches):

Figure A-2. General information options on Bridge Information window

Span Description

Span 1 Description

Span Length (ft):

Member Selection

☐ Prismatic Member

☒ Non-Prismatic Member

Member Type

☐ 2 sections (1 to 2)

☐ 3 sections (1 to 3)

☐ 4 sections (1 to 4)

☒ 5 sections (1 to 5)

Member Cross Section

☒ Define

☐ Standard Steel

☐ Iowa P/C

☐ AASHTO P/C

Beam Material

☒ Steel

☐ Concrete

Moment of Inertia (ft⁴) and Section Modulus (ft³) for each section

E (ksi):

Calculator	I1	S1(+)	S1(-)	A1L
Calculator	I2: 1939	S2(+): 1904	S2(-): 1904	A2L: 15
Calculator	I3: 1972	S3(+): 1730	S3(-): 1730	A3L: 10
Calculator	I4: 1577	S4(+): 1406	S4(-): 1406	A4L: 10
Calculator	I5: 2493	S5(+): 2396	S5(-): 2396	

Section Length (ft)

A1L:

A2L:

A3L:

A4L:

Diagram:

Section 1 | Section 2 | Section 3 | Section 4 | Section 5

A1L → A2L → A3L → A4L →

Span Length

Figure A-3. Span Description window

- Scenario 1 (Fig. A-4a) – when ‘Define’ option is selected in #9:
 - a. Select an option for the deck to be either composite or non-composite with the girder (#20).
 - b. Enter the modulus of elasticity and the thickness and effective width of the deck (#21).
 - c. Select a desired cross section shape among the nine general section types (#22). A corresponding figure that contains general information will be displayed in #23.
 - d. Enter the dimensions (#24) for each component.
 - e. Specify where sensors are to be placed (i.e., top and bottom sensor locations) (#25) for which the corresponding section modulus will be determined.
 - f. Press the ‘Click to Compute Properties’ (#26) to compute the section properties.
 - g. Click either ‘OK’ (#27) to copy the computed section properties into #13, #14 and #15 in the ‘Span Description’ window (#19) or ‘Cancel’ (#28) to cancel the actions performed here.
- Scenario 2 (Figs. A-4b, 4c and 4d) – when the ‘Standard Steel’, ‘Iowa P/C’ or ‘AASHTO P/C’ option is selected in #9:
 - a. Same as “step a” in Scenario 1.
 - b. Same as “step b” in Scenario 1.
 - c. Select the desired cross section shape among the available options in #32, #35 or #37. Corresponding contents for the selected section type will be listed in #33, #36 or #38.
 - d. Select a member from the list box (#33, #36 or #38) with a mouse click (when selected, it will be highlighted in blue). The corresponding cross section information will be displayed in #34.
 - e. Same as “step e” in Scenario 1.
 - f. Same as “step f” in Scenario 1.
 - g. Same as “step g” in Scenario 1.

The screenshot shows the 'Section Properties' dialog box in AutoCAD. The 'Non-Composite' checkbox is checked. The 'Deck' section shows a width of 36.00. The 'H-beam' section shows a height of 36.00. The 'Sensor Location' section shows a distance of 3.00. The 'Click to Compute Properties' button is highlighted. The 'Non-Composite' checkbox is checked. The 'Deck' section shows a width of 36.00. The 'H-beam' section shows a height of 36.00. The 'Sensor Location' section shows a distance of 3.00. The 'Click to Compute Properties' button is highlighted.

(a) Section properties for ‘Define’ option

Section Properties

☐ Non-Composite **(20)** ☒ Composite **(21)**

E(deck): 3640 **(21)**

H: 10 W: 48

E: elastic modulus (ksi)
H: height (inches)
W: width (inches)

Standard Steel

☒ W Shape **(32)**

W44x326 **(33)**
W44x327
W44x328
W44x329
W44x330
W44x331
W44x332
W44x333
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W44x757
W44x758
W4

(b) Section properties for 'Standard Steel' option

Figure A-4. Section Properties window

Section Properties (19)

Non-Composite (20)

Composite (21)

Beam Information (34)

Area: 352.5 in²

Depth: 30 in

Y bottom: 17.08 in

Ix: 6200 in⁴

Section Location (25)

On distance from top of beam: 3 in

Gb distance from bottom of beam: 3 in

Click to Compute Properties (26)

Non-Composite (29)

Yt: 2.471818988 ft

Ix: 2.871851971 ft⁴

Sx: 32.3258847229 ft³

Zx: 3.094365242 ft³

Yb: 2.5518932993 ft

Iy: 18.6333421085 ft⁴

Sy: 4.3368228242 ft³

Zy: 2.5518932993 ft³

Composite (30)

Yt: 2.471818988 ft

Ix: 2.871851971 ft⁴

Sx: 32.3258847229 ft³

Zx: 3.094365242 ft³

Yb: 2.5518932993 ft

Iy: 18.6333421085 ft⁴

Sy: 4.3368228242 ft³

Zy: 2.5518932993 ft³

Composite (31)

Yt: 2.083718548 ft

Ix: 7.0826762294 ft⁴

Sx: 7.843614837 ft³

Zx: 3.0196377130 ft³

Yb: 7.0826762294 ft

Iy: 7.0826762294 ft⁴

Sy: 7.843614837 ft³

Zy: 3.0196377130 ft³

(c) Section properties for 'Iowa P/C' option

Section Properties

Deck

Elastic modulus (ksi)

H: height (inches)

W: width (inches)

AASHTO IRC

Slab Beams

Box Beams

I-Beams

Deck-Tees

Beam Information

Area: 708 in²

Depth: 54 in

Y bottom: 24.73 in

Ix: 268730 in⁴

Sensor Location (inches)

G1: 3 G2: 3

G1: distance from top of beams

G2: distance from bottom of beams

Click to Compute Properties

Non-Composite

Yt: 2.664873333 ft

It: 2.52371847222 ft⁴

Slope: 5.743387665 ft³

Skew: 5.943545495 ft³

Composite

Yt: 3.448538796 ft

It: 29.6685122670 ft⁴

Slope: 54.7647127983 ft³

Skew: 18.252514149 ft³

Composite

Yt: 2.642262603 ft

It: 26.1722305475 ft⁴

Slope: 11.8126768996 ft³

Skew: 8.799583094 ft³

(d) Section properties for ‘AASHTO P/C’ option

Figure A-4. (continued)

- xii. For non-prismatic members, check to see if the desired section properties (moment of inertia in #13, section modulus in #14 and #15) are specified for each segment. Different values can be manually entered if needed.
- xiii. For non-prismatic members, enter the length of each section (#16) in a manner that corresponds to the figure displayed in #17. This step can be skipped if prismatic option is selected in step vi (or in #7).

- xiv. Click 'Next' (#4) to move on. If the bridge is composed of more than one span, repeat the steps v through xiv until all information for each span is specified.
- xv. Select a load option (#40, #41 or #42) that will be applied to the bridge (Fig. A-5).

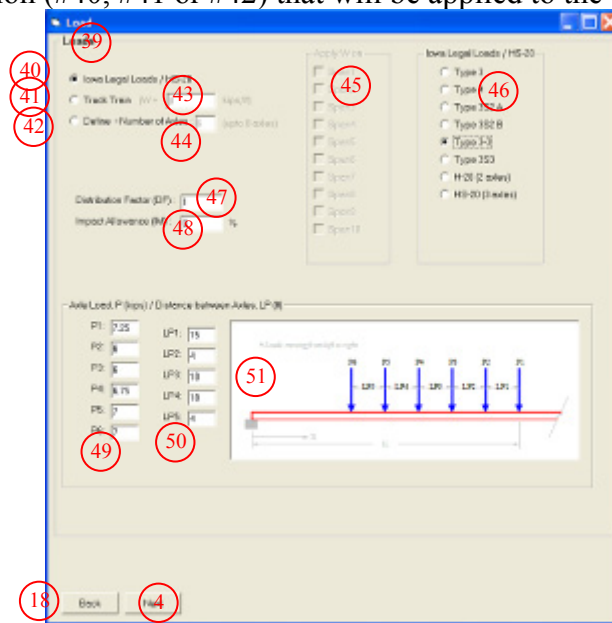
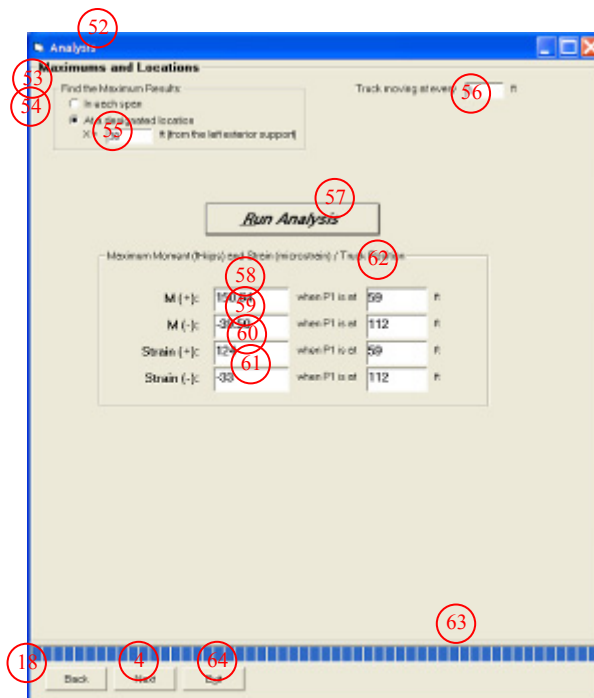
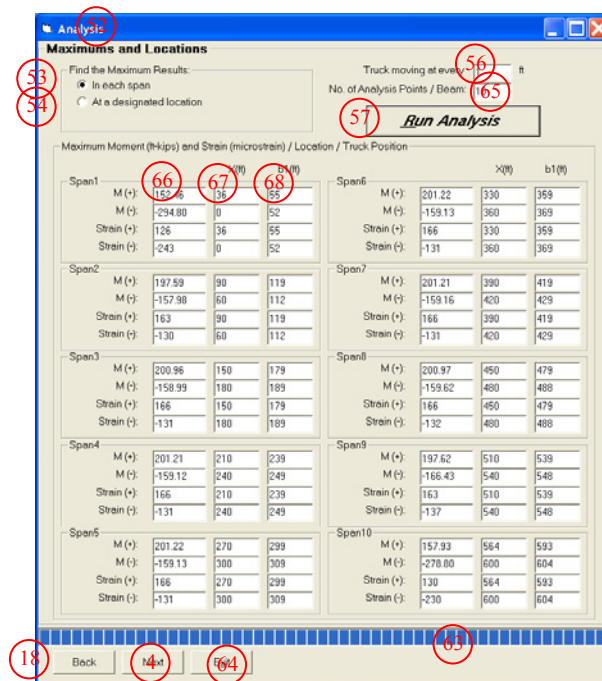


Figure A-5. Load window

- For the 'Iowa Legal Loads/HS-20' option (#40), choose a live load in the 'Iowa Legal Loads/HS-20' frame (#46). The axle weight and configuration displayed in #49, #50 and #51 will change depending on a type selected here.
 - For the 'Truck Train' option (#41), enter the magnitude of uniformly distributed load in #43 and select a span or spans (#45) in which the uniformly distributed load will be applied.
 - For the 'Define' option (#42), enter the number of axles (#44), the axle weights (#49) and the distance between each axle (#50). The indicator #51 will be disabled if a live load has a single axle.
- xvi. Enter distribution factor (#47) and impact allowance (#48) that will be used in the analysis.
- xvii. Click 'Next' (#4) to open the 'Analysis' window (#52 shown in Fig. A-6).



(a) 'At a designated location' option



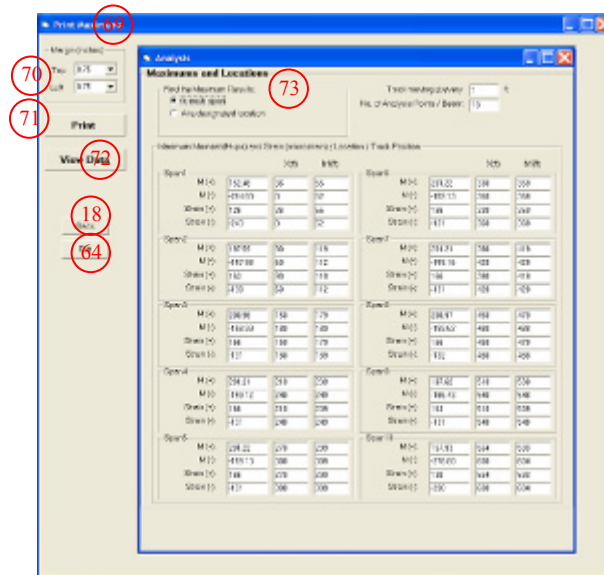
(b) 'In each span' option

Figure A-6. Analysis window

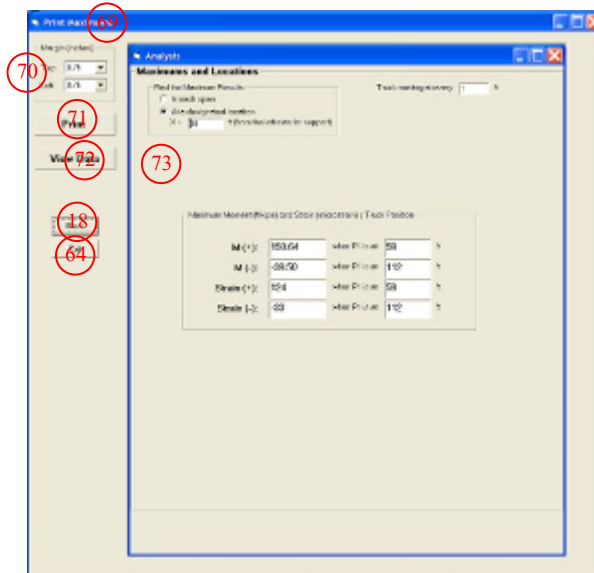
xviii. Choose an appropriate option for viewing results (#53 or #54).

- For the 'In Each Span' option, enter the increment (#56) at which a live load will move along the model bridge. Enter the number of analysis points that will be used in the analysis.

- For the ‘At a Designated Location’ option, enter the increment (#56).
- xix. Click the ‘Run Analysis’ command button (#57) to run the program. While running, its status will be displayed in the progress bar indicator (#63). If the analysis is successfully completed, a prompt dialog box with a text message, ‘Analysis Complete’, will appear. Click ‘OK’ in the dialog box to view the maximum moments and strains and the corresponding locations which will be displayed in the correct format according to the option selected in step xviii.
- xx. Click ‘Next’ (#4) to move to the ‘Print Maximums’ window (#69 shown in Fig. A-7).
- xxi. Set the top and left margins (#70) to be used.
- xxii. Click ‘Print’ (#71) to print the image displayed in the display box (#73).
- xxiii. Click ‘View Data’ (#72) to move to the ‘View Data’ window (#74 shown in Fig. A-8). Check the data display box (#75) for ‘moment and strain vs. truck position’ analysis results or envelopes.
- xxiv. Click ‘Save to a File’ (#76) to save the displayed data to a text file for later retrieval. When prompted, use the browse button to specify the directory and type the name under which the data file will be saved.
- xxv. Click ‘Plot Data’ (#77) to move to the ‘Plot’ window (#78 shown in Fig. A-9).
- xxvi. Set the top and left margins (#70) to be used.
- xxvii. Click ‘Print Plot’ (#79) to print the image displayed in the display box (#80).
- xxviii. Click ‘Back’ (#4) to move back to the previous window or ‘Exit’ (#64) to terminate the program.

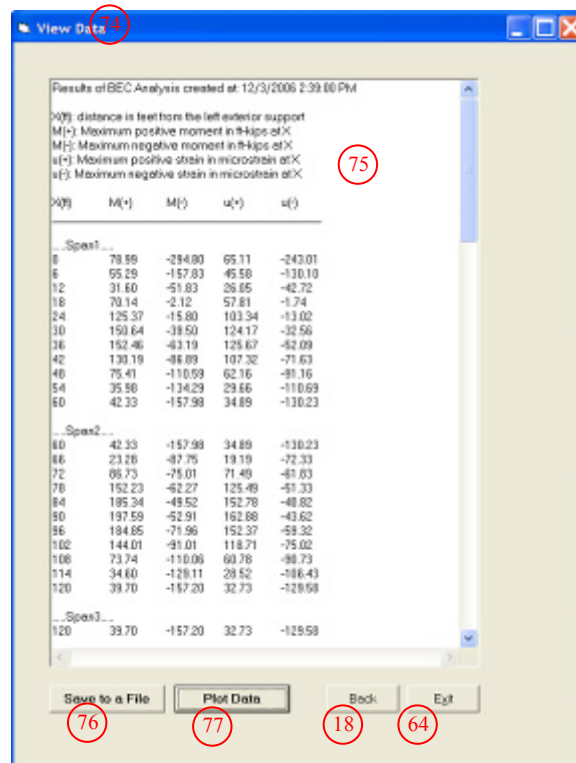


(a) When 'In each span' option is selected

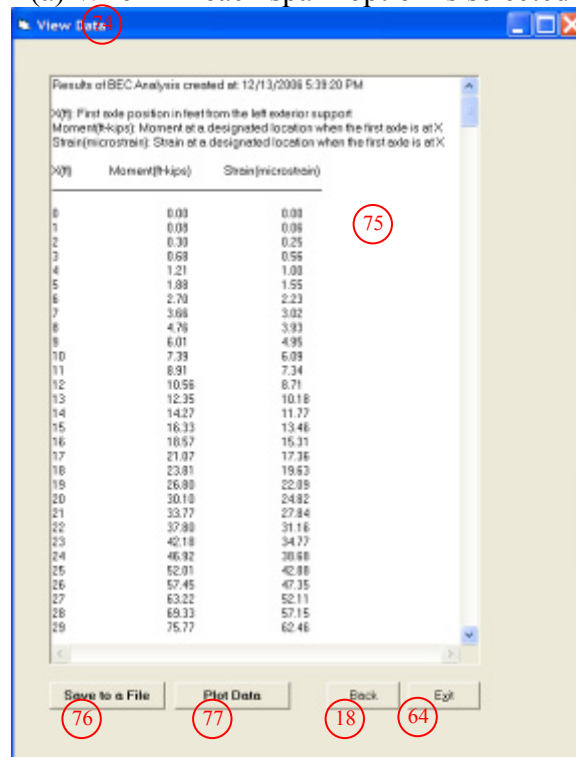


(b) When 'At a designated location' option is selected

Figure A-7. Print Maximums Window

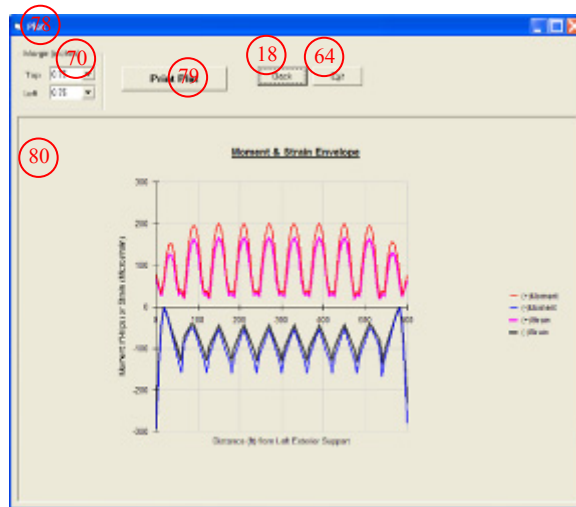


(a) When 'In each span' option is selected

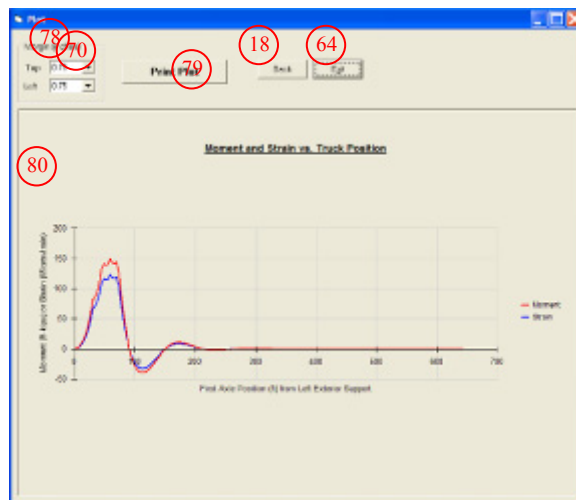


(b) When 'At a designated location' option is selected

Figure A-8. View Data Window



(a) When 'In each span' option is selected



(b) When 'At a designated location' option is selected

Figure A-9. Plot Window

APPENDIX B

Principle Procedures in Running the Field Monitoring Software

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B1. 1 Preliminary DAQ.VI (shown in Fig. B-1)

- i. Enter a device name (#1). The device name used here must match what was used during the hardware system setup.
- ii. Enter a sample rate (#2) at which the data acquisition is to be performed (number of samples per second).
- iii. Select the channels of a connected StrainBook/616 and, if applicable, a WBK16 expansion module to be activated (#3 & #4). More than one channel can be selected by 'Ctrl + Mouse click'.
- iv. Configure each channel (#5) based upon the specific type of strain sensor being used.
- v. Apply and select a calibration file, which was created during the sensor calibration process, by setting the LED (#6) to true (bright green) and by assigning a calibration file path (#7).
- vi. Designate a folder directory (#8) in which the data will be saved. The recommended directory name is 'C:\SHM Folder\Preliminary Data Folder'. Users can use the 'Browse' button to display a tree of all directories available on the host PC.
- vii. Enter the time duration in control #9 for which each data file will be saved.
- viii. Start data collection by clicking on the 'START' control (#10).
- ix. Check the acquisition status in indicator #11. When the 'START' control is pressed, it searches the data acquisition instrument specified in control #1. One of the following situations will occur:
 - o The check mark on the status check box stays green and the indicators #12, #13, #14 and #15 will display real time data, elapsed time, beginning time at which data acquisition is initialized and current time of data acquisition, respectively. This indicates that the data acquisition instrument was found and all input parameters are correctly defined.
 - o The check mark on the status check box turns red and a message appears on the message box along with an error code. This indicates that either the data acquisition instrument was not found, or one or more input parameters are missing. In order to resolve this error, users must check either (or both) the hardware and IOtech software installation setup or (and) the input parameters before running the program again.
- x. Once the data acquisition is completed, click the 'STOP' button (#16). This will terminate the program.

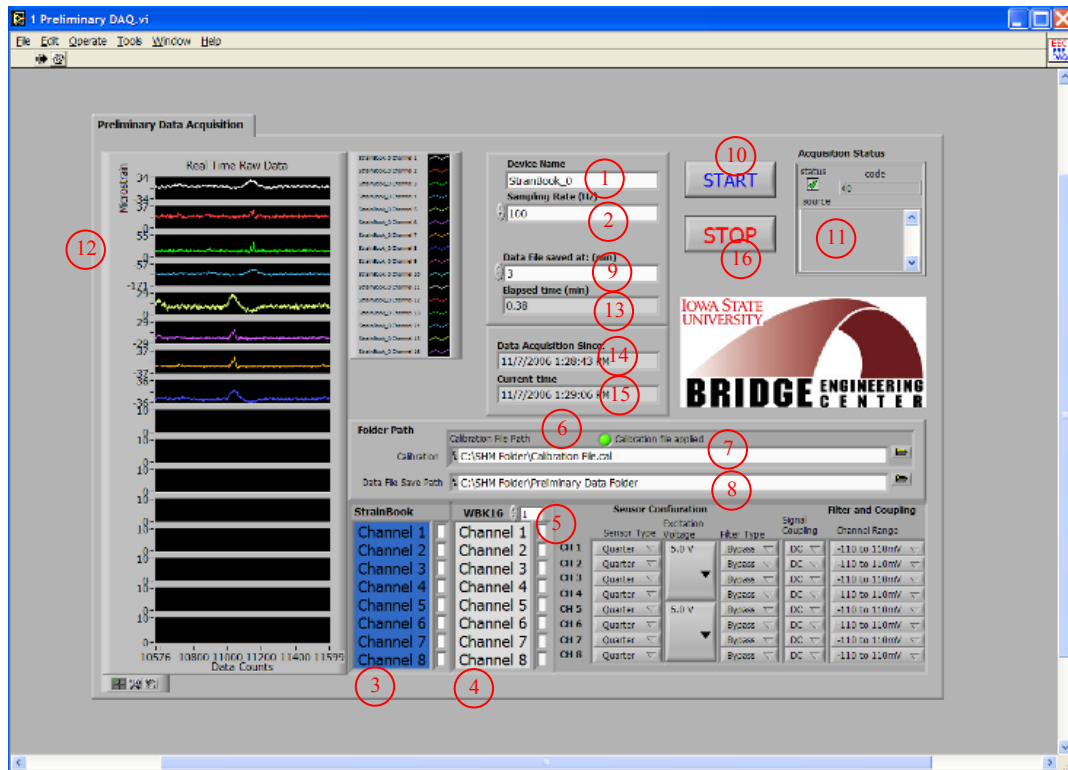


Figure B-1. Screen shot of 1 Preliminary DAQ.VI front panel

B2. 2 FFT-PSD Analysis.VI (shown in Fig. B-2)

- x. Select a data file from those that were saved in the 'Preliminary Data Folder' by using the browsing tool in control #1.
- xii. Under the 'FFT-PSD Analysis' tab control (#2), enter a sample rate in Hertz (#3). Note that the sample rate used here must be the same as the one used while acquiring the data.
- xiii. Choose a time-domain window (#4) to be used in the FFT analysis and PSD development. The recommended option is 'Hanning' and is set as the default.
- xiv. Run the program by clicking the run button (#5). As soon as the run button is pressed, the status indicator (#6) will turn red indicating that the FFT-PSD analysis is running. Indicator #7 will display the data file read progress. When the data file reading is completed, the total number of sensors used during the preliminary data acquisition will be displayed.
- xv. Upon completion of the FFT-PSD analysis, the status indicator (#6) will turn bright green indicating that PSD plots for each sensor are ready to be viewed.
- xvi. Select a sensor with a mouse click within control #8. Then, the indicator #9 will display the selected sensor and a PSD plot for the selected sensor will be displayed in indicator #10.
- xvii. Identify the dominant frequencies from ambient traffic plus noise or noise alone (depending upon a sample file selected) and determine the desired cutoff frequency for the filter (note: more detail on how to determine the desired cutoff frequency will be discussed in Chapter 3).

- xviii. Move to the 'Strain History' tab control (#11) and enter the cutoff frequency determined in step vii.
- xix. Click the "Plot Strain History" control (#14) to see the effect of filtering for the selected sensor. Indicator #17 will display the strain history.
- xx. Go back to the 'FFT-PSD Analysis' tab control (#2) and repeat "step vi" through "step ix" to see the effect of filtering for all sensors.
- xxi. Repeat the "step i" through "step x" until an appropriate cutoff frequency is determined. This may require examining several data files, one at a time. By comparing the dominant frequencies of traffic plus noise induced and noise alone induced, an appropriate cutoff frequency can be determined.

Once the FFT-PSD analysis is completed and the desired cutoff frequency has been determined, the second task can be performed to establish the appropriate filter parameters and to see if events (peaks) are properly identified. The following steps are required to perform this task:

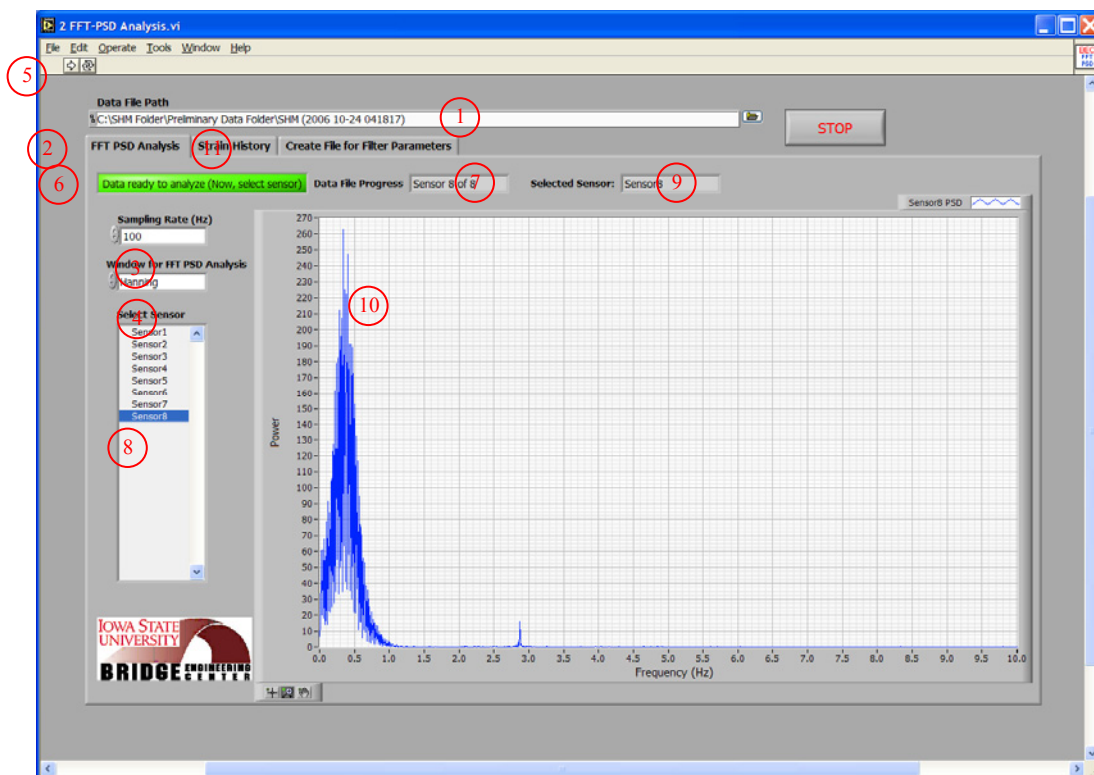
- xxii. Perform the "step i" through "step v", but this time, select a data file that contains traffic plus noise induced strain.
- xxiii. Select a sensor with a mouse click within control #8 and move to the 'Strain History' tab (#11).
- xxiv. Enter three filter parameters (#12) that will be applied to the selected strain data: cutoff frequency (Hz), ripple (dB), and filter order.
 - d. The cutoff frequency is determined by investigating dominant frequencies of traffic plus and noise induced and noise alone induced.
 - e. A ripple of 0.0435 dB, which is equivalent to 0.5% passband allowable error, is set as a default as it is often a good choice for digital filters [4]. The 0.5% passband allowable error was converted to 0.0435 ripple in dB as follows:

$$0.0435 \text{ dB} = \left| 20 \log \left(\frac{100\% - 0.5\%}{100\%} \right) \right|$$
 - f. The order of a Chebyshev filter is equal to the number of poles in the transfer function of the filter. In general, a filter is considered to work better with more poles. However, this may not be always true. Therefore, several attempts (trial and error) may be necessary to determine the appropriate filter order. The default is set as 2nd order and the order must be an even number.
- xxv. Enter event detection thresholds (#13) that will be applied to the selected strain data. The event detection thresholds should be determined such that peaks are not identified from the free vibration response of the bridge (more detail will be discussed in Chapter 3). Once set, only those events that exceed the event detection thresholds will be recognized by the program and displayed in indicator #17.
- xxvi. Press the 'Plot Strain History' control (#14) to plot strain history and view the effects of filtering the selected strain data. When pressed, indicator #15 will display the selected sensor and the status indicator (#16) will turn red indicating that plotting strain history is in progress.
- xxvii. Upon completion, the status indicator will turn bright green and a strain history plot for the selected sensor is displayed on the graph indicator #17.
- xxviii. At this point, the user needs to decide if the filter parameters used are adequate to minimize noise while identifying proper peaks or events. If the user desires to alter the filter parameter settings, new parameters need to be defined in #12 and the 'Plot Strain History'

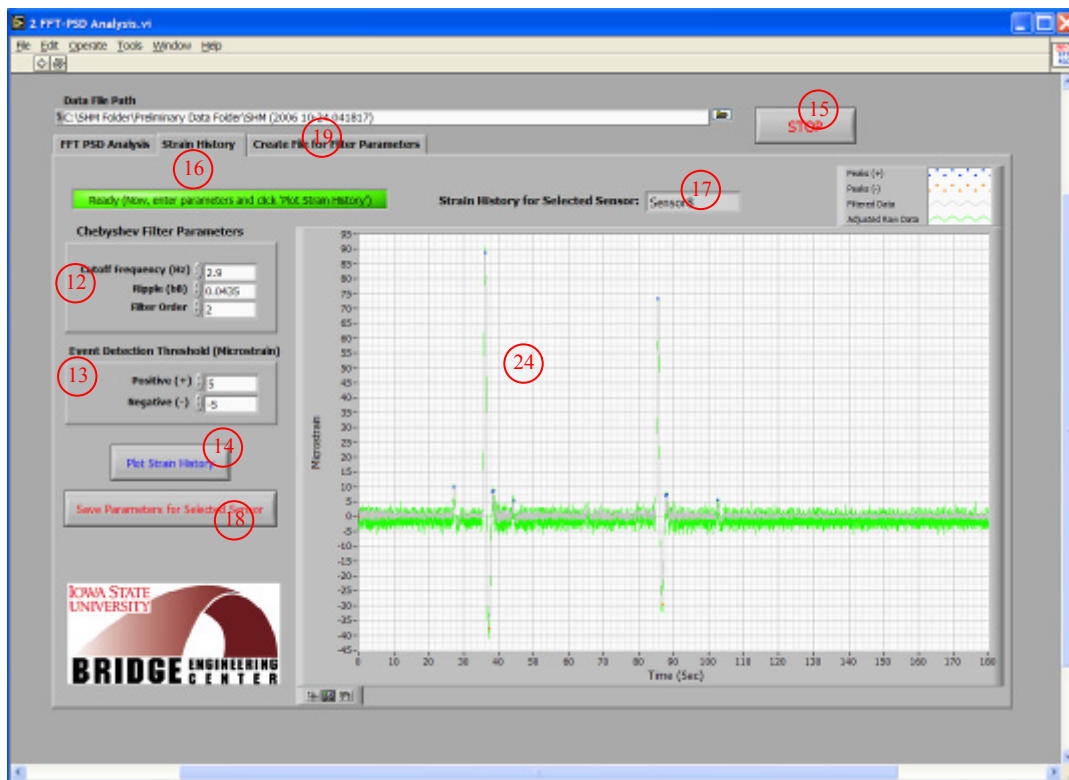
control (#14) needs to be pressed again. Otherwise, save the filter parameter settings for the selected sensor by pressing the ‘Save Parameters for Selected Sensor’ control (#18).

The next task requires the user to check if the parameter settings are stored for each selected sensor, one-by-one, and create a text file that will contain the filter parameters and event detection thresholds for all sensors. The following tasks must be performed:

- xxix. Move to the ‘Create File for Filter Parameter’ tab control (#19) and check if the filter parameters and event detection thresholds for the selected sensor are stored in the table indicator (#20) where each row represents the settings for the sensor specified in the first column named ‘Sensor’.
- xxx. Repeat “steps xiii” through “step xix” until the filter parameters and the event detection thresholds have been established for all sensors.
- xxxi. Set the path (#21) to which the filter parameters and event detection thresholds will be saved. The default file name and directory is ‘C:\SHM Folder\Filter Parameters.txt’.
- xxxii. Click the ‘Create File for Filter Parameters’ control (#22) to create a text file that contains the filter parameters and event detection thresholds for all sensors.
- xxxiii. Click the ‘STOP’ control (#23) to stop the program.

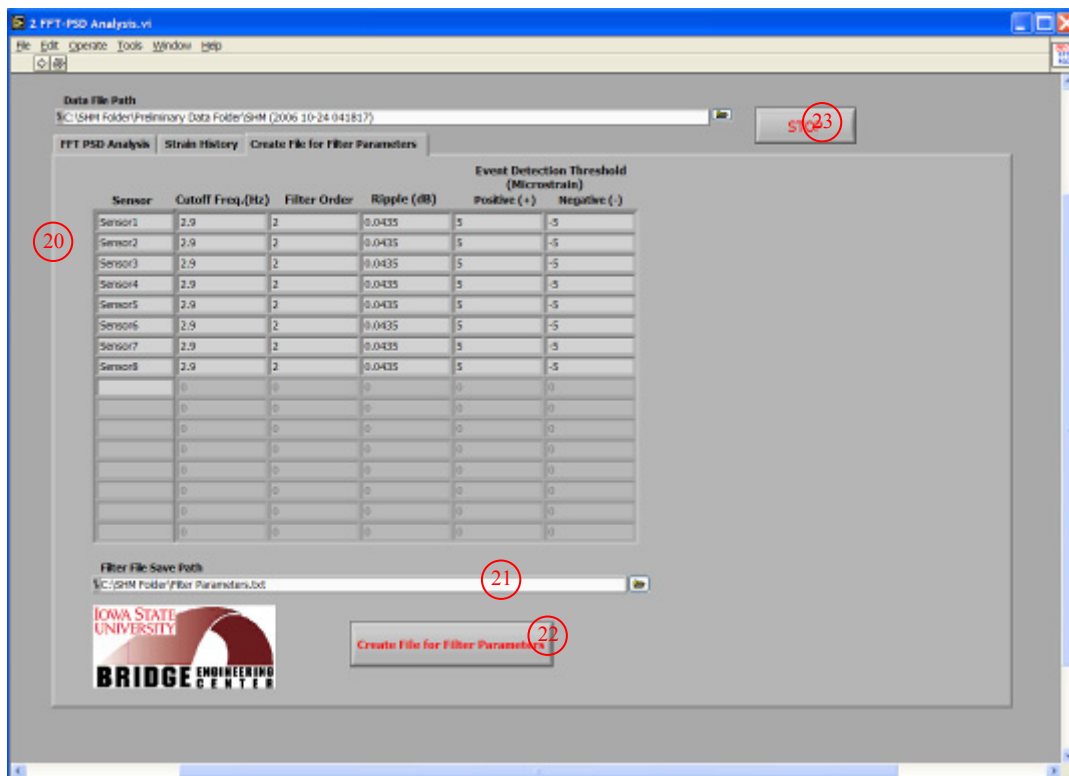


(a) FFT-PSD plot display for the selected sensor



(b) Strain record display for the selected sensor

Figure B-2. Screen shots of 2 FFT-PSD Analysis.VI front panel



(c) Filter parameters display

Figure B-2. (continued)

B3. 3 Input.VI (shown in Fig. B-3)

- xxxiv. Select the channels of a connected StrainBook/616 and, if applicable, a WBK16 expansion module to be activated (#1 & #2). More than one channel can be selected by 'Ctrl + Mouse click'.
- xxxv. Configure each channel (#3) based on the type of strain sensor and its setting used.
- xxxvi. Enter the device name in control #4. The device name used here must match what was used during the hardware system setup.
- xxxvii. Enter the sample rate (#5) at which the data acquisition is to be performed (number of samples per second).
- xxxviii. Enter the impact event threshold in control #6. The impact event threshold is a ratio of the absolute difference between the magnitude of an event and that of a peak detection threshold with respect to the time difference between a start index and a peak index in a strain record (a single event or traffic response). The impact event threshold is used to determine the type of the alarm event (overload or impact, both of which exceed the overload event threshold specified in control #8).
- xxxix. Enter the plus and minus event detection thresholds (#7) that will be applied to the collected strain data.
- xl. In the 'Overload Event Threshold' control (#8), enter the overload event threshold for each sensor that was determined from the structural analysis software (*BEC Analysis*). Also, with a mouse click, select LED options for each sensor to which the overload event threshold will be applied. If set to true (bright green), any overload event (an event that exceeds the specified overload event threshold) for the selected sensor will be recorded and temporarily stored within 4 *MainDAQ.VI*.
- xli. Select the type of data files, with a mouse click (#9), to be sent via email (LED options). Given that the internet connection is available, if users desire to receive monthly data files only, for example, the LED option for 'Monthly Data' must be selected (bright green) with a mouse click and other options must remain unselected (dark green). Six options are available as follows:
 - g. Hourly Data: allows users to receive hourly-generated reduced data files, each of which contains event history in the preceding hour
 - h. Daily Data: allows users to receive daily-generated data files, each of which contains event history in a day
 - i. Weekly Data: allows users to receive weekly-generated data files, each of which contains event history in the preceding week
 - j. Monthly Data: allows users to receive monthly-generated data files, each of which contains event history in the preceding month
 - k. Yearly Data: allows users to receive yearly-generated data files, each of which contains event history in the preceding year
 - l. Alarm Message: allows users to receive a text message of an alarm event upon occurrence
- xlii. Enter email information that the reduced data files are sent from/to (#10) and set the LED option, 'Check if email inputs are entered', to true (bright green) by a mouse click to activate this option within 4 *MainDAQ.VI*. Three pieces of information are required:
 - d. Return address: email address of the file and/or message sender

- e. Mail server: the name or IP address of an SMTP server
 - f. Recipients: email addresses of the file and/or message recipients. Each address can be a separate array element
- xliv. Apply the calibration file (#11), which was created during the sensor calibration process, by setting the LED option to true (bright green) and by assigning the calibration file path.
- xliv. Designate the folder directory in which raw strain data file are to be written and saved (#12). The default is 'C:\SHM Folder\1 Raw Data'. This is one of the sub-directories created during the initial setup.
- xlvi. Designate the folder directory to which the raw data are moved for data reduction and evaluation (#13). The default is 'C:\SHM Folder\2 Data Process'. This is one of the sub-directories created during the initial setup.
- xlvi. Designate the folder directory in which all the reduced data files (Hourly, Daily, Weekly, Monthly and Yearly Data files) will be saved. The default is 'C:\SHM Folder\3 Data File Folder'. This is one of the sub-directories created during the initial setup.
- xlvi. Set the path (#15) for the filter parameters file that contains the peak detection thresholds and filter parameters.
- xlvi. Once the input settings are entered, users can execute the program by pressing the 'Create and Save Input File' control (#16). This will result in the creation of a 'DAQ Inputs' file in the main directory (C:\SHM Folder\DAQ Inputs). If a previously created input file exists in the main directory, the program will prompt the users to choose if the existing input file is to be replaced by a new input file.
- xlvi. Once the input file is created, stop the program by pressing the STOP control (#17).

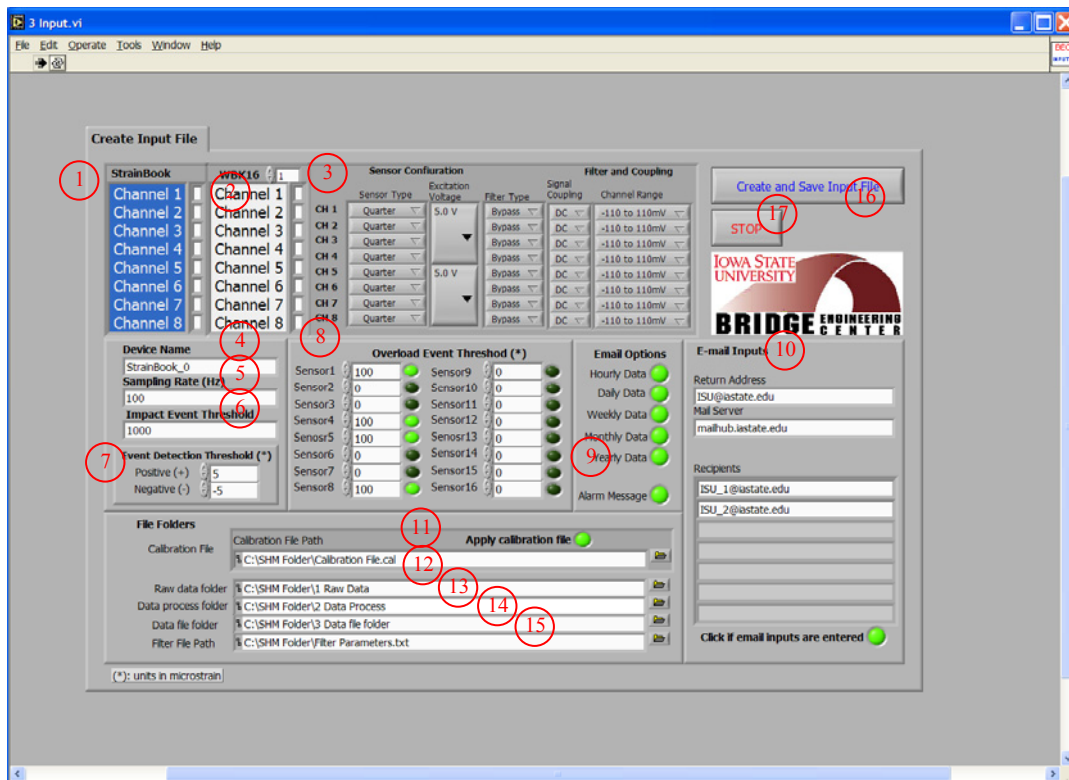
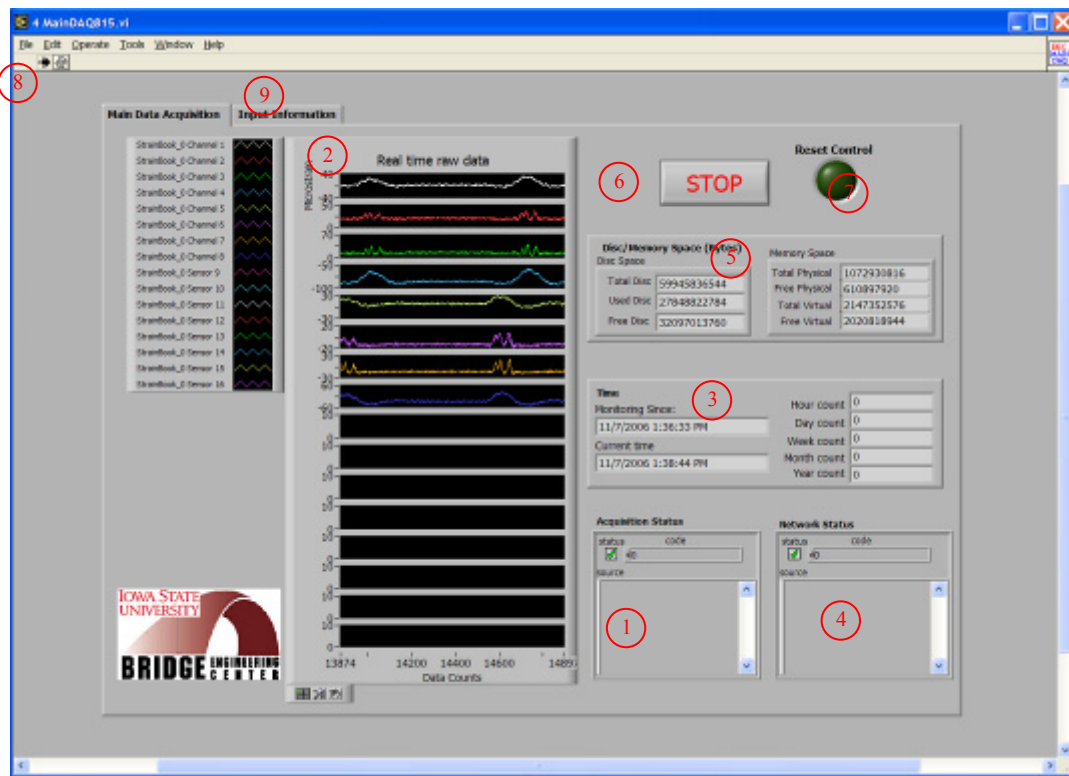


Figure B-3. Screen shot of 3 Input.VI front panel

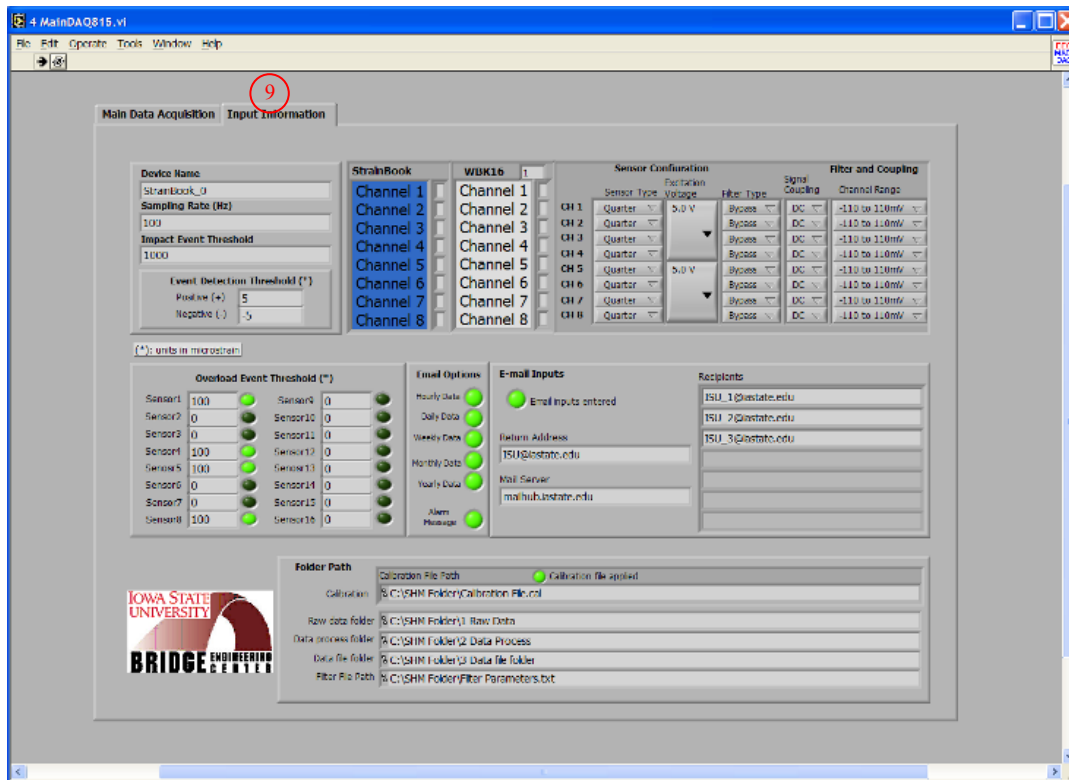
B4. 4 MainDAQ815.VI (shown in Fig. B-4)

- l.* As soon as 4 MainDAQ815.EXE is installed as a service program, it will be automatically initialized.
- li.* Given that the data acquisition was successfully initialized, as depicted in Fig. D-4, the Acquisition Status control (#1) will display a green check mark in the 'status' check box and no error message will appear in the 'source' dialog box. While the program is running, the following information will be displayed on the control panel of the program shown in Fig. D-4:
 - Real time raw data for each sensor in the graph indicator (#2).
 - The 'Time' indicator (#3) displays information on
 - time at which data acquisition was initialized
 - current time
 - count of elapsed hour, day, week, month and year, which also indicates the number of data files created and available for report generation
 - Network status (#4). One of the following situations will occur:
 - The check mark on the status check box is green and no error message appears on the message box. This indicates that the network connection is established and alarm messages and data files created by the program can be sent via email to the recipients specified during input information setting. It should be noted that even when the status indicates no error, information may not be sent to the recipients due to a security settings. Typically used virus scan software is designed to block access from any unknown programs. Therefore, users need to make appropriate changes on the security settings so that the execution program 4 MainDAQ815.VI is unblocked. Since the security settings may vary depending on Windows types (2000, XP, NT, etc.) and virus scan software used, users may need to consult with a system analyst to resolve this.
 - The check mark on the status check box turns red and a message appears on the message box along with an error code. This indicates that the network connection is either unavailable (or not established). It should be noted that this error will not cause the program to stall or stop. All other functions except the email will still be functioning. The program is programmed such that when an error related to network connection occurs, the program will skip that step and carry on other tasks. Also note that since all data files created by the program will be saved in '3 Data File Folder' in the main directory, users can always retrieve the data files manually.
 - Available disc and memory space on the field PC. The total, used and free (available) disc and physical memory space of the field PC will be displayed in Bytes in the 'Disc/Memory Space' indicator (#5).
- lii.* If the user desires to change input settings or restart (reset) the program, stop the program by pressing the 'STOP' control (#6), set the 'Reset' control (LED option in #7) to true (bright green) and re-run the VI by pressing the 'Run' control (#9). These actions will result in autonomously creating an 'Old Data File Folder' to which previously archived data files will be moved. Meanwhile, newly collected data will be saved in '3 Data File Folder'.



(a) Illustration of Main Data Acquisition tab

Figure B-4. Screen shots of 4 MainDAQ815.VI front panel



(b) Illustration of Input Information tab

Figure B-4. Screen shots of 4 MainDAQ815.VI front panel (continued)

B5. 5 View Strain History.VI (shown in Fig. B5)

- liii. Select the data file (#1) that contains collected strain records.
- liv. Set the path (#2) to the filter parameters file that contains the event detection thresholds and filter parameters that were previously established.
- lv. Enter the sample rate (#3) that was used during data acquisition.
- lvi. Press the 'Plot Strain History' control button (#4) to execute the program. When this button is pressed, the status indicator (#5) will turn red indicating that the operation is in progress. Upon completion, the indicator will turn bright green and the strain history for each sensor will be displayed on the graph indicator (#6). The strain history for each sensor can be accessed by selecting the tabs designated for each sensor.
- lvii. Stop the program by pressing STOP button control (#7).

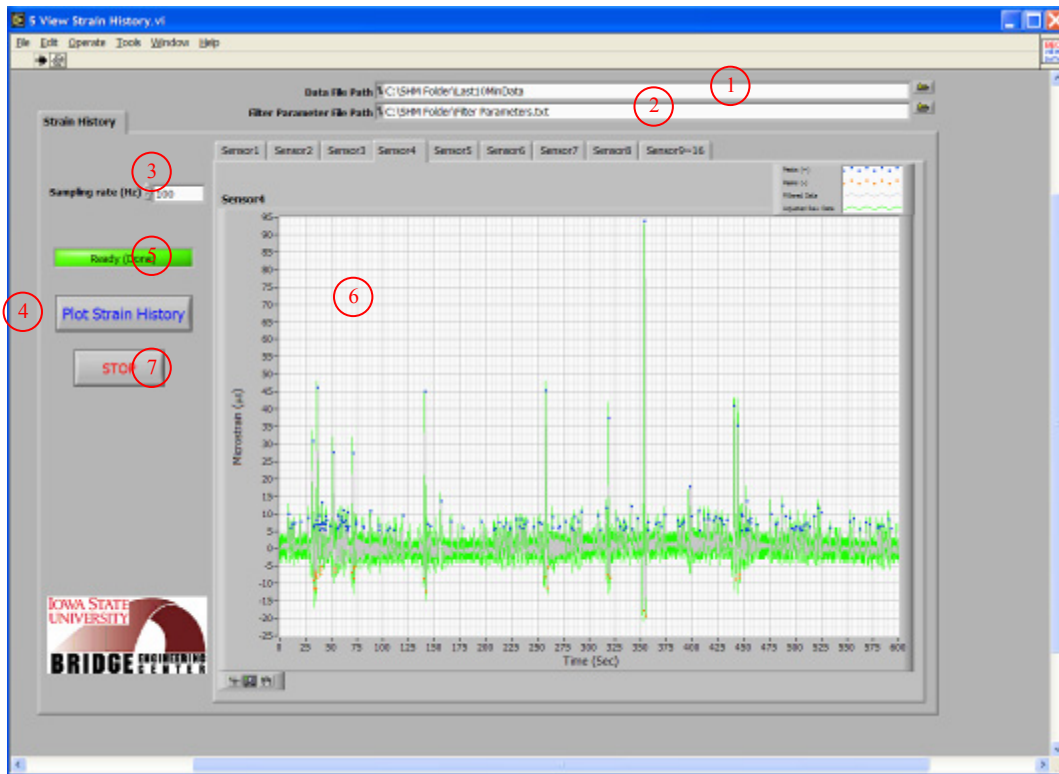


Figure B-5. Screen shot of 5 View Strain History.VI front panel

B6. 6 View Hourly File.VI (shown in Fig. B-6)

- lviii. Select the directory (#1) in which the hourly data files are archived. The default is set as 'C:\SHM Folder\3 Data File Folder'. If users want to access an hour file received via email, the path to the folder that contains the received file must be selected.
- lix. Select a monitoring period (#2). The number in the text box indicates the hour since monitoring began (starting with zero). For example, if the user wants to open an hour file that contains the event history obtained during the first hour of monitoring, '0' must be entered; if the user wants to access a hour file occurring 56 days, 3 hours later, the user would enter '1346'.
- lx. To view the data file in an Excel Worksheet, set the LED option (#3) to true (bright green).
- lxi. Configure the histogram setting (#4). This option allows users to change five variables: number of bins, and maximum and minimum bins for both positive and negative events.
- lxii. Press the 'Click to View Hour File' control (#5) to execute the program. The event history and histogram, monitoring period and alarm messages will be displayed in the indicators #6, #7 and #8, respectively. The event history and histogram for each sensor can be accessed by selecting the tabs designated for each sensor.
- lxiii. Stop the program by pressing STOP control (#9).

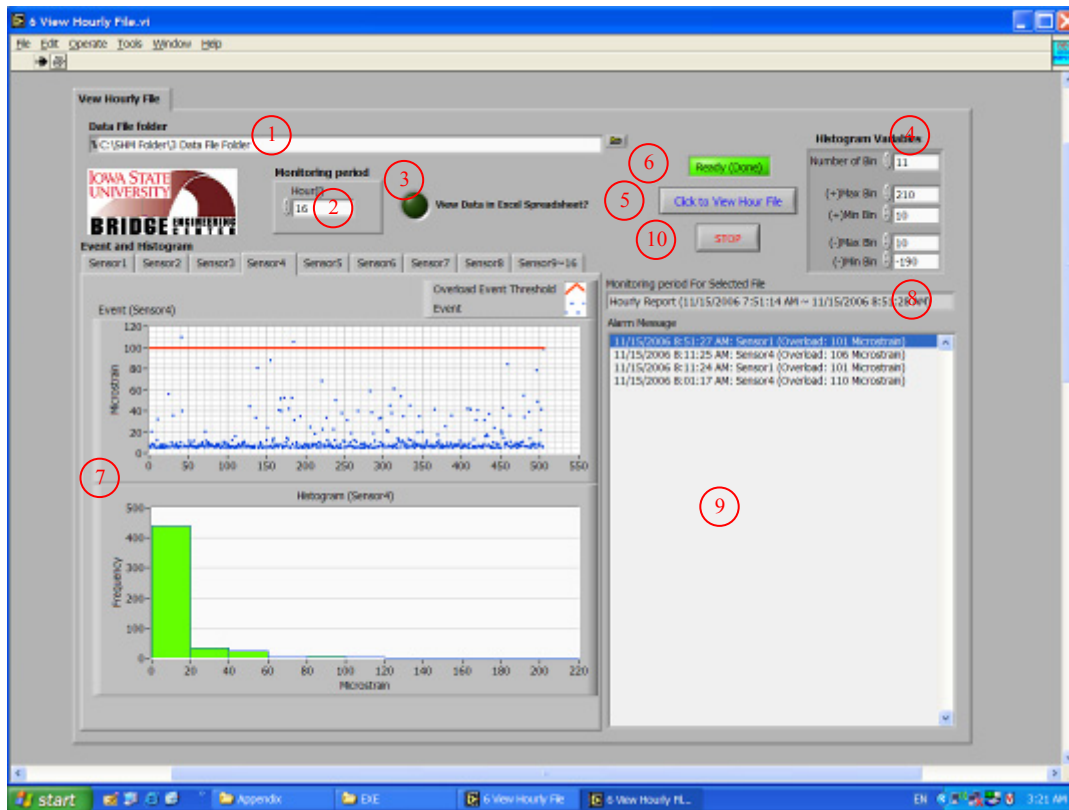


Figure B-6. Screen shot of 6 View Hourly File.VI front panel

B7. 7 Create Report (From Single File).VI (shown in Fig. B-7) and 8 Create Report (From Multiple Files).VI (shown in Fig. B-8)

- lxiv. Select the directory (#1) in which the data files are archived. The default is set to 'C:\SHM Folder\3 Data File Folder.'
- lxv. In the 'Monitoring Period' control (#2), select data file(s) to be plotted and processed for the report generation. See Note-1 below for detailed description.
- lxvi. To view the data file in an Excel Worksheet, set the LED option (#3) to true (bright green).
- lxvii. Select the print options (#4). This allows the user to print the report either (or both) in a paper copy or (and) in PDF format given that corresponding option(s) are selected (bright green).
- Select the report content options (#5). This allows the user to choose the contents that will be included in the report. Four options are available:
 - e. Strain histogram (numeric table): numerical count of events in each bin where the bin size is specified by users
 - f. Strain histogram (graph): graphical representation of numerical count of events
 - g. Statistic Trends (numeric table): numerical values of absolute maximum events, average events (hourly or daily depending upon the data file selected), and average trend line over the selected monitoring period.
 - h. Statistic Trends (graph): graphical representation of events over the selected monitoring period.

- lxviii. Configure the event histogram variables (#6). This option allows users to change five variables: number of bins, and maximum and minimum bins for positive and negative events.
- lxix. Press the 'Click to Create Report' control (#7) to execute the program. As soon as the program is executed, the status indicator (#8) will turn red indicating that the program is in progress. Upon completion, the indicator will turn bright green and the following results will be generated:
- results displayed on the front panel for immediate view
 - i. the time at which the data acquisition was initialized: #9
 - ii. the monitoring period: #10
 - iii. alarm messages recorded during the monitoring period: #11
 - iv. event history, event histogram, and statistical trends for each sensor: #12, #13 and #14, respectively (see Note-2 below for more detail).
 - an Excel Worksheet, hard copy, and/or PDF file depending upon the selected options (#3, #4, and #5).
- lxx. Stop the program by pressing STOP control (#15).

Note-1: As can be seen in Figs. D-7 and D-8, controls and indicators used on the front panels of each program are exactly the same with the exception of the Monitoring Period control (#2). *7 Create Report (From Single File).VI* is designed to access one data file at a time while *8 Create Report (From Multiple Files).VI* allows users to open multiple files at once. Consequently, different options in control #2 for selecting data files were utilized. For *7 Create Report (From Single File).VI*, users can choose a different type (daily, weekly, monthly and yearly) of data file from provided tabs where the title of each tab represents a time duration for which one file is created and archived. For example, if users want to access information obtained during the second week of monitoring, the user must select 'Weekly' tab and enter a number '1' in the text box. Note that the index 'i' starts from zero. For *8 Create Report (From Multiple Files).VI*, users can access multiple data files given that those data files are already created and archived. Three options are available as listed below:

- d. Up to date: allows the user to access all daily data files created
- e. Day (i) ~ Day (j): allows to access multiple daily data files created during user specified time period
- f. Last (i) days: allows to access multiple daily files created during the last user specified days

Note that, except in the 'Up to date' tab, users can select a monitoring period by using the up and down arrows to increase or decrease number in the text box, or simply type in the desired number.

Note-2: Plots of event history, event histogram and statistical trends are displayed on separate tabs to avoid clutter on the front panel. The appearance (scale and format) of any graphic display can be modified (pan or zoom) while the program is running or stopped through the use of the graphic palette located on the left bottom corner of each graph (or by right clicking the graph and selecting Visible Items>>Graph Palette from the shortcut menu). The formats used to display event history and event histogram are the same for both programs. Also, the format used to display statistical trends in *8 Create Report (From Multiple Files).VI* is the same. However, the format of the graph indicator for displaying statistical trends in *7 Create Report (From Single File).VI* can change depending on the

tabs (or pages) selected in the Monitoring Period control (#2). If users select a monitoring period in the 'Daily' tab, the graph indicator will display statistical trends of each hour for 24 hours. On the other hand, if users choose a monitoring period in 'Weekly', 'Monthly' or 'Yearly' tabs, it will display statistical trends of each day for user specified monitoring periods. For example, if a monitoring period is selected in the 'Weekly' tab on the front panel of *7 Create Report (From Single File).VI*, it will access one of the weekly created data files, each of which contains collected information for seven days. Therefore, it will display statistical trends of each day for 7 days.

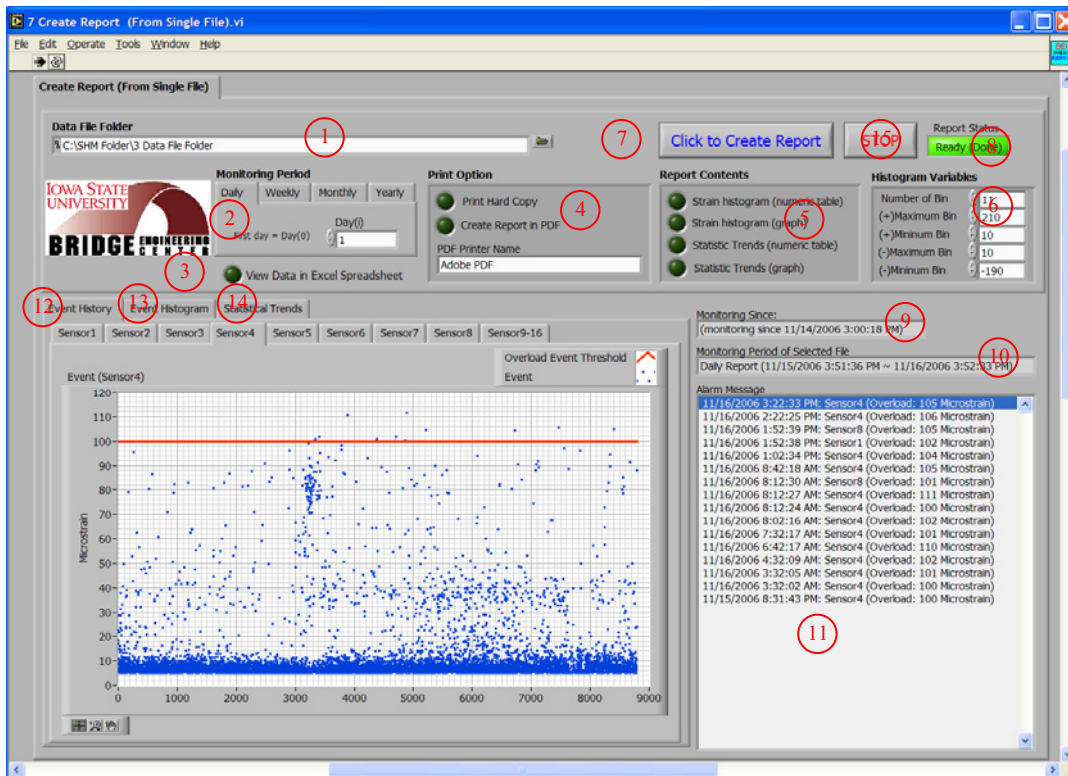


Figure B-7. Screen shot of *7 Create Report (From Single File).VI* front panel

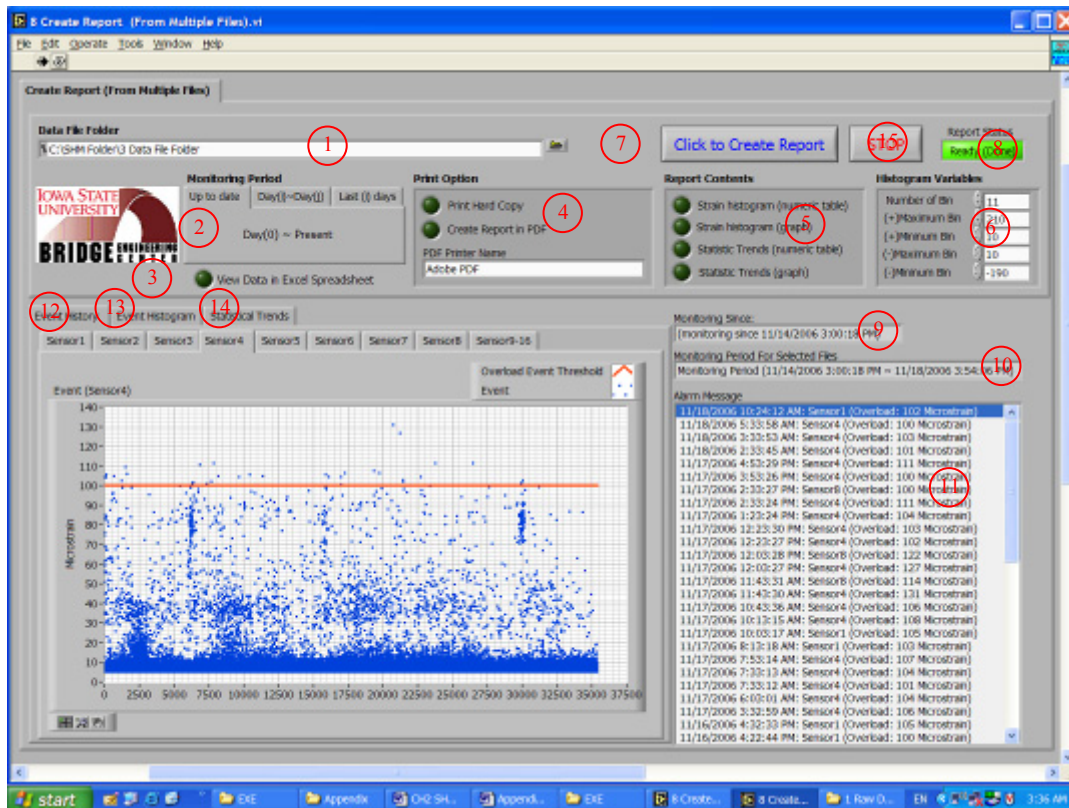


Figure B-8. Screen shot of 8 Create Report (From Multiple Files).VI front panel

Description on controls and indicators

Table B-1. Description of selected controls and indicators in 1 Preliminary DAQ.VI

#	Control or Indicator	Description
1	Device Name Control	Name of a StrainBook/616 assigned during IOtech software installation (described elsewhere).
2	Sampling Rate Control (Hz)	Sampling rate at which strain records are to be collected (number of samples per second).
3	StrainBook/616 Channel Control	Channels of StrainBook/616 to be activated. When selected (Ctrl + mouse click), the indicator turns blue.
4	WBK16 Channel Control	Channels of WBK16 expansion module to be activated. When selected (Ctrl + mouse click), the indicator turns blue.
5	Sensor Configuration Controls	Parameters that need to be configured for each sensor.
6	Calibration File Applied Control (LED option)	If set to true (bright green), a selected calibration file is applied.
7	Calibration File Path Control	Path to calibration file created during calibration process (see Appendix C)
8	Data File Save Path Control	Directory in which raw strain data files are to be saved.

9	Data File Saved at Control (Minutes)	Time duration for which each raw strain data file is saved.
10	Start Control	When pressed, data acquisition will begin.
11	Acquisition Status Indicator	Error dialog box that displays a numeric error code and a corresponding error message upon occurrence of error (error = red, no error = green in the status check box).
12	Real Time Raw Data Indicator	Displays real time raw strain data.
13	Elapsed Time Indicator (Minutes)	Displays elapsed time since the beginning of the data acquisition.
14	Data Acquisition Since: Indicator:	Displays date and time at which data acquisition is initialized.
15	Current Time Indicator	Displays current date and time.
16	Stop Control	When pressed, the program will stop.

Table B-2. Description of selected controls and indicators in 2 FFT-PSD Analysis.VI

#	Control or Indicator	Description
1	Data File Path Control	Path to the “preliminary data” file.
2	FFT-PSD Analysis Tab Control	Contains controls and indicators used for FFT-PSD analysis.
3	Sampling Rate Control (Hz)	Sampling rate at which strain records are to be collected. Note that the sampling rate must be the same with what was used during the preliminary data acquisition.
4	Window for FFT-PSD Analysis Control	Time-domain window to be used in FFT-PSD analysis.
5	Run Button Control	When pressed, the program will be executed and the FFT-PSD analysis for the selected data file will be initialized.
6	FFT-PSD Analysis Status Indicator	Provides the status of FFT-PSD analysis progress. If being processed, it displays ‘In Progress (Wait)’ and turns red. Upon completion, it displays ‘Data ready to plot (Now, select sensor)’ and turns bright green.
7	Data File Progress Indicator	Displays the progress of data file input. When completed, a total number of columns that represents the total number of sensors available will be displayed.
8	Select Sensor Control	Allows users to select (with mouse click) a sensor for displaying a PSD plot. If selected, it will be highlighted in blue.
9	Selected Sensor Indicator	Displays a selected sensor.
10	FFT-PSD Plot Indicator	Displays FFT-PSD plot for the selected sensor.
11	Strain History Tab Control	Contains controls and indicators used for displaying strain history.
12	Chebyshev Filter Parameters Control	Allows users to enter parameters that will be used in filtering.
13	Event Detection	Plus and minus event detection thresholds within which

	Threshold Control (Microstrain)	no peak (or event) will be detected.
14	Plot Strain History Control	When pressed, strain history will be displayed in graph indicator #16 for a selected sensor.
15	Strain History for Selected Sensor Control	Displays a selected sensor.
16	Strain History Plot Progress Indicator	Provides the status of FFT-PSD analysis and/or strain history plot progress. If being processed, 'In Progress (Wait)' is shown and turns red. Upon completion of FFT-PSD analysis and/or the strain history plot, 'Ready (Now, enter parameters and click Plot Strain History)' is shown and turns bright green.
17	Graph Indicator	Displays strain history in microstrain for a selected sensor.
18	Save Parameters for Selected Sensor Control	When pressed, filter parameters and event detection threshold specified in control #12 for a selected sensor will be stored (#20).
19	Create File for Filter Parameters Tab Control	Contains controls and indicators used for writing and saving filter parameters and event detection thresholds for each sensor in a text file.
20	Parameters Table Indicator	Temporarily stores the filter parameters and event detection thresholds for each sensor specified in control #12.
21	Filter File Save Path Control	Path to which a text file that contains filter parameters and event detection thresholds for each sensor will be saved.
22	Create File for Filter Parameters Control	When pressed, a file containing filter parameters and event detection thresholds for each sensor will be saved to the path specified in #20.
23	STOP Control	When pressed, the program will stop.

Table B-3. Description of selected controls and indicators in 3 Input.VI

#	Control or Indicator	Description
1	StrainBook/616 Channel Control	Channels of StrainBook/616 to be activated. When selected (Ctrl + mouse click), the indicator turns blue.
2	WBK16 Channel Control	Channels of WBK16 expansion module to be activated. When selected (Ctrl + mouse click), the indicator turns blue.
3	Sensor Configuration Controls	Parameters that need to be configured for each sensor.
4	Device Name Control	Name of a StrainBook/616 assigned during IOtech software installation (described elsewhere).
5	Sampling Rate Control (Hz)	Sampling rate at which strain records are collected (number of samples per second).
6	Impact Event Threshold Control	Ratio of the absolute difference between the magnitude of an event and that of the event detection threshold with respect to the time difference between a start index and a peak index in a strain record.
7	Event Detection Threshold Controls (Microstrain)	Plus and minus event detection thresholds within which no peak (or event) will be detected.
8	Overload event threshold Control (Microstrain)	Thresholds that are used to determine overload events for each sensor.
9	Email Options Controls	Options that allow users to receive collected information via email.
10	Email Inputs Control	Email addresses and mail server that the collected information are sent from/to
11	Calibration File Controls	Path to a calibration file created during calibration process (see Appendix C) and a LED option to apply it.
12	Raw Data Folder Control	Directory into which the raw strain data file will written.
13	Data Process Folder Control	Directory into which the raw strain data file will be moved for processing.
14	Data File Folder Control	Directory into which reduced data files will be archived after being processed and evaluated.
15	Filter File Path Control	Path to a file that contains event detection thresholds and filter parameters.
16	Create and Save Input File Control	When pressed, an input file will be created and saved in the 'SHM Folder' main directory (C:\SHM Folder).
17	Stop Control	When pressed, the program will stop.

Table B-4. Description of selected controls and indicators in 4 MainDAQ815.VI

#	Control or Indicator	Description
1	Acquisition Status Indicator	Error dialog box that displays a numeric error code and a corresponding error message upon occurrence of error (error = red, no error = green in the status check box).
2	Real Time Raw Data Indicator	Displays real time raw strain data.
3	Time Indicators	Displays (1) date and time at which data acquisition is initialized (2) current date and time (3) count of elapsed hour, day, week, month and year.
4	Network Status Indicator	Error dialog box that displays a numeric error code and a corresponding error message upon occurrence of error (error = red, no error = green in the status check box).
5	Disc/Memory Space Indicators (Bytes)	Displays a total, used and free (available) disc and physical memory space in the local host PC.
6	Stop Control	When pressed, the program will be stopped.
7	Reset Control	A LED option that will initialize new acquisition. The default is false (dark green). If set to true (bright green), upon program execution, a directory 'Old Data File Folder' will be created and the data files saved up to that point will be moved to this directory. Then, new data files will be saved into the directory (3 Data File Folder).
8	Run Button Control	When pressed, the program will begin.
9	Input Information Tab Control	Contains indicators that display the input settings specified by 3 Input.VI.

Table B-5. Description of selected controls and indicators in 5 View Strain History.VI

#	Control or Indicator	Description
1	Data File Path Control	Path to the data file created during the data acquisition.
2	Filter Parameters File Path Control	Path to the text file that contains event detection thresholds and filter parameters for Chebyshev low-pass filter.
3	Sampling Rate Control (Hz)	Sampling rate at which strain records were collected during the main data acquisition (number of samples per second).
4	Plot Strain History Control	When pressed, strain history will be displayed in indicator #6 for each sensor.
5	Strain History Plot Progress Indicator	Provides the status of strain history plot progress. If being processed, 'In Progress (Wait)' is shown and turns red. If completed, 'Ready (Done)' is shown and turns bright green.
6	Graph Indicator	Displays strain history in microstrain for each sensor.
7	Stop Control	When pressed, the program will stop.
8	Graph Palette Control	Changes the scale and the format of the plot while the program is running (or stopped).

Table B-6. Description of selected controls and indicators in 6 View Hourly File.VI

#	Control or Indicator	Description
1	Data File Folder Control	Directory into which the data files created during the main data acquisition are archived.
2	Monitoring Period Control	Option for selecting a data file to be plotted.
3	View Data In Excel Spreadsheet? Control	LED option that allows users to view the data files in Excel Worksheet. The default is false (dark green). If set to true (bright green), information contained in a selected file will be displayed in Excel Worksheet.
4	Histogram Variables Controls	Allows users to change the format of the histogram plot.
5	Click to View Hour File Control	When pressed, event history and event histogram will be displayed in the graph indicator (#7) for each sensor. Also, an Excel Spreadsheet containing information processed by the program will be created if the LED option (#3) is set to true.
6	Plotting Progress Indicator	Provides the status of the plotting progress. If being processed, 'Wait' is shown and turns red. If completed, 'Ready (Done)' is shown and turns bright green.
7	Graph Indicator	Displays event history and event histogram for each sensor.
8	Monitoring Period of Selected File Indicator	Displays the monitoring duration in date and time for a selected file.
9	Alarm Message Indicator	Displays alarm messages recorded during the monitoring period displayed in indicator #8.
10	Stop Control	When pressed, the program will stop.

Table B-7. Description of selected controls and indicators in 7 Create Report (From Single File).VI and 8 Create Report (From Multiple Files).VI

#	Control or Indicator	Description
1	Data File Folder Control	Directory into which data files created during the main data acquisition are archived.
2	Monitoring Period Control	Options for selecting data file(s) from which monitoring results are to be displayed and reports are to be generated.
3	View Data In Excel Spreadsheet? Control	LED option that allows users to view the data in Excel Worksheet. The default is false (dark green). If set to true (bright green), information contained in a selected file will be displayed in Excel Worksheet.
4	Print Option Controls	Options for printing the results in hardcopy and/or PDF (false = dark green, true = bright green).
5	Report Contents Controls	Options for selecting contents to be included in the report (false = dark green, true = bright green).
6	Histogram Variables	Allows users to change the format of histogram plot.

	Controls	
7	Click to Create Report Control	When pressed, the event history, the event histogram and the statistical trends will be displayed for each sensor in the graph indicators under 'Event History' (#12), 'Event Histogram' (#13) and 'Statistical Trends' (#14) tabs, respectively. Also, a report and an Excel Spreadsheet containing the information processed by the program will be created based upon the options (#3, #4 and #5) selected.
8	Report Generation Progress Indicator	Provides the progress of displaying the results and generating reports. If in progress, 'Wait' is shown and turns red. If completed, 'Ready (Done)' is shown and turns bright green.
9	Monitoring Since Indicator	Displays the date and time since the beginning of the data acquisition.
10	Monitoring Period of Selected File Indicator	Displays the monitoring duration in date and time for selected file(s).
11	Alarm Message Indicator	Displays summarized alarm messages recorded over the monitoring period displayed in #10.
12	Event History Tab Control	Contains graph indicators that display strain history for each sensor.
13	Event Histogram Tab Control	Contains graph indicators that display event histogram for each sensor
14	Statistical Trends Tab Control	Contains graph indicators that display statistical trends for each sensor
15	STOP Control	When pressed, the program will stop.
16	Graph Palette Control	Changes the scale and the format of the plot while the program is running (or stopped).

APPENDIX C

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*(*For more information, product manuals can be downloaded from IOtech website at www.iotech.com)*

C1. Setup and Connecting to the Ethernet

C1.1. System Requirements

Setup and Connecting to the Ethernet

5

System Requirements 5-1

Software Installation 5-2

Ethernet Connection and System Power-up 5-3

System Requirements

Before setting up the hardware or installing the software, verify that you have the following items.

- StrainBook/616 data acquisition system
- Power supply with cord (see power note below)
- Data acquisition CD

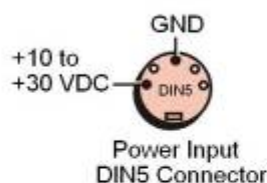
In addition, verify that your computer meets the following **minimum** requirements.

- Intel™, Pentium® III processor
- 10/100BaseT Ethernet port
- 64 MB memory
- 100 MB hard disk space
- Monitor: SVGA, 800 x 600 resolution
- One of the following Microsoft® Windows operating systems:
 - Windows 2000
 - Windows XP
 - Windows NT

Power Note:

StrainBook requires an input voltage between +10 and +30 VDC. The DC source should be filtered but not necessarily regulated. The TR-40U AC-to-DC power adapter is recommended for AC-line applications. However, StrainBook can be powered from any isolated +10 to +30 VDC source of at least 25 W.

Before plugging the unit in, make sure the power switch is in the "0" (OFF) position.



If you will be using an AC-to-DC power adapter [such as the TR-40U] plug it into an AC outlet; then connect the DIN5 end of the cable to the StrainBook's 10 to 30 VDC Input connector.

If you are using another power source [such as a battery] ensure the leads are connected to the proper DIN5 pins as indicated in the figure.

CAUTION



Do not exceed the 5 amp maximum DC current limit of the POWER IN DIN5 connector.

C1.2. IOtech Software Installation

Software Installation



Remove any previous version *WaveView* driver. This can be done through Microsoft's *Add/Remove Programs* feature.

1. Start Windows.
2. Close all running applications.
3. Insert the Data Acquisition CD into your CD-ROM drive and wait for the CD to auto-run.

If the CD does not start on its own:

- (a) click the desktop's <Start> button
- (b) choose the Run command
- (c) select the CD-ROM drive, then select the **setup.exe** file.
- (d) click <OK>.

An *Opening Screen* will appear.

4. Click the <ENTER SETUP> button.
5. From the hardware selection screen [which follows a licensing agreement], select **StrainBook/616** from the drop-down list and follow the on-screen instructions.



Reference Notes:

Adobe Acrobat PDF versions of documents pertaining to StrainBook/616 are automatically installed onto your PC's hard-drive as a part of product support at the time of software installation. The default location is the **Programs** group, which can be accessed via the *Windows Desktop Start Menu*.

C.1.3. Ethernet Connection and System Power-up

Ethernet Connection and System Power-up



Ethernet connectivity can only be used with Windows NT, Windows 2000, or Windows XP operating systems.

Overview



StrainBook/616, Rear Panel

StrainBook/616 connects directly to an Ethernet port on a PC or network hub, via the unit's built-in 10/100BaseT Ethernet interface. An Ethernet patch cable CA-242 (1.5 foot) or CA-242-7 (7 foot) cable is used to make the connection. Note that either a straight-through or a cross-over cable may be used. The circuitry automatically adjusts for the cable type to ensure proper connection.



Connecting a StrainBook/616 to the Ethernet

CAUTION



Turn off power to the system devices and externally connected equipment before connecting cables. Electric shock or damage to equipment can result even under low-voltage conditions.



Take ESD precautions (packaging, proper handling, grounded wrist strap, etc.)

**Reference Note:**

Adobe PDF versions of user manuals will automatically install onto your hard drive as a part of product support. The default location is in the **Programs** group, which can be accessed from the *Windows Desktop*. You can also access documents directly from the data acquisition CD via the <View PDFs> button located on the CD's opening screen.

STEP 1 – Install the Software

Install the software prior to connecting the StrainBook/616 to the Ethernet. If you have not already installed the software, do so at this time. Refer to the section entitled *Software Installation*, page 5-2.

STEP 2 – Determine the type of Network Connection

To properly connect and configure a StrainBook/616, you must determine the type of network that the device will become part of. This is because the type of network used has a direct bearing on the IP address of the device.

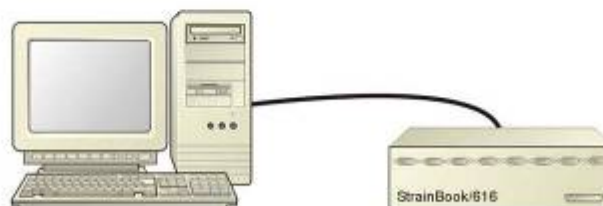
The four network types are as follows:

- **Dedicated Network - with a direct cable connection from the PC to the device**
- **Dedicated Network - making use of a network hub or switch**
- **LAN with a DHCP server**
(Local Area Network with a Dynamic Host Configuration Protocol)
- **LAN without a DHCP server**
(Local Area Network with no Dynamic Host Configuration Protocol)

Brief descriptions and illustrations follow.

Dedicated Network - with a direct cable connection from the PC to the device

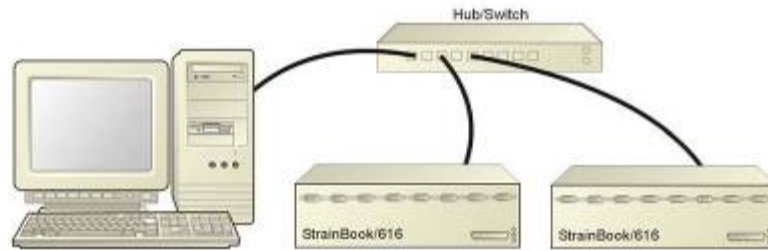
In this scenario a StrainBook/616 is connected directly to an Ethernet jack on a host computer.



Dedicated Network using a Direct Cable Connection

Dedicated Network - making use of a network hub or switch

In this scenario the StrainBook/616 connects to the Ethernet through a network hub or switch. At least one computer is also connected to the hub.



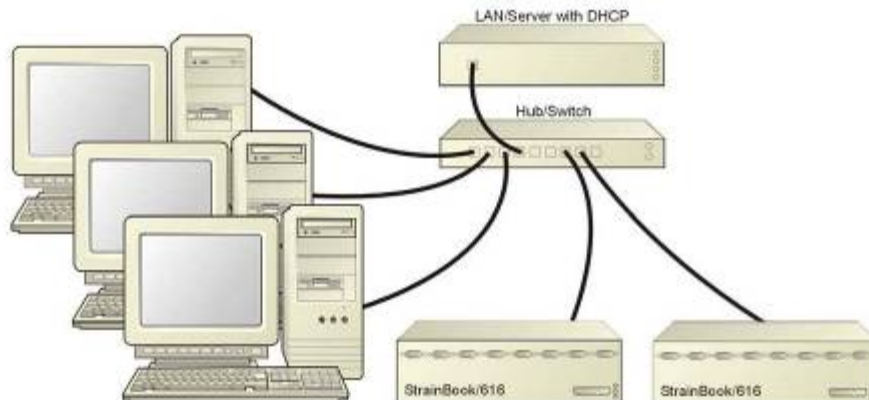
Dedicated Network using a Hub/Switch



Some network devices such as a *wireless access point* may act as a DHCP server. If this is the case, follow the instructions for the LAN with a DHCP server. For detailed information consult the documentation that is specific to your network device.

LAN with a DHCP Server (Local Area Network with a Dynamic Host Configuration Protocol server)

Many corporations use the LAN/Server with DHCP arrangement for their networks. In this type of setup several computers are typically connected to a network that makes use of a DHCP server. In addition, a StrainBook/616 is connected to the network hub/switch.



LAN with a DHCP Server

Notes:

- + Using a StrainBook/616 on a typical LAN may affect the speed of the network and internet data transfer. Because of this we recommend adding a network card to the computer and using one of the two dedicated network configurations.
- + Contact your network administrator before connecting a StrainBook/616 to a corporate network.

LAN with no DHCP Server

(Local Area Network with no Dynamic Host Configuration Protocol server)

This scenario looks the same as that shown in the previous illustration, except there is no Dynamic Host Configuration Protocol (DHCP). In this type of setup, one or more computers are connected to a network, and each computer has a static IP address.

STEP 3 – Connect the System Components



Reference Note:

For examples of StrainBook/616 system connections, including cable use, refer to Chapter 3, *Connectors and Indicators* and Chapter 11, *System Expansion*.

What you will need to connect a StrainBook/616 to the Ethernet:

- ✦ An available connection to the Ethernet. The connection can be either
 - an Ethernet jack on a computer or
 - an Ethernet jack on a hub that is connected to the Ethernet.
- ✦ An Ethernet patch cable, e.g., a CA-242 (1.5 foot cable) or a CA-242-7 (7-foot cable).

1. Connect the Ethernet cable to the Ethernet jack on the StrainBook/616.
2. Connect the other end of the Ethernet cable to the Ethernet jack on the host computer or network hub.

STEP 4 – Power-up the System Components



When powering up a StrainBook/616 system it is important that the StrainBook/616 is powered last, and that the most remote system components are powered first. Other power-up sequences may result in software's failure to recognize all components.*

- ✦ First, power-on the WBK expansion modules, if applicable.
- ✦ Second, power-on the StrainBook/616.

* An exception to this power-up scheme is to power-on the entire system at once.

What you will need:

One or more +10 to +30 VDC power supplies with a male DIN5 connector. The number of supplies depends on the devices in your acquisition system.

Note: The switching-mode power supply that is commonly used with these systems has an input range of 100 VAC to 240 VAC at 50 Hz to 60 Hz. The power supply's output [to the device] is typically 15 VDC @ 3.33 amps via a DIN5 connector.

It is likely that you will use a TR-40U AC power adapter with your StrainBook/616 and a separate TR-40U for each WBK expansion module, if applicable.

Note: Various AC adapter models support power grids of USA, Europe, Japan, and Asia.

How to make the connection:

1. Using the unit's power switch, turn the StrainBook/616 "OFF."
The switch will be in the "0" position and the Power LED will be unlit.
2. Connect the DIN5 end of the adapter's cable to the Power Input connector on the StrainBook/616.
3. Connect the adapter's plug to a standard AC outlet.
4. If your adapter has a power switch, position it to "ON."
5. Turn ON the StrainBook/616 by placing the power switch to the "1" position.
The Power LED will light up.

STEP 5 - Configure the Computer's Network Settings [Applies to "dedicated networks" only]



The StrainBook/616 Ethernet port typically requires 30 seconds after power-up to configure, before the unit can be accessed via the network.



If using a LAN (Local Area Network), which has a DHCP server, skip this section and continue with *STEP 7 - Configure and Test the System using the DaqConfiguration Applet* (page 5-11).



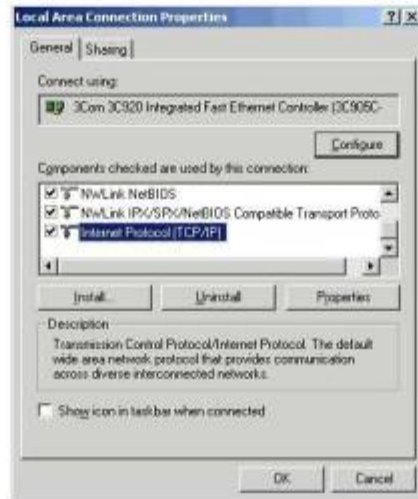
If using a LAN (Local Area Network), which has no DHCP server, skip this section and continue with *STEP 6 - Configure Device Network Settings using DaqIPConfig* (page 5-10).

1. Open the Control Panel by navigating from the Windows Desktop as follows:
Start Menu ⇒ Settings ⇒ Control Panel.
2. Double-click the "Network and Dial-up Connections" icon.
3. Double-click the "Network Connection" icon for the network StrainBook/616 is connected to.



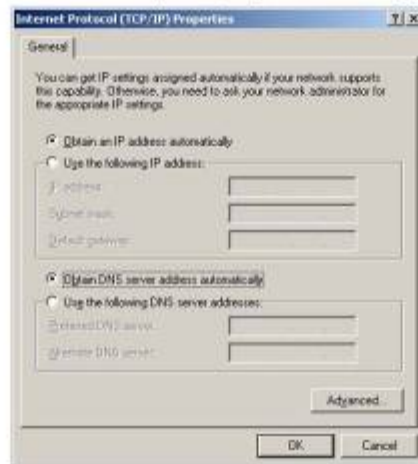
Local Area Connection Status

4. In the "Local Area Connection Status" box (previous figure), click on the <Properties> button. The "Local Area Connection Properties" box will appear (following figure).



Local Area Connection Properties

5. Double-click the "Internet Protocol (TCP/IP)" component (previous figure). The "Internet Protocol (TCP/IP) Properties" box will appear (following figure).



Internet Protocol (TCP/IP) Properties

Configure the Computer's TCP/IP settings as follows.



Internet Protocol (TCP/IP) Properties

6. Select the "Use the following IP Address" radio button.
7. Set the IP address field to 10.0.0.x where x is some number from 1 to 254.
Make sure that each computer on the dedicated network has a unique IP address.
8. Set the Subnet mask to 255.0.0.0. Note that the remaining fields can be left unchanged.

STEP 6 - Configure Device Network Settings using DaqIPConfig

Applies only to a LAN (Local Area Network), which has a no DHCP server.



If using a LAN (Local Area Network), which has a DHCP server, skip this section and continue with *STEP 7 - Configure and Test the System using the DaqConfiguration Applet* (page 5-11).



Multiple devices on a LAN are each identified by their unique (device-specific) serial number. Ensure that the serial number displayed for the unit [being configured] agrees with the serial number on the MAC label, located on the rear panel of the device.

The *DaqIPConfig* applet allows you to change the IP address of a device to match the address of a host computer. The applet is located in the program group for the associated device and can be accessed from the Windows Desktop via the start menu.



Reference Note:
Appendix A contains general information regarding how to use the Daq Configuration Applet.

1. Locate the *DaqIPConfig* Applet.

Locate the *DaqIPConfig* applet by navigating from the Windows' Desktop as follows:

Start Menu
 ⇒ Programs
 ⇒ StrainBook/616 Software
 ⇒ DaqIPConfig

2. Open the *DaqIPConfig* Applet.

Click on the *DaqIPConfig* selection to open the applet.

3. Select the device that is to have the address change.

Note: In the above figure there is only one device to select, i.e., StrainBook/616.

4. Set the internet protocol (TCP/IP) settings to be compatible with host computer.

- (a) Select the radio button labeled "Use the following IP address."
- (b) Enter the new internet protocol settings. If needed, consult your network administrator for acceptable numbers.
- (c) Click the <OK> button.

5. Reboot the device.

The new IP address will not take affect until the device has been powered-off, then powered back on.

6. Repeat steps 3, 4, and 5 for other devices in the system.

After configuring the network settings for all devices, proceed to Step 7.



STEP 7 - Configure and test the System using the Daq Configuration Applet

The *Daq Configuration* applet is located in the Windows *Control Panel*. It allows you to add or remove a device and change configuration settings. The included test utility provides feedback on the validity of current configuration settings, as well as performance summaries.

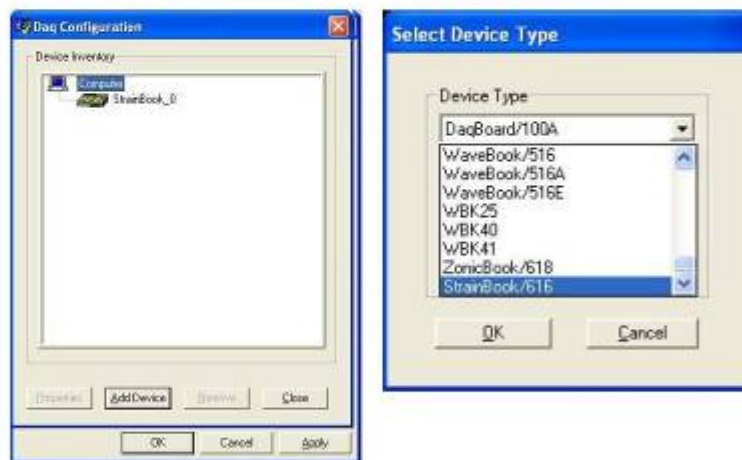
1. Open the Daq Configuration Applet.

- Open the Control Panel by navigating from the Windows' Desktop as follows:
Start Menu ⇒ Settings ⇒ Control Panel
- From the Control Panel, double-click the *Daq Configuration* icon.

2. Add the first-level device to the list of installed devices.

The first-level device is the device that will be connected directly to the Ethernet, via a host computer's Ethernet jack or a jack on a network hub. The StrainBook/616 is an example of a first-level device.

- Select the Computer image in the Device Inventory configuration tree (following figure).
- Click the <Add Device> button. The "Select Device Type" box will appear.
- Select the StrainBook/616 from the list of devices, as applicable.
- Click the <OK> button. The "Properties" box will appear for the selected device.



Using Daq Configuration Device Inventory & Select Device Type to Add a Device

3. Set the properties of the first-level device.

In this step you will set the device properties according to one of the following two methods, depending on whether you have a “Dedicated Network” or a “LAN with DHCP Server Network.”

Users of **Dedicated Networks** follow these 2 steps.

- Enter the **Serial Number** of the first-level device (StrainBook/616). In the following screen shots the Serial Number is 800000.
- Select the “**Auto IP Setting**” radio button. Note that the IP Address of the StrainBook/616 will automatically be calculated and displayed in the IP Address field as indicated in the following left-hand figure.
- Click the <OK> button.



For **DEDICATED** Networks



For **LAN with DHCP** Server Networks

Daq Configuration, Properties Dialog Boxes

Users of **LAN with DHCP Server Networks** follow these 3 steps.

The *DaqIPConfig* applet provides the Serial Number and the IP Address of the device. Users of LAN with DHCP Server Networks will need to enter both numbers in the *Daq Configuration, Properties* dialog boxes (previous right-hand figure). Page 5-10 includes instructions for accessing *DaqIPConfig*.

If needed, refer to the upper right-hand figure in regard to radio-button and data entry locations.

- Enter the base 10 version of the **Serial Number** of the StrainBook/616.
- Select the “**Manual IP Setting**” radio button.
- In the **IP Address** field, enter the IP address.
- Click the <OK> button.



Partial View of DaqIP Config
Showing IP Address & Serial Number



Provide your network administrator with the information on the device's MAC label. Also, find out from the administrator if the IP Address will be changing. If so, see if you can obtain a permanent IP Address dedicated specifically to your device.

4. Test the system connections.

- a. Make sure the device has been properly installed and is powered-on.
- b. Make sure all cables are properly and securely connected.
- c. Click the "Test Hardware" tab.
- d. Click the <TCP/IP Test> button. This tests the Transmission Control Protocol / Internet Protocol.
The TCP/IP test results have two components: *Pinging Device and TCP Connection*. *Appendix B, TCP/IP and Resource Tests*, includes a brief explanation of each.
- e. Upon completion of the TCP/IP test, click the <Resource Test> button.
The Resource Test consists of two components: *Resource Tests* and *Performance Tests*. *Appendix B, TCP/IP and Resource Tests*, includes a brief explanation of each.



When testing a StrainBook/616, if the unit does not respond after 30 seconds perform the following steps:

- 1) reboot the system
- 2) upon power-up, re-open the *Daq Configuration* applet
- 3) select another configuration setting
- 4) reinitiate the test

This completes the procedure for connecting a StrainBook/616 to the Ethernet. At this point you should refer to other sections of the manual, e.g., information on system expansion and data acquisition.



Reference Notes:

Although the signal conditioning aspect of the WBK16 is inherent in the StrainBook/616 and is therefore discussed in this manual, specific WBK16 documentation is contained within the *WBK Options Manual* (p/n 489-0902).

Note: You can access PDF documents directly from the opening screen of the data acquisition CD via the <View PDFs> button.

Bridge Configurations

6

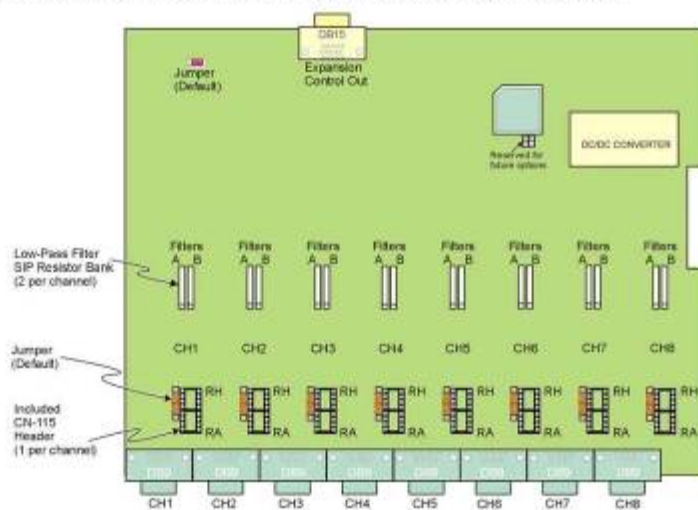
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Introduction

The strain gage is connected to the amplifiers through the Bridge Completion and Shunt Cal Network. This network consists of user-supplied / user-installed resistors for bridge completion. Several combinations of resistors and 3 different shunt values may be installed simultaneously. External connector tie points and the programmable Input Configuration & Cal MUX determine the actual configuration in use.

Once the network is fully configured, most bridge configurations and resistances can be accommodated without re-opening the box. The shunt resistors allow each bridge to be put into a known imbalance condition for setting or verifying channel calibration. Shunt calibration allows a full-scale gain to be set without physically loading the bridge. Page 6-12 discusses a DB9 Adapter option that provides a means of easily setting up a bridge configuration.

The following board layout shows locations of components referenced to in this chapter. The jumper positions are default locations. Information regarding the CN-115 header and associated jumpers follows.



StrainBook Board Layout

StrainBook's upper circuit board (see preceding figure) is used to:

- Customize low-pass filter frequencies using resistor networks
- Install Bridge completion resistors
- Install Shunt calibration resistors



A fan draws air through the unit and exhausts it through the side. To maintain sufficient cooling, it is important to keep the fan and vents free of obstruction.

CN-115 Headers, Associated Jumpers, and Plug-In Options

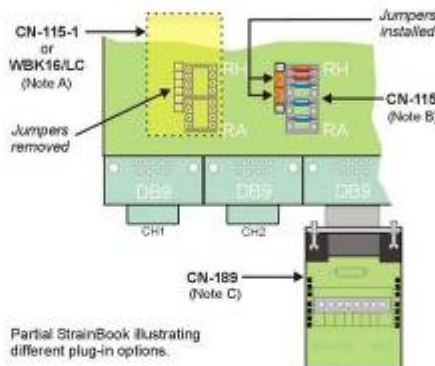
Each channel has a CN-115 2x8 resistor socket header and two associated jumpers (JP101 and JP102) located on the StrainBook's main board. The jumpers, associated with a given channel, must be installed if a CN-115 will be used for that channel. The associated jumpers must be removed if a CN-115-1 or a WBK16/LC option will be used for configuring a channel.

Installing a CN-115-1 or a WBK16/LC (Note A)

StrainBook jumpers must be removed for CN-115-1 and WBK16/LC.

CN-115-1 is a removable plug-in board that can be pre-configured for various bridge options. It differs from the CN-115 only in form factor.

WBK16/LC can be used for virtually all single value shunt calibration requirements, some of which are not possible with the internal FET/analog switch provisions in the standard channel configurations.



Partial StrainBook illustrating different plug-in options.

Installing a CN-115 (Note B)

StrainBook jumpers must be installed for CN-115.

CN-115 is a removable plug-in adaptor that can be pre-configured for various bridge options. It differs from the CN-115-1 only in form factor.

Installing a CN-189 (Note C)

CA-189 is an external screw-terminal option. It can be used in conjunction with a CN-115 or a CN-115-1. If used alone (without either plug-in) the associated channel jumpers must be installed in the default position.



When installing a plug-in device, be careful to avoid bending the pins and ensure that the option is correctly oriented. Information for these options can be found using the reference notes below.

Note A - The *Note A* region represents a CN-115-1 or a WBK16/LC option plugged into the board's CN-115 header for channel 1. The dashed-rectangle indicates the relative size and orientation of these options. For both the CN-115-1 and the WBK16/LC the two jumpers (left edge of header) must be removed.

Note B - The CN-115 plug-in adapter fits directly over the header. When using a CN-115 the two jumpers (left edge of header) must be installed as indicated in the figure.

Note C - The CN-189 includes two 7-pad jumpers and a 9-slot screw-terminal block. With use of the terminal block and appropriate shorting of jumper pads, the user can easily configure the option to utilize the components of an installed CN-115 or CN-115-1. The CN-189 screw-terminal option plugs into a DB9 connector.



Reference Notes:

- ◆ Schematics of various bridge configurations can be found on pages 6-8 through 6-11. These configurations apply to both the CN-115 and the CN-115-1.
- ◆ The WBK16/LC Load Cell Shunt Cal Internal Option is discussed on page 6-15.
- ◆ The CN-115-1 User-Configurable Plug-In Card performs the same function as the CN-115 Header Plug-in Option. CN-115-1 is discussed on page 6-20.
- ◆ DB9 connector information, including use of the optional CN-189 adapter, begins on page 6-12.

Bridge Applications

All strain-gage bridge configurations consist of a 4-element network of resistors. The *quarter*, *half* or *full* designation of a strain gage refers to how many elements in the bridge are strain-variable. A quarter-bridge has 1 strain-variable element; a half-bridge has 2 strain-variable elements; and a full-bridge has 4 strain-variable elements.

Full-bridges generally have the highest output and best performance. Output signal polarity is determined by whether the strain-variable resistance increases or decreases with load, where it is located in the bridge, and how the amplifier inputs connect to it. Configuration polarity is not important in StrainBook due to an internal software-selected inversion stage. This simplifies bridge configuration.

Each of the 8 input channels has locations for five bridge-completion resistors. These BCR's are for use with *quarter* and *half-bridge* strain gages. The resistors make up the fixed values necessary to complete the 4-element bridge design.

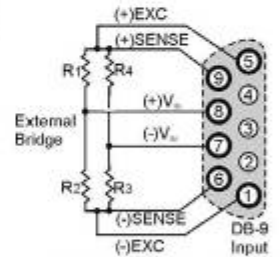
A full-bridge gage requires no internal completion resistors. However, the resistors may still be installed for other configurations in use. The additional resistors will be ignored when the software has selected full-bridge mode.

Quarter-bridge and half-bridge gages require an internal half-bridge consisting of header positions Rg and Rh. The recommended minimum values are 0.1%, <5 PPM/°C drift, 1 K Ω , and 0.25-watt resistors. Lower values will dissipate more power and add heat. Values >1K Ω will increase the amount of drift and noise. The same value half-bridge resistors can be used for any resistance strain gage. This internal half-bridge will be automatically selected by the software when needed.



**Internal 1 M Ω shunt resistors are used to avoid open circuits.
These resistors are not suitable for high-accuracy/low-noise applications.**




A quarter-bridge gage additionally requires a resistor of equal value to itself. Up to 3 different values may be installed simultaneously in header positions Ra, Rc, Re. All of these resistors are connected to the (-) excitation terminal. An external jumper at the input connector determines which resistor is utilized. Therefore, 3 different quarter-bridge values can be supported without opening the enclosure. Each different value bridge would simply have the jumper in a different location; when the gage is plugged in, the proper resistor is then already selected. Configurations with the completion resistor on the (+) excitation are redundant, due to the internal inversion stage, and not used.



Kelvin-Type Excitation Leads

The upcoming strain-gage configurations are presented in 4 groups: Full-bridge, half-bridge, quarter-bridge, and high-gain voltmeter. Many of these configurations can coexist but are shown individually for clarity.

Removing the Cover Plate

CAUTION	
	Remove the StrainBook from power and disconnect the unit from the host PC and from all externally connected equipment prior to connecting cables, signal lines, and/or removing the cover to install or remove components. Electric shock or damage to equipment can result even under low-voltage conditions.
	Take ESD precautions (packaging, proper handling, grounded wrist strap, etc.) Use care to avoid touching board surfaces and onboard components. Only handle boards by their edges (or ORBs, if applicable). Ensure boards do not come into contact with foreign elements such as oils, water, and industrial particulate.
	Be careful to avoid component damage while the StrainBook is open. Always remove bridge completion headers (CN-115) from the unit before soldering resistors in the headers.



The Cover Plate Is Secured by 4 Screws [2 Screws per side]

1. Remove the StrainBook from power and disconnect the unit from the host PC and from all externally connected equipment prior to removing the cover. As stated in the above CAUTION, electric shock or damage to equipment can result even under low-voltage conditions.
2. Ensure you have taken proper ESD precautions (proper handling, grounded wrist strap, etc.)
3. Remove the top inward screw from each of the four mounting brackets [2 screws per bracketed side].
4. Carefully remove the cover.

Excitation Connection

Remote sense inputs are provided for the excitation regulators. The excitation voltage will be most accurate at points where remote sense lines are connected, preferably at the bridge (this is often referred to as a 6-wire connection). Long cables will reduce the voltage at the bridge, due to current flow and wire resistance, if remote sense is not used.

If the 6-wire approach is not used, the remote sense inputs must be jumpered to the excitation outputs at the input connector. Internal 1 M Ω resistors are also connected where the jumpers would be located to prevent circuit discontinuities. These 1 M Ω resistors are not suitable for high-accuracy excitation-voltage regulation.

3-wire quarter-bridge configurations do not benefit from external remote sense connections. The lead resistance is actually a balanced part of the bridge. If the + remote sense input is connected to the + input on a quarter-bridge, the voltage is regulated across the bridge completion resistor. This results in a constant-current linearized quarter-bridge; otherwise quarter-bridges are not perfectly linear.

Shunt-Calibration Resistors. StrainBook provides three physical locations for internal shunt-calibration resistors for each channel. Each shunt resistor is switched in from the EXCITATION (-) to the IN (+) of the Instrumentation Amp by a FET switch to create a repeatable bridge imbalance. Internal resistance of the circuit is about 1 k Ω ; the exact amount is automatically accounted for in the software. The software also allows selection of the three shunt resistors (B, D, F). An internal inversion stage insures correct polarity during the shunt calibration process; which arm is shunted is therefore irrelevant. Header positions Rb, Rd, Rf correspond to the software shunt resistor selections of B, D, F.

For any balanced bridge, a resistance value can be placed in parallel with one element to create a predictable imbalance and output voltage. This shunt-resistance value can be calculated by the following equation, where V_{out} is the differential output voltage of the gage.

Example:

$$R_{Shunt} = R_{Bridge\ Arm} [(V_{Excitation} / 4 (V_{out})) - 0.5]$$
$$R_{Shunt} = 350 [(10 / 4(0.020)) - 0.5] = 43,575\Omega$$

CAUTION



Be careful to avoid component damage while StrainBook enclosure is open. Always remove bridge completion headers (adapter plugs) from the unit before soldering resistors in the headers.





Configuring the Bridge Completion Resistor Modules. For each channel, the board has a 2x8 resistor socket with rows designated A through H. The removable adapter plugs are included for soldering in the resistors. Additional adapter plugs are available for convenient changeover of alternate configurations. Resistor Ra is located nearest the front panel.

- o Half-bridge completion resistors consist of Rg and Rh.
- o Quarter-bridge completion resistors consist of Ra, Rc, and Re.
- o Shunt resistors consist of Rb, Rd, and Rf.

Inserting resistors directly into the socket makes an unreliable connection and is not recommended. Remove the plug from the main board; then solder resistors to the adapter plug as indicated. To avoid damaging the pin alignment on the plug, solder with minimal heat. After soldering, the resistor leads should be snipped off close to the support.



Installing a CN-115

CAUTION	
	Remove the StrainBook from power and disconnect the unit from the host PC and from all externally connected equipment prior to connecting cables, signal lines, and/or removing the cover to install or remove components. Electric shock or damage to equipment can result even under low-voltage conditions.
	Take ESD precautions (packaging, proper handling, grounded wrist strap, etc.) Use care to avoid touching board surfaces and onboard components. Only handle boards by their edges (or ORBs, if applicable). Ensure boards do not come into contact with foreign elements such as oils, water, and industrial particulate.
	Be careful to avoid component damage while the StrainBook is open. Always remove bridge completion headers (CN-115) from the unit before soldering resistors in the headers.
	Be careful to avoid bending the pins and ensure that the plug-in is correctly oriented. Note that the associated channel's two jumpers (located on the StrainBook board) must be installed for CN-115 applications; but removed for CN-115-1 or WBK16/LC applications.

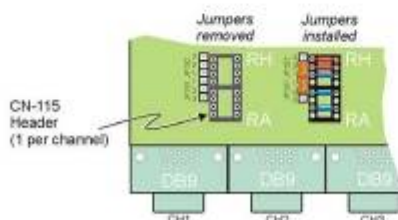
You can easily install a CN-115 as follows:

Note: If you need to add or remove resistors to the CN-115 plug-in, do so prior to the installing it. Configuration diagrams begin on page 6-8.

1. Review the preceding CAUTIONS.
2. Remove the StrainBook [or WBK16] from power and disconnect the unit from all external devices and signals.
3. Observe proper ESD precautions.
4. Remove the cover from the StrainBook [or WBK16].
5. Locate the CN-115 channel header(s) in which the plug-in is to be installed.
6. If the header socket is occupied, remove the CN-115-1, WBK16/LC, or previous CN-115 to expose the header socket.
7. Add one shunt jumper to each of the two 3-pin headers. The 3-pin headers are located at the edge of the CN-115 16-pin header sockets (see figures).

Note: For each channel the jumper headers are labeled in sets of two: JP101/JP102 for channel 1, through JP801/JP802 for channel 8. The first digit after "JP" signifies the associated channel number.

8. Carefully plug the CN-115 into the header socket.
9. Re-install the cover to the StrainBook [or WBK16].



CN-115 Headers for Channels 1 and 2

Channel 1 has jumpers removed. Channel 1 has no CN-115 installed. Channel 2 shows a CN-115 installed and proper jumper installation.

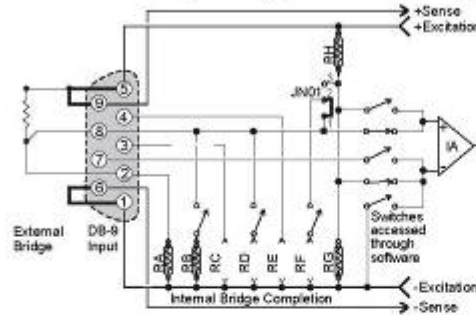


Required Jumper Placement for CN-115 Plug-in

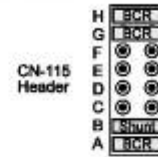
For each channel that has a CN-115 installed, pins must be jumpered as indicated above. Each channel has a jumper header next to the edge of its CN-115 header.

Three-Wire Quarter-Bridge Configurations

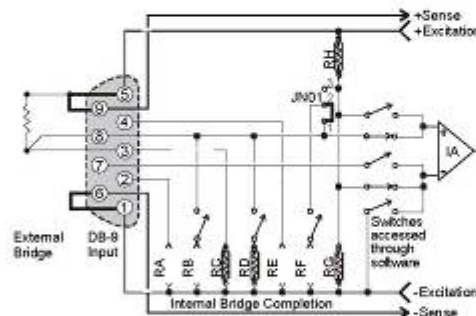
The three-wire quarter-bridge has only one strain-variable element and requires three bridge completion resistors (BCRs). The internal half-bridge may be any two matched values, but the remaining resistor must match the external quarter-bridge value precisely. Three of these values may be installed simultaneously when connected as shown below; the connector pins determine which resistor is used. With all three values installed, WBK16 can accommodate all three quarter-bridge values without changing the internal resistors.



Three-Wire Quarter-Bridge (+),
Using RA (120-Ohm nominal), B Shunt Resistor



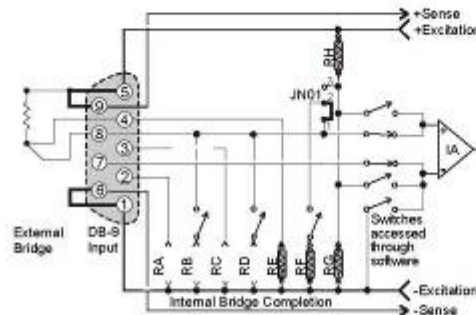
A 120-ohm resistor and its corresponding shunt value may be installed as shown.



Three-Wire Quarter-Bridge (+),
Using RC (350-Ohm nominal), D Shunt Resistor



A 350-ohm resistor and its corresponding shunt value may be installed as shown.



Three-Wire Quarter-Bridge (+),
Using RE (1-KOhm nominal), F Shunt Resistor



A 1000-ohm (or other value) resistor and its corresponding shunt value may be installed as shown.



Cable Pinout*

CA-177 Strain-Gage Cable Pinout*			Cable CA-177 Specifications
DB9 Male End (P1)	Unterminated End (P2)		
Pin 1	Brown wire		P1 Cable End: DB9 male, assembled metal hood with thumbscrews (solder cup DB9). P2 Cable End: Unterminated, blunt cut. Cable Type: Belden 9614 or equivalent. Wire Gauge: 24 AWG. Outer Shield: Foil and 65% braid. Number of Conductors: Nine (9) plus drain. Dimensions: Length: 72" ± 4", Connector width: 1.220" maximum P1-to-P2 Pinout Specifications: As indicated at left.
Pin 2	Red wire		
Pin 3	Orange wire		
Pin 4	Yellow wire		
Pin 5	Green wire		
Pin 6	Blue wire		
Pin 7	Purple wire		
Pin 8	Black wire		
Pin 9	White wire		
Shell	Drain wire	---	

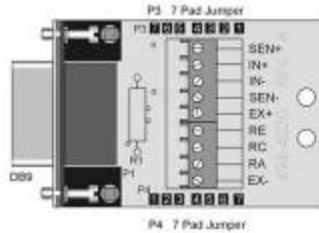
*Cable DB9 numbering is opposite of that found on the StrainBook to allow for correct pin mating.

CN-189, DB9 Adapter Option

CAUTION	
	Remove the StrainBook from power and disconnect the unit from the host PC and from all externally connected equipment prior to connecting cables, signal lines, and/or removing the cover to install or remove components. Electric shock or damage to equipment can result even under low-voltage conditions.
	Take ESD precautions (packaging, proper handling, grounded wrist strap, etc.) Use care to avoid touching board surfaces and onboard components. Only handle boards by their edges (or ORBs, if applicable). Ensure boards do not come into contact with foreign elements such as oils, water, and industrial particulate.
	<p>If the CN-189 will be used (a) with a CN-115 installed in the associated channel, or (b) will be used alone, then the associated channel's CN-115 header jumpers must be installed as indicated in the figure.</p>

The CN-189 option consists of two 7-pad jumpers (P3 and P4), a DB9 connector, and a 9-slot screw-terminal block. The adapter plugs into channel input DB9 connectors on StrainBooks and WBK16 expansion modules.

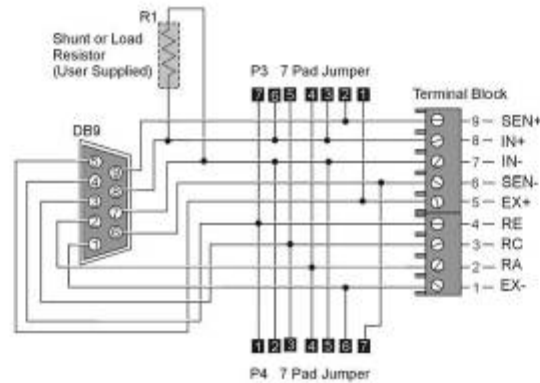
With use of the terminal block and appropriate shorting of jumper pads, the user can easily set up the desired bridge configuration. A table indicating bridge types and the respective CN-189 jumper pad shorts follows shortly. In some cases, the user may want to install a resistor at location R1. The electrical relation of CN-189 components is shown in the following schematic.



CN-189 DB-9 Adapter Option



The CN-189 is intended for convenience and is not shielded. Higher signal quality will be obtained with the use of shielded cables, such as the CA-177 strain gage cable.



CN-189 Schematic

The CN-189 can be configured to utilize the components of an installed CN-115 or CN-115-1 in accordance with the following table.

CN-189 DB9 Adapter for WBK16, Configuration Table				
Function	P3 (on CN-189)	P4 (on CN-189)	Resistor Used in R1	
1 Internal Excitation Sense	Short 1 and 2	Short 6 and 7		
2 ¼ Bridge Using (RA) 2-Wire	Short 3 and 4			
3 ¼ Bridge Using (RC) 2-Wire	Short 5 and 6			
4 ¼ Bridge Using (RE) 2-Wire	Short 6 and 7			
5 High Gain Amp Ground Path (Short)		Short 5 and 6		
6 High Gain Amp (Resistive) Ground Path (EXT)		Resistor between 5 and 6		
7 High Gain Amp (RE) Ground Path (INT)		Short 1 and 2		
8 High Gain Amp (RC) Ground Path (INT)		Short 2 and 3		
9 High Gain Amp (RA) Ground Path (INT)		Short 4 and 5		
10 Current Measurement (Differential)			Shunt resistor in R1	
11 Differential Load Resistor			Load resistor in R1	



For the functions listed in the preceding table, internal StrainBook configurations still apply as indicated on pages 6-8 through 6-11.

C3. Sensor Calibration

Sensor Calibration

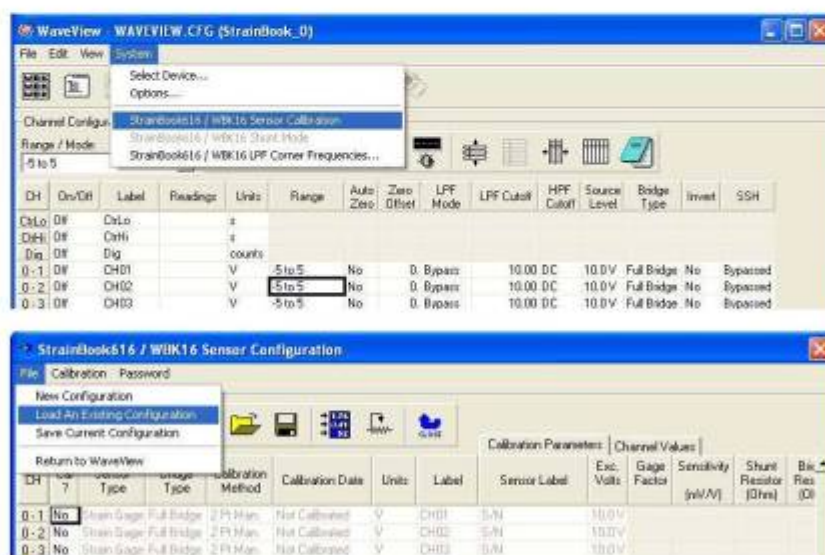
To use the Sensor Calibration Program you must first launch WaveView. This can be done from a shortcut on the desktop, or by selecting WaveView from the Programs group, accessed from the desktop Start menu.

WaveView holds user-configured parameters that can be saved to disk. The default configuration filename is **WAVEVIEW.CFG**. When WaveView starts up, it proceeds to search the working directory for this file. WaveView also holds a default sensor calibration file. The **WAVEVIEW.CFG** file holds the name of this calibration file so that all sensor calibration information from the last WaveView session is also loaded into WaveView during initial boot-up. If the default configuration file is found, all the required setup information will be extracted from it, and the application's main window will open. When connection is established, the application's main window will open with the default setting. If these options fail, a dialog box will ask if you want to open a different setup file.



Reference Notes:

- For detailed WaveView startup information, refer to the *WaveView* PDF. The document can be accessed from the data acquisition CD via the <View PDFs> button on the CD's opening screen.
- The WBK16/LC Load Cell Shunt Cal internal option board may be required to calibrate load cells and transducers that have internal shunt cal resistors. See the WBK16/LC section of chapter 6 for details.



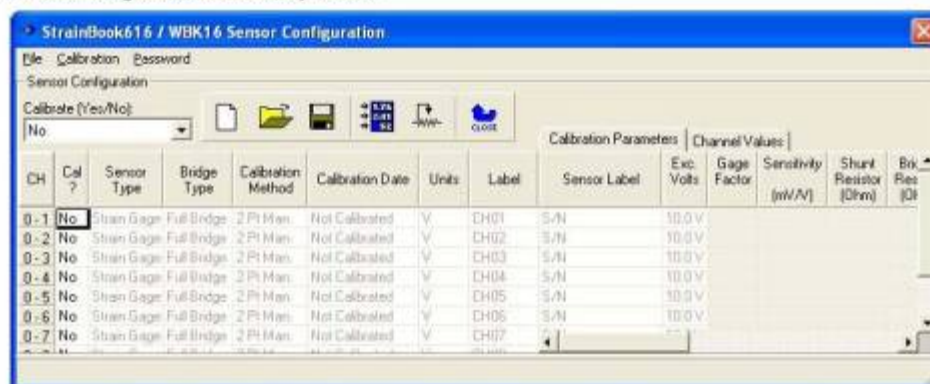
WaveView Configuration Main Window(Top) and Sensor Configuration [Calibration] Window (Bottom)



To open the Sensor Configuration [Calibration] window, click on WaveView's **Sensor Calibration button**. The button is depicted at the left and pointed out in the upper portion of the previous figure. You can also open the window from WaveView's **System pull-down menu**.

You can use the Sensor Configuration window's File pull-down menu to **Load an Existing Configuration**. This option opens a standard dialog box that allows you to select and open the desired file.

Sensor Configuration Main Components



Sensor Configuration [Calibration] Window

Sensor Configuration Toolbar and Pull-Down Menus

Control functions in the sensor configuration window are available through the pull-down menus or the toolbar. For descriptions of button functions, see the related menu selections. Note that some menu selections have no corresponding button.

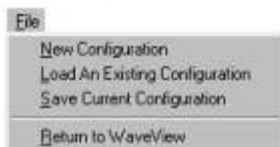


Sensor Configuration Window Toolbar

- 1 – New Configuration
- 2 – Load an Existing Configuration
- 3 – Save Current Configuration
- 4 – Take a Single Reading
- 5 – Calibrate Enabled Channels
- 6 – Return to WaveView

File

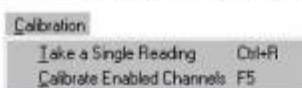
The *File* menu provides four functions:



New Configuration	Set all parameters to their default startup setting.
Load An Existing Configuration	Load a saved sensor calibration configuration.
Save Current Configuration	Save the current sensor calibration configuration for later recall.
Return to WaveView	Exit the <i>Sensor Configuration</i> window and return to WaveView.

Calibration

The *Calibration* menu provides two functions:



Take a Single Reading	This command allows the user to take a single reading and display the values in the <i>Sensor Configuration</i> window.
Calibrate Enabled Channels	This command will calibrate all enabled channels.

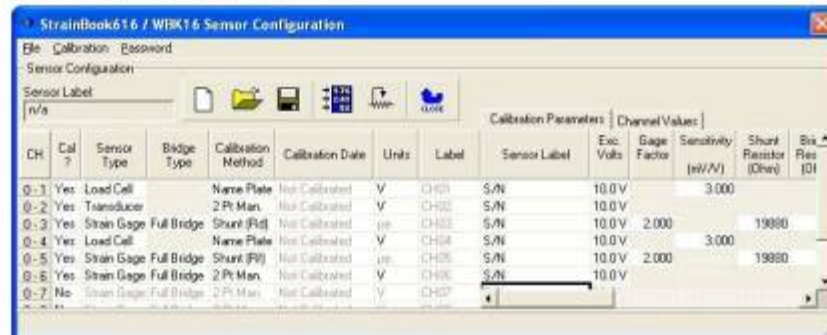
Password

The sensor calibration application provides password protection. If you calibrate any StrainBook channels [or WBK16 expansion channels] and then choose the password protection option WaveView will prevent other users from making changes to your calibration file. The *Password* menu provides three functions:



Enter Password	Use this command to enter a previously selected password, enabling you to change parameters.
Set a New Password	This command allows the user to select a 4-7 character password. A message box will prompt you to enter a new password. Type a password and press "enter", or click on the "OK" button.
Clear Password	This command clears the password protection. A message box will prompt you to enter the current password. Type the current password and press "enter", or click on the "OK" button.

Calibration Parameters Tab Selected



Sensor Configuration Window

Column	Description
Calibrate?	"Yes" enables the selected channel to be calibrated with the "calibrate enabled channels" option. "No" prevents the channel from being calibrated. All other columns for that channel will be disabled if "no" is selected. The channel can still be turned on in WaveView.
Sensor Type	Provides a means of selecting the sensor type. The three available sensor types are Strain Gage , Load Cell , and Transducer .
Bridge Type	Provides a means of selecting the bridge type. Choices are full-bridge , half-bridge , and quarter-bridge . This option is only available for a strain gage sensor in the calibration program. The bridge type for any sensor can be changed from the <i>Sensor Configuration</i> window.
Calibration Method	Allows the calibration method to be selected. Possible selections are indicated in the figure to the right. These calibration methods are explained later in the document. <div data-bbox="998 877 1302 1012" data-label="Image"> </div>
Calibration Date	Displays the time and date that the channel was calibrated. If the channel has not been calibrated, "Not Calibrated" appears in the box.
Units	To change the units: highlight the desired box, type-in the new parameters, and then press <Enter> on the keyboard or select another box with the mouse. Up to 5 characters can be entered into this column. To fill the entire column with the value of channel one, make sure "yes" is selected in the "Calibrate" column. Then click on the column label with the mouse. A message box will appear. Click on "yes". All channels with the "calibrate" function enabled will be filled. Changing the units here will also change the units column in the <i>WaveView Configuration</i> main window.
Label	Used to label channels.
Sensor Label	A serial number or other identifying label for the sensor can be entered here. Up to 39 characters may be entered and 16 will be displayed. The fill option is available for this column (see Units).

Calibration Parameters		Channel Values					Calibration Parameters		Channel Values				
Sensor Label	Exc. Vols	Gage Factor	Sensitivity (mV/V)	Shunt Resistor (Ohm)	Bridge Resistor (Ohm)	Full R. L. (Ohm)	Full Rated Load (Units)	Max Appl. Load (Units)	Quiescent Load (Units)	Point 1 (mV)	Point 1 (Units)	Point 2 (mV)	Point 2 (Units)
S/N	10.0 V	2.000		19980	350				3000.0	0.0			
S/N	10.0 V		3.000			30	3000.0	3000.0	0.0		0.0		
S/N	10.0 V							3000.0	0.0				3000.0
S/N	10.0 V	2.000		19980	350			3000.0	0.0				
S/N	10.0 V		3.000			30	3000.0	3000.0	0.0				
S/N	10.0 V	2.000		19980	350			3000.0	0.0				
S/N	10.0 V							3000.0	0.0		0.0		3000.0
S/N	10.0 V							3000.0	0.0				3000.0
S/N	10.0 V							3000.0	0.0				3000.0

Calibration Parameters Section of Window
Two Views Obtained by Scroll Bar Movement

Column	Description
Exc. Volts	Used to change the excitation voltage. Choose between 10.0, 5.0, 2.0, 1.0, .5, and "Off." Changing the excitation voltage on any channel between one and four will change the value on all four lower channels. Likewise, changing the excitation voltage on any channel five through eight will change the value on all four upper channels. Changing the Excitation Voltage here will also change the Source Level column in the WaveView Configuration main window.
Gage Factor	Used for calibrating strain gages with the Name Plate calibration method. To change this value, select the box and enter a number greater than 0 and less than 1000. The fill option is available for this column (see Units).
Sensitivity (mV/V)	This column is used for calibrating a load cell or transducer using the Name Plate calibration method. To change this value, select the box and enter a number greater than 0 and less than 1000. The fill option is available for this column (see Units).
Shunt Resistor (Ohm)	This column is used for calibrating any sensor using the Shunt calibration method. The value must equal the value of the shunt resistor in ohms. To change the value, select the box and enter a number greater than 0 and less than 1000000. The shunt value must not exceed the value entered as the maximum load. The fill option is available for this column (see Units).
Bridge Resistor (Ohm)	Used for calibrating any sensor using the Shunt calibration method. The value refers to the bridge arm that is shunted during shunt calibration. To change the value, select the box and enter a number from 60 to 1000. The fill option is available for this column (see Units).
Full Rated Load (Units)	This column is used for calibrating a load cell or transducer using the Name Plate calibration method. To change this value, select the box and enter a number greater than 0 and less than 100000. The full-rated load must be greater than the value entered for the maximum applied load. The fill option is available for this column (see Units).
Max Applied Load (Units)	Used for calibrating any sensor using any calibration method . To change the value, select the box and enter a number greater than 0 and less than 1000000. This value must be greater than the quiescent/tare value. The fill option is available for this column (see Units).
Quiescent/Tare (Units)	This column is used for calibrating any sensor using any calibration method . The value entered is the value of the quiescent load on the sensor. To change the value, select the box and enter a number between -1000000 and 1000000. This value must be less than the maximum applied load value. The fill option is available for this column (see Units).
Point 1 (mV)	This column is used for calibrating any sensor using the Shunt, or 2-Point Automatic calibration method. The number must equal the input value, in mV, of the first point in the calibration. To change the value, select the box and enter a number between -10000 and 10000. The fill option is available for this column (see Units).
Point 1 (Units)	This column is used for calibrating any sensor using the Shunt, 2-Point Automatic, or 2-Point Manual calibration method. The number must equal the value, in the selected units, of the first point in the calibration. To change the value, select the box and enter a number between -1000000 and 1000000. The fill option is available for this column (see Units).
Point 2 (mV)	Used for calibrating any sensor using the 2-Point Automatic calibration method . The number must equal the input value, in mV, of the second point in the calibration. To change the value, select the box and enter a number between -10000 and 10000. The fill option is available for this column (see Units).
Point 2 (Units)	This column is used for calibrating any sensor using the 2-Point Automatic, or 2-Point Manual calibration method . The number must equal the value, in the selected units, of the second point in the calibration. To change the value, select the box and enter a number between -1000000 and 1000000. The fill option is available for this column (see Units).

Shunt (Internal Shunt) Calibration

The Shunt calibration method pertains to an internal shunt. For this method two readings are acquired from a bridge. The first reading is obtained with the bridge in its quiescent state; the second is taken with one leg of the bridge shunted by one of three selectable resistors. The resistors are located on a plug-in header inside the StrainBook or WBK16 module. Shunt calibration appears as "Shunt (RB)", "Shunt (RD)", and "Shunt (RF)" in the list of calibration methods.

The Internal Shunt Calibration requires that the user enter the following 7 parameters:

Excitation - The value of the constant voltage source used to excite the gage.

Gage Factor - The Gage Factor value of the gage used in the bridge. A Gage Factor of 2 is typical.

Shunt Ohms - The value in Ohms of the shunt resistor mounted on the header inside the StrainBook or WBK16 module.

Bridge Ohms - The resistance value of the gage. Typically 120 or 350 Ohms.

Max Load - The maximum load value the gage is expected to measure. This value could be less than the max rated load of the gage.

Quiescent Load - The *at rest* value of the load applied to the gage. If no load will be applied to the gage in its quiescent state, enter "0" zero.

Point 1 Units - The minimum load value the gage is expected to measure. This value could be greater than the minimum rated load of the gage.

Example: Excitation voltage is set to 2 volts. A Quarter Bridge circuit employing a 350 Ohm strain gage with a Gage Factor of 2 and a full load rating of +/- 1500 μ e is connected to a StrainBook [or WBK16 channel]. The gage will be used in an environment where the expected range of measurement is limited to -200 to +1000 μ e. This gage [in its quiescent state] has a 500 μ e load. A 349,650 Ohm precision resistor is available that will be mounted on the plug-in header in Shunt location R(B). Instructions for installing shunt resistors are provided elsewhere in the document. In this example the user would enter the following values in the Calibration Parameters spreadsheet:

Cal Method Shunt R(B)
Excitation = 2V.
Gage Factor = 2
Shunt Ohms = 349,650
Bridge Ohms = 350
Max Load = 1000
Quiescent Load = 500
Point 1 Units = -200

The accuracy of Shunt Calibration is directly related to the tolerances of the Shunt resistor, Gage(s), and Bridge Completion resistors used in the circuit. In the event that a precision shunt resistor is unavailable, WaveView provides an alternate way of calculating Shunt calibration constants. This method is as follows:

- Install an appropriate non-precision shunt resistor of a value that creates the degree of bridge imbalance desired.
- Press and hold the <Alt> key on the computer's keyboard; then start the calibration process.
- Once the calibration process has started you release the <Alt> key.

This *alternate* Shunt Calibration method calculates the shunted load value from shunted and un-shunted bridge voltage measurements; and then performs the equivalent of a 2 Point Manual calibration.

C3a. Sensor Calibration Example

- Sensor type: Hitec Product weldable quarter-bridge strain gage
- Gage Factor: 2.0
- Number of sensors: 10 strain gages
 - 8 channels for StrainBook/616: '0-1' to '0-8'
 - 2 additional channels for WBK16 expansion module: '1-1' and '1-2'
- Bridge completion resistor (BCR): 350 Ω
- Shunt calibration resistor: 57933 Ω

This is an example of calibrating 10 quarter-bridge strain gages and the required procedures illustrated in Figs. C-1 and C-2 are as follows:

- lxxi. Turn on the StrainBook/616 and WBK16 expansion module (note: the module first and then the StrainBook/616). Once the equipment is on, start 'WaveView' software.
- lxxii. Go to 'File' and select 'New'.
- lxxiii. Under 'On/Off' column (#1), select channels to be activated (i.e., switch to 'On').
- lxxiv. Click 'Hide Inactive Channel Rows' (#2) to have only activated channels displayed.
- lxxv. Select 'mV' (#3), '-30.3 to 30.3' (#4), '5V' (#5), and '1/4 Bridge' (#6) for all activated channels as illustrated in Fig. C-1.
- lxxvi. Click 'Calibration' (#7) which will open up a window, 'StrainBook616/WBK16 Sensor Configuration' shown in Fig. C-2.
- lxxvii. Select the channels to be calibrated (i.e., switch to 'Yes') in the 'Cal?' column (#8) and configure each sensor as follows:
 - Sensor Type (#9): Strain Gage
 - Bridge Type (#10): 1/4 Bridge
 - Calibration Method (#11): Shunt (Rd)
 - Exc. Volts (#12): 5V
 - Gage Factor (#13): 2.0
 - Shunt Resistor (#14): 57983
 - Bridge Resistor (#15): 350
 - Max Appl. Load (#16): 3000
 - Point 1 (#17): -3000
- lxxviii. Click 'Calibration Enabled Channel' (#18) to calibrate the selected channels.
- lxxix. Once the calibration is completed, click 'Close' (#19) and save the calibration file.

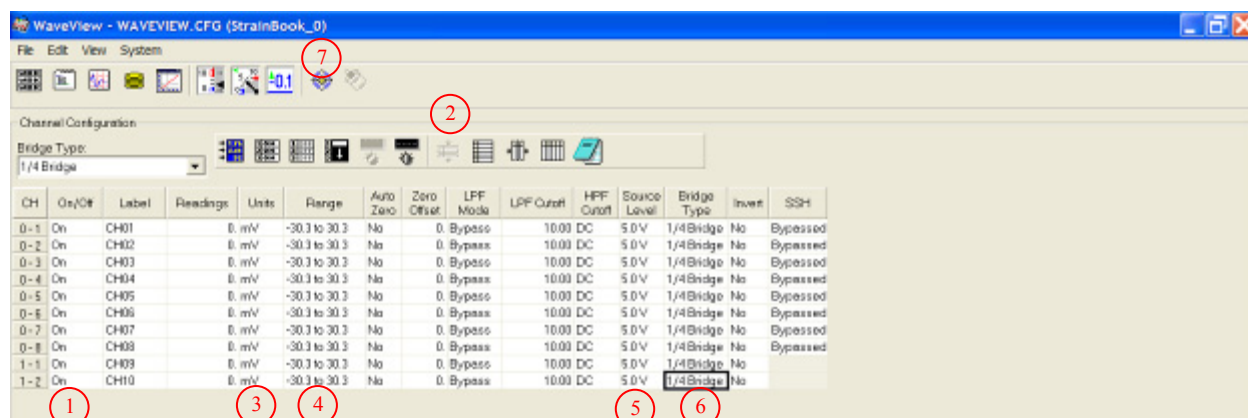


Figure C-1.

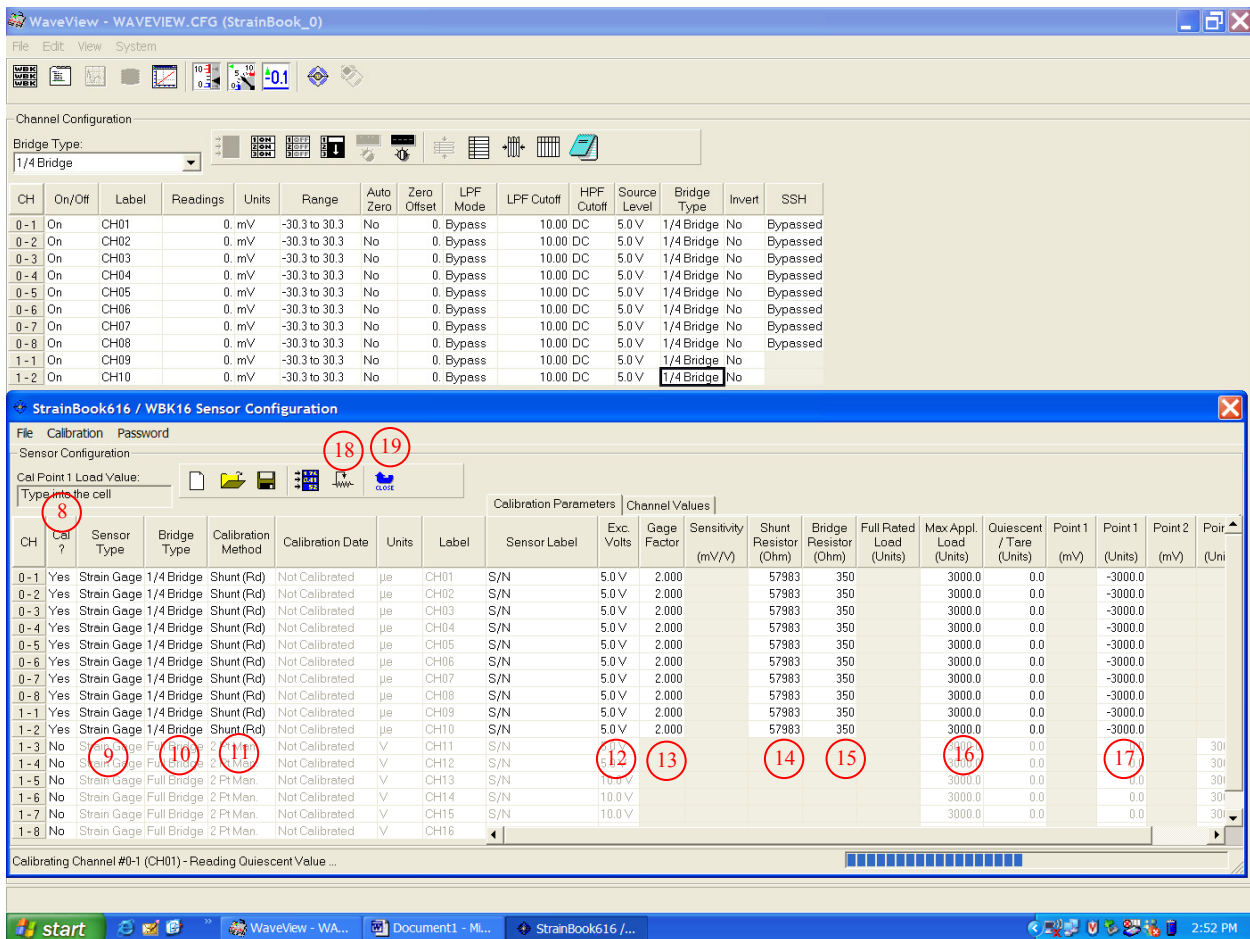


Figure C-2.

APPENDIX D

Installation of 4 *MainDAQ815.EXE* as a Service Program

- lxxx.* Install FireDaemon software.
- lxxxi.* Double click on the FireDaemon Service Manager icon (shown in Fig. D-1).
- lxxxii.* In the FireDaemon Pro Service Manager window, go to 'Select' in the menu bar and select 'New' option as shown in Fig. D-2.
- lxxxiii.* Under the 'Program' tab in the 'New Service Definition' window (shown in Fig. D-3a),
 - a. Type in the name of a service program to be created (using alphabetic-numeric characters only) in the 'Short Name' and 'Display Name' text boxes available in the 'Service Identification Program' frame.
 - b. Using the browse tool available, select the EXE program (*4 MainDAQ815.EXE*) to be installed as a service program. By doing this, its working directory will automatically be assigned.
 - c. Enter the start-up time (the time for which the program is forced to wait before it automatically resumes) in the 'Start-up Time' text box. 60000 ms is recommended (which is equivalent of 60 seconds).

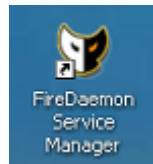


Figure D-1. FireDaemon Service Manager icon

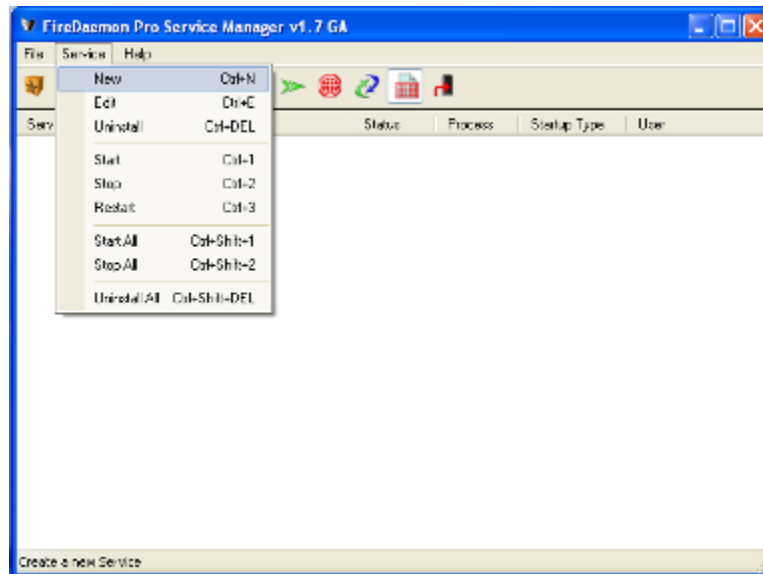
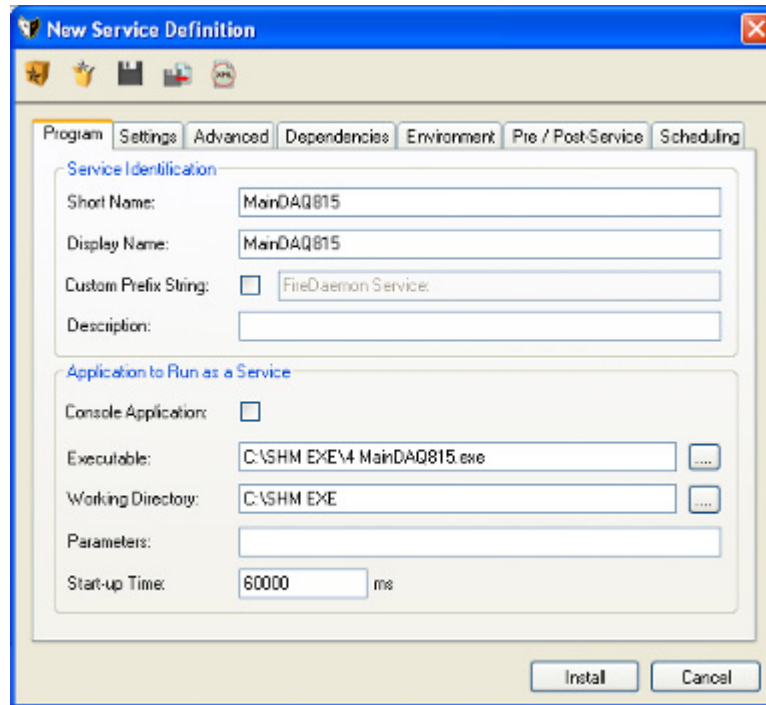
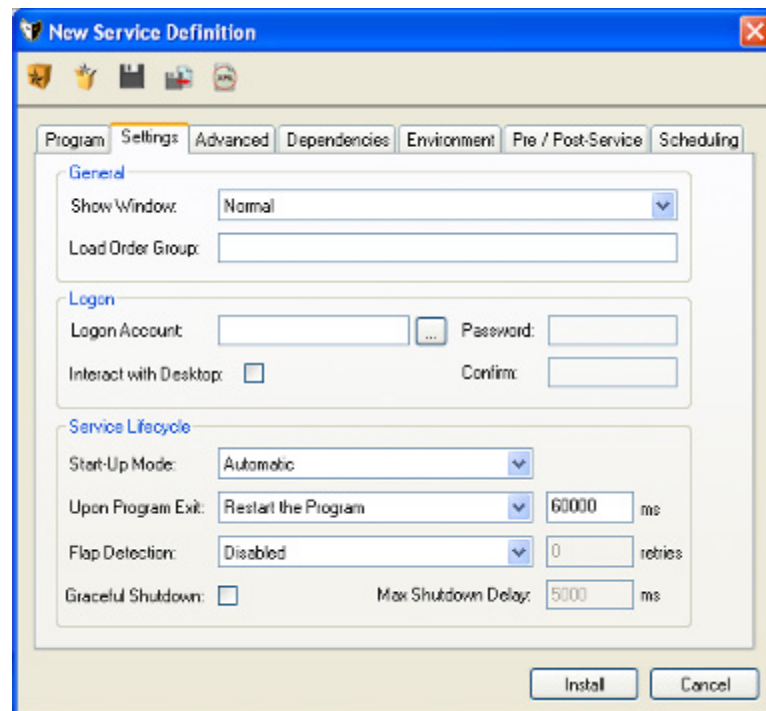


Figure D-2. Creating a new service program in the FireDaemon Pro Service Manager window



(a) Program tab



(b) Settings tab

Figure D-3. New Service Definition window

- lxxxiv.* Under the 'Settings' tab in the 'New Service Definition' window (shown in Fig. D-3b)
- Enable the 'Interact with Desktop' option by clicking the check box (if selected, a green check mark will appear in the check box).
 - Set the 'Start-Up Mode' to 'Automatic'
 - Set the 'Upon Program Exit' to 'Restart the Program' and enter the time for which the program is forced to wait before it automatically resumes (60000 ms recommended).
 - Click 'Install' to install *4 MainDAQ815.EXE* as a service program.
- lxxxv.* If successfully installed, a prompt dialog box will appear indicating that the installation process is completed (Fig. D-4) and the service program created will be listed in the FireDaemon Pro Service Manager window as shown in Fig. D-5.

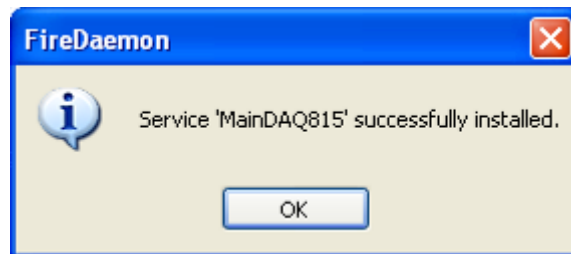


Figure D-4. Prompt dialog box

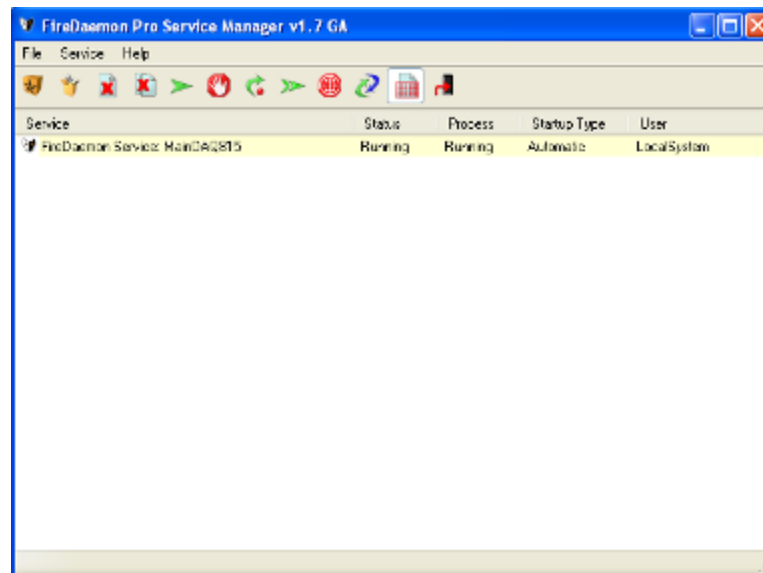
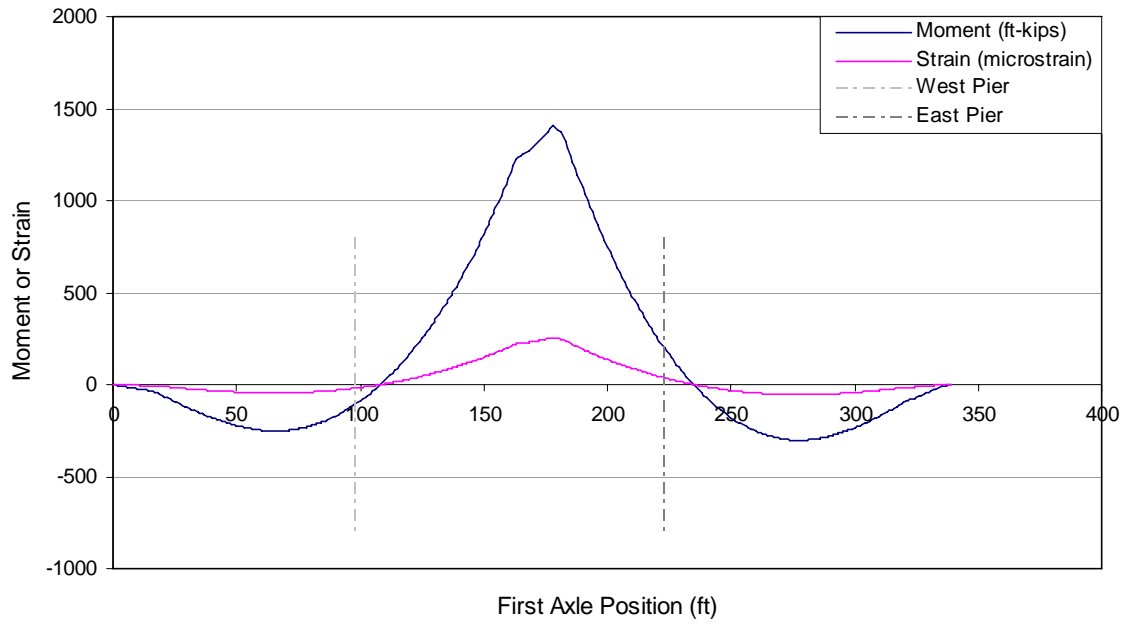


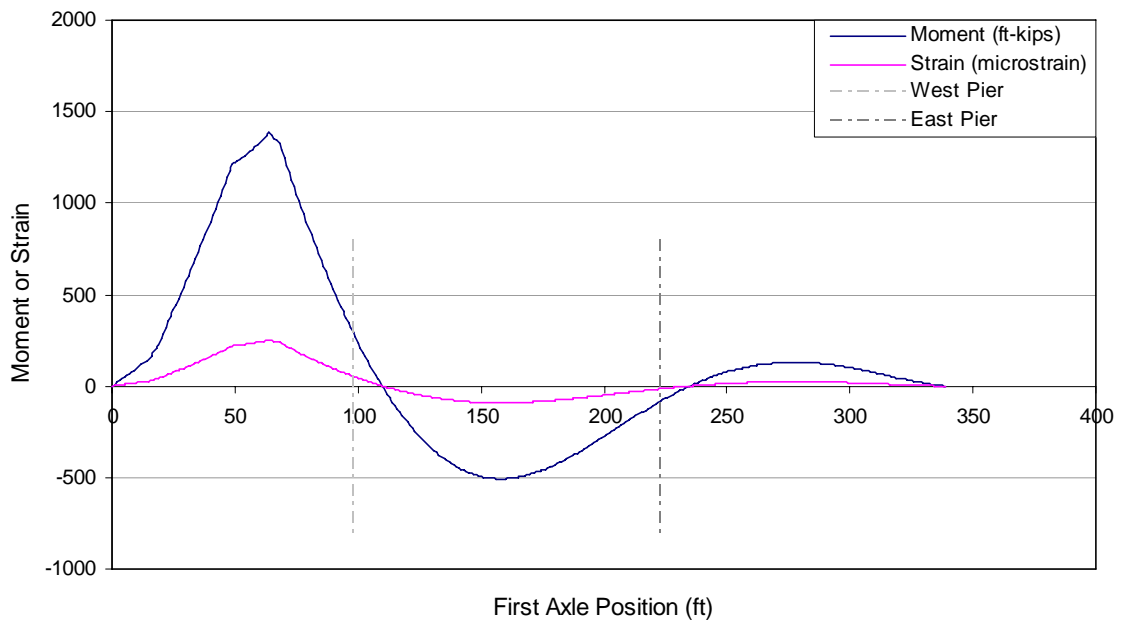
Figure D-5. FireDaemon Pro Service Manager window (service MainDAQ815 installed)

APPENDIX E

Plots of the theoretical moments and strain due to each design load

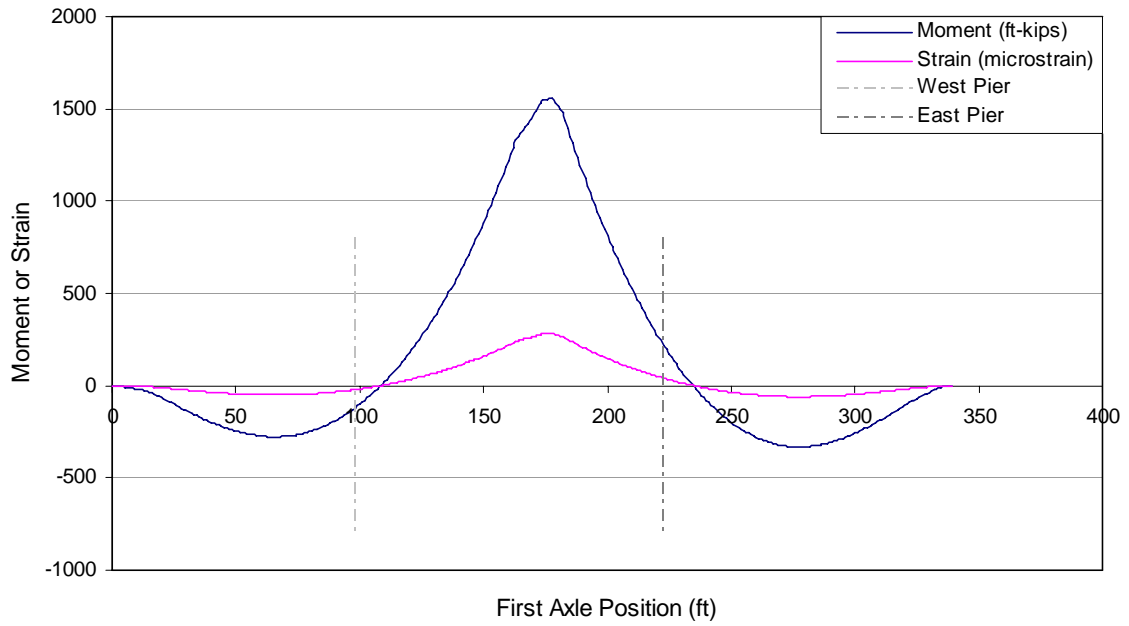


(a) Sensors 1 and 4 in the center span

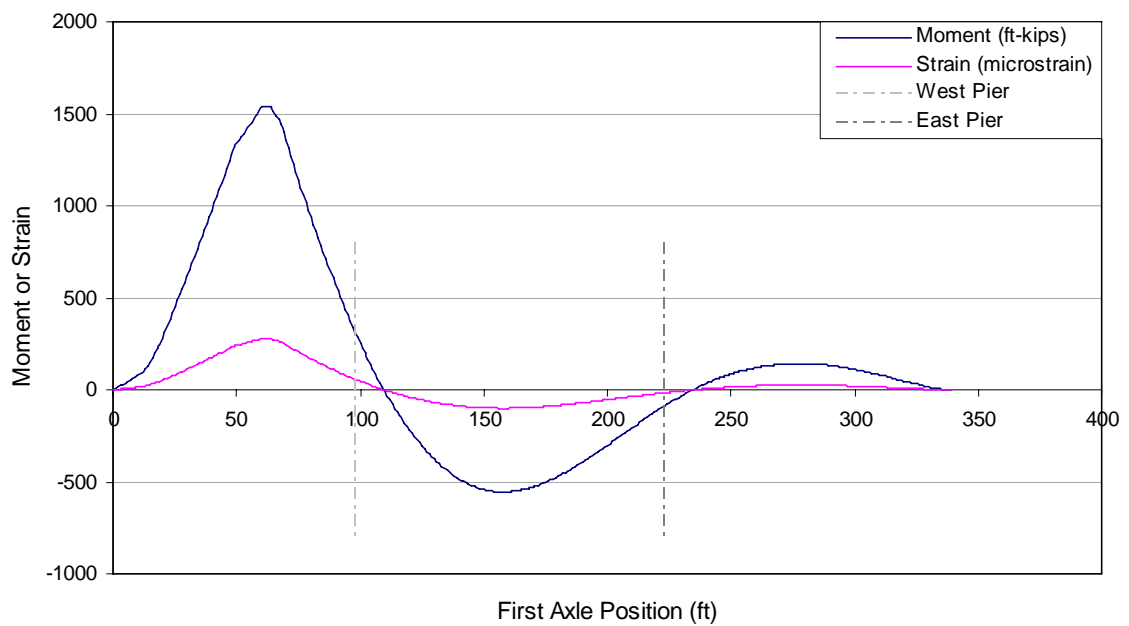


(b) Sensors 5 and 8 in the west end span

Figure E-1. Moments and strain due to Iowa legal truck (Type 3) at the sensor locations with respect to the first axle position

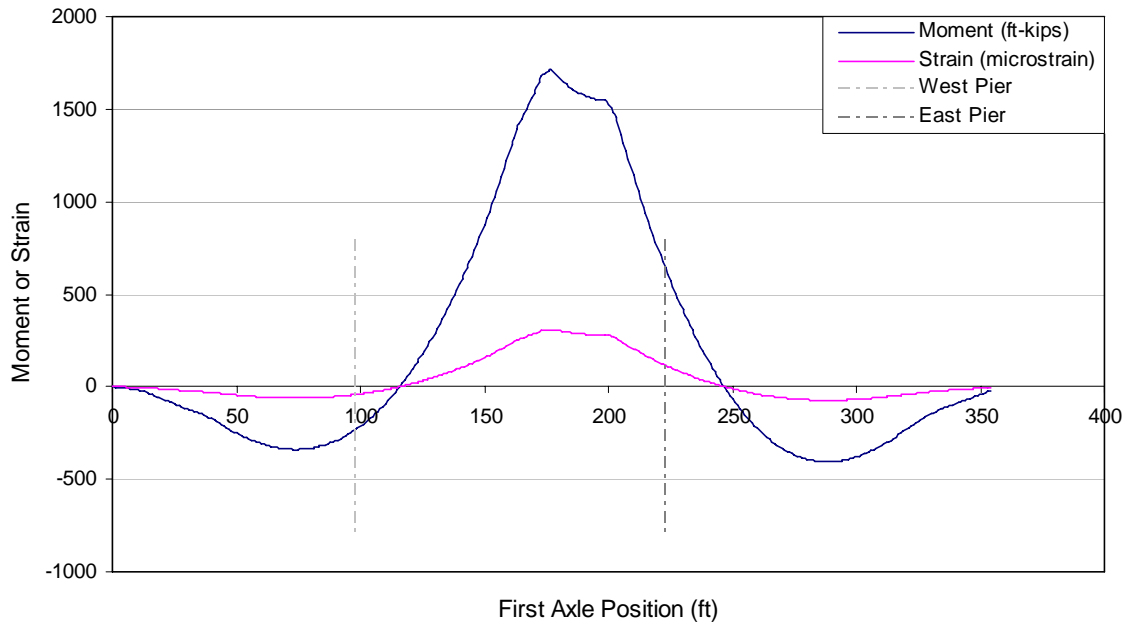


(a) Sensors 1 and 4 in the center span

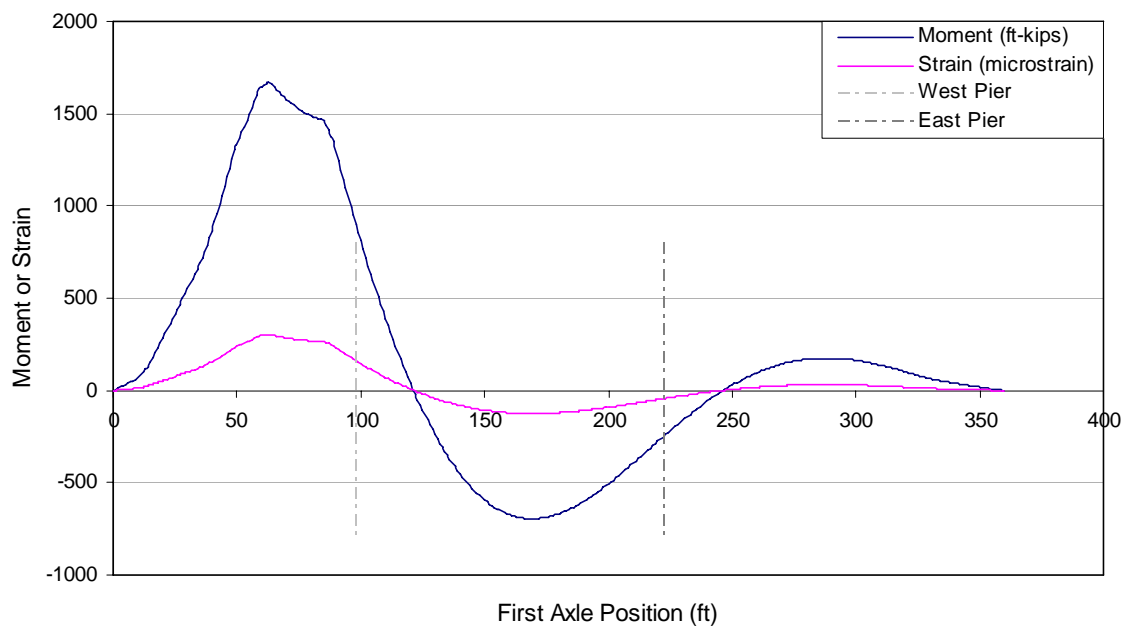


(b) Sensors 5 and 8 in the west end span

Figure E-2. Moments and strain due to Iowa legal truck (Type 4) at the sensor locations with respect to the first axle position

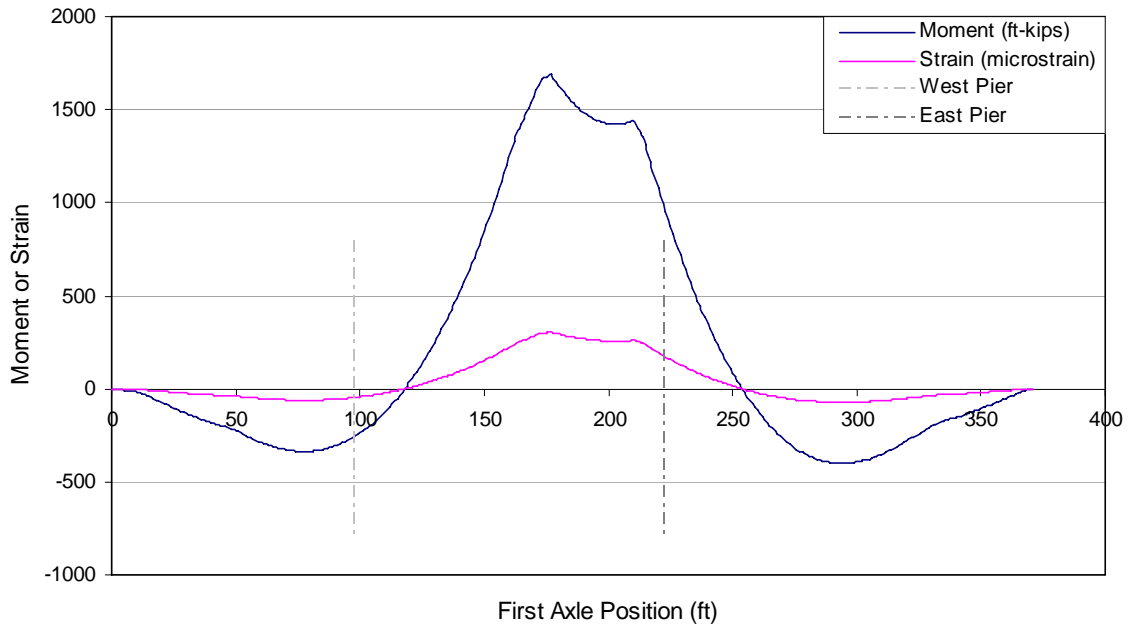


(a) Sensors 1 and 4 in the center span

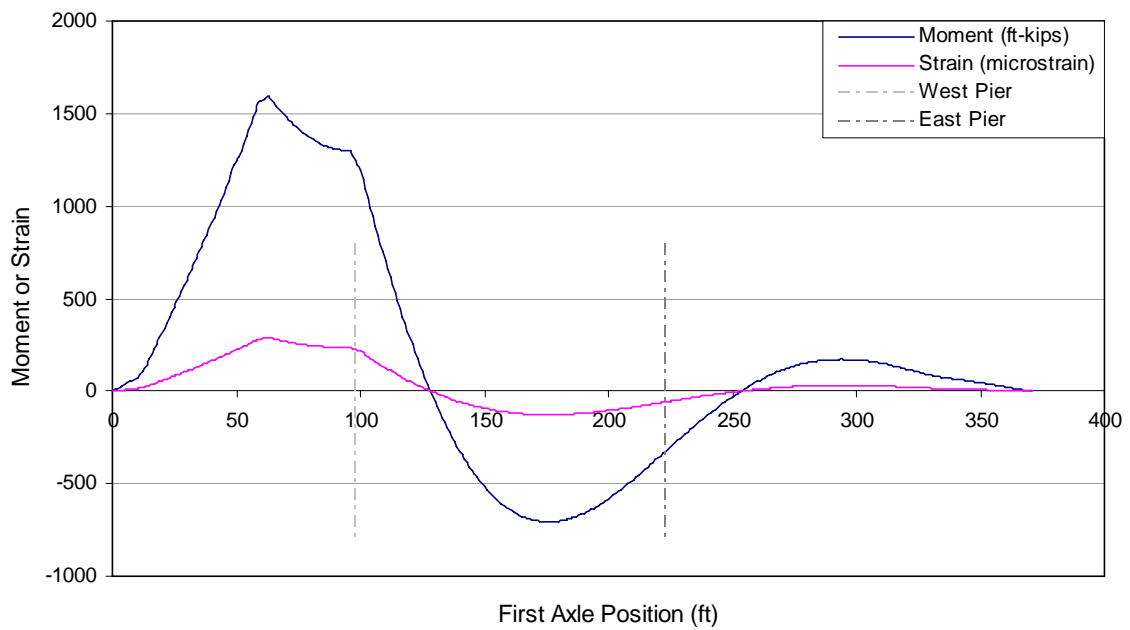


(b) Sensors 5 and 8 in the west end span

Figure E-3. Moments and strain due to Iowa legal truck (Type 3S2 A) at the sensor locations with respect to the first axle position

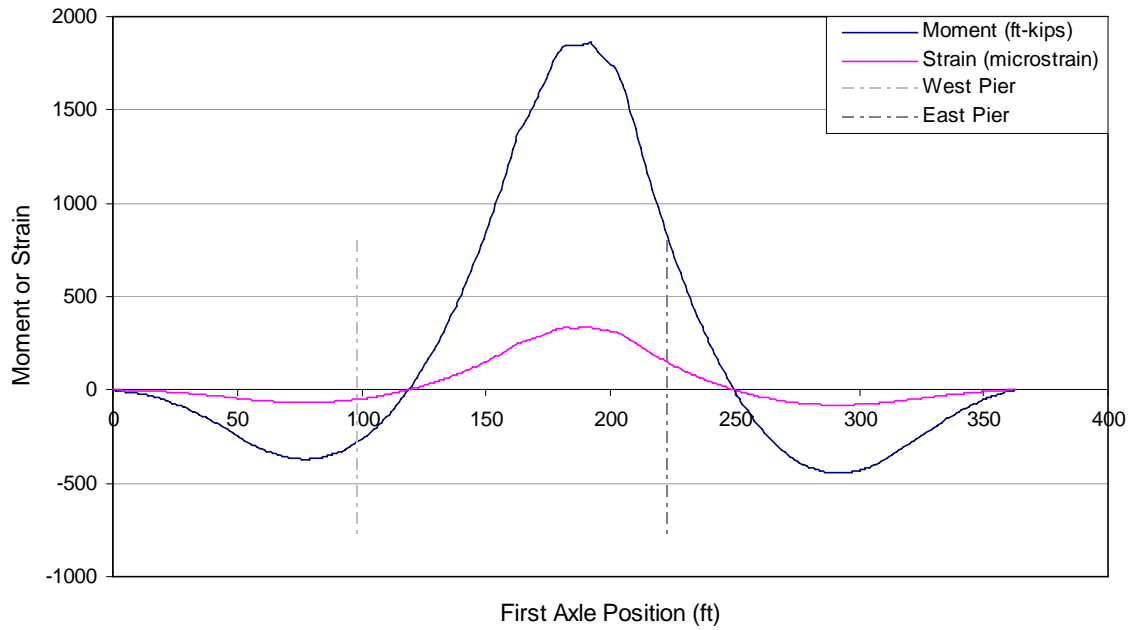


(a) Sensors 1 and 4 in the center span

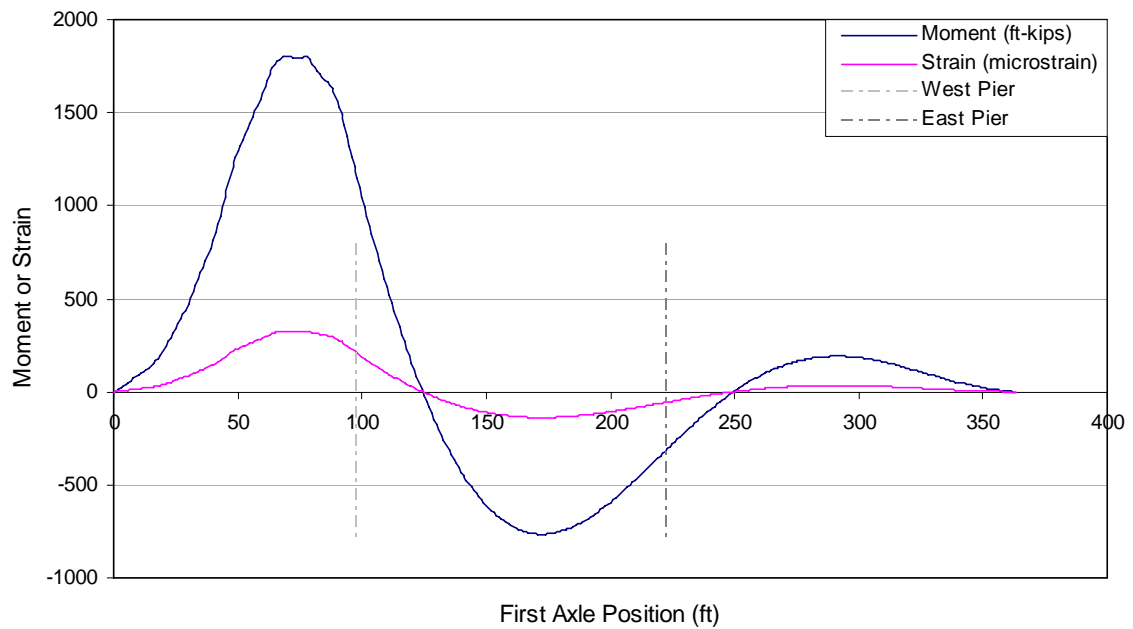


(b) Sensors 5 and 8 in the west end span

Figure E-4. Moments and strain due to Iowa legal truck (Type 3S3 B) at the sensor locations with respect to the first axle position

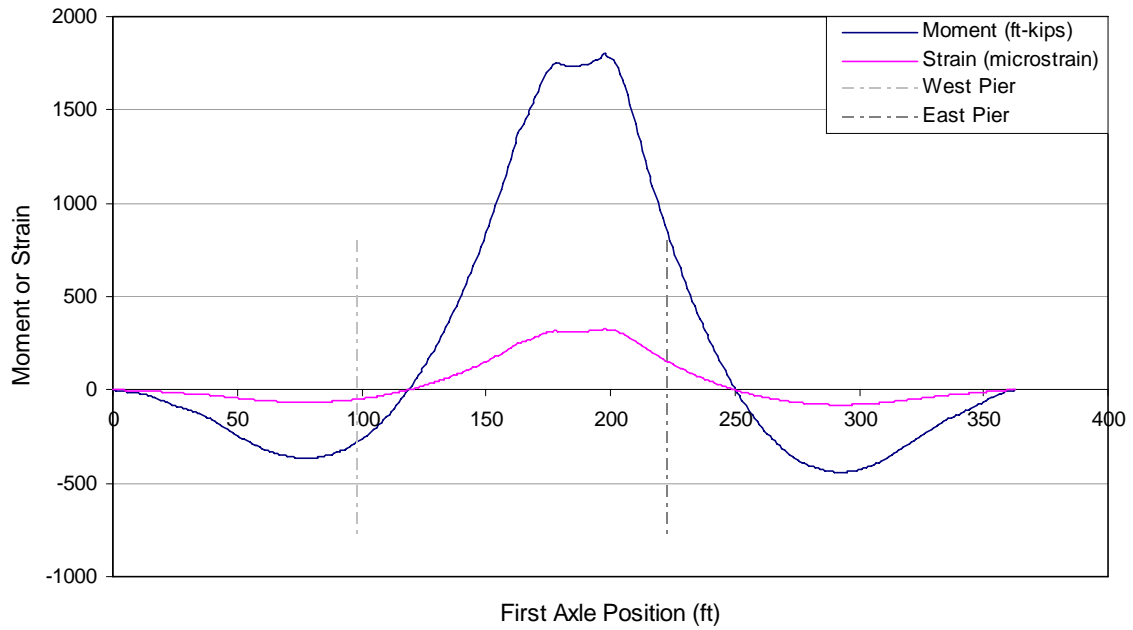


(a) Sensors 1 and 4 in the center span

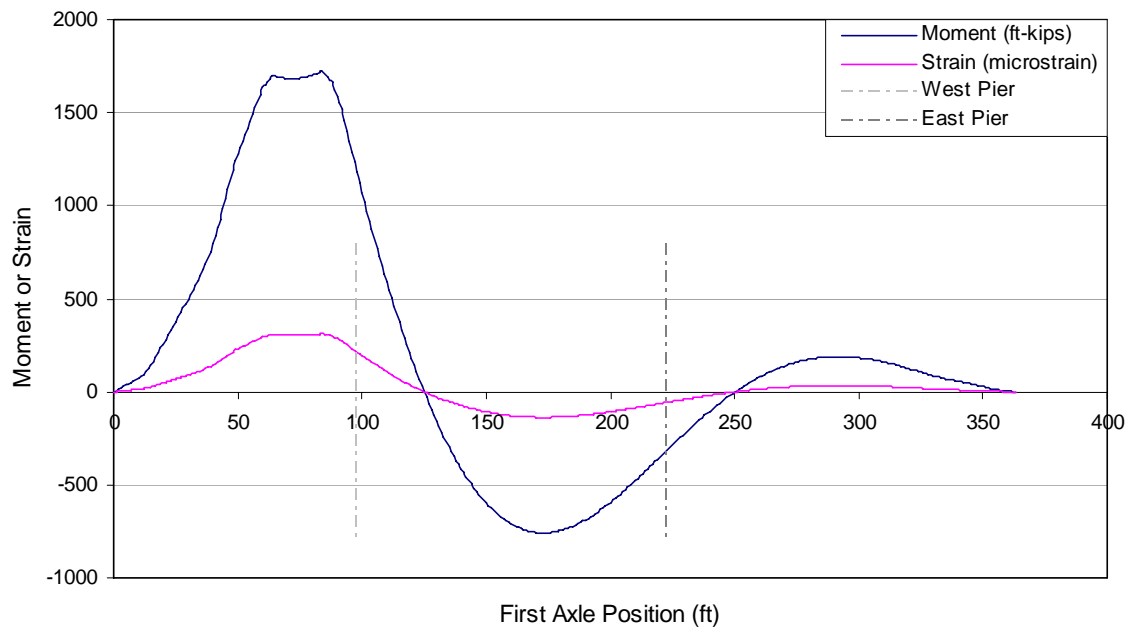


(b) Sensors 5 and 8 in the west end span

Figure E-5. Moments and strain due to Iowa legal truck (Type 3-3) at the sensor locations with respect to the first axle position

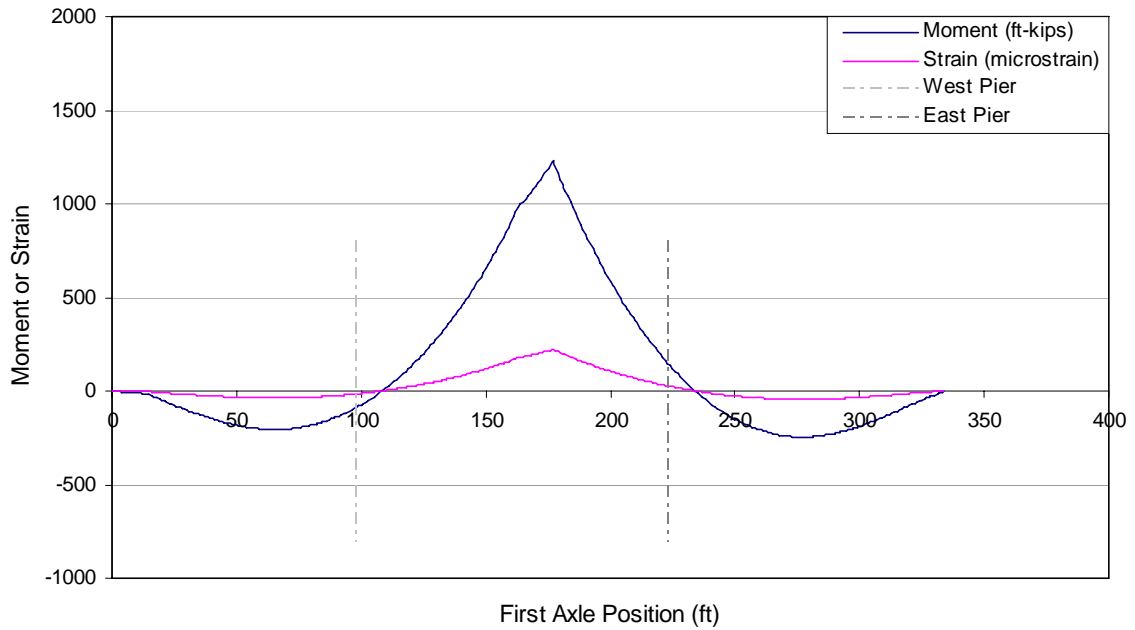


(a) Sensors 1 and 4 in the center span

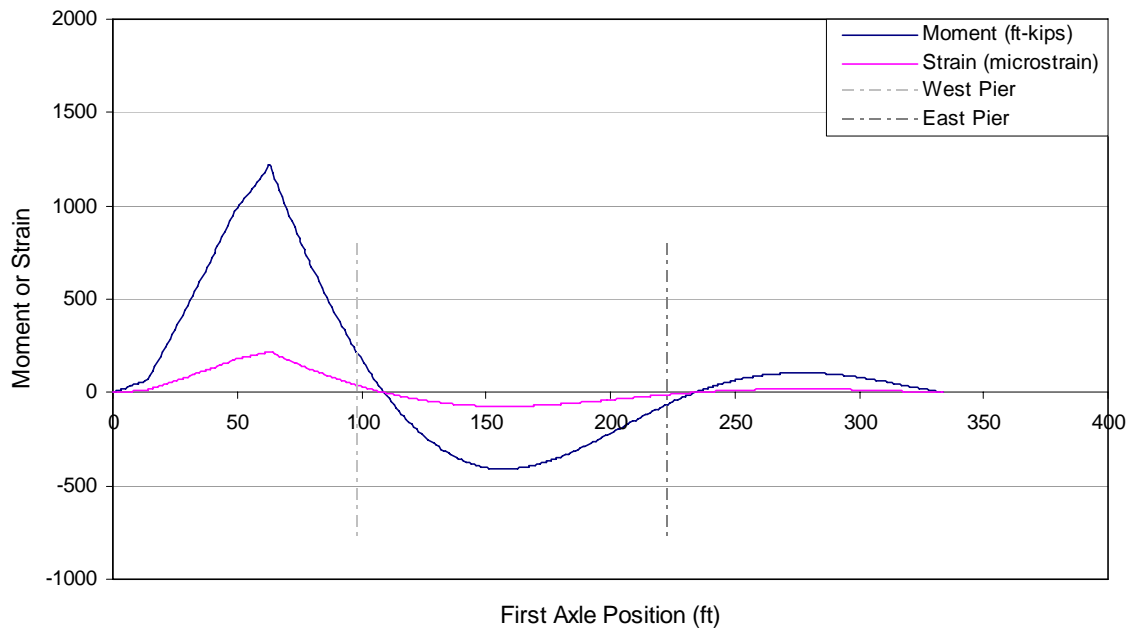


(b) Sensors 5 and 8 in the west end span

Figure E-6. Moments and strain due to Iowa legal truck (Type 3S3) at the sensor locations with respect to the first axle position

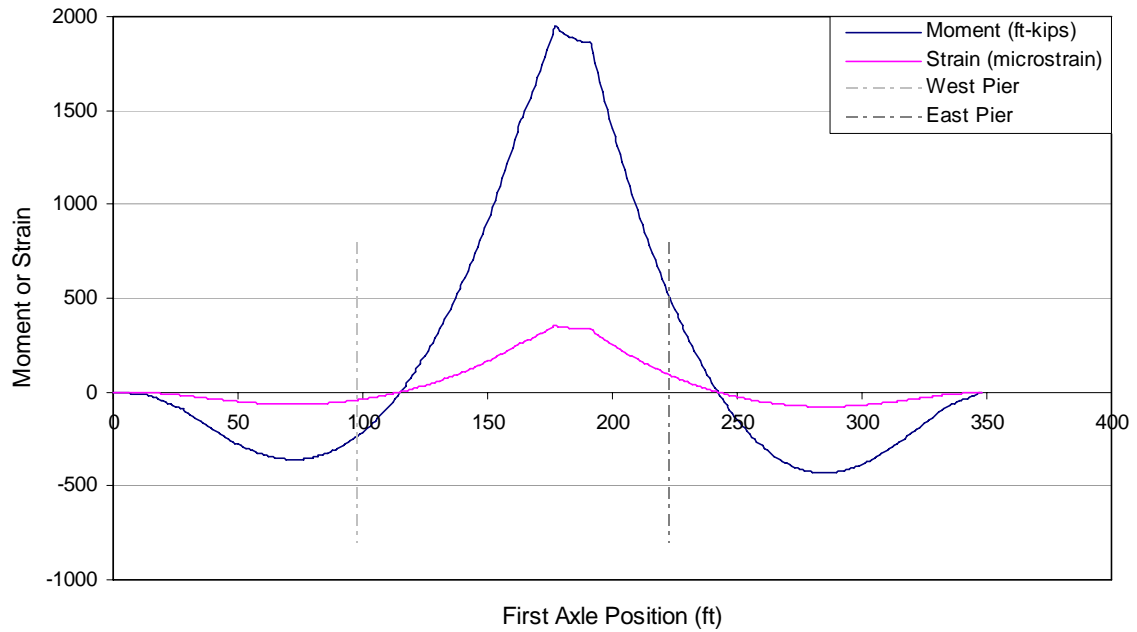


(a) Sensors 1 and 4 in the center span

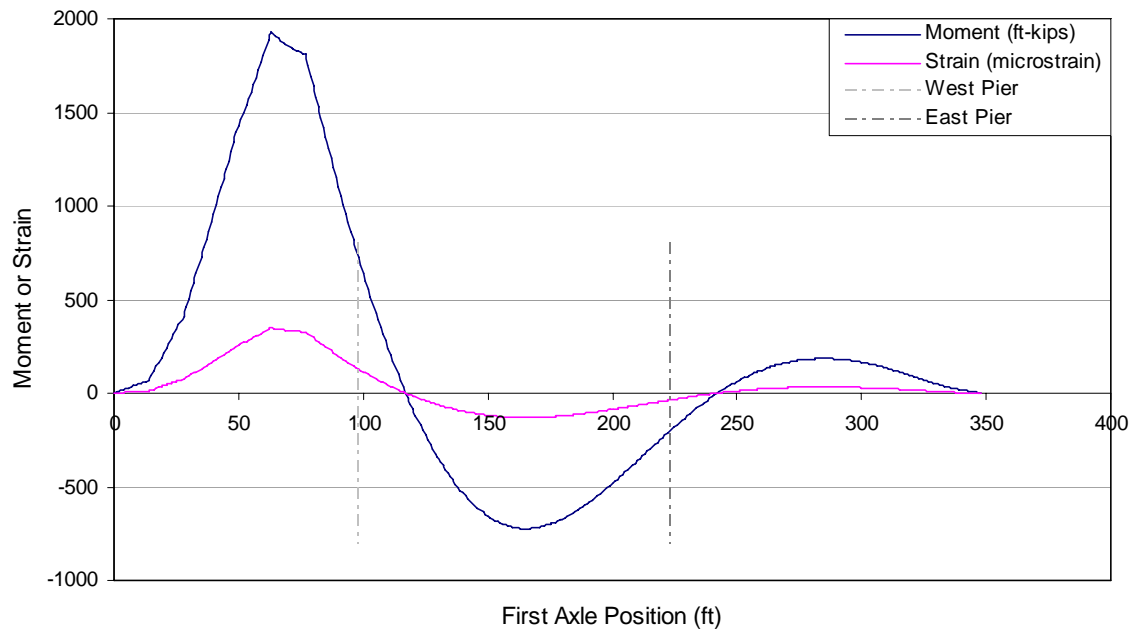


(b) Sensors 5 and 8 in the west end span

Figure E-7. Moments and strain due to H 20 truck (2 axles) at the sensor locations with respect to the first axle position

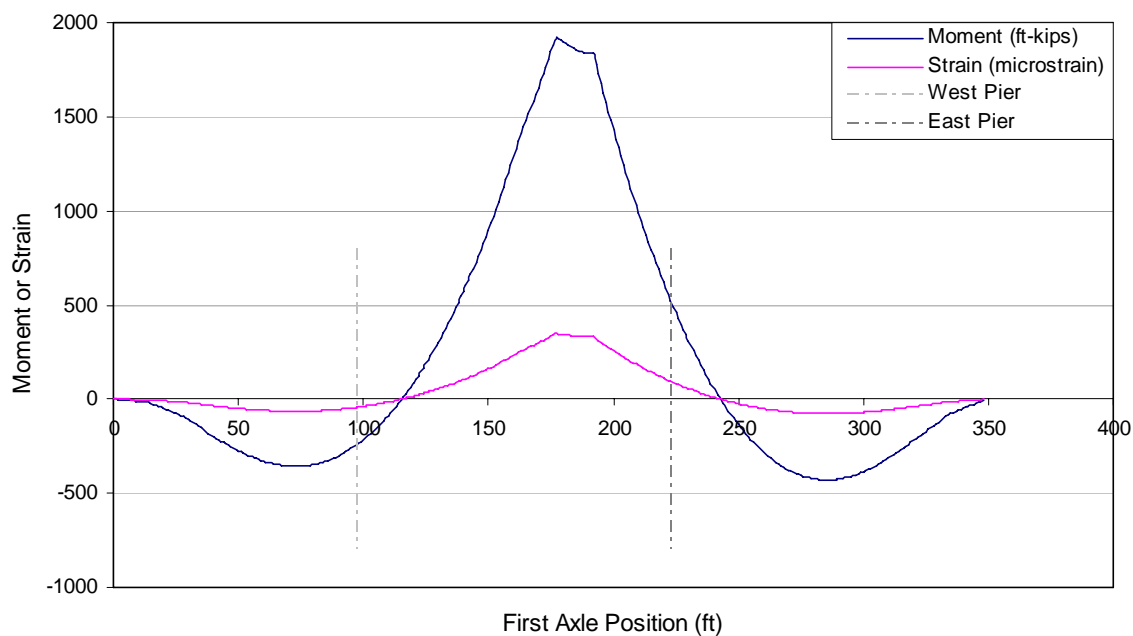


(a) Sensors 1 and 4 in the center span

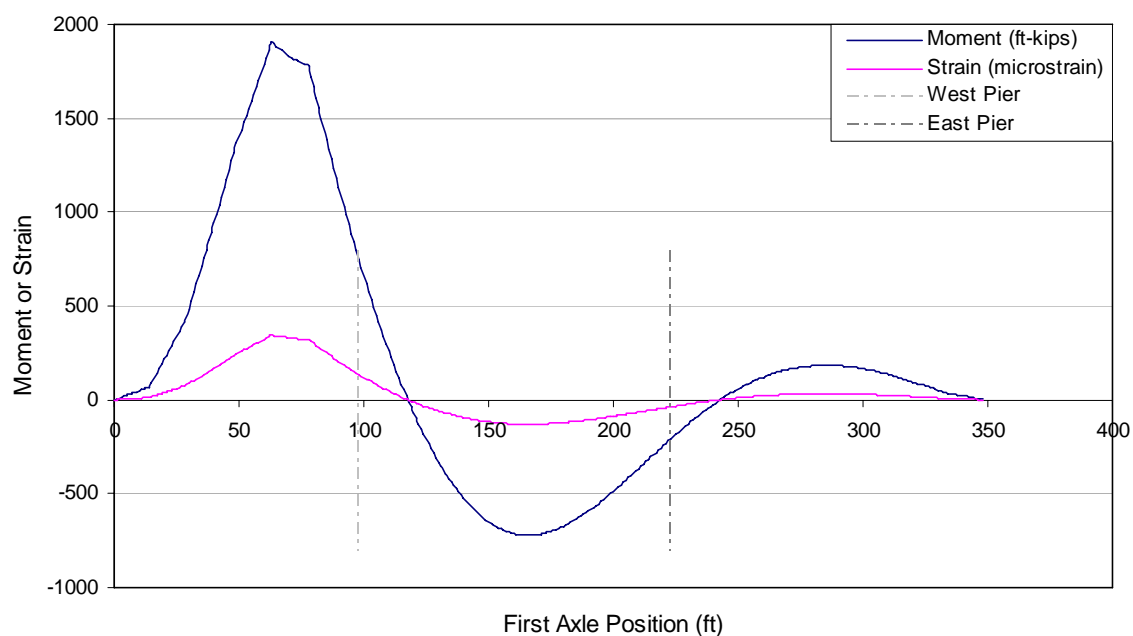


(b) Sensors 5 and 8 in the west end span

Figure E-8. Moments and strain due to HS 20 truck (3 axles – 14 ft) at the sensor locations with respect to the first axle position

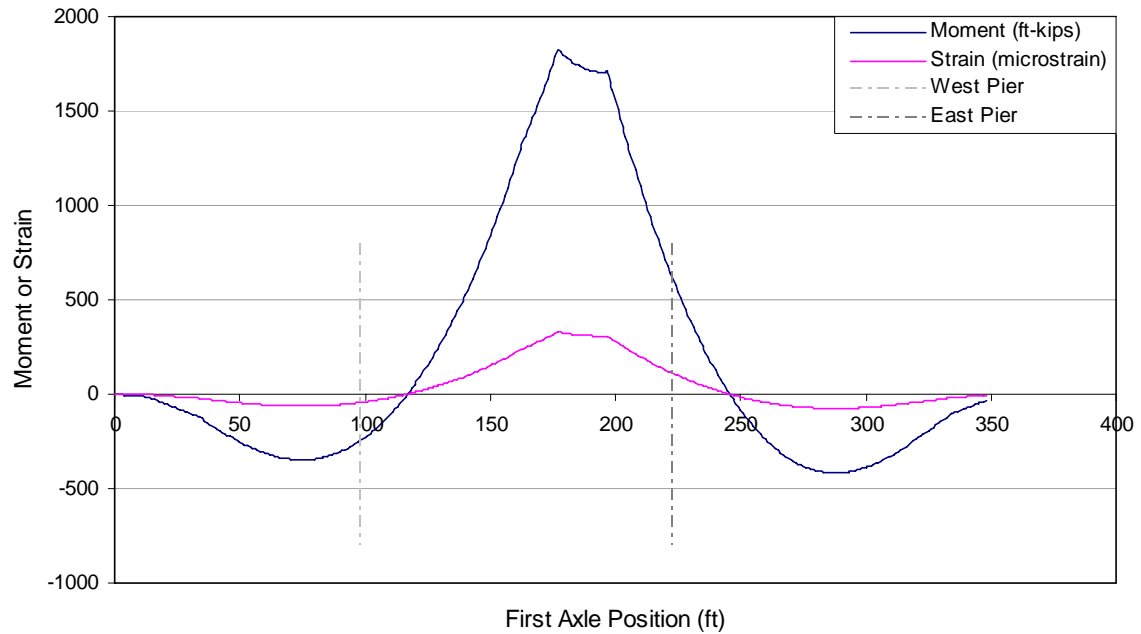


(a) Sensors 1 and 4 in the center span

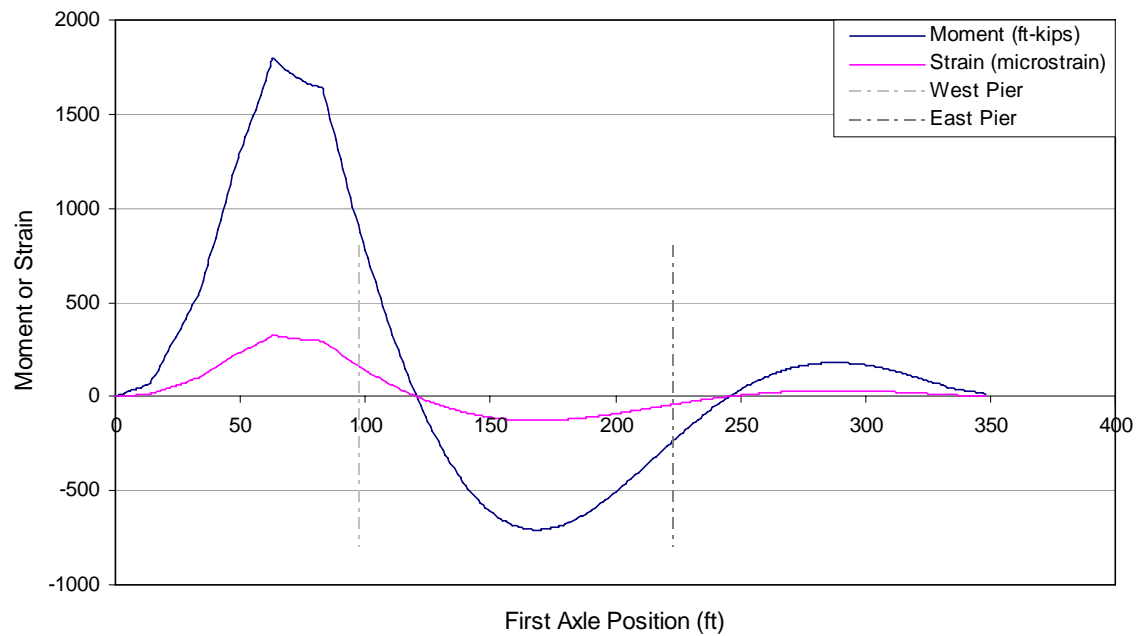


(b) Sensors 5 and 8 in the west end span

Figure E-9. Moments and strain due to HS 20 truck (3 axles – 15 ft) at the sensor locations with respect to the first axle position

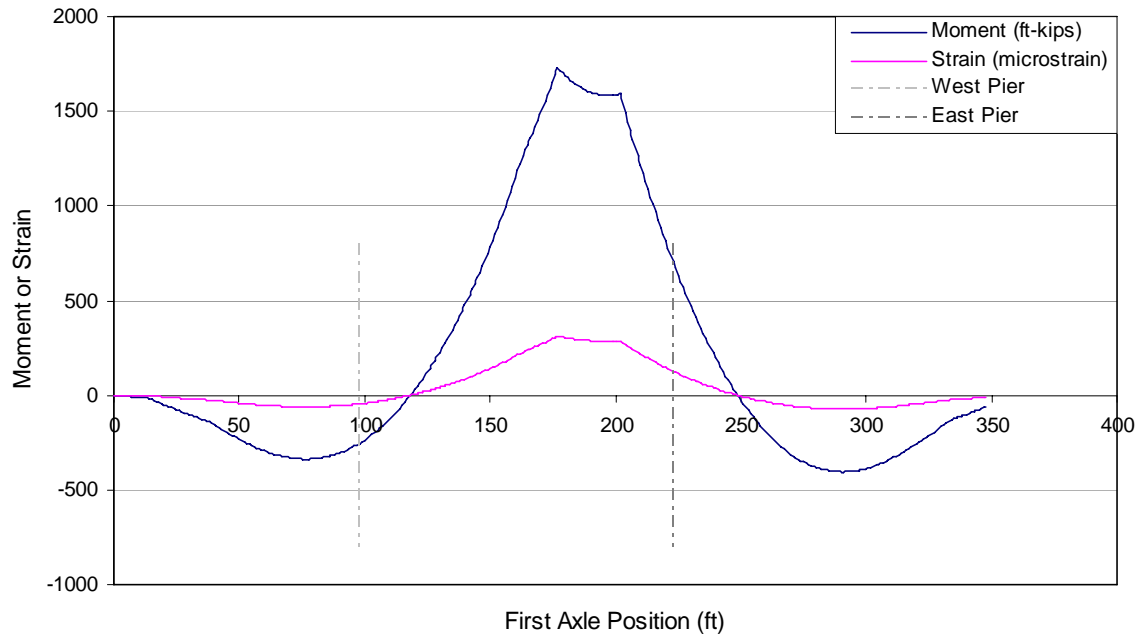


(a) Sensors 1 and 4 in the center span

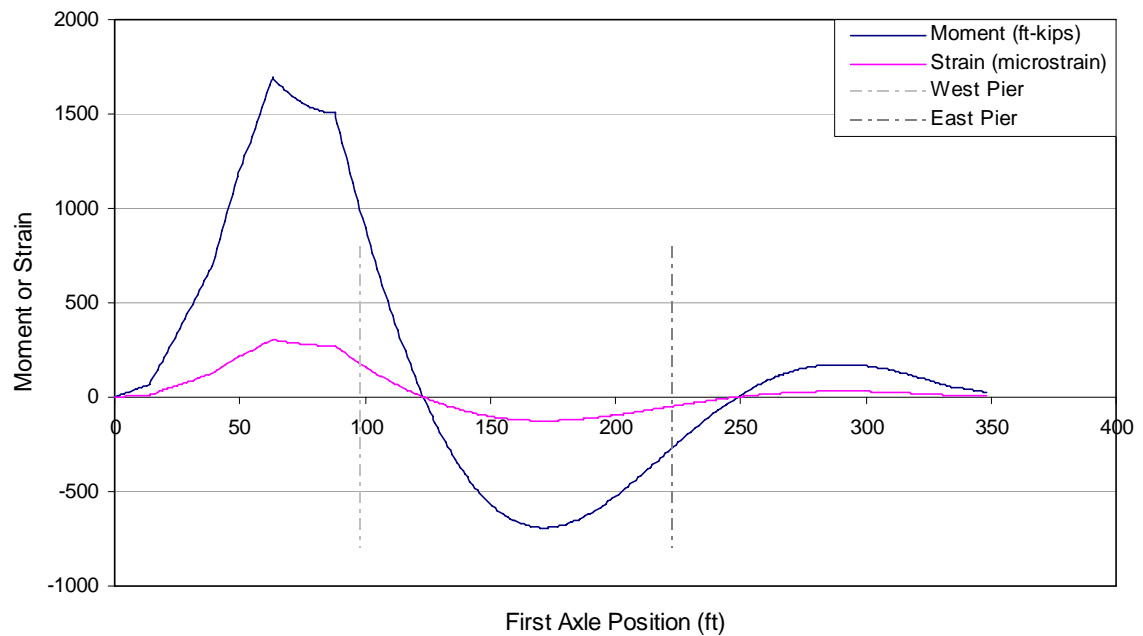


(b) Sensors 5 and 8 in the west end span

Figure E-10. Moments and strain due to HS 20 truck (3 axles – 20 ft) at the sensor locations with respect to the first axle position

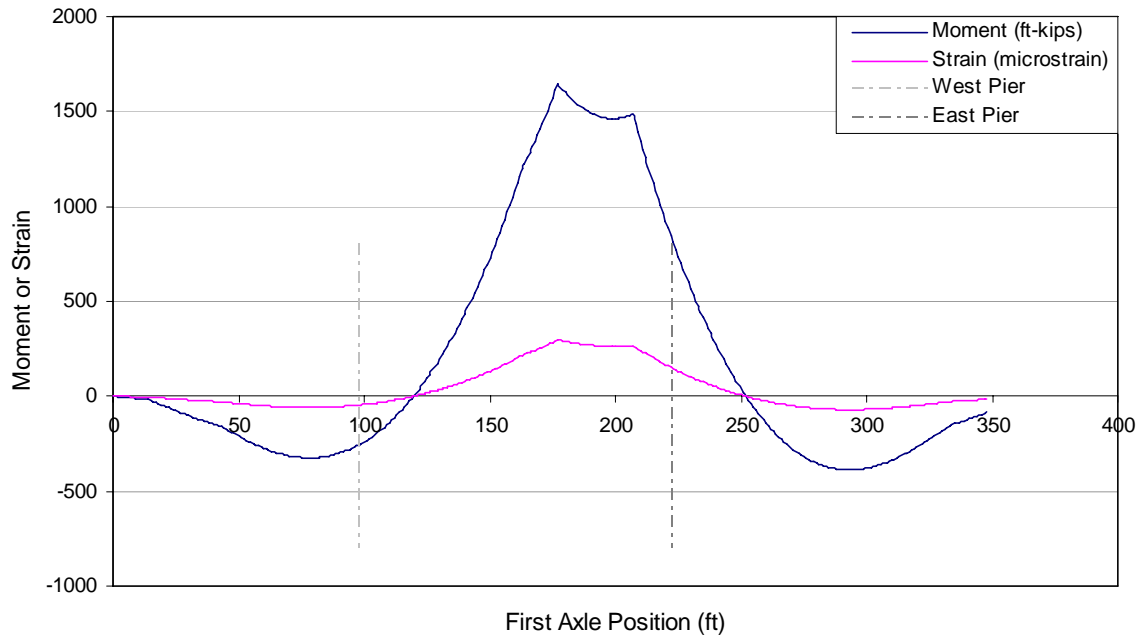


(a) Sensors 1 and 4 in the center span

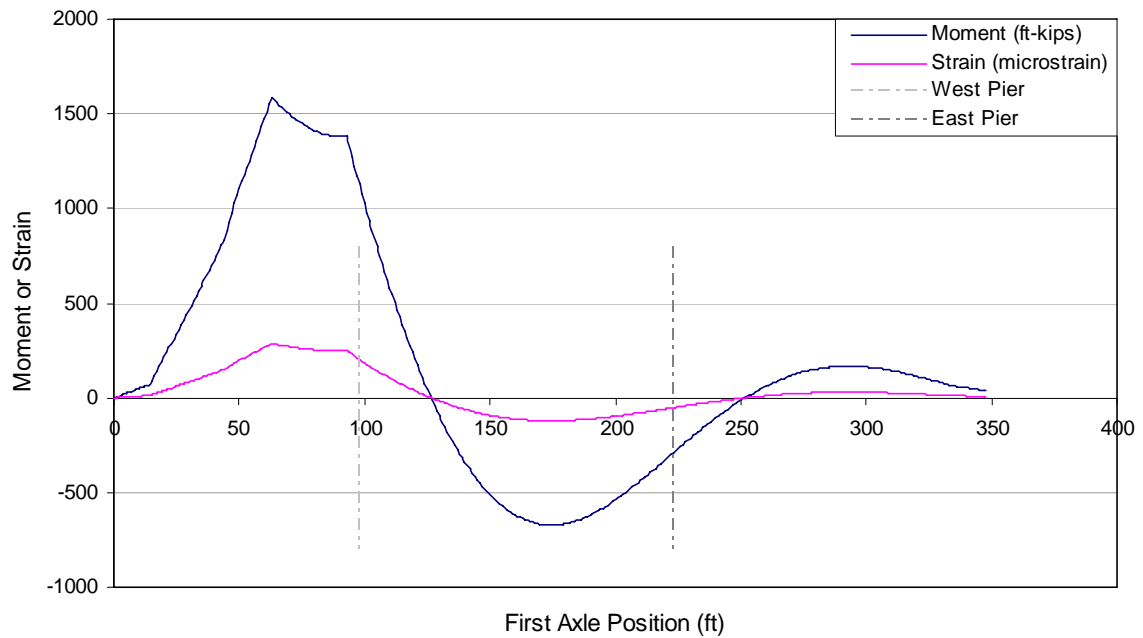


(b) Sensors 5 and 8 in the west end span

Figure E-11. Moments and strain due to HS 20 truck (3 axles – 25 ft) at the sensor locations with respect to the first axle position

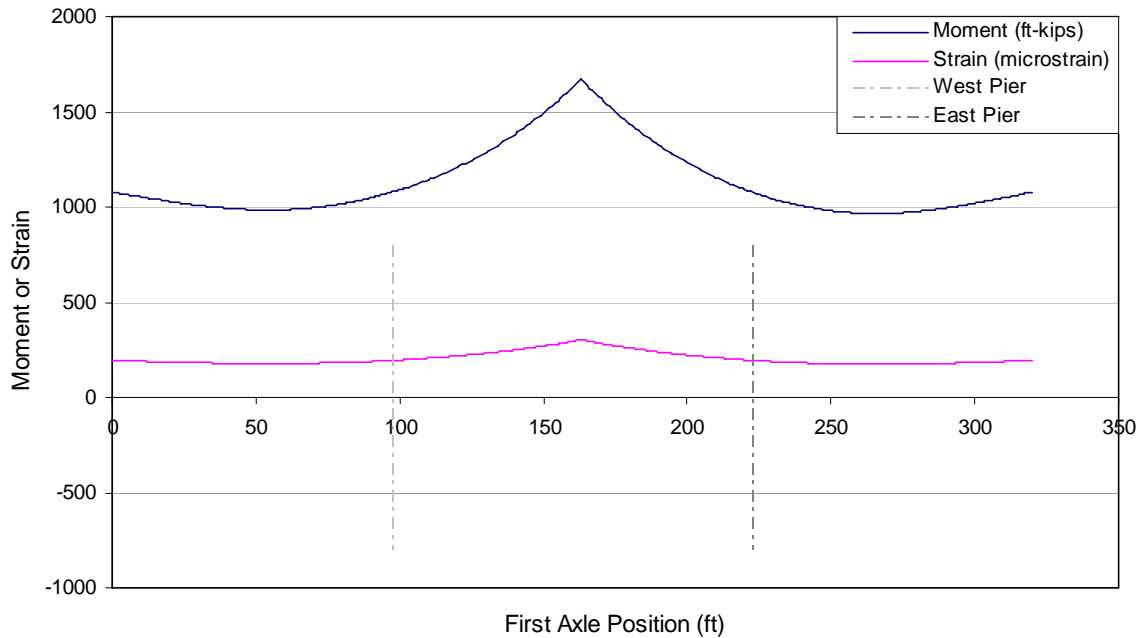


(a) Sensors 1 and 4 in the center span

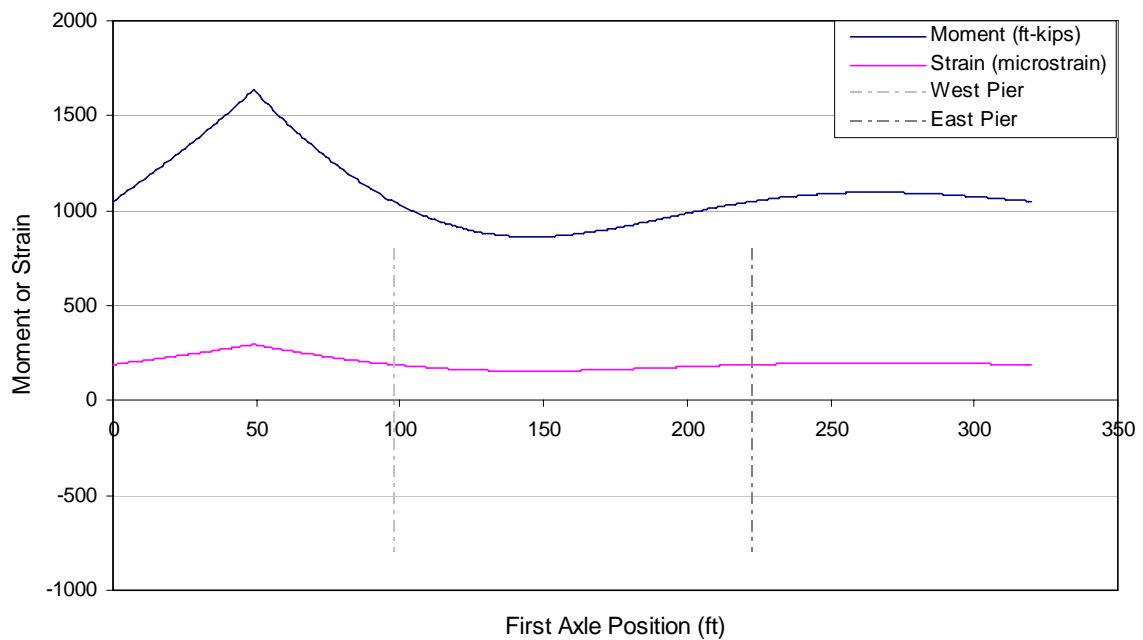


(b) Sensors 5 and 8 in the west end span

Figure E-12. Moments and strain due to HS 20 truck (3 axles – 30 ft) at the sensor locations with respect to the first axle position



(a) Sensors 1 and 4 in the center span



(b) Sensors 5 and 8 in the west end span

Figure E-13. Moments and strain due to HS 20 truck train (lane) loading at the sensor locations with respect to the first axle position

APPENDIX F

Evaluation Report (November 14th, 2006 ~ December 14th, 2006)

Monitoring Period (11/14/2006 3:00:18 PM ~ 12/14/2006 4:37:46 PM)

Monitoring Summary (microstrain)

	Sensor1	Sensor2	Sensor3	Sensor4	Sensor5	Sensor6	Sensor7	Sensor8
Overload Event Threshold	221	0	0	221	219	0	0	219
Maximum	165	79	91	174	156	103	116	167
Average	10	12	13	10	10	10	9	10
Average Slope	0	0	0	0	0	0	0	0

Alarm Event (Overload/Impact)

1. 0

Number of Event (bin width: 20 microstrain)

Bin Minimum	0	20	40	60	80	100	120	140	160	180	200
Sensor1	137949	6093	2456	271	452	56	5	1	1	0	0

Bin Minimum	0	20	40	60	80	100	120	140	160	180	200
Sensor2	32636	5971	34	2	0	0	0	0	0	0	0

Bin Minimum	0	20	40	60	80	100	120	140	160	180	200
Sensor3	38967	8773	223	3	1	0	0	0	0	0	0

Bin Minimum	0	20	40	60	80	100	120	140	160	180	200
Sensor4	245901	8469	4899	2018	2133	199	12	5	1	0	0

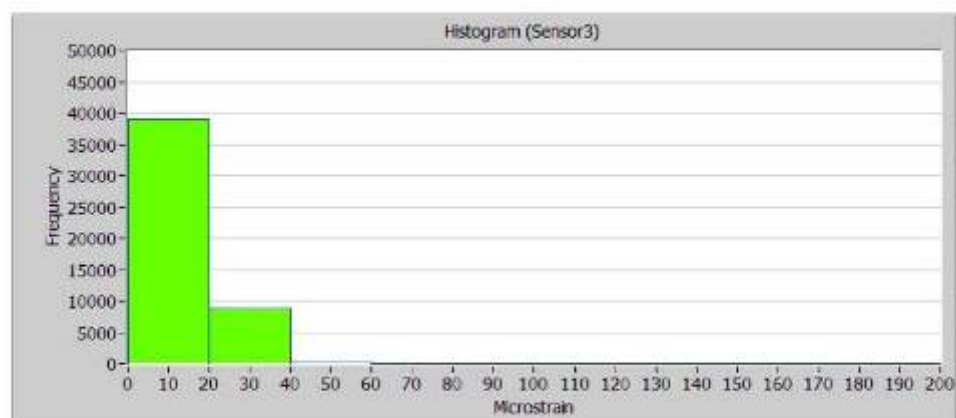
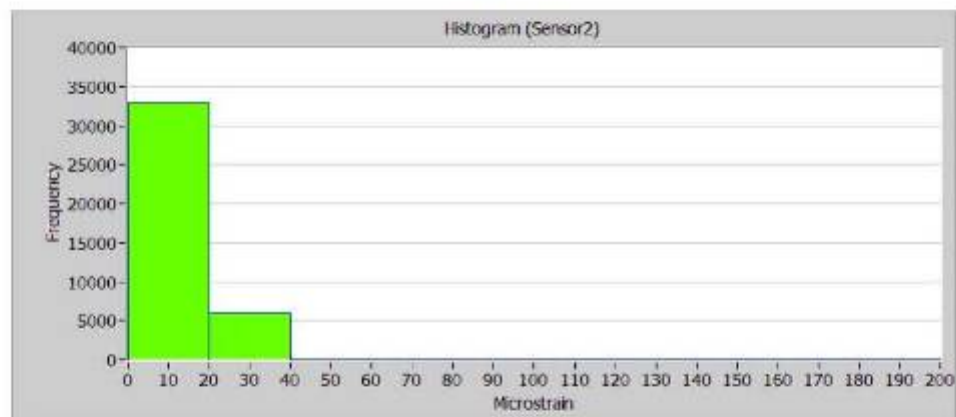
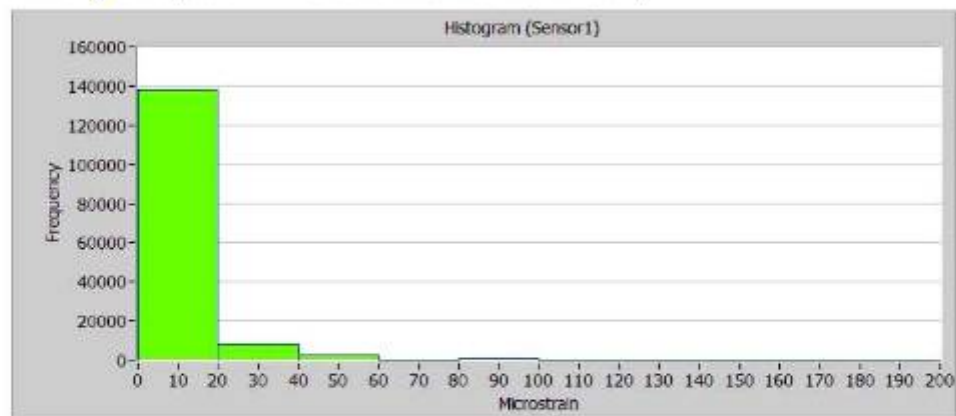
Bin Minimum	0	20	40	60	80	100	120	140	160	180	200
Sensor5	85521	7369	630	500	163	7	2	1	0	0	0

Bin Minimum	0	20	40	60	80	100	120	140	160	180	200
Sensor6	92610	9170	1331	296	5	2	0	0	0	0	0

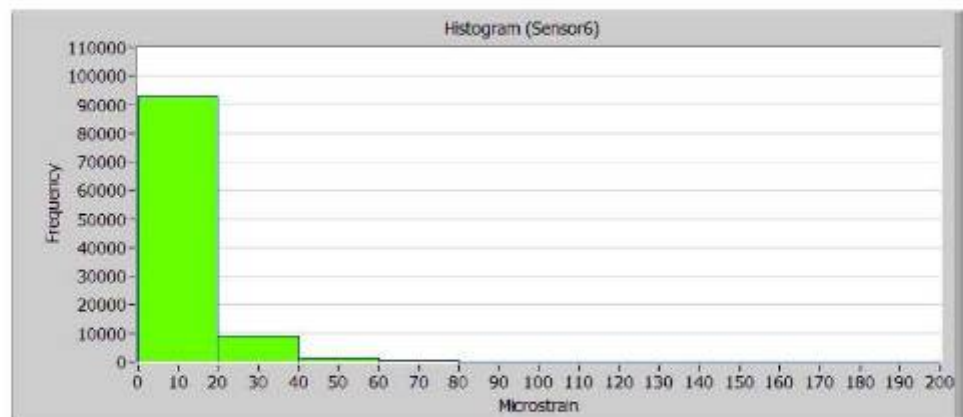
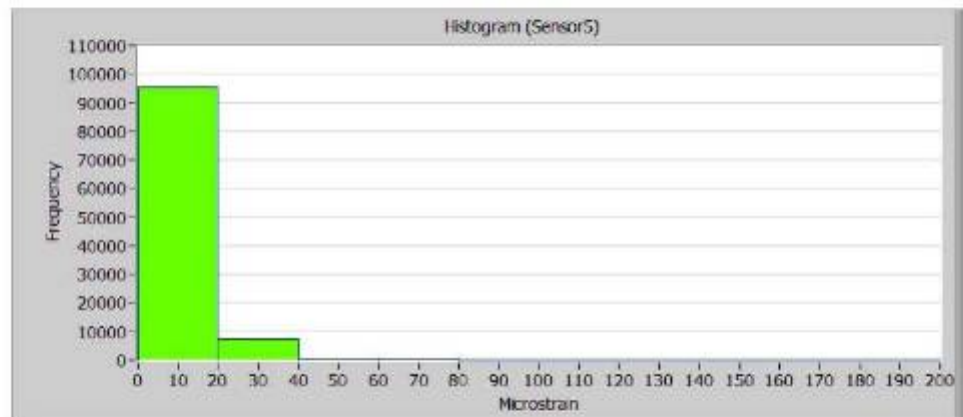
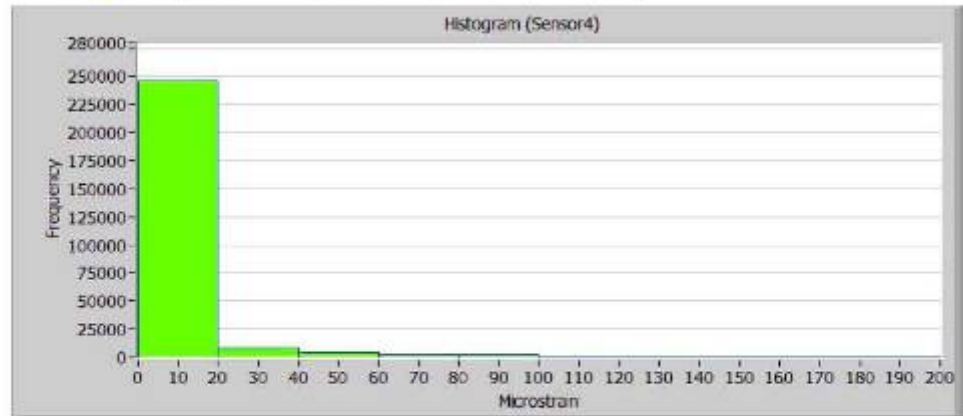
Bin Minimum	0	20	40	60	80	100	120	140	160	180	200
Sensor7	191547	10198	5769	594	13	4	0	0	0	0	0

Bin Minimum	0	20	40	60	80	100	120	140	160	180	200
Sensor8	256114	10187	3903	2600	919	22	9	2	1	0	0

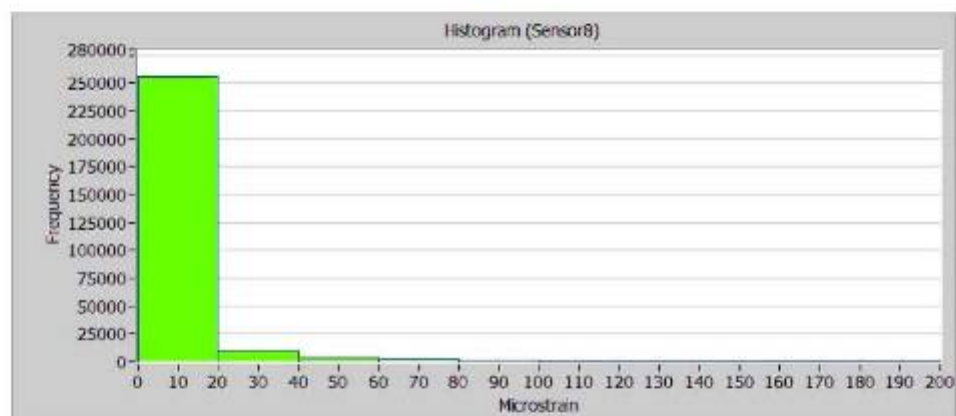
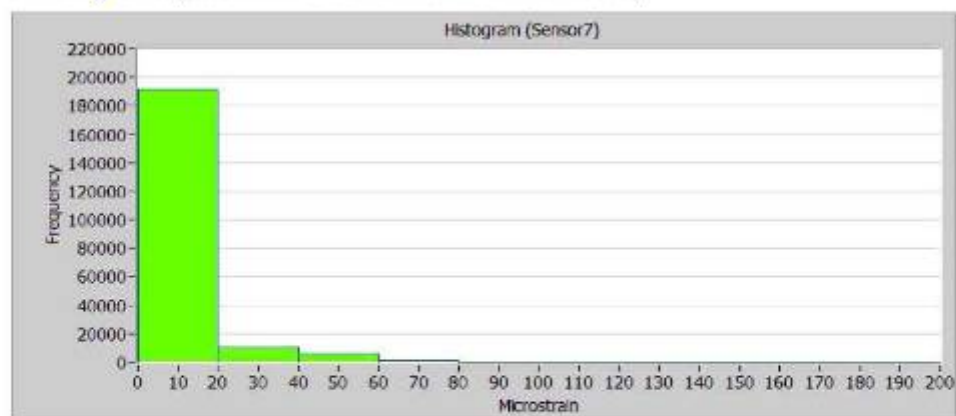
Monitoring Period (11/14/2006 3:00:18 PM ~ 12/14/2006 4:37:46 PM)



Monitoring Period (11/14/2006 3:00:18 PM ~ 12/14/2006 4:37:46 PM)



Monitoring Period (11/14/2006 3:00:18 PM ~ 12/14/2006 4:37:46 PM)



Daily Trends (Maximum & Average)

Maximum (microstrain)	Sensor1	Sensor2	Sensor3	Sensor4	Sensor5	Sensor6	Sensor7	Sensor8
Day0	105	61	47	113	53	60	60	106
Day1	102	47	46	111	59	76	71	105
Day2	105	47	64	121	55	77	104	122
Day3	102	41	47	111	61	74	68	98
Day4	97	42	45	99	69	65	67	98
Day5	105	37	47	109	60	60	73	106
Day6	113	37	46	113	54	67	75	100
Day7	137	61	60	134	112	60	101	110
Day8	96	37	46	104	65	67	72	96
Day9	165	47	46	109	56	84	74	103
Day10	94	36	46	108	70	67	60	102
Day11	82	34	56	103	75	64	62	91
Day12	110	35	46	145	59	69	66	122
Day13	118	36	62	115	124	71	86	103
Day14	103	36	62	103	61	70	81	111
Day15	120	76	51	129	114	69	62	100
Day16	109	37	45	108	108	69	67	94
Day17	101	36	46	105	87	65	60	90

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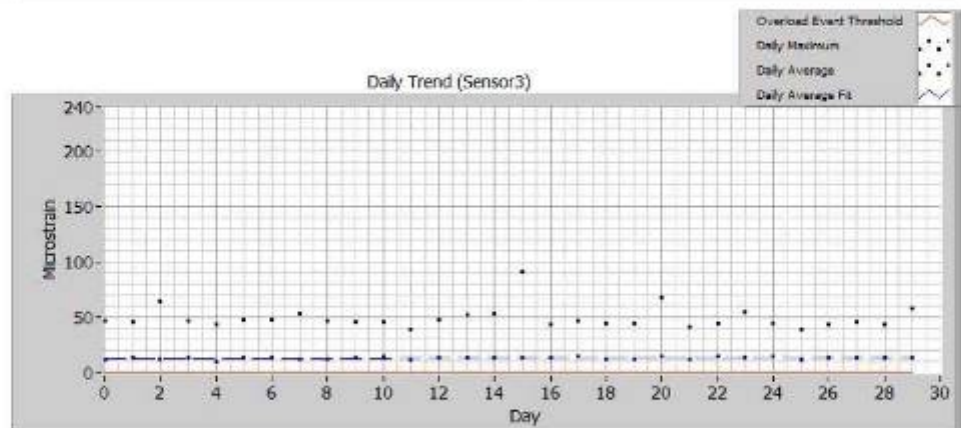
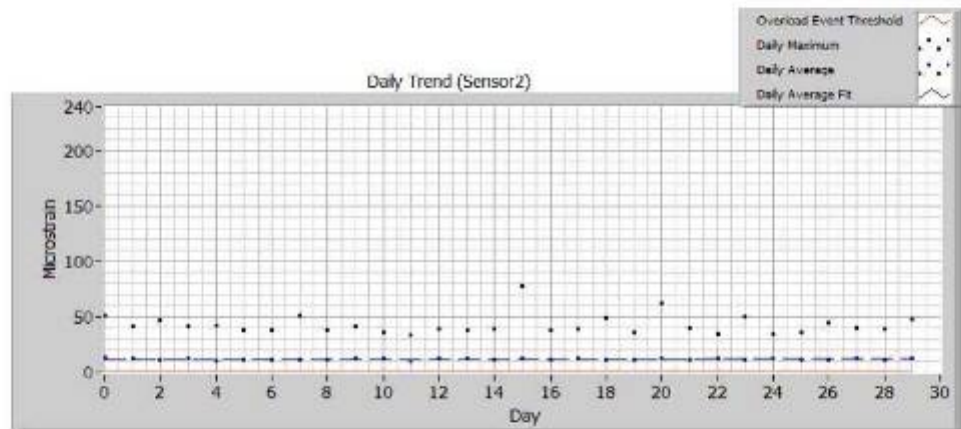
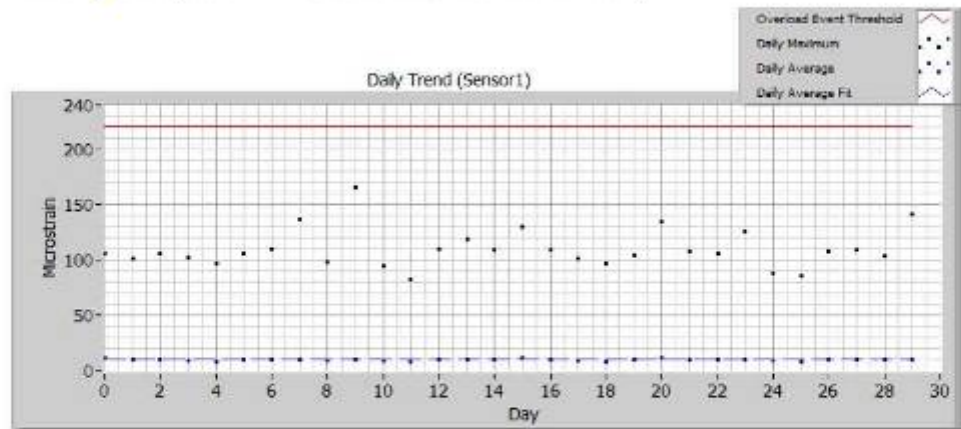
Monitoring Period (11/14/2006 3:00:18 PM ~ 12/14/2006 4:37:46 PM)

	Sensor1	Sensor2	Sensor3	Sensor4	Sensor5	Sensor6	Sensor7	Sensor8
Day18	97	49	45	98	77	90	82	90
Day19	104	35	45	109	90	65	71	104
Day20	134	62	68	150	102	103	116	129
Day21	107	40	41	129	96	69	74	134
Day22	108	35	45	141	102	66	72	151
Day23	126	50	54	125	99	92	90	131
Day24	87	35	45	112	85	63	73	99
Day25	95	36	39	96	79	57	62	84
Day26	108	44	43	118	97	75	69	105
Day27	109	40	46	129	98	68	70	109
Day28	103	39	43	111	90	65	72	96
Day29	141	48	58	174	120	96	97	167

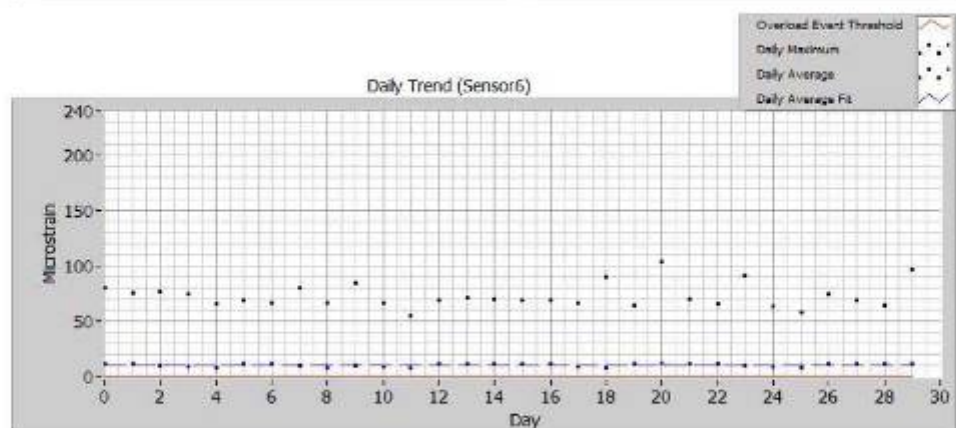
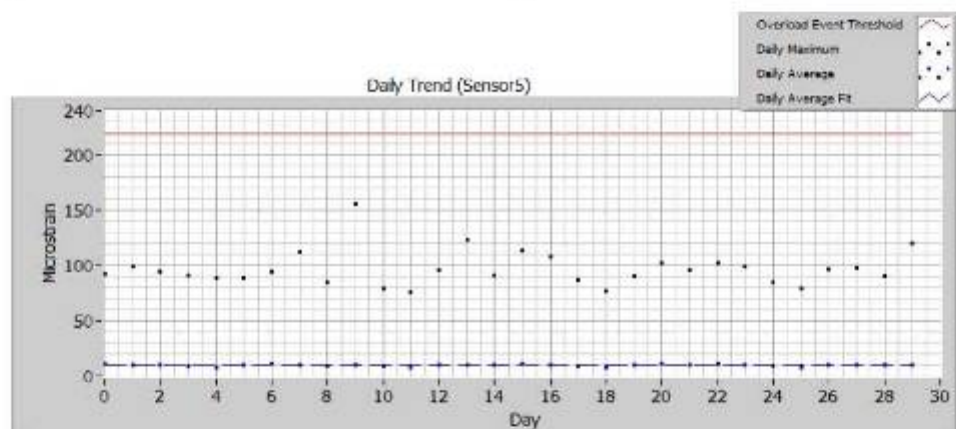
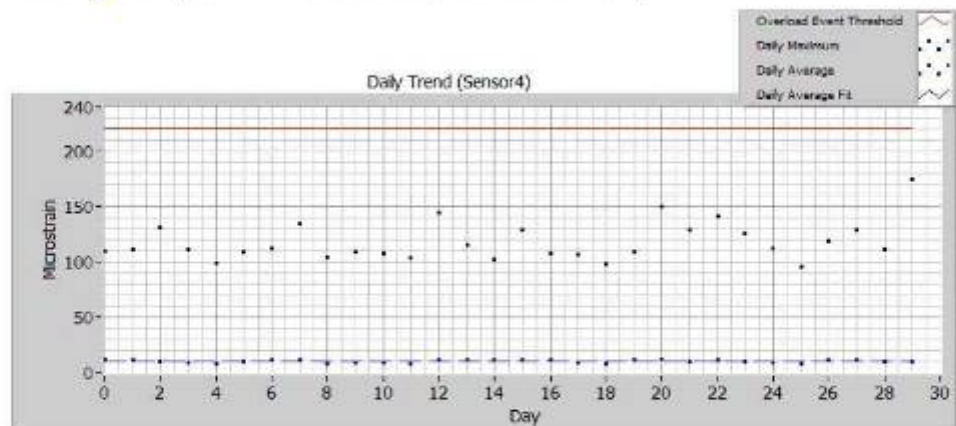
Average (microstrain)

	Sensor1	Sensor2	Sensor3	Sensor4	Sensor5	Sensor6	Sensor7	Sensor8
Day0	11	13	11	12	11	11	11	11
Day1	11	12	13	11	11	11	11	10
Day2	10	11	13	10	9	10	10	10
Day3	9	12	13	9	9	9	8	9
Day4	8	10	10	8	8	7	7	8
Day5	10	11	13	10	10	11	10	10
Day6	10	12	13	11	11	11	11	11
Day7	10	11	12	11	10	10	10	10
Day8	8	11	12	8	8	8	7	8
Day9	10	12	13	9	10	10	8	9
Day10	9	13	14	9	9	9	8	8
Day11	8	10	11	8	8	7	7	7
Day12	10	12	13	11	10	11	10	10
Day13	10	12	14	11	10	11	11	11
Day14	10	11	13	11	10	11	10	10
Day15	11	12	14	12	11	11	11	11
Day16	10	12	13	11	10	11	10	10
Day17	9	13	14	9	9	8	8	8
Day18	8	12	12	8	8	8	7	7
Day19	10	11	12	11	11	11	10	10
Day20	11	12	14	12	11	12	11	11
Day21	10	11	13	10	10	11	10	10
Day22	10	12	14	11	11	12	11	10
Day23	10	11	13	10	10	10	10	10
Day24	9	12	14	9	9	9	8	8
Day25	8	11	12	8	8	7	7	7
Day26	10	11	13	11	10	11	10	10
Day27	10	12	14	11	10	11	11	10
Day28	10	11	13	10	10	11	10	10
Day29	10	12	13	11	10	11	10	10

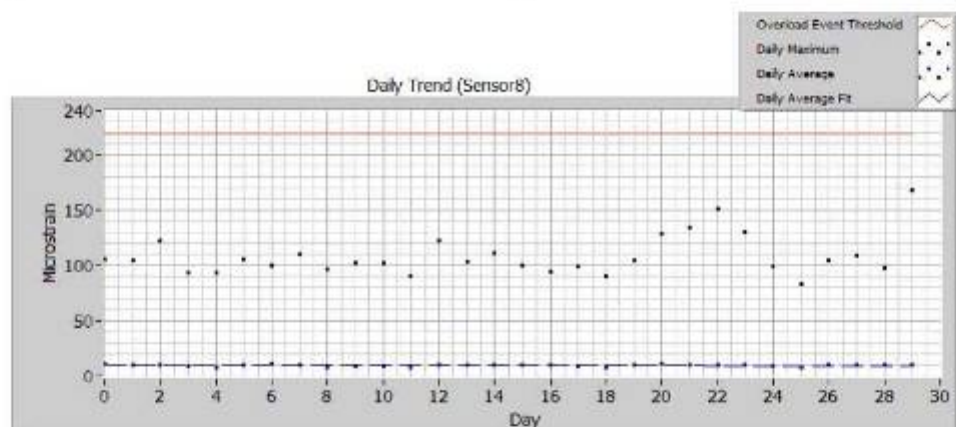
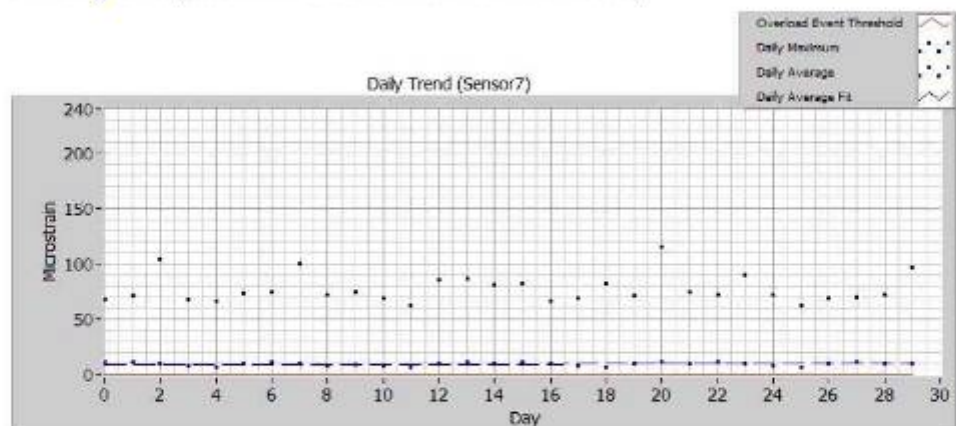
Monitoring Period (11/14/2006 3:00:18 PM ~ 12/14/2006 4:37:46 PM)



Monitoring Period (11/14/2006 3:00:18 PM ~ 12/14/2006 4:37:46 PM)



Monitoring Period (11/14/2006 3:00:18 PM ~ 12/14/2006 4:37:46 PM)



End of Report
(Monitoring since 11/14/2006 3:00:18 PM)

