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Development of a structural health monitoring system for bridges and components

by

Yoon-Si Lee

A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Civil Engineering (Structural Engineering)

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Ames, Iowa

2007

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ABSTRACT

This dissertation summarizes the development of 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 that tracks usage and structural changes. Second, the system helps bridge owners to identify overload occurrence, vehicle collision to the structure, damage and deterioration.

The primary objective of this research was to develop a SHM system that could 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 the tools to better manage bridge assets and were accomplished by completing three distinct work tasks.

The first task involved developing bridge-specific live load structural analysis software, *BEC Analysis*. Like many analysis software packages, the fundamental algorithm was based upon classic beam theory and the direct stiffness method structural analysis. *BEC Analysis* can be used for (1) analyzing beams or girders under moving loads, (2) computing absolute maximums in each span or at a specific location, 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 software was designed to automatically collect, process, and evaluate the measured response of a bridge. Its use may allow bridge owners to quantitatively monitor a bridge for potential damage as well as gradual change in behavior. Significant effort was given to developing algorithms that include temperature compensation and fundamental sound data reduction and data mining techniques.

After 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 system was validated and several observations were given concerning the overall bridge performance during the brief monitoring period.

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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, an autonomous, continuous structural health monitoring (SHM) system that can be used to monitor typical girder bridges was developed. 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.

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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. DISSERTATION CONTENT

This dissertation is divided into four chapters. Chapter 1 presents the project background and objective, and literature reviews summarizing a general overview of the bridge SHM. 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 Appendices.

1.4. LITERATURE REVIEW

As mentioned previously, numerous technologies associated with SHM applications have been well publicized [1, 2]. This section provides a general overview of the bridge SHM. To provide a summary of bridge evaluation history, the development of the major programs that have been established and legislated to provide funding and to ensure bridge safety are summarized. In addition, the current use of testing and structural health monitoring and other current trends in bridge evaluation are also summarized here.

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1.4.1. Chronology of Bridge Evaluation

1.4.1.1. Bridge Programs and Inspection Requirements

The first bridge construction boom started with the extensive road construction program mandated by the Federal Highway Act of 1956, which was initiated when President Eisenhower signed a bill creating the National System of Interstate and Defense Highways [3]. During this time, most emphasis was placed on the economical construction of new bridges. Consequently, little effort was given to safety inspection or preventative maintenance of bridges. The safety of the bridge network came into question in the late 1960's when the U.S. Highway 35 Silver Bridge, a 2,235 ft pin-connected link suspension bridge connecting Point Pleasant, West Virginia and Kanauga, Ohio, suddenly collapsed on December 17, 1967 [4]. This sudden catastrophic collapse, which was the first major failure of a structure since the wind-induced failure of the Tacoma Narrows Bridge in 1940, prompted the recognition of the deterioration of the national bridge network, and the need for periodic and consistent bridge evaluations and training of bridge inspectors. As a result, the Federal Highway Administration (FHWA) established the National Bridge Inspection Program (NBIP) in 1970 requiring State highway agencies to inspect their bridges every 2 years and to submit the inspection results to the FHWA, where they are maintained in the National Bridge Inventory (NBI) database. In the following year, the first National Bridge Inspection Standards (NBIS) were established in cooperation with the American Association of State Highway Officials (AASHO) under the Federal-Aid Highway Act of 1971. This landmark legislation was enacted on April 27, 1971 and, for the first time in the US, set uniform, national standards for bridge inspection and safety evaluation including a national policy related to frequency and qualifications of bridge inspectors, report formats, and inspection and rating procedures [4].

The collapse of the Silver Bridge was certainly a catastrophic disaster that resulted in the loss of 46 lives and disrupted commerce in the Midwestern US for several months. Nonetheless, it was the catalyst for what became a comprehensive bridge safety inspection program that was mandated by the NBIS. Engineers became more knowledgeable about bridge deterioration and, therefore, bridge structures were designed, and maintained for better quality and with at least some consideration for future evaluation and maintenance. Also, the Silver Bridge catastrophe highlighted the need to replace and/or rehabilitate bridges or members of bridges before they failed. The Special Bridge Replacement Program (SBRP) was also established under the Federal-Aid Highway Act of 1971 to provide funds to help States replace bridges. It was later expanded for rehabilitative activities and

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replaced with the Highway Bridge Replacement and Rehabilitation Program (HBRRP) in the Surface Transportation Assistance Act of 1978.

Despite the efforts of these bridge evaluation programs, other unforeseen events resulting in the collapse of bridges continued and periodically necessitated expansion of further effort. In June 1983, the collapse of the 100-foot section of the Mianus River Bridge on Interstate 95 in Greenwich, Connecticut, killing three people and critically injuring three others, caused more concern regarding fatigue and fracture-critical bridges. The National Transportation Safety Board (NTSB) determined that the failure of the span was caused by an undetected lateral displacement of the hangers of the pin and hanger suspension assembly by corrosion-induced forces that were undetected due to deficiencies in the bridge safety inspection and maintenance program. Following this incident, and further investigation, significant research regarding fatigue of steel connections was conducted and special fracture-critical inspections were recommended to be mandated.

Scour-induced failures at the Schoharie Creek Bridge in New York in April 1987 and at the Hatchie River Bridge in Tennessee in April 1989 [4] illustrated the importance of designing bridge piers to resist scour and illustrated the need to better understand and design for scour effects. Consequently, guidance for scour assessment was provided and an underwater bridge inspection program for all structures at risk and susceptible to scour damage was initiated.

Over the decades, much has been learned in the field of bridge inspection, and many training and funding programs, including the NBIP and HBRRP, have been implemented. In some cases, the catastrophic problems had been foreseen and the possible dangers were identified by some engineers. However, potential solutions were sometimes delayed due to either excessive cost associated with existing technologies or by reluctance to adopt new technologies that had not been widely proven. In some of these cases, improved inspection technologies might have allowed the problems to be spotted even early and for the tragedies to have been avoided. As a result, it was recognized that research was often reactive, conducted in response to emergencies, and thus, a proactive research program that would provide solutions to prevent the catastrophic failure was needed.

Since the Federal-Aid Highway Act of 1971, the development of the NBIS and other associated bridge programs have incrementally enhanced bridged evaluation. Overall, approximately $55 billon in HBRRP funding and other sources of funding from Federal and State bridge programs have been allocated and used to improve the condition and safety of the nation's bridges. The following summarizes the major bridge inspection and funding programs and the notable associated changes [5]:

- Federal-Aid Highway Act of 1971

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  - Inventory requirements for all bridges on the Federal-aid system
  - Established minimum data collection requirements
  - Established minimum inspector qualifications and inspector training programs
  - Established SBRP
- Surface Transportation Assistance Act of 1978
  - Established HBRRP
  - Extended inventory requirements to all bridges on public roads in excess of 20 feet
  - Provided $4.2 billion for the HBRRP over 4 years
- Highway Improvement Act of 1982
  - Provided $7.1 billion for the HBRRP over 4 years
- Surface Transportation and Uniform Relocation Assistance Act of 1987
  - Provided $8.2 billion for the HBRRP over 5 years
  - Added requirements for underwater inspections and fracture critical inspections
  - Allowed increased inspection intervals for certain types of bridges
- Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA-1991)
  - Provided $16.1 billion for the HBRRP over 6 years
  - Mandated State implementation of a quantitative computerized bridge management systems
- National Highway System Designation Act of 1995
  - Repealed mandate for management system implementation
- Transportation Equity Act for the 21st Century (TEA-21, 1998-2003)
  - Provided $20.4 billion in HBRRP funding over 6 years

In addition to the bridge programs, many standards, manuals, and technical advisories have been developed with respect to bridge inspection. Most of these were developed by the FHWA or the American Association of State Highway and Transportation Officials (AASHTO), formally known as the AASHO. A list of the major publications related to bridge inspection and their issued dates follow [4]:

- AASHO Manual for Maintenance Inspection of Bridges (1970)
- AASHTO Manual for Maintenance Inspection of Bridges (1974, 1978, 1983, and 1993)
- AASHTO Manual for Condition Evaluation of Bridges (1994)
- FHWA National Bridge Inspection Standards (1971, 1979, and 1988)

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- FHWA Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation 's Bridges (1972, 1979, 1988, 1991, and 1995)
- FHWA The Bridge Inspector 's Manual for Movable Bridges (1977)
- FHWA Bridge Inspector 's Training Manual 70 (1979)
- FHWA Culvert Inspection Manual (about 1979)
- FHWA Inspection of Fracture Critical Bridge Members (1986)
- FHWA Scour at Bridges, a technical advisory (1988)
- FHWA Hydraulic Engineering Circular No. 18 (about 1988)
- FHWA Bridge Inspector 's Training Manual 90 (1991)
- FHWA Engineering Concepts for Bridge Inspectors (1994)

Areas of concern and emphasis related to bridge safety issue are changing and expanding as new problems become apparent and newer bridge types and materials become more common. Yet, one factor remains constant: the ability to effectively evaluate bridge components and materials and to make sound evaluations with accurate ratings is critical to maintaining the safety and efficiency of the transportation system.

Current bridge inspection protocol calls for a biannual inspection. The NBIS requires that inspectors periodically perform inspections on the Nation's bridges and report their conditions in a standardized format with the condition ratings ranging from zero to nine for each of three bridge components: the superstructure, substructure, and bridge deck. The FHWA also recommends that the bridge inspection be supplemented with a program that identifies the needs for preventive maintenance on an annual basis.

1.4.1.2. Current Use of Bridge Testing

The need to facilitate a more accurate and rapid determination of the safe load carrying capacity of bridges was recognized in the 1980's and the National Cooperative Highway Research Program (NCHRP) launched a project, 'Nondestructive Load Testing for Bridge Evaluation and Rating', in an effort to develop guidelines for load testing of highway bridges to augment the codified rating process [6]. The product of this research was a report that provided a comprehensive review of literature related to bridge load testing and a summary of the current status of load-test technologies. Since that time, the use of bridge testing for bridge evaluation has become more available, thereby allowing a limited level of funds to be targeted to bridges that are most in need. Today, the use of the load rating

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procedure that incorporates diagnostic load testing results has become an accepted practice for addressing bridge conditions by many public agencies.

The basic approach for using testing and analysis in load rating is very similar to that used in both standard highway and railroad bridge design codes. The only exception is that instead of relying on estimated distribution factors and assumed member behavior, actual measured field data are used to develop an accurate analytical model of the structure which is used for the subsequent evaluation.

Academia has been using bridge testing for decades as a valuable tool to assess the performance of new bridge systems, new bridge repairs, and retrofit schemes. Early references cite the use of manual dial gages and/or surveying instruments to collect behavior information. The electronic collection of behavior data began as early as the 1970s. Advancements in available sensors have ensured that bridge testing remained an economical and useful tool for in-depth study of structural systems.

Today, a few academic institutions have extensive in-house expertise on the application and use of bridge testing equipment [7, 8, 9, 10]. In many cases, this expertise requires personnel familiar with sensor installation, data acquisition system operation, and interpretation of test results. Institutions with staff and faculty with these skills can frequently provide innovative testing solutions to bridge owners nationwide.

1.4.2. Typical Structural Health Monitoring Technologies

In this section, SHM components/characteristics considered to be “advanced” in nature, but not part of a complete system are briefly discussed. While not complete, these components/characteristics may form the basis for configuring a SHM system that has desirable properties and features.

1.4.2.1. Sensors

The most common type of sensors used in SHM application includes displacement sensors, strain sensors, vibrating wire sensors (both temperature and strain), force sensors, and temperature sensors. Typically kinematic quantities (e.g., strain, displacement and acceleration) and environmental quantities (e.g., temperature, humidity, wind, etc.) are the two main quantities that are typically desired by a sensor based SHM system. For example, displacement transducers and settlement devices can be used to measure and monitor deflection, settlement, joint openings, and other movements of bridge members. Strain sensors are normally used to measure the change in the length of an object per unit length. Numerous research projects and technical reviews have shown that conventional sensors are easily be affected by changes in external factors such as temperature,

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humidity, cable length, magnetic or electric fields, etc. These factors make it difficult to obtain stable and reliable readings over the long term. These common problems that are often encountered with conventional sensors can be overcome as advanced sensing technologies become more available for bridge applications.

Smart Structures, LLC of Rantoul, Illinois [17] developed magnetoelastic (ME) sensors that can be used to monitor stress and corrosion in steel. The principle employed to develop the ME sensor was based on the magnetic permeability of a material that can be measured indirectly by using a charge coil placed next to, or around, the material allowing the varying current or voltage to be related to the stress quantity. The sensor was developed to fit with a magnetic shield to isolate it from external dynamic and static magnetic fields. It is capable of monitoring the stress within bridge cables and certain type of steel reinforcement in concrete. A sensitivity study showed that the sensor was insensitive to varying environmental conditions [16].

Most conventional corrosion monitoring systems for steel reinforced structures utilize embeddable probes that generate low amplitude electric signals and are subject to corruption from nearby electromagnetic interference (EMI) sources such as power lines, radios, cell phones. To address these limitations, Virginia Technologies, Inc. of Charlottesville, Virginia [18] developed a fully embeddable corrosion monitoring sensor, called the embedded corrosion instrument (ECI-1), incorporating electrodes and signal processing electronics. It is capable of measuring parameters important to long-term corrosion monitoring including linear polarization resistance, open circuit potential, resistivity, chloride ion concentration and temperature. The ECI-1 contains a chloride threshold indicator, a temperature sensor, conductivity and resistivity sensor, a polarization resistance sensor, and an open-circuit potential sensor. Each ECI-1 is a digital peripheral connected on an embedded local area network. They communicate with each other and an external datalogger using the SDI-12 industry standard protocol. The data can be collected on-site with a laptop computer or accessed remotely with RF/wireless data connection.

1.4.2.2. Data Acquisition and Processing

Typically two different methods have widely been used for collecting and recording data from sensors. For a local SHM system with a small number of sensors or for a system that only requires a measurement at infrequent intervals, a portable or hand held indicator can be used to collect and store the data. Traditionally, SHM systems had analog sensors and Analog/Digital (A/D) converters at the data acquisition location to convert the analog signal into a digital format. Newer systems incorporate digital sensors to avoid A/D conversion at the central point to enable more reliable

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communication and relieve the central data acquisition from the conversion load. Some devices allow measured parameter values to be read directly in the proper engineering units and storing the data that are later downloaded for further analysis. For a global SHM system with a large number of sensors, or for a system that requires data to be collected and processed frequently or continuously, more complex systems are employed that can collect and process data from an array of sensors at predetermined time intervals.

Some deficiencies to system integrity may occur when sensors are located far from the data acquisition system. In practice, the distance from sensors to a data acquisition system can normally range from couple of feet to several hundreds of feet. As the distance becomes longer, the analog signal may degrade due to unexpected noise sources present along the cable length. Also, it is possible that the change in monitored response from structural damage may be smeared and blended in with those from other factors such as temperature and excitation. Since data are normally measured under varying conditions, data normalization is very important in data processing. Data normalization is a procedure to separate signal changes caused by operational and environmental variations of the system from structural changes. If various unknown sources are involved, where not all sources directly related to structural changes can be eliminated, statistical quantification through appropriate measurements can be employed. Significant research is currently underway for optimizing the data acquisition regimes for maximizing benefits from the real-time data while minimizing the data processing and archival costs.

The CR series data acquisition systems, developed by Campbell Scientific, Inc. [19], have been used in numerous SHM projects. The CR series include basic systems with just a few channels to expandable systems that measure hundreds of channels that are compatible with most commercially available sensors. Channel types include analog (single-ended and differential), pulse counters, switched excitation, continuous analog output, digital I/O, and anti-aliasing filtered. Scan rates can be programmed from a few hours up to 100,000 times per second, depending on the model used. Limited data processing can be performed on-board with no additional post processing required in some cases. The data collection platform provides a server based archiving system. This combined with the processing capabilities can provide a reliable foundation for short- and long-term bridge monitoring.

1.4.2.3. Communication

Traditional data collection systems are mostly based on wire-connected instrumentation where sensors are placed at critical points along a structure and connected to a central data acquisition

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system with cables of various types (e.g., coaxial, etc.). These wire-based systems typically have high installation and maintenance costs. The use of an Ethernet local area network (LAN) can mitigate the problems associated with thick bundles of transmission wires and make a SHM system robust against electromagnetic interference. By using Ethernet LAN in SHM applications, multiple sensor types can also be interconnected, thereby reducing the number and length of wires, and changes to the SHM system can be easily implemented by simply adding more connections.

Another way to overcome problems associated with wired communication is to use wireless technology. Advanced Telemetrics International (ATI) of Spring Valley, Ohio [20] developed a wireless remote telemetry system known as the ATI 2000. The ATI 2000 series can be used for remote monitoring or testing of bridges. Up to 32 remote wireless transmitters connect directly to sensors and transmit any type of sensor signal to conveniently located receivers, eliminating the need for cabling. Some features of the ATI 2000 series include; immunity to electromagnetic interference, dust, oil, moisture, etc.; remote power transmitter management from the receiver; transmitter auto turn off when battery is too low (prevents damage to the battery); autozero for each channel at the receiver; transmitter battery-low and data transmission status indicators at the receiver; and initial offset indicators at the transmitter (indicates if excessive offset present). A recently developed 2060B series transmitter, housed in a weatherproof NEMA 4x enclosure, can supply excitation to sensors and transmit signals up to 4 miles (line of sight).

1.4.2.4. Data Management

As current trends in SHM move toward the development of a real-time, continuous monitoring paradigm, the ability to efficiently transfer and manage a large amount of data is required. Even with digital signal processing (DSP) boards and algorithms, massive data transfer is still required if the monitoring is performed remotely. Also, if not properly processed, data may be subjected to a loss of some useful information hidden in the recorded data through data compression and condensation. Experience has shown that the data transfer and management tasks involved in traditional SHM systems is non-cost effective [21]. In recent years, the economic considerations and other challenges have led the traditional SHM system to evolve toward serial systems, in which the number of transmission mediums is reduced by utilizing a robust communication protocol such as the Universal Serial Bus (USB). Concurrently, modern Internet-based database technologies allow utilizing various conceptual retrieval interfaces, and corresponding visualization and analysis tools for a better management of the large amount of data and information.

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An Internet-based monitoring system, called the Real-time Integrated Surveillance and Control System (RISCS), was developed by the Drexel Intelligent Infrastructure and Transportation Safety Institute and implemented on the Commodore Barry Bridge (CBB) that spans the Delaware River between Pennsylvania and New Jersey [23, 23]. The developers constructed an Internet-based measurement and image database utilizing various conceptual retrieval interfaces, and corresponding visualization and analysis tools. The Internet portal interface and database were designed to allow an authorized viewer to navigate raw data, preview data graphs, extract specified information (such as analytical data, reports, images, video clips and CBB CAD models), save the retrieved data to a local computer hard-disk and modify information. The database system is capable of providing fast and various displays, dynamic webpages and multimedia displays. Research is currently underway for optimizing the data acquisition regimes for maximizing the benefits from the real-time data while minimizing the data processing and archival costs.

Although currently available hardware technologies appear to allow large amount of data to be collected, the ability to analyze and understand the massive datasets in a concise manner appears to be still lacking. In most SHM applications, the raw data alone is rarely of direct benefit to a bridge owner. The true value is predicated when useful information and knowledge are extracted for decision support or exploration on structural health status (e.g., as to whether the structure is healthy enough to continue fulfilling its functions). Clearly, the main issue of the current SHM community is not the lack of measurements, but rather is how to analyze and extract useful information.

1.4.3. Emerging Structural Health Monitoring Technologies

1.4.3.1. Fiber Optic Sensors

Fiber optic sensor (FOS) technology is based on the principle in which the micromechanical resonator acts as the sensitive element of the sensor and has the promise of providing an alternative measurement method not previously available. They are used for detecting structural performance by sending light beams down the fiber optic cable at regular intervals and by measuring changes in time-of-flight.

Various types of FOS are currently being developed and used in bridge applications. Each type is based on a different property of the light waves traveling down the fiber. For example, Fabry-Perot sensor measures interference fringes while the measuring parameter of Fiber Bragg Grating sensors is frequency. Multiple Bragg Grating type sensors can be photo-imprinted along the same fiber, making it feasible to install large scale networks of 1,000 sensors or more with a minimum of cables. Another type of fiber optic based sensor technology that has been recently getting attention is

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the use of Brillouin optical time-domain reflectometry (BOTDR). It is a distributed optical fiber strain sensor whose operation is based on the Brillouin scattering phenomena.

FOS allows a structure to be continuously monitored with confidence in the usability of the long-term data record. FOS is known to exhibit low mechanical hysteresis and have high shock survivability. They are capable of measuring strains at multiple orders (two or three) of magnitude better than conventional electrical resistance gages. The use of the FOS can also reduce the number of sensors needed for the structure since they are capable of detecting damage along the entire length of the sensor (in the specific case of long-gauge FOS). Advantages of FOS over conventional sensors include its compactness, and freedom from drift and electromagnetic interference [24]. Other advantages include that they can easily be incorporated into various types of measuring devices (e.g., accelerometers, displacement transducers, etc.), and many physical quantities can be measured simultaneously with the proper system design and calibration [25]. Its durability issue, however, is of a concern to overcome (e.g., it is fragile and can be easily damaged during handling and installation).

1.4.3.2. Micro-electromechanical Sensors (MEMS)

Another advanced sensing technology that is being popularly explored by numerous manufactures and institutions is MEMS. MEMS are miniature electromechanical sensor and actuator systems that are capable of being optimized in their design for a specific application. The advantage of MEMS is that they can be used in an environment to both sense and actuate. The key difference between conventional sensing technologies and MEMS sensing technologies lies in their intelligence capabilities. The majority of MEMS devices contain an on-board microprocessor within the system. The microprocessor can be typically used for digital processing, conversion from analog to digital, performing basic calculations, and providing interfacing functions.

One advantage of using this technology and its design paradigm in bridge applications is the miniaturization associated with MEMS; MEMS features are typically on the scale of microns (10^{-6}m). This small size allows them to be implemented in applications where conventional devices would be intrusive. The manufacturing process, known as vary large scale integration technology (VLSI), which is similar to those used for manufacturing computer chips, gives a great potential for the mass production of a particular sensor in a cost-effective manner.

One MEMS sensor development currently underway is being completed by Advanced Design Consulting (ADC), Inc. that is developing tether-free, passive sensors [26]. These detectors are slightly larger than a pin-head and can be poured along with the concrete into a bridge deck or road bed with an expected life of 100 years. ADC plans to combine radio frequency identification (RFID)

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devices with its MEMS sensors. This ultra-small sensor is being designed to monitor moisture, temperature, pH, and the concentration of chloride, sodium and potassium ions within concrete. It will be powered by electrical energy radiated from a hand-held monitoring device and it transmits data and identity information by reradiating that signal. At other times, the sensor remains unpowered.

1.4.3.3. Wireless Sensors for Corrosion Monitoring

While corrosion monitoring sensors have been available for some time, they have inherent limitations when embedded in concrete. Current sensors typically need power, which increases their size, limits the life span, or require the use of significant cabling. SRI International, working with Caltrans, is currently developing a wireless sensor, called a "Smart Pebble", that contains a chloride sensor and utilizes a radio-frequency identification (RFID) chip that can be queried remotely for monitoring the level of chloride ingress into concrete bridge decks [27, 28]. The 1.5 in. diameter wireless devices, with a weight of a typical piece of the rock aggregate, are expected to cost less than $100 each. The sensors can be activated by a $1,000 handheld or vehicle-mounted RF identification data logger that gathers the data as it passes over them. The Smart Pebble is designed to remotely powered, thus precluding the need for any lifetime-limiting batteries, and it can monitor chloride ingress to depths of up to 4 in. The sensor is designed to be inserted in the bridge deck either during the construction (or refurbishment) or in a back-filled core hole.

The Johns Hopkins University Applied Physics Laboratory (APL), working with the Maryland State Highway Department, is developing a Wireless Embedded Sensor Platform (WESP), which can be used with a variety of different sensing capabilities, into a unit called the "Smart Aggregate" [29]. The "Smart Aggregate" is an embeddable sensor, which is expected to be suitable for the long-term field monitoring of corrosion in bridge decks. The Smart Aggregate sensors can be embedded during concrete placement. The data reader, which can be mounted on a car or truck, powers the Aggregates as it passes over them and stores the sensor data on a connected PC. Each sensor contains wireless power receiver and data transmission coils and is designed using ceramic hybrid integrated circuit technology to withstand mechanical stresses and the high pH environment of concrete. The sensor, which is roughly the size of a quarter and could cost less than $20 each, is being designed to last for 50 years. The wireless power transmission and data collection approach could eliminate potential problems with batteries, cables and connectors. Researchers have installed several prototype Smart Aggregates in a bridge deck in Montgomery County, Maryland, and are gathering performance data. Two types of different versions of Smart Aggregates are being

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developed: (i) those measuring the concentration of chloride ions and (ii) those measuring the actual corrosion rate using a sacrificial sensor.

1.4.3.4. Wireless Communication

As was mentioned previously, as a viable alternative to the wired systems, emerging wireless technologies such as radio frequency communication links, cellular phone networks, and others provide an opportunity to remedy the recurring cabling problem of conventional monitoring systems. Due to the potential advantages of wireless technologies over a conventional wired sensing system, a change in the communication industry is shifting the existing technologies into a new system. One example is the General Packet Radio Service (GPRS), a global system for mobile communications that provide users with packet data service over GSM radio channels and external packet data networks. This type of technology is being explored for SHM systems. The most popular protocols that are currently available for transmitting data includes Bluetooth and Zigbee.

1.4.3.5. Data Processing and Management

The emerging knowledge discovery in databases (KDD) technology may provide a tool for creating an object-oriented information scheme for diagnostic interpretation of data [30]. KDD systems have created opportunities for computational tools that have a degree of cognitive intelligence; commonly referred to as artificial intelligence (AI). As a growing engineering area, the AI concept is frequently being evaluated as a tool for solutions that intelligently understand problems. This intelligent tool evolved from the intersection of research in various fields such as databases, statistics, machine learning, pattern recognition, reasoning with uncertainty, knowledge acquisition for expert systems, data visualization, information retrieval, and high-performance computing [15]. The common AI technology currently being explored is Artificial Neural Networks (ANN). The objective of using ANN approach is to transform the collected data and information into meaningful outputs from collected inputs. As a supervised learning technique, ANN came from the idea of developing an artificial system capable of simulating the function of a human brain or neural system [31]. Due to its powerful capabilities at universal approximation of nonlinear mapping functions with an arbitrary complexity, the ANN approach has been successfully used in different fields of science and engineering. The ANN resembles the human neurons in two respects. First, the network acquires knowledge through a learning process and training. The learning process can be perceived as a type of optimization process. Second, the inter-network connection weights (known as “synapse weights”) are used to store the knowledge, which can then be used to solve new problems. Since its

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introduction, the use of ANN has been gaining interest in bridge monitoring applications as a statistical pattern classifier to identify and predict damage, which can be defined by the occurrence, location, and extent, in structural systems. The use of the AI technology may allow automating the entire process of data analysis, implementing specific algorithms for pattern extraction from data, and integrating the inferred knowledge from data with damage inferring indices for structural health assessment and decision making. Many researchers are currently focusing their effort on integrating the technology with a data management system.

1.4.4. Review of Selected Structural Health Monitoring Systems

1.4.4.1. Acoustic-based Monitoring System

The lack of reliable inspection equipment to detect wire breaks within strands or cables can pose a serious problem for bridge owners. In order to address concerns about this problem, Pure Technologies, Ltd (of Calgary, Alberta, Canada) developed an acoustic-based monitoring system, called 'SoundPrint,' that can continuously detect wire breaks in prestressed beams and other cable supported structures [11]. The system uses an array of acoustic sensors distributed throughout a structure to measure the energy or dynamic response generated when tensioned steel wires fail. When the system detects a possible wire break, the data from the events are filtered and automatically transmitted via the Internet to a central data center where proprietary software is used to generate reports summarizing the time, location and classification of each recorded event through signal processing and analysis. An alarm is automatically triggered when a wire break is detected and an authorized engineer is notified for an appropriate action to be taken. Since its introduction in 1994, the SoundPrint acoustic monitoring system has demonstrated its capabilities and effectiveness in monitoring the deterioration of prestressing tendons and cables of suspension bridges, cable-stayed bridges, prestressed concrete bridges, and other structures in many countries.

1.4.4.2. Fiber Optic Sensor-based Monitoring System

Recent advances in fiber optic technologies are making the application of non-intrusive, ubiquitous, multipurpose SHM systems more feasible. A SHM system with the fiber optic sensing capability offers key advantages including high-resolution and measurement capabilities that are immune to radio frequency (RF) interference, electromagnetic interference, random drift, and temperature interferences that may not be possible with traditional sensing technologies. An optical fiber-based SHM system for the global monitoring of structures, called SOFO monitoring system, was developed by SMARTEC SA of Switzerland [12] and has been used on numerous bridges throughout the world.

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It is a real-time, continuous and autonomous monitoring system capable of measuring deformations over a long measurement basis and providing quantitative data on structural behavior with a micrometer resolution and long-term stability. The SOFO software allows automatic and scheduled measurements and real-time, simultaneous display of several different views within the same window. It is also capable of the management of warning states in the form of pre-warnings and thresholds; the software can trigger an alarm based on a user-defined action (e.g., sound, phone call, e-mail, etc.). The system has proved to be effective in different applications when specific thresholds can be pre-defined.

A similar fiber optic sensor (FOS) based monitoring technology was developed by OSMOS [13]. It is a long-term, continuous remote monitoring system for monitoring global structural changes through an integration of components in or on the structure. A signal processing monitoring station used by the OSMOS system consists of a master unit and a slave unit and is used for measuring, evaluating and displaying signals from various sensors. The slave registers measurement values from the sensors, while the master processes and displays the signals. A database server archives the raw data and accumulated configuration data. Operating via a modem and a webserver, the entire system can be configured online. A patented 'dashboard' feature provides the information concerning the state of the monitored structure. The system also allows alarms to be generated via e-mail, fax, or any other user specified means when exceeding predetermined thresholds.

The Iowa State University Bridge Engineering Center has developed a FOS-based monitoring system that combines “State-of-the-Art” sensors, wireless communication, real-time web-based viewing of bridge performance, “on-the-fly” data checking, and off-line conversion to engineering parameters. This system, that combines off-the-shelf technologies with specially developed software algorithms, is believed to be the first system capable of removing both long- and short-term temperature effects from long-term continuous data. The system is capable of providing information for assessing the current state of a structural system and for evaluating the long-term performance trends through common engineering parameters (e.g., load distribution, end restraint, stress-cycle counting, etc.).

1.4.4.3. Integrated, Internet-based On-line Monitoring System

The idea of a Internet-based SHM system is to provide automatically processed information to the end user via the widely accessible world wide web (WWW). Kinemetrics, Inc. of Pasadena, California developed an On-line Alerting of Structural Integrity and Safety (OASIS) system that provides real-time, continuous on-line monitoring of structures [14]. The OASIS system is an

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integrated hardware and software system that combines high-resolution dynamic measurements with real-time data communications and data processing, capable of reporting a current state, and the likely future state of the structure or components. It is also capable of providing autonomous, real-time graphical alerting of structural and environmental conditions using on-screen imaging and audible alarms.

A long-term, on-line monitoring system, called Wind and Structural Health Monitoring System (WASHMS), has been developed by the Hong Kong Polytechnic University and implemented on three long-span cable-supported bridges (Tsing Ma Bridge, Kap Shui Mun Bridge and Ting Kau Bridge) in Hong Kong [15]. The WASHMS for these three bridges consists of over 800 permanently installed sensors including accelerometers, strain gauges, displacement transducers, anemometers, temperature sensors, level sensors and weigh-in-motion sensors installed on each bridge combined with recently developed data management systems. The system was designed so that the data could be transferred to an Internet server through a telecommunication system to control the entire system and to provide information on the condition of the bridges. Due to a large amount of data generated, the system utilizes a geographic information system (GIS) technology that is capable of providing a computerized database management system for the capture, storage, retrieval, analysis, and display of temporal-spatial data. Currently the developers are working on developing tools to analyze the large volume of generated data.

1.4.4.4. Real-time Kinematic GPS-based Monitoring System

Recent advances in Global positioning system (GPS) technology make displacement measurements under static and dynamic conditions easier. The advantage of GPS systems is that relative displacements can be measured in real time to assess potential damage to a structure. In 1999, the State of California Department of Transportation (Caltrans) launched a GPS-based SHM project on the Vincent Thomas Bridge in Los Angeles Harbor, the San Francisco Bay Bridge, and the Golden Gate Bridge in San Francisco, California to evaluate the feasibility and capability of GPS technologies for monitoring long-span bridges [16]. The system utilized a high precision Real-Time Kinematic GPS (RTK-GPS) and wireless communication technologies. In general, a networked RTK system uses a differential carrier-phase positioning with at least two GPS receivers (one base and one or more rover receivers). A RTK system transmits raw code and carrier data from the base and rover receivers to a computer that processes and calculates the positions. This effectively reduces the processing requirements needed in the GPS receivers by using the processing power of a separate personal computer. Caltrans demonstrated that networked RTK-GPS is a good tool for identifying

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differential movements that may indicate potential problems in a post-disaster situation. With the initial success with the RTK-GPS technology, a new SHM project was deployed on the Carquinez Bridge in California in early 2004 for monitoring real-time displacement measurements under traffic, wind, and seismic loads.

1.4.5. Technologies for Identifying Overloaded Vehicles

As the volume of heavy vehicles is steadily increasing and these heavy vehicles are the major cause of wear and damage to pavements and key components of bridge members, there has been a great deal of work to develop systems for monitoring, controlling and/or reducing the likelihood of overloaded vehicles. Traditional method of weighing trucks and enforcing weight regulations is through the use of stationary weigh stations. While the use of stationary weigh stations is the simplest method of controlling and identifying overloaded vehicles, it is not always the most effective; besides requiring the vehicles to stop and being costly to staff and maintain, they are easily and often avoided by drivers of overweight vehicles since their location can be known miles in advance through driver communication.

Weigh-in-motion (WIM) system is a technology that weighs vehicles while they are in motion. Types of WIM systems can fall into two main categories: systems mounted (1) on the road surface and (2) in the roadbed. While the use of WIM may offer a solution to the limitations that exist with the use of weigh stations since it is relatively low-cost and requires no traffic intervention, its use still has some limitations. Most WIM systems require sensors (e.g., bending plates, bar sensors, capacitive mats, piezoceramic strips, etc.) installed on the top of the road surface or embedded in the pavement, and therefore, they can measure the axle load only for the fraction of a second when the vehicles pass over the sensors. Consequently, the accuracy of these WIM systems is greatly influenced by the dynamic nature of the vehicle motion and the road profiles (i.e., roughness of the road surface). In addition, the sensor durability is always a major concern as they are exposed (or very close to the pavement surface) and in direct contact with the traffic load. In Europe, extensive research efforts such as WAVE [100] were taken in the 1990's to address these issues and to improve and develop new WIM technologies, preferably at low cost and under a wide range of environmental and traffic condition, including the use of fiber optic sensors, multiple-sensor WIM and bridge based WIM systems.

As an alternative approach to pavement WIM, many countries have developed bridge based WIM. Bridge weigh-in-motion (BWIM) system uses an existing (or new) bridge as a weighing scale. As the measurements are made through the period in which the whole vehicle traverses over the

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bridge, the influence of the dynamic effects due to vehicle-bridge interaction is accounted for and, therefore, the BWIM system has less dynamic effects than the pavement WIM system where measurements are made only for the fracture of a second. BWIM concept was initially introduced in the late 1970's by Moses [101]. Moses algorithm is based on the assumption that the sum of girder strains is proportional to the gross bending moment from which vehicle axle weights can be extracted. Based on Moses algorithm, the first commercial BWIM system was developed by Bridge Weighing Systems Inc. in 1989 [102]. Recent research efforts through COST323 action and WAVE [103] and other researches on BWIM have improved accuracy and performance of BWIM systems. Included in the developments are BWIM with new dynamic algorithms [104], use of optimization techniques and multiple sensor locations [105 & 106] and the use of free axle detector systems which allows axle weight and spacing determined purely from strain measurements, eliminating the need for axle detectors.

The use of WIM systems outweigh the costs involved with its initial implementation and operation. It allows transportation planning personnel to monitor and control illegal overloads and provides better access to valuable traffic information that can be used in planning, maintenance and construction of their infrastructure. Due to its advantage such as its relative ease of implementation and price efficiency, WIM systems have been beneficial in the past and are gaining popularity in many countries. WIM systems provides important tools for the future and many engineer believe that its use will provide both short and long term benefits to the industry, state and public.

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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 considerations of typical scenarios. Manually analyzing structures is very labor intensive and an error prone task. Although structural analyses may be performed with commercially available software, it typically takes considerable effort and can be computationally expensive. While some analysis programs are available and can be used to model bridge structures, it appears that engineers frequently desire easier-to-use tools. In order to address this need, a user friendly, easy-to-use structural analysis program that would reduce such effort while providing reliable analysis results was developed. This software was developed specifically to integrate into the other components of the SHM system. Significant attention was given to addressing issues that are widely known to hinder effective use of advanced technologies in SHM. In particular, considerable effort has been allocated towards developing algorithms for temperature compensation, data reduction and data mining. As a result of the overall development effort, two computer software programs – a structural analysis program and a field monitoring program – have been developed that integrate with off-the-shelf hardware to create a turnkey system.

An overall schematic for the SHM system is illustrated in Fig. 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.

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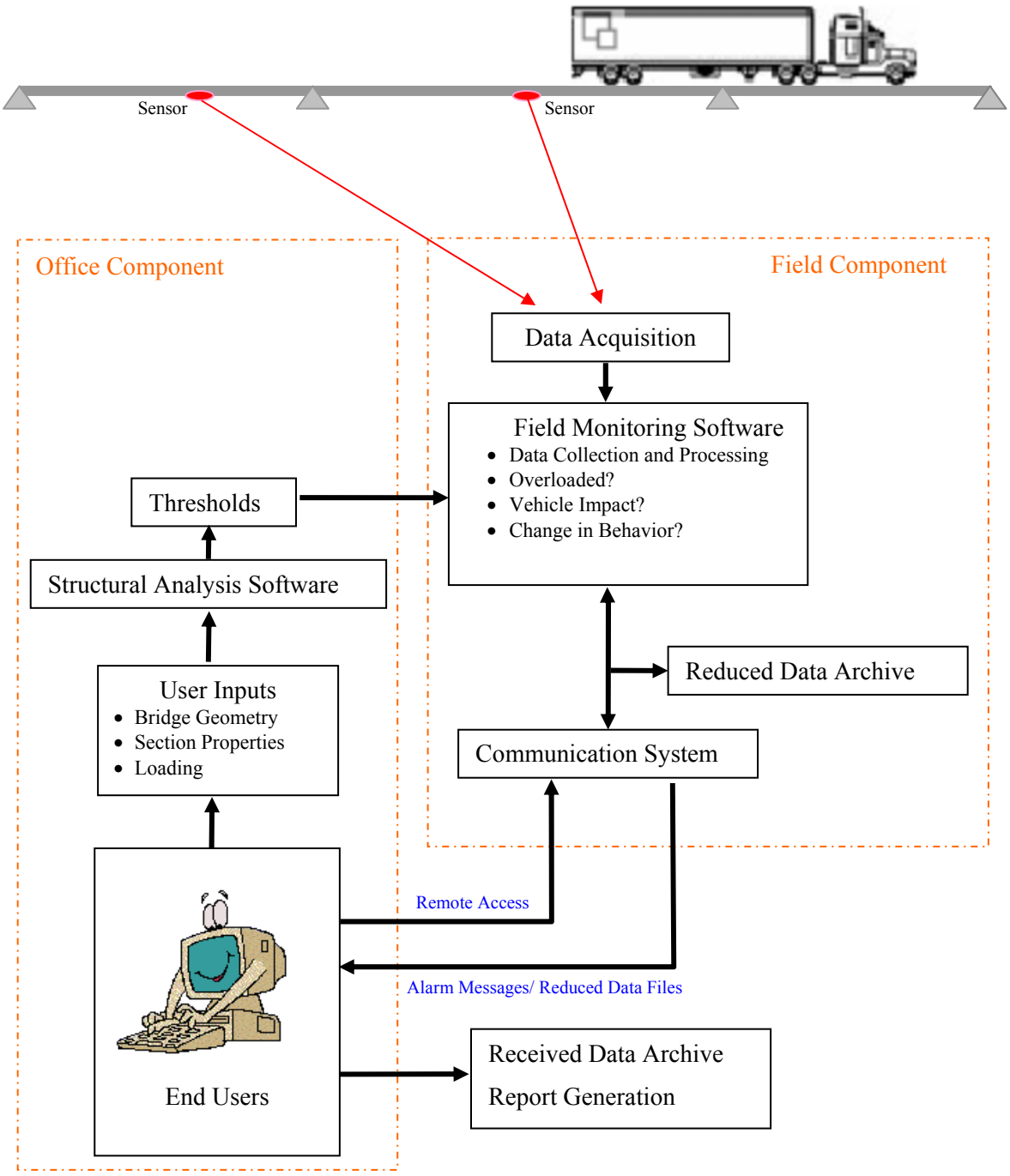

Figure 2-1. Overall schematic of SHM system.

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2.1. STRUCTURAL ANALYSIS SOFTWARE

A Windows-based, two dimensional, live load structural analysis program, *BEC Analysis*, was created, using the Microsoft Visual Basic 6.0 programming language, to simplify determination of some of the bridge specific SHM system parameters. The use of a graphical user interface (GUI) like the one used in the developed software is convenient in that a pictorial representation of the user inputs provides an easier modeling experience and can help avoid erroneous inputs.

BEC Analysis is capable of analyzing a bridge beam or girder with various boundary conditions and member geometries under various moving load conditions. One unique feature of *BEC Analysis* is that it allows users to easily determine maximum results (e.g., maximum moment and strain) at any location along the length of a bridge. In addition, it contains many convenient features which allow relatively quick analysis of a bridge. In general, one may use *BEC Analysis* for (1) analyzing beams or girders under moving loads, (2) computing absolute maximums in each span or at a desired location, and (3) generating envelopes of maximum moments and strains. The following summarizes some of the features that are included in *BEC Analysis*:

- Text fields and click-to-select options used to define bridge parameters.
- Input defaults that will help novice users.
- Library of various member cross section properties.
- Calculator that computes section properties of virtually any member cross section.
- Capable of modeling non-prismatic members.
- Run multiple analyses without exiting the program.
- Supports the AASHTO Standard Specification for Highway Bridges, Sixteenth Edition [39].
- Supports various loading conditions.
- Graphic diagrams.
- Print/Save results.

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

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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. The results of the absolute maximums can be printed at the users' discretion. Moreover, users can review the analysis results graphically or save them for later review. More details are provided in the following sections.

Section 2.1.1 presents the general theory and methodology used in the development of *BEC Analysis*. In Section 2.1.2, detailed descriptions on numerous features and components within *BEC Analysis* are provided.

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 upon 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 composite sections, the moment of inertia of the entire transposed section is used.
- Non-prismatic spans may be approximated with stepped prismatic members.

The relationship between the applied loads, member properties, and the induced displacements can be represented in matrix form. 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. If the cross section of the member varies along its entire length or along its segments, the section properties, such as area of the cross section and its moment of inertia, become variable and the analytical expressions for the coefficients of the unit displacement stiffness matrix and for the fixed end forces

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due to applied loads become more involved. The general matrix formulation for the member end forces can, therefore, be expressed as below:

$$\{MA\} = \{MF\} + [KS]\{D\} \tag{2.1}$$

where, $\{MA\}$ = Member end force vector

$\{MF\}$ = Fixed end moment vector

$[KS]$ = Unit displacement stiffness matrix

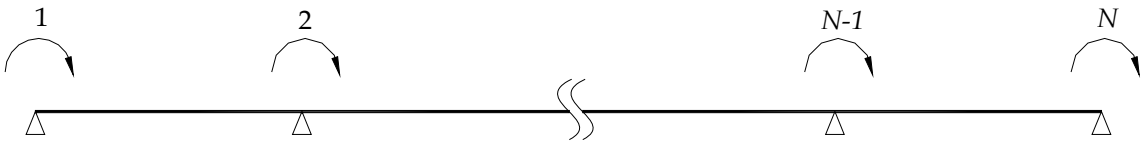
$\{D\}$ = Nodal displacement vector ($\{D\} = -[S]^{-1}\{Z\}$)

$\{Z\}$ = Nodal force vector

$[S]$ = Stiffness matrix

The matrices $[KS]$ and $[S]$ are functions of the structure while the vectors $\{MF\}$ and $\{Z\}$ are functions of loading condition on a structure. Figure 2-2 shows a theoretical model bridge with the global and member degree of freedom used at each joint. In all cases, the first step in the solution is to construct the unit displacement stiffness matrix $[KS]$, coefficients which are the member end forces induced by unit displacements. This requires establishing the member stiffness matrix for each member. This is most easily understood by finding the inverse of the flexibility matrix given that the directions of the applied load and the corresponding displacement (or rotation) are the same.

A member flexibility matrix with a variable section property can be obtained by using the virtual work method and by performing integration numerically using quadrature formulas which express an integral as a linear combination of a selected set of integrands. Note that although the results of a numerical integration are approximate, this method has been widely used and known to generate sufficient accuracy.



(a) Global degree of freedom for $[S]$, $\{D\}$ and $\{Z\}$

(b) Member degree of freedom for $[KS]$, $\{MF\}$ and $\{MA\}$

Figure 2-2. A model structure with global and member degree of freedom at each joint.

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Figure 2-3 illustrates a member with a variable moment of inertia and the moment diagrams correspond to the condition where a unit force is applied at each joint. Using the virtual work method, the member flexibility matrix and its coefficients considering bending deformations only can be expressed as follows [40]:

$$[f] = \frac{L}{EI_0}\begin{bmatrix} f_{aa} & f_{ab} \\ f_{ba} & f_{bb} \end{bmatrix} \tag{2.2}$$

$$f_{aa} = \int \frac{m_a^2 dx}{EI_x} = \frac{1}{EI_0}\int \frac{m_a^2 dx}{(I_x / I_0)} \tag{2.3}$$

$$f_{ba} = \int \frac{m_b m_a dx}{EI_x} = \frac{1}{EI_0}\int \frac{m_b m_a dx}{(I_x / I_0)} \tag{2.4}$$

$$f_{ab} = \int \frac{m_a m_b dx}{EI_x} = \frac{1}{EI_0}\int \frac{m_a m_b dx}{(I_x / I_0)} \tag{2.5}$$

$$f_{bb} = \int \frac{m_b^2 dx}{EI_x} = \frac{1}{EI_0}\int \frac{m_b^2 dx}{(I_x / I_0)} \tag{2.6}$$

where, $[f]$ = member flexibility matrix

f_{ij} = element of member flexibility matrix

E = modulus of elasticity

I_0 = reference cross section with the minimum moment of inertia

I_x = moment of inertia at x

L = span length

By finding an inverse of the flexibility matrix established in Eq. 2.2, the member stiffness matrix $[K]$ can be found and expressed in a general form relative to two degrees of freedom as shown in Fig. 2-3a.

$$[K] = [f]^{-1} = \frac{EI_0}{L}\begin{bmatrix} C_a & C \\ C & C_b \end{bmatrix} \tag{2.7}$$

where C_a, C_b and C = coefficients of member stiffness matrix

Once all the member stiffness matrices have been found, one can assemble them into a unit displacement stiffness matrix $[KS]$, relative to the member degree of freedom shown in Fig. 2-2b, and the stiffness matrix $[S]$, relative to the global degree of freedom shown in Fig. 2-2a. The coefficients of these matrices can be obtained by utilizing the principle of superposition, whose effects are caused

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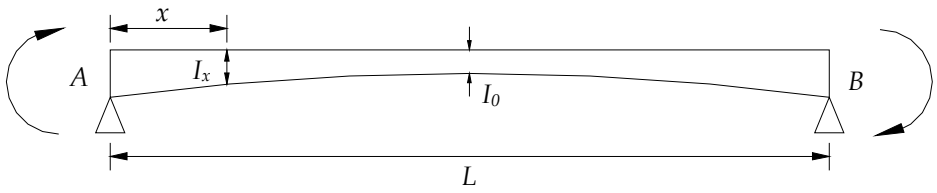
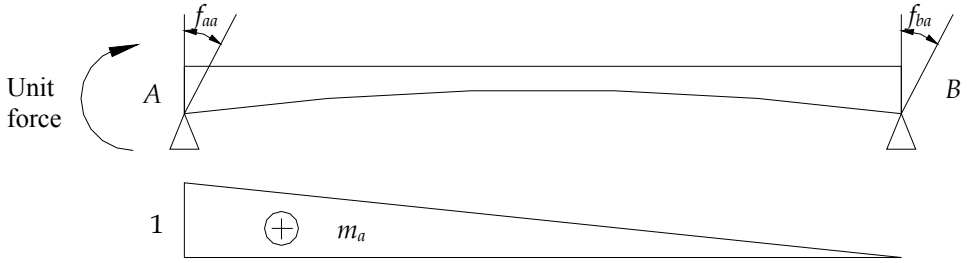
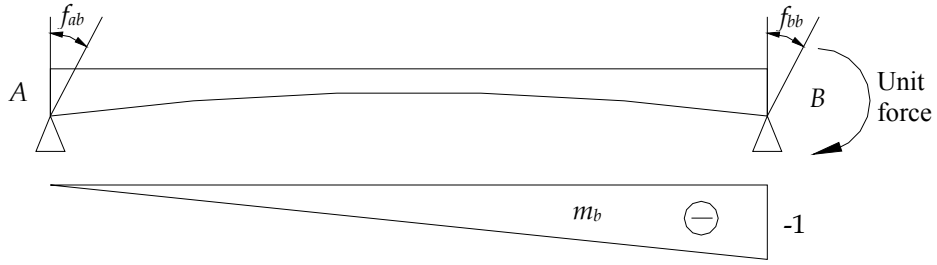
by unit displacements applied at the global degree of freedom, one at a time, while all others are restrained. The elements in the first columns of [*KS*] and [*S*] are those obtained by applying a unit displacement at the global degree of freedom '1' ($D_1 = 1$) when all other joints are suppressed for any movement (i.e., $D_2 = \cdots = D_{N-1} = D_N = 0$) as illustrated in Fig. 2-4a. The rest of the elements are obtained in a very similar manner. The only difference is the location of the global degrees of freedom at which unit displacements are applied. As illustrated in Figs. 2-4b and 2-4c, for example, the elements in the second and N^{th} columns are those obtained when a unit displacement is applied at the global degree of freedom '2' and '*N*', respectively.



(a) Member with a varying moment of inertia



(b) Flexibility coefficients and a moment diagram due to a unit force applied at joint 2.



(b) Flexibility coefficients and a moment diagram due to a unit force applied at joint B.

Figure 2-3. Flexibility coefficients for a member with a varying moment of inertia.

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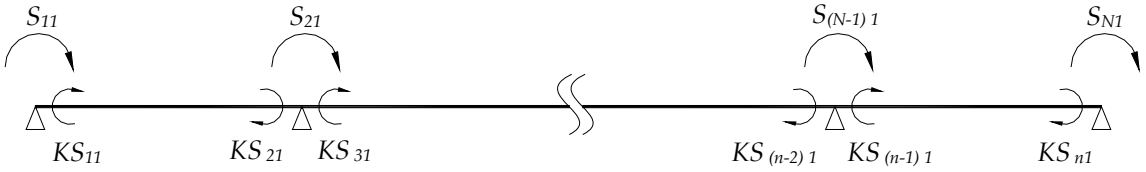
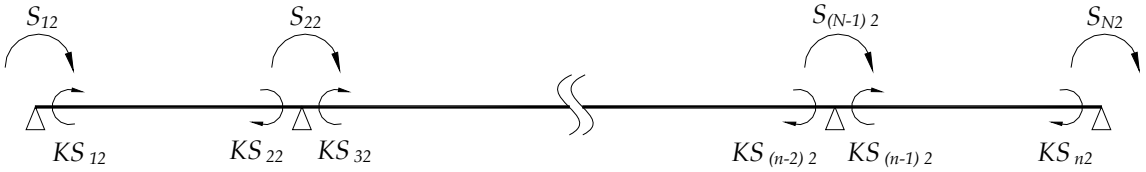


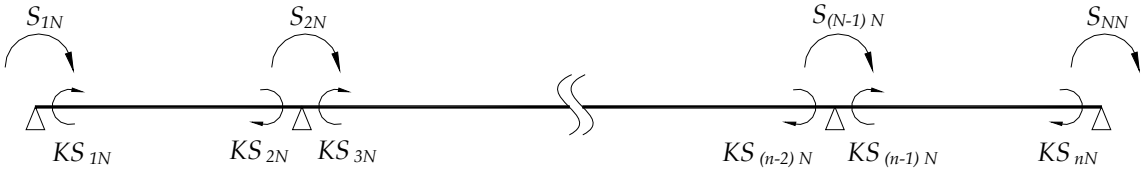
$D_1 = 1$ *and* $D_2 = \cdots = D_{N-1} = D_N = 0$

(a) First column of [*KS*] and [*S*]



$D_2 = 1$ *and* $D_1 = D_3 = D_4 = \cdots = D_{N-1} = D_N = 0$

(b) Second column of [*KS*] and [*S*]



$D_N = 1$ *and* $D_1 = D_2 = \cdots = D_{N-1} = 0$

(C) Nth column of [*KS*] and [*S*]

Figure 2-4. Elements of [*KS*] and [*S*] due to unit displacements.

With the stiffness matrices [*KS*] and [*S*] established, the next step is to determine the vectors {*MF*} and {*Z*}. The elements of {*MF*} are the fixed end forces as defined by the member degrees of freedom in Fig. 2-2b and can be obtained with the following equation:

$$MF_i = \pm[CW_i \cdot W \cdot L^2 + \sum_{a=1}^{m} CP_{ia} \cdot P_a \cdot L] \tag{2.8}$$

where, MF_i = ith element of {*MF*}

CW_i = fixed end force coefficient for an uniformly distributed load

W = uniformly distributed load

CP_{ia} = fixed end force coefficient for a concentrated load

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P_a = concentrated load

m = number of concentrated loads

Fixed end moments for each member can be determined by multiplying their coefficients by WL^2 for uniform load and PL for concentrated load in which W is the load per linear foot, P is the intensity of concentrated load and L is the length of the span under consideration. The procedures for determining fixed end force coefficients for uniformly distributed and concentrated loads are described in Section 2.1.1.1.

The nodal force vector $\{Z\}$ is obtained from the elements of the fixed end moment vector $\{MF\}$, which are summed at the global degrees of freedom, and can be expressed as

$$\begin{Bmatrix} Z_1 \\ Z_2 \\ \vdots \\ Z_{N-1} \\ Z_N \end{Bmatrix} = \begin{Bmatrix} MF_1 \\ MF_2 + MF_3 \\ \vdots \\ MF_{n-2} + MF_{n-1} \\ MF_n \end{Bmatrix} \tag{2.9}$$

When all the nodal forces acting on the structure are incorporated in the vector $\{Z\}$, the following relationship can be established by utilizing the principle of superposition:

$$[S]\{D\} + \{Z\} = 0 \tag{2.10}$$

Now, the nodal displacement vector $\{D\}$ as defined by Fig. 2-2a can be obtained by multiplying the inverse of the stiffness matrix to the nodal force vector.

$$\begin{Bmatrix} D_1 \\ D_2 \\ \vdots \\ D_{N-1} \\ D_N \end{Bmatrix} = -\begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1(N-1)} & S_{1N} \\ S_{21} & S_{22} & \cdots & S_{2(N-1)} & S_{2N} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ S_{(N-1)1} & S_{(N-1)2} & \cdots & S_{(N-1)(N-1)} & S_{(N-1)N} \\ S_{N1} & S_{N2} & \cdots & S_{N(N-1)} & S_{NN} \end{bmatrix}^{-1} \begin{Bmatrix} Z_1 \\ Z_2 \\ \vdots \\ Z_{N-1} \\ Z_N \end{Bmatrix} \tag{2.11}$$

Finally, the member end forces $\{MA\}$ specified in Fig. 2-2b will then be

$$\begin{Bmatrix} MA_1 \\ MA_2 \\ \vdots \\ MA_{n-1} \\ MA_n \end{Bmatrix} = \begin{bmatrix} KS_{11} & KS_{12} & \cdots & KS_{1(N-1)} & KS_{1N} \\ KS_{21} & KS_{22} & \cdots & KS_{2(N-1)} & KS_{2N} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ KS_{(n-1)1} & KS_{(n-1)2} & \cdots & KS_{(n-1)(N-1)} & KS_{(n-1)N} \\ KS_{n1} & KS_{n2} & \cdots & KS_{n(N-1)} & KS_{nN} \end{bmatrix} \begin{Bmatrix} D_1 \\ D_2 \\ \vdots \\ D_{N-1} \\ D_N \end{Bmatrix} \tag{2.12}$$

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2.1.1.1. Fixed End Force Coefficient for a Member with a Variable Section Property

A methodology used to determine fixed end moment coefficients for uniformly distributed and concentrated loads is presented in this section. Unlike the case with prismatic members (those having a constant moment of inertia along their entire length), fixed end moments in a non-prismatic member depend on the geometry of the member's cross section. Since the structural analysis program is intended to be used for analyzing bridges consisting of either (or both) prismatic or (and) non-prismatic members, a member with up to five variable sections, each of which may contain different moment of inertia, as shown in Fig. 2-5 was considered in the development.

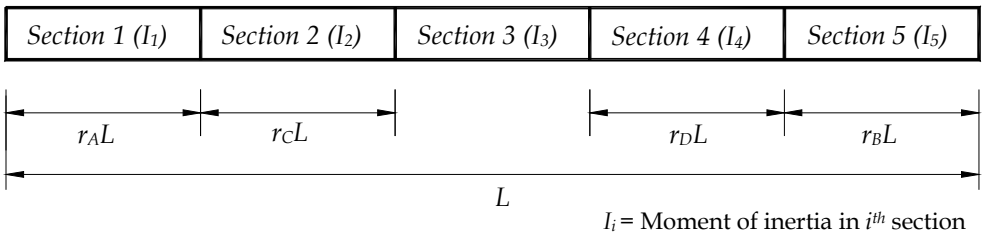

Figure 2-5. Member with five variable sections and moment of inertia.

One of the most commonly used techniques to evaluate fixed-end forces for a member with a variable section property is the moment area method. The moment area method is related to the principle that the slope is the area under the curve and the deflection is the moment of area. Starting with the moment-curvature relationship, a second order equation for the deflection, slope, and *M/EI* can be expressed as shown below.

$$\frac{d^2v}{dx^2} = \frac{d\theta}{dx} = \frac{M}{EI} \tag{2.13}$$

From the definition,

$$d\theta = \frac{M}{EI}dx \tag{2.14}$$

Equation 2.14 can be integrated between arbitrary points *A* and *B* to obtain

$$\theta_{AB} = \int_A^B \frac{M}{EI}dx \tag{2.15}$$

The *M/EI* diagram can be obtained from dividing each ordinate of the bending moment diagram by the corresponding value of the member flexural rigidity (*EI*) at the ordinate. According to the principles of the moment of area theorem and conjugate beam method, the slope of the tangents to the elastic curve of a member at a point equals the shear at that point if the beam is loaded with *M/EI*

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diagram. For a member with fixed supports at both ends, the slopes will be zero at both ends due to the imposed restraints. Therefore, one can relate the member shear (or reaction) and *M/EI* to the slope and loads (i.e., the slopes as the end reactions of a simply supported beam loaded with the *M/EI* diagrams), that is, the slopes of the tangents to the elastic curve at the supports are the end reactions of a simply supported member loaded with the *M/EI* diagrams [41].

Fixed end moment coefficient for uniformly distributed load

Illustrated in Fig. 2-6 is a moment diagram for a member with a variable section property with both ends fixed and a uniformly distributed load of *W* applied. The bending moment diagram for fixed end moments, MF_{AB} and MF_{BA}, is imposed upon the diagram. The equations for the reactions at joints *A* and *B* are established in Eqs. 2.16 and 2.17, respectively.

$$MF_{BA}\int_A^B \frac{x^2 dx}{I_x} + MF_{AB}\int_A^B \frac{(L-x)xdx}{I_x} + \frac{WL}{2}\int_A^B \frac{(L-x)x^2 dx}{I_x} = 0 \tag{2.16}$$

$$MF_{BA}\cdot a1 + MF_{AB}\cdot a2 + \frac{WL}{2}\cdot a3 = 0 \tag{2.16a}$$

$$MF_{BA}\int_B^A \frac{(L-x_1)x_1 dx_1}{I_x} + MF_{AB}\int_B^A \frac{x_1^2 dx_1}{I_x} + \frac{WL}{2}\int_B^A \frac{(L-x_1){x_1}^2 dx_1}{I_x} = 0 \tag{2.17}$$

$$MF_{BA}\cdot a4 + MF_{AB}\cdot a5 + \frac{WL}{2}\cdot a6 = 0 \tag{2.17a}$$

Equations 2.16 and 2.17 are expressed in general and can be applied to any member with a known moment of inertia along the member length. Note that the moment of inertia for each section shown in Fig. 2-5 can be easily determined by the structural analysis program discussed in Section 2.1.2.

Each term of Eqs. 2.16 and 2.17 needs to be evaluated in five steps since the member may be comprised of different moment of inertia values. As was shown in Fig. 2-5, a member with up to five sections was considered and it was assumed that the moment of inertia in each section is constant. From the joint *A* to *B* as defined in Fig. 2-6, the integral in the first term of Eq. 2.16, which is specified as $a1$, can be evaluated as follows:

$$a1 = \int_A^B \frac{x^2 dx}{I_x} = c1 + c2 + c3 + c4 + c5 \tag{2.18}$$

$$c1 = \int_0^{r_A L} \frac{x^2 dx}{I_1} = \frac{{r_A}^3 L^3}{3I_1} \tag{2.19}$$

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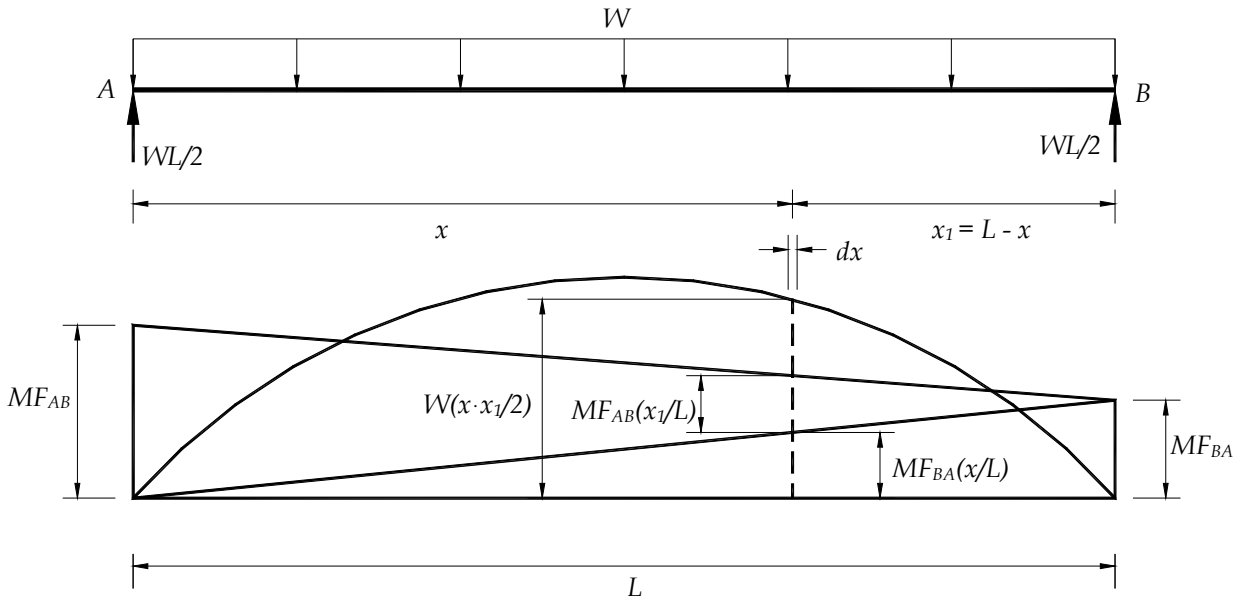

Figure 2-6. Moment diagram due to a uniformly distributed load.

$$c2 = \int_{r_A L}^{(r_A+r_C)L} \frac{x^2 dx}{I_2} = \frac{L^3[(r_A + r_C)^3 - r_A{}^3]}{3I_2} \tag{2.20}$$

$$c3 = \int_{(r_A+r_C)L}^{(1-r_B-r_D)L} \frac{x^2 dx}{I_3} = \frac{L^3[(1 - r_B - r_D)^3 - (r_A + r_C)^3]}{3I_3} \tag{2.21}$$

$$c4 = \int_{r_B L}^{(r_B+r_D)L} \frac{(L-x)^2 dx}{I_4} = \frac{L^3 r_D}{3I_4}(3 - 6r_B - 3r_D + 3r_B{}^2 + 3r_B r_D + r_D{}^2) \tag{2.22}$$

$$c5 = \int_{0}^{r_B L} \frac{(L-x)^2 dx}{I_5} = \frac{L^3 r_B}{3I_5}(3 - 3r_B + r_B{}^2) \tag{2.23}$$

Note that integrals $c1$, $c2$ and $c3$ are evaluated from left to right while the integral $c4$ and $c5$ are evaluated from right to left. The integral in the second term of Eq. 2.16, specified as $a2$, is

$$a2 = \int_A^B \frac{(L-x)x dx}{I_x} = L\int_A^B \frac{x dx}{I_x} - \int_A^B \frac{x^2 dx}{I_x} = z1 - a1 \tag{2.24}$$

Only the integral in the first term of Eq. 2.24 needs to be evaluated as the second term has already been evaluated in Eq. 2.18, which was specified as $a1$. By expanding the integral in the first term to five integrals and evaluating them,

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$$z1 = L\int_A^B \frac{xdx}{I_x} = c6 + c7 + c8 + c9 + c10 \tag{2.25}$$

$$c6 = L\int_0^{r_A L} \frac{xdx}{I_1} = \frac{L^3 {r_A}^2}{2I_1} \tag{2.26}$$

$$c7 = L\int_{r_A L}^{(r_A+r_C)L} \frac{xdx}{I_2} = \frac{L^3[(r_A + r_C)^2 - {r_A}^2]}{2I_2} \tag{2.27}$$

$$c8 = L\int_{(r_A+r_C)L}^{(1-r_B-r_D)L} \frac{xdx}{I_3} = \frac{L^3[(1 - r_B - r_D)^2 - (r_A + r_C)^2]}{2I_3} \tag{2.28}$$

$$c9 = L\int_{r_B L}^{(r_B+r_D)L} \frac{(L-x)dx}{I_4} = \frac{L^3 r_D}{2I_4}(2 - 2r_B - r_D) \tag{2.29}$$

$$c10 = L\int_0^{r_B L} \frac{(L-x)dx}{I_5} = \frac{L^3 r_B}{2I_5}(2 - r_B) \tag{2.30}$$

Similarly, the integral in the third term of Eq. 2.16 is

$$a3 = \int_A^B \frac{(L-x)x^2 dx}{I_x} = L\int_A^B \frac{x^2 dx}{I_x} - \int_A^B \frac{x^3 dx}{I_x} = L \cdot a1 - z2 \tag{2.31}$$

As shown in Eqs. 2.18 through 2.23, that the integral in the first term of Eq. 2.31 has already been evaluated and specified as $a1$ but the second term, specified as $z2$, involves the third power of x and has not yet been evaluated. As before, this term can be integrated in five steps as follows:

$$z2 = \int_A^B \frac{x^3 dx}{I_x} = c11 + c12 + c13 + c14 + c15 \tag{2.32}$$

The integrals $c11$, $c12$, $c13$, $c14$ and $c15$ are

$$c11 = \int_0^{r_A L} \frac{x^3 dx}{I_1} = \frac{L^4 {r_A}^4}{4I_1} \tag{2.33}$$

$$c12 = \int_{r_A L}^{(r_A+r_C)L} \frac{x^3 dx}{I_2} = \frac{L^4[(r_A + r_C)^4 - {r_A}^4]}{4I_2} \tag{2.34}$$

$$c13 = \int_{(r_A+r_C)L}^{(1-r_B-r_D)L} \frac{x^3 dx}{I_3} = \frac{L^4[(1 - r_B - r_D)^4 - (r_A + r_C)^4]}{4I_3} \tag{2.35}$$

$$c14 = \int_{r_B L}^{(r_B+r_D)L} \frac{(L-x)^3 dx}{I_4} = \frac{L^4 r_D(2 - r_D - 2r_B)(2{r_B}^2 - 4r_B + 2r_B r_D - 2r_D + 2 + {r_D}^2)}{4I_4} \tag{2.36}$$

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$$c15 = \int_0^{r_B L} \frac{(L-x)^3 dx}{I_5} = \frac{L^4 r_B}{4I_5}(4 - 6r_B + 4{r_B}^2 - {r_B}^3) \tag{2.37}$$

The evaluations involved in Eq. 2.17 are very similar to those used in solving Eq. 2.16. The difference is that the equation is expressed with respect to x_1 instead of x and the integrals are solved from the joint B to A. The integral in the first term of Eq. 2.17, specified as $a4$, can be expanded to

$$a4 = \int_B^A \frac{(L-x_1)x_1 dx_1}{I_x} = L\int_B^A \frac{x_1 dx_1}{I_x} - \int_B^A \frac{{x_1}^2 dx_1}{I_x} = z3 - a5 \tag{2.38}$$

Note that the second term in Eq. 2.38, specified as $a5$, is the same as the integral in the second term of Eq. 2.17, and it can be expanded to five integrals and evaluated as follows:

$$a5 = \int_B^A \frac{{x_1}^2 dx_1}{I_x} = c16 + c17 + c18 + c19 + c20 \tag{2.39}$$

$$c16 = \int_0^{r_B L} \frac{{x_1}^2 dx_1}{I_5} = \frac{L^3 {r_B}^3}{3I_5} \tag{2.40}$$

$$c17 = \int_{r_B L}^{(r_B + r_D)L} \frac{{x_1}^2 dx_1}{I_4} = \frac{L^3[(r_B + r_D)^3 - {r_B}^3]}{3I_4} \tag{2.41}$$

$$c18 = \int_{(r_B + r_D)L}^{(1 - r_A - r_C)L} \frac{{x_1}^2 dx_1}{I_3} = \frac{L^3[(1 - r_A - r_C)^3 - (r_B + r_D)^3]}{3I_3} \tag{2.42}$$

$$c19 = \int_{r_A L}^{(r_A + r_C)L} \frac{(L - x_1)^2 dx_1}{I_2} = \frac{L^3 r_C}{3I_2}(3 - 6r_A - 3r_C - 3{r_A}^2 + 3r_A r_C + {r_C}^2) \tag{2.43}$$

$$c20 = \int_0^{r_A L} \frac{(L - x_1)^2 dx_1}{I_1} = \frac{L^3 r_A}{3I_1}(3 - 3r_A + {r_A}^2) \tag{2.44}$$

As before, the first term of Eq. 2.38 must be evaluated in five steps; therefore,

$$z3 = L\int_B^A \frac{x_1 dx_1}{I_x} = c21 + c22 + c23 + c24 + c25 \tag{2.45}$$

$$c21 = L\int_0^{r_B L} \frac{x_1 dx_1}{I_5} = \frac{L^3 {r_B}^2}{2I_5} \tag{2.46}$$

$$c22 = L\int_{r_B L}^{(r_B + r_D)L} \frac{x_1 dx_1}{I_4} = \frac{L^3[(r_B + r_D)^2 - {r_B}^2]}{2I_4} \tag{2.47}$$

$$c23 = L\int_{(r_B + r_D)L}^{(1 - r_A - r_C)L} \frac{x_1 dx_1}{I_3} = \frac{L^3[(1 - r_A - r_C)^2 - (r_B + r_D)^2]}{2I_3} \tag{2.48}$$

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$$c24 = L\int_{r_A L}^{(r_A+r_C)L} \frac{(L-x_1)dx_1}{I_2} = \frac{L^3 r_C}{2I_2}(2-2r_A-r_C) \tag{2.49}$$

$$c25 = L\int_{0}^{r_A L} \frac{(L-x_1)dx_1}{I_1} = \frac{L^3 r_A}{2I_1}(2-2r_A) \tag{2.50}$$

Finally, the integral in the third term of Eq. 2.17, specified as *a*6, can be expanded to

$$a6 = \int_B^A \frac{(L-x_1){x_1}^2 dx_1}{I_x} = L\int_B^A \frac{{x_1}^2 dx_1}{I_x} - \int_B^A \frac{{x_1}^3 dx_1}{I_x} = L\cdot a5 - z4 \tag{2.51}$$

The integral in the first term of Eq. 2.51 is same as *a*5 which has been already previously evaluated. However, the second term, *z*4, which involves the third power of x_1 is not yet evaluated and can be integrated in five steps which give

$$z4 = \int_B^A \frac{{x_1}^3 dx_1}{I_x} = c26 + c27 + c28 + c29 + c30 \tag{2.52}$$

$$c26 = \int_0^{r_B L} \frac{{x_1}^3 dx_1}{I_5} = \frac{L^4 {r_B}^4}{4I_5} \tag{2.53}$$

$$c27 = \int_{r_B L}^{(r_B+r_D)L} \frac{{x_1}^3 dx_1}{I_4} = \frac{L^4[(r_B+r_D)^4 - {r_B}^4]}{4I_4} \tag{2.54}$$

$$c28 = \int_{(r_B+r_D)L}^{(1-r_A-r_C)L} \frac{{x_1}^3 dx_1}{I_3} = \frac{L^4[(1-r_A-r_C)^4 - (r_B+r_D)^4]}{4I_3} \tag{2.55}$$

$$c29 = \int_{r_A L}^{(r_A+r_C)L} \frac{(L-x_1)^3 dx_1}{I_2} = \frac{L^4 r_C(2-r_C-2r_A)(2{r_A}^2 - 4r_A + 2r_A r_C - 2r_C + 2 + r_C^2)}{4I_2} \tag{2.56}$$

$$c30 = \int_0^{r_A L} \frac{(L-x_1)^3 dx_1}{I_1} = \frac{L^4 r_A}{4I_1}(4 - 6r_A + 4{r_A}^2 - {r_A}^3) \tag{2.57}$$

Once all the integrals are evaluated and solving Eqs. 2.16a and 2.17a simultaneously, one can establish a relationship as follows:

$$\begin{Bmatrix} MF_{BA} \\ MF_{AB} \end{Bmatrix} = \begin{bmatrix} a1 & a2 \\ a4 & a5 \end{bmatrix}^{-1} \begin{Bmatrix} a3 \\ a6 \end{Bmatrix} \cdot \left(-\frac{WL}{2}\right) = \begin{Bmatrix} -CW_{BA}\cdot WL^2 \\ -CW_{AB}\cdot WL^2 \end{Bmatrix} \tag{2.58}$$

MF_{AB} and MF_{BA} in Eq. 2.58 are the fixed end moments at the left and right joints induced by a uniformly distributed load, *W*, applied on a member with a variable moment of inertia, and CW_{AB} and CW_{BA} are the coefficients of the fixed end moments.

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Fixed end moment coefficient for concentrated load

Illustrated in Fig. 2-7 is the moment diagram for a fixed end beam with a concentrated load, P, applied at a distance tL from the left joint A and t_1L from the right joint B. The procedures involved in determining the fixed end moments due to concentrated loads is very similar to those used for a uniformly distributed load in that the integrals are evaluated in steps. The major difference can be found in evaluating integrals in the third and fourth terms of Eqs. 2.59 and 2.60. Since the concentrated load, P, can be applied at any point along the member, the evaluation of these integrals depends on the location of the applied load, that is, the limits of various parts of the integrals are variable. Therefore, a total of five cases must be considered; P is in the region of (1) *Section 1,* (2) *Section 2,* (3) *Section 3,* (4) *Section 4* and (5) *Section 5* as shown in Fig. 2-5. The general expression for the reaction at B with respect to x is given as

$$MF_{BA}\int_A^B \frac{x^2dx}{I_x} + MF_{AB}\int_A^B \frac{(L-x)xdx}{I_x} + Pt_1L\int_A^{tL} \frac{x^2dx}{I_x} + PtL\int_{tL}^B \frac{(L-x)xdx}{I_x} = 0 \tag{2.59}$$

$$MF_{BA}\cdot a1 + MF_{AB}\cdot a2 + PL\cdot(a7,\ a9,\ a11,\ a13\ or\ a15) = 0 \tag{2.59a}$$

Similarly, the general expression for the reaction at A with respect to x_1 is

$$MF_{BA}\int_B^A \frac{(L-x_1)x_1dx_1}{I_x} + MF_{AB}\int_B^A \frac{x_1^2dx_1}{I_x} + PtL\int_B^{t_1L} \frac{x_1^2dx_1}{I_x} + Pt_1L\int_{t_1L}^A \frac{(L-x_1)x_1dx_1}{I_x} = 0 \tag{2.60}$$

$$MF_{BA}\cdot a4 + MF_{AB}\cdot a5 + PL\cdot(a8,\ a10,\ a12,\ a14\ or\ a16) = 0 \tag{2.60a}$$

The first and second terms of Eqs. 2.59 and 2.60 are exactly the same as those in Eqs. 2.16 and 2.17. Therefore, the evaluation for these two terms will not be repeated. The third and fourth terms in Eqs. 2.59 and 2.60, respectively, must be evaluated in five steps depending on the location of P in reference to the sections illustrated in Fig. 2-8. Once the third and fourth terms in Eqs. 2.59 and 2.60 are evaluated, these two terms will be combined into one that includes one of the evaluations ($a7$ through $a16$ depending on the location of P) illustrated in Eqs. 2.59a and 2.60a.

Case 1: *P on Section 1 ($t \le r_A$)*: The first case to be considered is when P is on *Section 1*, that is, $t \le r_A$ as illustrated in Fig. 2-8a. The integral in the third term of Eq. 2.59, specified as $d1$, can be evaluated as

$$d1 = \int_A^{tL} \frac{x^2dx}{I_x} = \int_0^{tL} \frac{x^2dx}{I_x} = \frac{L^3t^3}{3I_1} \tag{2.61}$$

The integral in the fourth term of Eq. 2.59, specified as $d2$, can be expanded to $d3$ and $d4$, thereby, noting the identity

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$$d2 = \int_{tL}^{B} \frac{(L-x)xdx}{I_x} \equiv \left[\int_{B}^{t_1 L} \frac{(L-x_1)x_1 dx_1}{I_x} = L\int_{B}^{t_1 L} \frac{x_1 dx_1}{I_x} - \int_{B}^{t_1 L} \frac{x_1{}^2 dx_1}{I_x} = d3 - d4 \right] \tag{2.62}$$

The integrals $d3$ and $d4$ must be evaluated in steps for each section as follows:

$$d3 = L\int_{B}^{t_1 L} \frac{x_1 dx_1}{I_x} = L\int_{0}^{r_B L} \frac{x_1 dx_1}{I_5} + L\int_{r_B L}^{(r_B+r_D)L} \frac{x_1 dx_1}{I_4} + L\int_{(r_B+r_D)L}^{(1-r_A-r_C)L} \frac{x_1 dx_1}{I_3}$$
$$+ L\int_{r_A L}^{(r_A+r_C)L} \frac{(L-x_1)dx_1}{I_2} + L\int_{tL}^{r_A L} \frac{(L-x_1)dx_1}{I_1} \tag{2.63}$$

$$d3 = c21 + c22 + c23 + c24 + d5 \tag{2.63a}$$

$$d4 = \int_{B}^{t_1 L} \frac{x_1{}^2 dx_1}{I_x} = \int_{0}^{r_B L} \frac{x_1{}^2 dx_1}{I_5} + \int_{r_B L}^{(r_B+r_D)L} \frac{x_1{}^2 dx_1}{I_4} + \int_{(r_B+r_D)L}^{(1-r_A-r_C)L} \frac{x_1{}^2 dx_1}{I_3}$$
$$+ \int_{r_A L}^{(r_A+r_C)L} \frac{(L-x_1)^2 dx_1}{I_2} + \int_{tL}^{r_A L} \frac{(L-x_1)^2 dx_1}{I_1} \tag{2.64}$$

$$d4 = c16 + c17 + c18 + c19 + d6 \tag{2.64a}$$

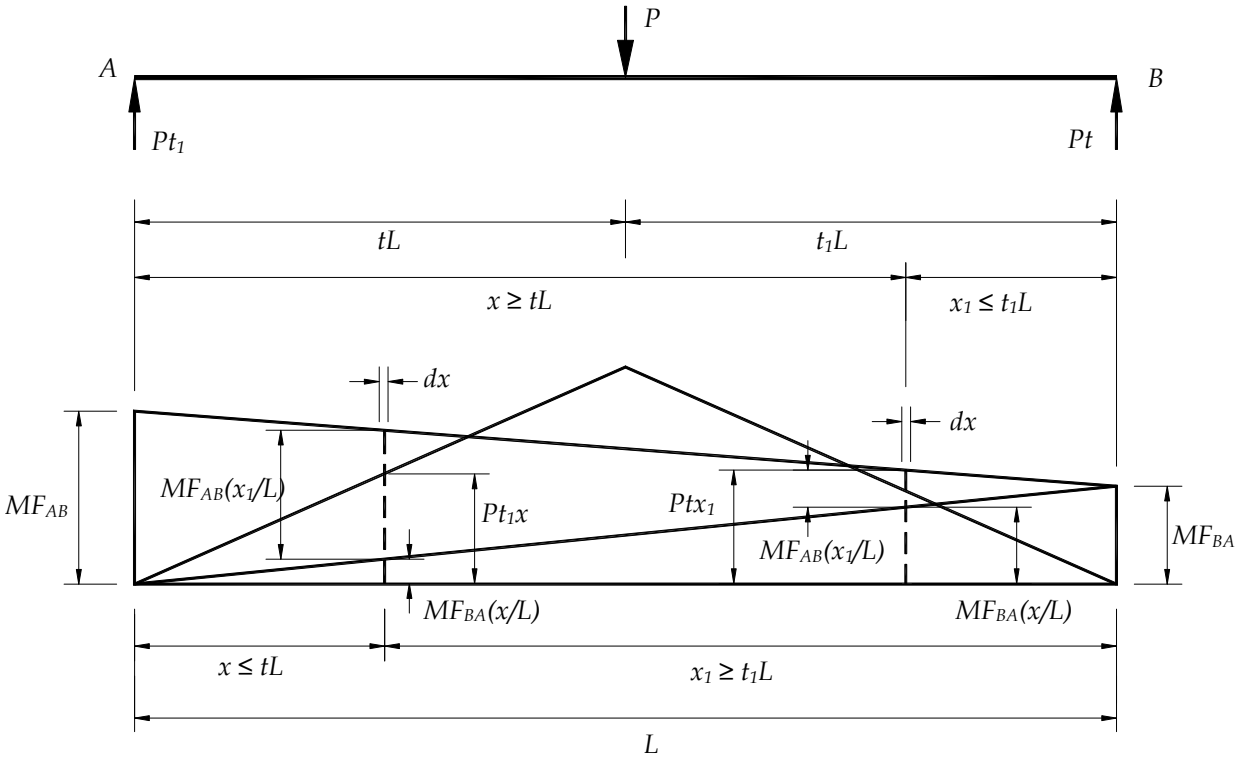

Figure 2-7. Moment diagram due to a concentrated load.

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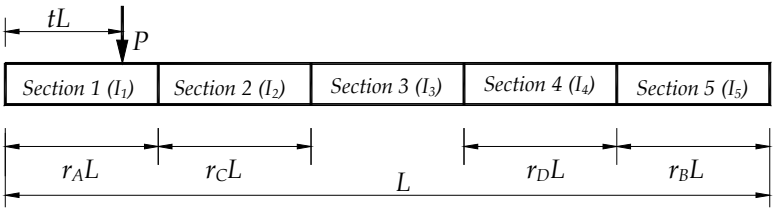
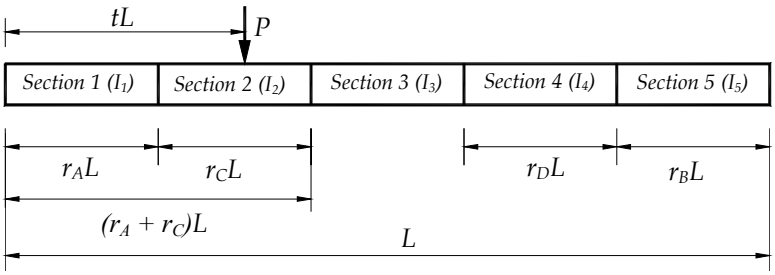
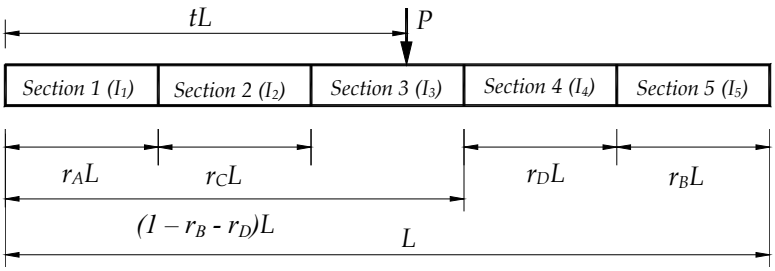


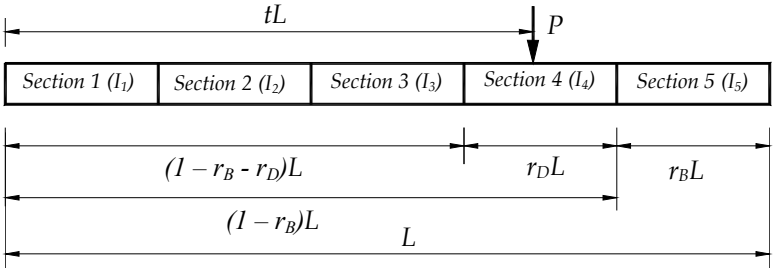
(a) Case 1: $t \leq r_A$



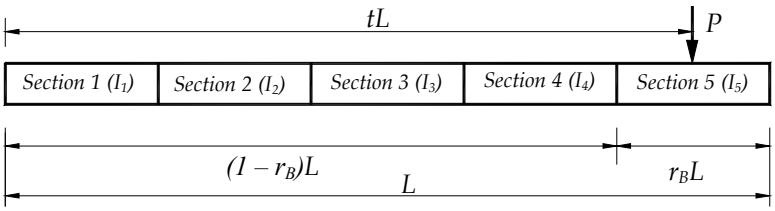
(b) Case 2: $r_A \leq t \leq (r_A + r_C)$



(c) Case 3: $(r_A + r_C) \leq t \leq (1 - r_B - r_D)$



(d) Case 4: $(1 - r_B - r_D) \leq t \leq (1 - r_B)$



(e) Case 5: $(1 - r_B) \leq t$

Figure 2-8. Location of concentrated load.

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The first four terms to the right of the equality sign in Eqs. 2.63 and 2.64 have already been evaluated in Eqs. 2.46 through 2.49 and 2.40 through 2.43, respectively, and, therefore, will not be repeated. The remaining integrals, *d*5 and *d*6 can be evaluated as follow:

$$d5 = L\int_{tL}^{r_A L} \frac{(L - x_1)dx_1}{I_1} = \frac{L^3(2r_A - {r_A}^2 - 2t + t^2)}{2I_1} \tag{2.65}$$

$$d6 = \int_{tL}^{r_A L} \frac{(L - x_1)^2 dx_1}{I_1} = \frac{L^3(3r_A - 3{r_A}^2 + {r_A}^3 - 3t + 3t^2 - t^3)}{3I_1} \tag{2.66}$$

Once *d*1 and *d*2, which represent the integrals in the third and fourth terms of Eq. 2.59, are completed, the expression for *a*7 in Eq. 2.59a can be established as shown below.

$$a7 = t_1 \cdot d1 + t \cdot d2 \tag{2.67}$$

The first and second terms of Eq. 2.60 also occur in Eq. 2.17 and their integrals have been illustrated in Eqs. 2.38 and 2.39. Also, the integral in the third term of Eq. 2.60 has already evaluated in Eq. 2.64 and specified as *d*4. By evaluating the integral in the fourth term of Eq. 2.60, one can obtain

$$d7 = \left[\int_{t_1 L}^{A} \frac{(L - x_1)x_1 dx_1}{I_x} \equiv \int_{A}^{tL} \frac{(L - x)xdx}{I_1} = \int_{0}^{tL} \frac{(L - x)xdx}{I_1}\right] = \frac{L^3 t^2(3 - 2t)}{6I_1} \tag{2.68}$$

With the evaluations of the integrals *d*4 and *d*7 available, therefore, one can establish the expression for *a*8 in Eq. 2.60a as

$$a8 = t \cdot d4 + t_1 \cdot d7 \tag{2.69}$$

Once all the integrals are evaluated and solving Eqs. 2.59a and 2.60a simultaneously, one can establish a relationship for the fixed end moments as follows:

$$\begin{Bmatrix} MF_{BA} \\ MF_{AB} \end{Bmatrix} = \begin{bmatrix} a1 & a2 \\ a4 & a5 \end{bmatrix}^{-1} \begin{Bmatrix} a7 \\ a8 \end{Bmatrix} \cdot (-PL) = \begin{Bmatrix} -CP_{BA} \cdot PL \\ -CP_{AB} \cdot PL \end{Bmatrix} \tag{2.70}$$

MF_{AB} and MF_{BA} in Eq. 2.70 are the fixed end moments at the left and right joints induced by a concentrated load, *P*, placed on *Section 1* ($t \le r_A$), and CP_{AB} and CP_{BA} are their coefficients.

Case 2: *P on Section 2* ($r_A \le t \le (r_A + r_C)$): The second case to be considered is when *P* is on *Section 2*, that is, $r_A \le t \le (r_A + r_C)$ as illustrated in Fig. 2-8b. The integral in the third term of Eq. 2.59 must be solved in two steps as illustrated in Eq. 2.71.

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$$g1 = \int_A^{tL} \frac{x^2 dx}{I_x} = \int_0^{r_A L} \frac{x^2 dx}{I_x} + \int_{r_A L}^{tL} \frac{x^2 dx}{I_x} = g2 + g3 \tag{2.71}$$

The integrals $g2$ and $g3$ can be evaluated as follows:

$$g2 = \int_0^{r_A L} \frac{x^2 dx}{I_1} = \frac{L^3 {r_A}^3}{3I_1} \tag{2.72}$$

$$g3 = \int_{r_A L}^{tL} \frac{x^2 dx}{I_2} = \frac{L^3 \left(t^3 - {r_A}^3\right)}{3I_2} \tag{2.73}$$

The integral in the fourth term of Eq. 2.59, specified as $g4$, can be solved in four steps, $g5$ through $g8$, thereby, noting the identity

$$g4 = \left[\int_{tL}^{B} \frac{(L-x)x dx}{I_x} \equiv \int_B^{t_1 L} \frac{(L-x_1)x_1 dx_1}{I_x} \right] = g5 + g6 + g7 + g8 \tag{2.74}$$

$$g4 = \int_B^{t_1 L} \frac{(L-x_1)x_1 dx_1}{I_x} = \int_0^{r_B L} \frac{(L-x_1)x_1 dx_1}{I_5} + \int_{r_B L}^{(r_B+r_D)L} \frac{(L-x_1)x_1 dx_1}{I_4}$$
$$+ \int_{(r_B+r_D)L}^{(1-r_A-r_C)L} \frac{(L-x_1)x_1 dx_1}{I_3} + \int_{(1-r_A-r_C)L}^{t_1 L} \frac{(L-x_1)x_1 dx_1}{I_2} \tag{2.74a}$$

The evaluations for the integrals for $g5$ and $g6$ are

$$g5 = \int_0^{r_B L} \frac{(L-x_1)x_1 dx_1}{I_5} = \frac{L^3 {r_B}^2 (3 - 2r_B)}{6I_5} \tag{2.75}$$

$$g6 = \int_{r_B L}^{(r_B+r_D)L} \frac{(L-x_1)x_1 dx_1}{I_4} = \frac{L^3 r_D \left(6r_B + 3r_D - 6{r_B}^2 - 6r_B r_D - 2{r_D}^2\right)}{6I_4} \tag{2.76}$$

The integral $g7$ can be expanded to two terms, $c23$ and $c18$, whose solutions have been illustrated in Eqs. 2.48 and 2.42.

$$g7 = \int_{(r_B+r_D)L}^{(1-r_A-r_C)L} \frac{(L-x_1)x_1 dx_1}{I_3} = L\int_{(r_B+r_D)L}^{(1-r_A-r_C)L} \frac{x_1 dx_1}{I_3} - \int_{(r_B+r_D)L}^{(1-r_A-r_C)L} \frac{{x_1}^2 dx_1}{I_3} = c23 - c18 \tag{2.77}$$

Similarly, the integral $g8$ can be expanded to two terms, $g9$ and $g10$ as shown below.

$$g8 = \int_{(1-r_A-r_C)L}^{t_1 L} \frac{(L-x_1)x_1 dx_1}{I_2} = L\int_{(1-r_A-r_C)L}^{t_1 L} \frac{x_1 dx_1}{I_2} - \int_{(1-r_A-r_C)L}^{t_1 L} \frac{{x_1}^2 dx_1}{I_2} = g9 - g10 \tag{2.78}$$

By evaluating the integrals $g9$ and $g10$, one can obtain

$$g9 = L\int_{(1-r_A-r_C)L}^{t_1 L} \frac{x_1 dx_1}{I_2} = \frac{L^3 [{t_1}^2 - (1-r_A-r_C)^2]}{2I_2} \tag{2.79}$$

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$$g10 = \int_{(1-r_A-r_C)L}^{t_1 L} \frac{x_1^{\,2} dx_1}{I_2} = \frac{L^3[t_1^{\,3} - (1-r_A-r_C)^3]}{3I_2} \tag{2.80}$$

Once $g1$ and $g4$, which represent the integrals in the third and fourth terms of Eq. 2.59 are completed, the expression for $a9$ in Eq. 2.59a can be established as shown below.

$$a9 = t_1 \cdot g1 + t \cdot g4 \tag{2.81}$$

The integral in the third term of Eq. 2.60, specified as $g11$, needs to be solved in four steps, whose solutions ($c16$, $c17$, $c18$ and $g10$) have been previously illustrated.

$$g11 = \int_B^{t_1 L} \frac{x_1^{\,2} dx_1}{I_x} = \int_0^{r_B L} \frac{x_1^{\,2} dx_1}{I_5} + \int_{r_B L}^{(r_B+r_D)L} \frac{x_1^{\,2} dx_1}{I_4} + \int_{(r_B+r_D)L}^{(1-r_A-r_C)L} \frac{x_1^{\,2} dx_1}{I_3} + \int_{(1-r_A-r_C)L}^{t_1 L} \frac{x_1^{\,2} dx_1}{I_2} \tag{2.82}$$

$$g11 = c16 + c17 + c18 + g10 \tag{2.82a}$$

By evaluating the integral in the fourth term of Eq. 2.60 into two steps,

$$g12 = \int_{t_1 L}^{A} \frac{(L-x_1)x_1 dx_1}{I_x} \equiv \left[\int_A^{tL} \frac{(L-x)x dx}{I_x} = \int_0^{r_A L} \frac{(L-x)x dx}{I_1} + \int_{r_A L}^{tL} \frac{(L-x)x dx}{I_2} = g13 + g14 \right] \tag{2.83}$$

and the solutions to the integrals $g13$ and $g14$ can be found as follows:

$$g13 = \int_0^{r_A L} \frac{(L-x)x dx}{I_1} = \frac{L^3 r_A^{\,2}(3-2r_A)}{6I_1} \tag{2.84}$$

$$g14 = \int_{r_A L}^{tL} \frac{(L-x)x dx}{I_2} = \frac{L^3\left(3t^2 - 2t^3 + 2r_A^{\,3} - 3r_A^{\,2}\right)}{6I_2} \tag{2.85}$$

With the evaluations of the integrals $g11$ and $g12$ available, therefore, one can establish the expression for $a10$ in Eq. 2.60a as

$$a10 = t \cdot g11 + t_1 \cdot g12 \tag{2.86}$$

Once all the integrals are evaluated and solving Eqs. 2.59a and 2.60a simultaneously, one can establish a relationship for the fixed end moments as follows:

$$\begin{Bmatrix} MF_{BA} \\ MF_{AB} \end{Bmatrix} = \begin{bmatrix} a1 & a2 \\ a4 & a5 \end{bmatrix}^{-1} \begin{Bmatrix} a9 \\ a10 \end{Bmatrix} \cdot (-PL) = \begin{Bmatrix} -CP_{BA} \cdot PL \\ -CP_{AB} \cdot PL \end{Bmatrix} \tag{2.87}$$

MF_{AB} and MF_{BA} in Eq. 2.87 are the fixed end moments at the left and right joints induced by a concentrated load, P, placed on *Section 2* ($r_A \le t \le (r_A + r_C)$), and CP_{AB} and CP_{BA} are their coefficients.

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Case 3: *P on Section 3 ($(r_A + r_C) \le t \le (1 - r_B - r_D)$)*: The third case to be considered is when *P* is on *Section 3*, that is, $(r_A + r_C) \le t \le (1 - r_B - r_D)$ as illustrated in Fig. 2-8c. The integral in the third term of Eq. 2.59 must be solved in three steps as illustrated in Eq. 2.88.

$$h1 = \int_A^{tL} \frac{x^2 dx}{I_x} = \int_0^{r_A L} \frac{x^2 dx}{I_1} + \int_{r_A L}^{(r_A + r_C)L} \frac{x^2 dx}{I_2} + \int_{(r_A + r_C)L}^{tL} \frac{x^2 dx}{I_3} = c1 + c2 + h2 \tag{2.88}$$

The first two integrals, specified as $c1$ and $c2$, have been previously evaluated and the remaining integral, $h2$, can be evaluated as

$$h2 = \int_{(r_A + r_C)L}^{tL} \frac{x^2 dx}{I_3} = \frac{L^3\left(t^3 - {r_A}^3 - 3{r_A}^2 r_C - 3 r_A {r_C}^2 - {r_C}^3\right)}{3 I_3} \tag{2.89}$$

Similarly, the integral in the fourth term of Eq. 2.59, specified as $h3$, can be solved in three steps, thereby, noting the identity

$$h3 = \left[\int_{tL}^{B} \frac{(L - x)x dx}{I_x} \equiv \int_B^{t_1 L} \frac{(L - x_1)x_1 dx_1}{I_x} \right] = g5 + g6 + h4 \tag{2.90}$$

$$h3 = \int_B^{t_1 L} \frac{(L - x_1)x_1 dx_1}{I_x} = \int_0^{r_B L} \frac{(L - x_1)x_1 dx_1}{I_5} + \int_{r_B L}^{(r_B + r_D)L} \frac{(L - x_1)x_1 dx_1}{I_4} + \int_{(r_B + r_D)L}^{t_1 L} \frac{(L - x_1)x_1 dx_1}{I_3} \tag{2.90a}$$

The evaluations for the integrals for $g5$ and $g6$ can be found in Eqs. 2.75 and 2.76. By solving the integral $h4$ in parts,

$$h4 = \int_{(r_B + r_D)L}^{t_1 L} \frac{(L - x_1)x_1 dx_1}{I_3} = L \int_{(r_B + r_D)L}^{t_1 L} \frac{x_1 dx_1}{I_3} - \int_{(r_B + r_D)L}^{t_1 L} \frac{{x_1}^2 dx_1}{I_3} = h5 - h6 \tag{2.91}$$

and the solutions to the integrals $h5$ and $h6$ are

$$h5 = L \int_{(r_B + r_D)L}^{t_1 L} \frac{x_1 dx_1}{I_3} = \frac{L^3({t_1}^2 - {r_B}^2 - 2 r_B r_D - {r_D}^2)}{2 I_3} \tag{2.92}$$

$$h6 = \int_{(r_B + r_D)L}^{t_1 L} \frac{{x_1}^2 dx_1}{I_3} = \frac{L^3({t_1}^3 - {r_B}^3 - 3{r_B}^2 r_D - 3 r_B {r_D}^2 - {r_D}^3)}{3 I_3} \tag{2.93}$$

Once $h1$ and $h3$, which represent the integrals in the third and fourth terms of Eq. 2.59 are completed, the expression for $a11$ in Eq. 2.59a can be established as

$$a11 = t_1 \cdot h1 + t \cdot h3 \tag{2.94}$$

The integral in the third term of Eq. 2.60, specified as $h7$, needs to be solved in three steps, and the solutions to each integral ($c16$, $c17$ and $h6$) have been previously illustrated.

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$$h7 = \int_B^{t_1 L} \frac{x_1^{\,2} dx_1}{I_x} = \int_0^{r_B L} \frac{x_1^{\,2} dx_1}{I_5} + \int_{r_B L}^{(r_B + r_D)L} \frac{x_1^{\,2} dx_1}{I_4} + \int_{(r_B + r_D)L}^{t_1 L} \frac{x_1^{\,2} dx_1}{I_3} = c16 + c17 + h6 \tag{2.95}$$

By evaluating the integral in the fourth term of Eq. 2.60 into three steps,

$$h8 = \left[\int_{t_1 L}^{A} \frac{(L - x_1) x_1 dx_1}{I_x} \equiv \int_A^{tL} \frac{(L - x) x dx}{I_x} \right] = \int_0^{r_A L} \frac{(L - x) x dx}{I_1} + \int_{r_A L}^{(r_A + r_C)L} \frac{(L - x) x dx}{I_2}$$

$$+ \int_{(r_A + r_C)L}^{tL} \frac{(L - x) x dx}{I_3} = g13 + h9 + h10 \tag{2.96}$$

The solution to the integral $g13$ is given in Eq. 2.84 and the integrals $h9$ and $h10$ can be evaluated as follows:

$$h9 = \int_{r_A L}^{(r_A + r_C)L} \frac{(L - x) x dx}{I_2} = \frac{L^3 r_C \left(6 r_A + 3 r_C - 6 r_A^{\,2} - 6 r_A r_C - 2 r_C^{\,2} \right)}{6 I_2} \tag{2.97}$$

$$h10 = \int_{(r_A + r_C)L}^{tL} \frac{(L - x) x dx}{I_3} = L \int_{(r_A + r_C)L}^{tL} \frac{x dx}{I_3} - \int_{(r_A + r_C)L}^{tL} \frac{x^2 dx}{I_3} = h11 - h2 \tag{2.98}$$

where the solution to the integral $h2$ has been given in Eq. 2.89 and the integral $h11$ can be evaluated as

$$h11 = L \int_{(r_A + r_C)L}^{tL} \frac{x dx}{I_3} = \frac{L^3 \left(t^2 - r_A^{\,2} - 2 r_A r_C - r_C^{\,2} \right)}{2 I_3} \tag{2.99}$$

With the evaluations of the integrals $h7$ and $h8$ available, therefore, one can establish the expression for $a12$ in Eq. 2.60a as

$$a12 = t \cdot h7 + t_1 \cdot h8 \tag{2.100}$$

Once all the integrals are evaluated and solving Eqs. 2.59a and 2.60a simultaneously, one can establish a relationship for the fixed end moments as follows:

$$\begin{Bmatrix} MF_{BA} \\ MF_{AB} \end{Bmatrix} = \begin{bmatrix} a1 & a2 \\ a4 & a5 \end{bmatrix}^{-1} \begin{Bmatrix} a11 \\ a12 \end{Bmatrix} \cdot (-PL) = \begin{Bmatrix} -CP_{BA} \cdot PL \\ -CP_{AB} \cdot PL \end{Bmatrix} \tag{2.101}$$

MF_{AB} and MF_{BA} in Eq. 2.101 are the fixed end moments at the left and right joints induced by a concentrated load, P, placed on *Section 3* ($(r_A + r_C) \le t \le (1 - r_B - r_D)$), and CP_{AB} and CP_{BA} are their coefficients.

Case 4: *P on Section 4* ($(1 - r_B - r_D) \le t \le (1 - r_B)$): The fourth case to be considered is when P is on *Section 4*, that is, $(1 - r_B - r_D) \le t \le (1 - r_B)$ as illustrated in Fig. 2-8d. The integral in the third term of Eq. 2.59 must be solved in four steps as illustrated in Eq. 2.102.

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$$j1 = \int_A^{tL} \frac{x^2 dx}{I_x} = \int_0^{r_A L} \frac{x^2 dx}{I_1} + \int_{r_A L}^{(r_A + r_C)L} \frac{x^2 dx}{I_2} + \int_{(r_A + r_C)L}^{(1-r_B - r_D)L} \frac{x^2 dx}{I_3} + \int_{(1-r_B - r_D)L}^{tL} \frac{x^2 dx}{I_4} \tag{2.102}$$

$$j1 = c1 + c2 + c3 + j2 \tag{2.102a}$$

The first three integrals, specified as $c1$, $c2$ and $c3$, have been previously evaluated and the remaining integral, $j2$, can be evaluated as

$$j2 = \int_{(1-r_B - r_D)L}^{tL} \frac{x^2 dx}{I_4} = \frac{L^3 \left[t^3 - (1 - r_B - r_D)^3 \right]}{3 I_4} \tag{2.103}$$

The integral in the fourth term of Eq. 2.59, specified as $j3$, can be solved in two steps, thereby, noting the identity

$$j3 = \left[\int_{tL}^{B} \frac{(L - x)x dx}{I_x} \equiv \int_B^{t_1 L} \frac{(L - x_1)x_1 dx_1}{I_x} \right] = \int_0^{r_B L} \frac{(L - x_1)x_1 dx_1}{I_5} + \int_{r_B L}^{t_1 L} \frac{(L - x_1)x_1 dx_1}{I_4} \tag{2.104}$$

$$j3 = g5 + j4 \tag{2.104a}$$

The evaluation for the integral for $g5$ has been illustrated in Eq. 2.75 and the integral $j4$ is

$$j4 = \int_{r_B L}^{t_1 L} \frac{(L - x_1)x_1 dx_1}{I_4} = \frac{L^3 (3 t_1^{\,2} - 2 t_1^{\,3} + 2 r_B^{\,3} - 3 r_B^{\,2})}{6 I_4} \tag{2.105}$$

Once $j1$ and $j3$, which represent the integrals in the third and fourth terms of Eq. 2.59 are completed, the expression for $a13$ in Eq. 2.59a can be established as

$$a13 = t_1 \cdot j1 + t \cdot j3 \tag{2.106}$$

The integral in the third term of Eq. 2.60, specified as $j5$, needs to be solved in two steps as shown in Eq. 2.107.

$$j5 = \int_B^{t_1 L} \frac{x_1^{\,2} dx_1}{I_x} = \int_0^{r_B L} \frac{x_1^{\,2} dx_1}{I_5} + \int_{r_B L}^{t_1 L} \frac{x_1^{\,2} dx_1}{I_4} = c16 + j6 \tag{2.107}$$

The integral $c16$ has been previously solved and the integral $j6$ can be evaluated as

$$j6 = \int_{r_B L}^{t_1 L} \frac{x_1^{\,2} dx_1}{I_4} = \frac{L^3 (t_1^{\,3} - r_B^{\,3})}{3 I_4} \tag{2.108}$$

By expanding the integral in the fourth term of Eq. 2.60 into two parts,

$$j7 = \left[\int_{t_1 L}^{A} \frac{(L - x_1)x_1 dx_1}{I_x} \equiv \int_A^{tL} \frac{(L - x)x dx}{I_x} \right] = L \int_A^{tL} \frac{x dx}{I_x} - \int_A^{tL} \frac{x^2 dx}{I_x} = j8 - j9 \tag{2.109}$$

Evaluating the integral $j8$ in four steps gives

$$j8 = L \int_A^{tL} \frac{x dx}{I_x} = L \int_0^{r_A L} \frac{x dx}{I_1} + L \int_{r_A L}^{(r_A + r_C)L} \frac{x dx}{I_2} + L \int_{(r_A + r_C)L}^{(1-r_B - r_D)L} \frac{x dx}{I_3} + L \int_{(1-r_B - r_D)L}^{tL} \frac{x dx}{I_4} \tag{2.110}$$

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$$j8 = c6 + c7 + c8 + j10 \tag{2.110a}$$

The first three integrals ($c6$, $c7$ and $c8$) have been previously evaluated and the solution to the integral $j10$ can be expressed as

$$j10 = L\int_{(1-r_B-r_D)L}^{tL} \frac{xdx}{I_4} = \frac{L^3\left[t^2 - (1-r_B-r_D)^2\right]}{2I_4} \tag{2.111}$$

Similarly, evaluating the integral $j9$ in four steps,

$$j9 = \int_A^{tL} \frac{x^2dx}{I_x} = \int_0^{r_AL} \frac{x^2dx}{I_1} + \int_{r_AL}^{(r_A+r_C)L} \frac{x^2dx}{I_2} + \int_{(r_A+r_C)L}^{(1-r_B-r_D)L} \frac{x^2dx}{I_3} + \int_{(1-r_B-r_D)L}^{tL} \frac{x^2dx}{I_4} \tag{2.112}$$

$$j9 = c1 + c2 + c3 + j2 \tag{2.112a}$$

The solutions to the integrals ($c1$, $c2$, $c3$ and $j2$) have already been illustrated. Once the evaluations for the integrals $j5$ and $j7$ are obained, therefore, one can establish the expression for $a14$ in Eq. 2.60a as

$$a14 = t \cdot j5 + t_1 \cdot j7 \tag{2.113}$$

Once all the integrals are evaluated and solving Eqs. 2.59a and 2.60a simultaneously, one can establish a relationship for the fixed end moments as follows:

$$\begin{Bmatrix} MF_{BA} \\ MF_{AB} \end{Bmatrix} = \begin{bmatrix} a1 & a2 \\ a4 & a5 \end{bmatrix}^{-1} \begin{Bmatrix} a13 \\ a14 \end{Bmatrix} \cdot (-PL) = \begin{Bmatrix} -CP_{BA} \cdot PL \\ -CP_{AB} \cdot PL \end{Bmatrix} \tag{2.114}$$

MF_{AB} and MF_{BA} in Eq. 2.114 are the fixed end moments at the left and right joints induced by a concentrated load, P, placed on *Section 4* ($(1 - r_B - r_D) \le t \le (1 - r_B)$), and CP_{AB} and CP_{BA} are their coefficients.

Case 5: *P on Section 5* ($(1 - r_B) \le t$): The last case to be considered is when P is on *Section 5*, that is, $(1 - r_B) \le t$ as illustrated in Fig. 2-8e. The integral in the third term of Eq. 2.59 must be solved in five steps as illustrated in Eq. 2.115.

$$q1 = \int_A^{tL} \frac{x^2dx}{I_x} = \int_0^{r_AL} \frac{x^2dx}{I_1} + \int_{r_AL}^{(r_A+r_C)L} \frac{x^2dx}{I_2} + \int_{(r_A+r_C)L}^{(1-r_B-r_D)L} \frac{x^2dx}{I_3} + \int_{r_BL}^{(r_B+r_D)L} \frac{(L-x)^2dx}{I_4}$$

$$+ \int_{t_1L}^{r_BL} \frac{(L-x)^2dx}{I_5} = c1 + c2 + c3 + c4 + q2 \tag{2.115}$$

The first four integrals, specified as $c1$, $c2$, $c3$ and $c4$ have been previously evaluated and the remaining integral, $q2$, can be evaluated as

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$$q2 = \int_{t_1 L}^{r_B L} \frac{(L-x)^2 dx}{I_5} = \frac{L^3(3r_B - 3r_B{}^2 + r_B{}^3 - 3t_1 + 3t_1{}^2 - t_1{}^3)}{3I_5} \tag{2.116}$$

The integral in the fourth term of Eq. 2.59, specified as $q3$, can be evaluated as

$$q3 = \left[\int_{tL}^{B} \frac{(L-x)x dx}{I_x} \equiv \int_{B}^{t_1 L} \frac{(L-x_1)x_1 dx_1}{I_5} \right] = \int_{0}^{t_1 L} \frac{(L-x_1)x_1 dx_1}{I_5} = \frac{L^3 t_1{}^2(3-2t_1)}{6I_5} \tag{2.117}$$

Once $q1$ and $q3$, which represent the integrals in the third and fourth terms of Eq. 2.59 are completed, the expression for $a15$ in Eq. 2.59a can be established as

$$a15 = t_1 \cdot q1 + t \cdot q3 \tag{2.118}$$

The integral in the third term of Eq. 2.60, specified as $q4$, can be evaluated as

$$q4 = \int_{B}^{t_1 L} \frac{x_1{}^2 dx_1}{I_x} = \int_{0}^{t_1 L} \frac{x_1{}^2 dx_1}{I_5} = \frac{L^3 t_1{}^3}{3I_5} \tag{2.119}$$

By expanding the integral in the fourth term of Eq. 2.60 into two parts,

$$q5 = \left[\int_{t_1 L}^{A} \frac{(L-x_1)x_1 dx_1}{I_x} \equiv \int_{A}^{tL} \frac{(L-x)x dx}{I_x} \right] = L\int_{A}^{tL} \frac{x dx}{I_x} - \int_{A}^{tL} \frac{x^2 dx}{I_x} = q6 - q1 \tag{2.120}$$

The solution to the integral $q1$ has been provided in Eq. 2.115. By evaluating the integral $q6$ in five steps, one can obtain

$$q6 = L\int_{A}^{tL} \frac{x dx}{I_x} = L\int_{0}^{r_A L} \frac{x dx}{I_1} + L\int_{r_A L}^{(r_A + r_C)L} \frac{x dx}{I_2} + L\int_{(r_A + r_C)L}^{(1-r_B - r_D)L} \frac{x dx}{I_3} + L\int_{r_B L}^{(r_B + r_D)L} \frac{(L-x)dx}{I_4}$$

$$+ L\int_{t_1 L}^{r_B L} \frac{(L-x)dx}{I_5} = c6 + c7 + c8 + c9 + q7 \tag{2.121}$$

The first four integrals ($c6$, $c7$, $c8$ and $c9$) have been previously evaluated and the solution to the integral $q7$ can be expressed as

$$q7 = L\int_{t_1 L}^{r_B L} \frac{(L-x)dx}{I_5} = \frac{L^3(2r_B - r_B{}^2 - 2t_1 + t_1{}^2)}{2I_5} \tag{2.122}$$

Since the integrals, $q4$ and $q5$, are solved, the expression a16 can be completed as shown in Eq. 2.123.

$$a16 = t \cdot q4 + t_1 \cdot q5 \tag{2.123}$$

Once all the integrals are evaluated and solving Eqs. 2.59a and 2.60a simultaneously, one can establish a relationship for the fixed end moments as follows:

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$$\begin{Bmatrix} MF_{BA} \\ MF_{AB} \end{Bmatrix} = \begin{bmatrix} a1 & a2 \\ a4 & a5 \end{bmatrix}^{-1} \begin{Bmatrix} a15 \\ a16 \end{Bmatrix} \cdot (-PL) = \begin{Bmatrix} -CP_{BA} \cdot PL \\ -CP_{AB} \cdot PL \end{Bmatrix} \tag{2.124}$$

MF_{AB} and MF_{BA} in Eq. 2.124 are the fixed end moments at the left and right joints induced by a concentrated load, P, placed on *Section 5 ($(1 - r_B) \leq t$)*, and CP_{AB} and CP_{BA} are their coefficients.

The general theories and methodologies 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 2-9 schematically depicts the organization and hierarchy of each window within *BEC Analysis*. Screen shots of each window are presented in Figs. 2-10 through 2-18 with the various windows, text box controls, frames, command buttons and other indicators numerically labeled in each figure. These labels correspond to the descriptions that follow. Note that in each window, a number of controls, indicators and commands are used for data entry and describing the geometrical and physical properties of a model bridge, for executing the program, and for accessing results. For example, 'Back' and 'Next' commands make the program to move from one window to another while numerous text boxes (controls and indicators) are used for data entry or results display. Only one window can be displayed at a time.

Each of the controls, indicators and command buttons are described below. The features included in each window and the general procedures for running *BEC Analysis* are discussed in the subsequent sections. In addition, the principle procedures required to run *BEC Analysis* are provided in Appendix A.

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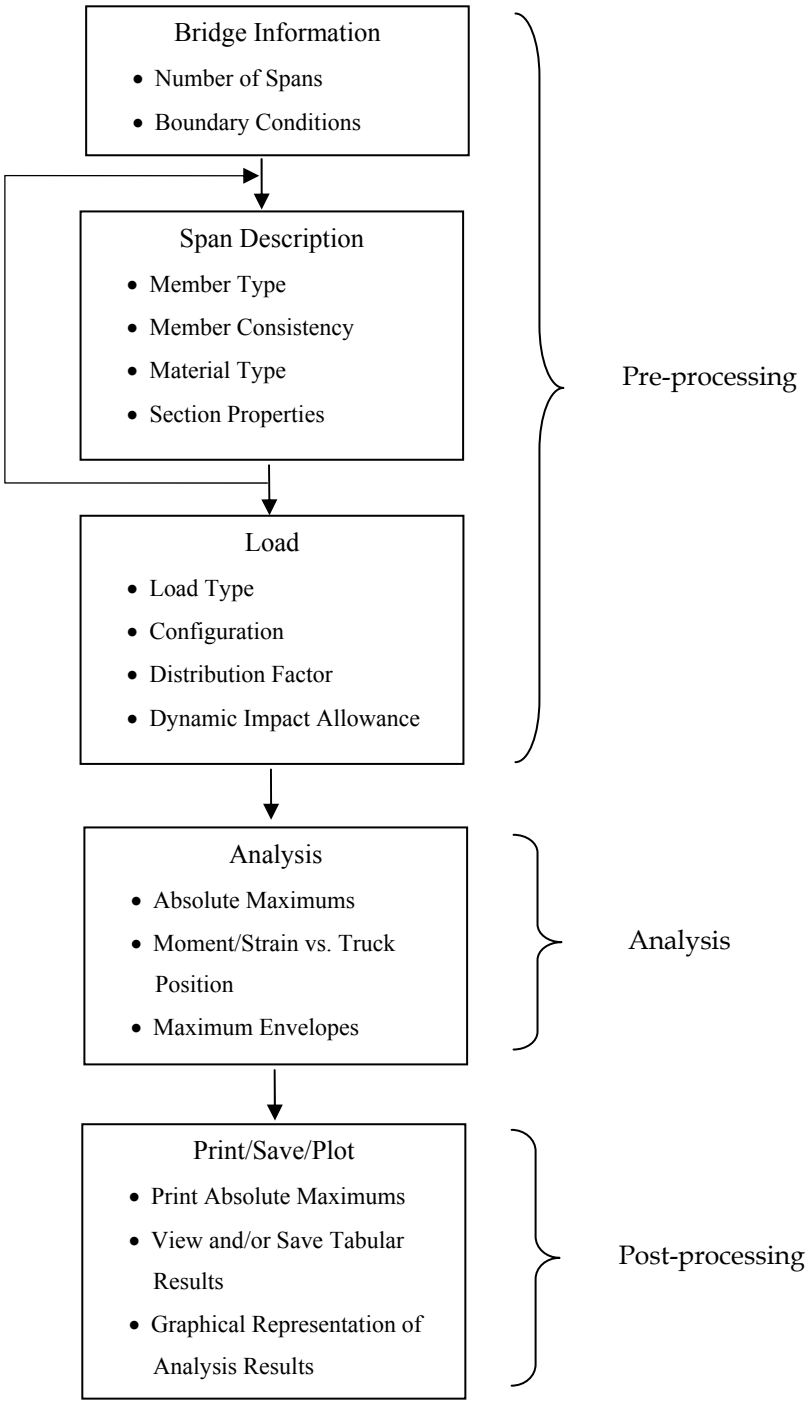

Figure 2-9. General flowchart illustrating the overall operation of *BEC Analysis*.

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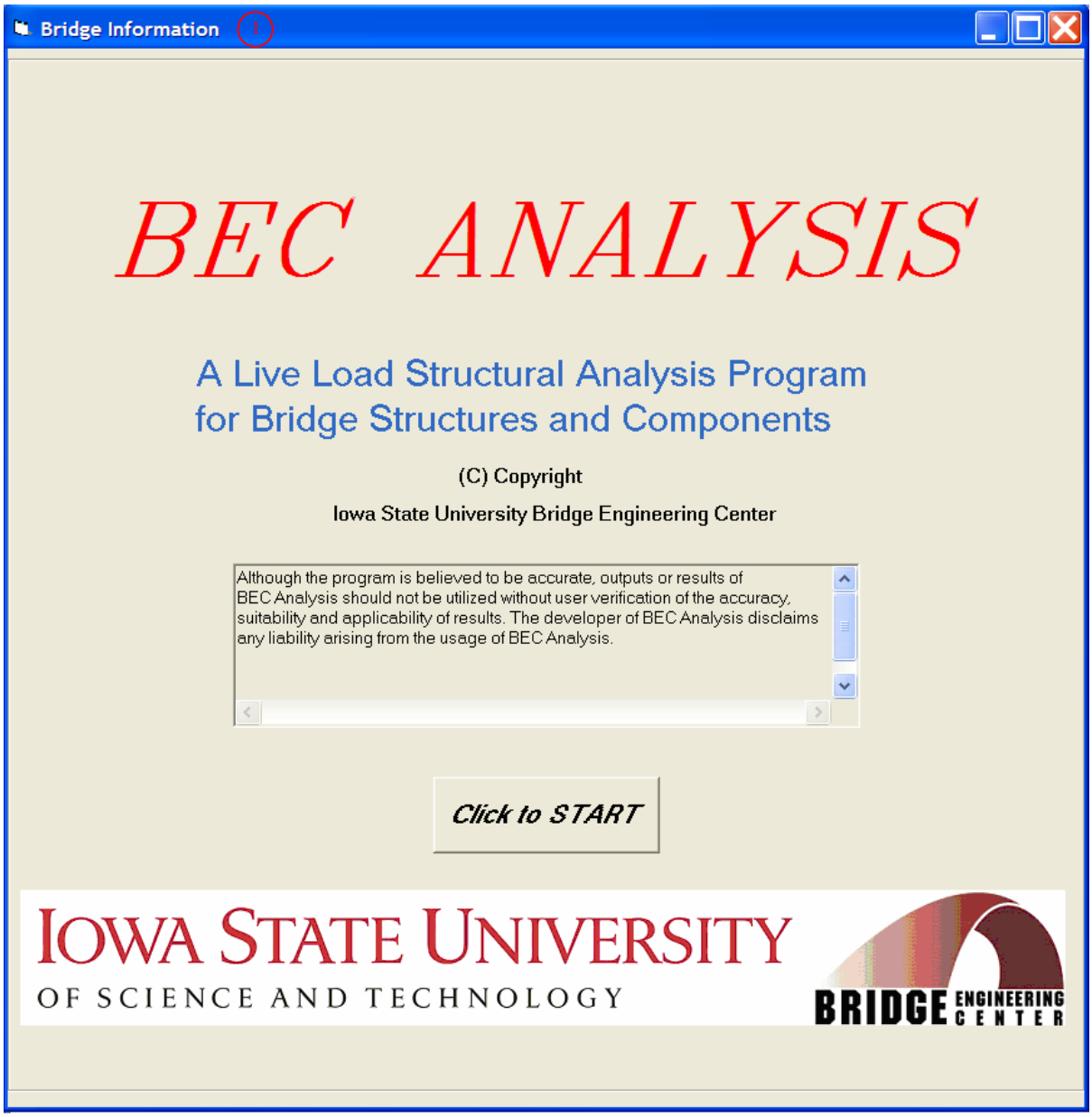

Figure 2-10. *BEC Analysis* title screen.

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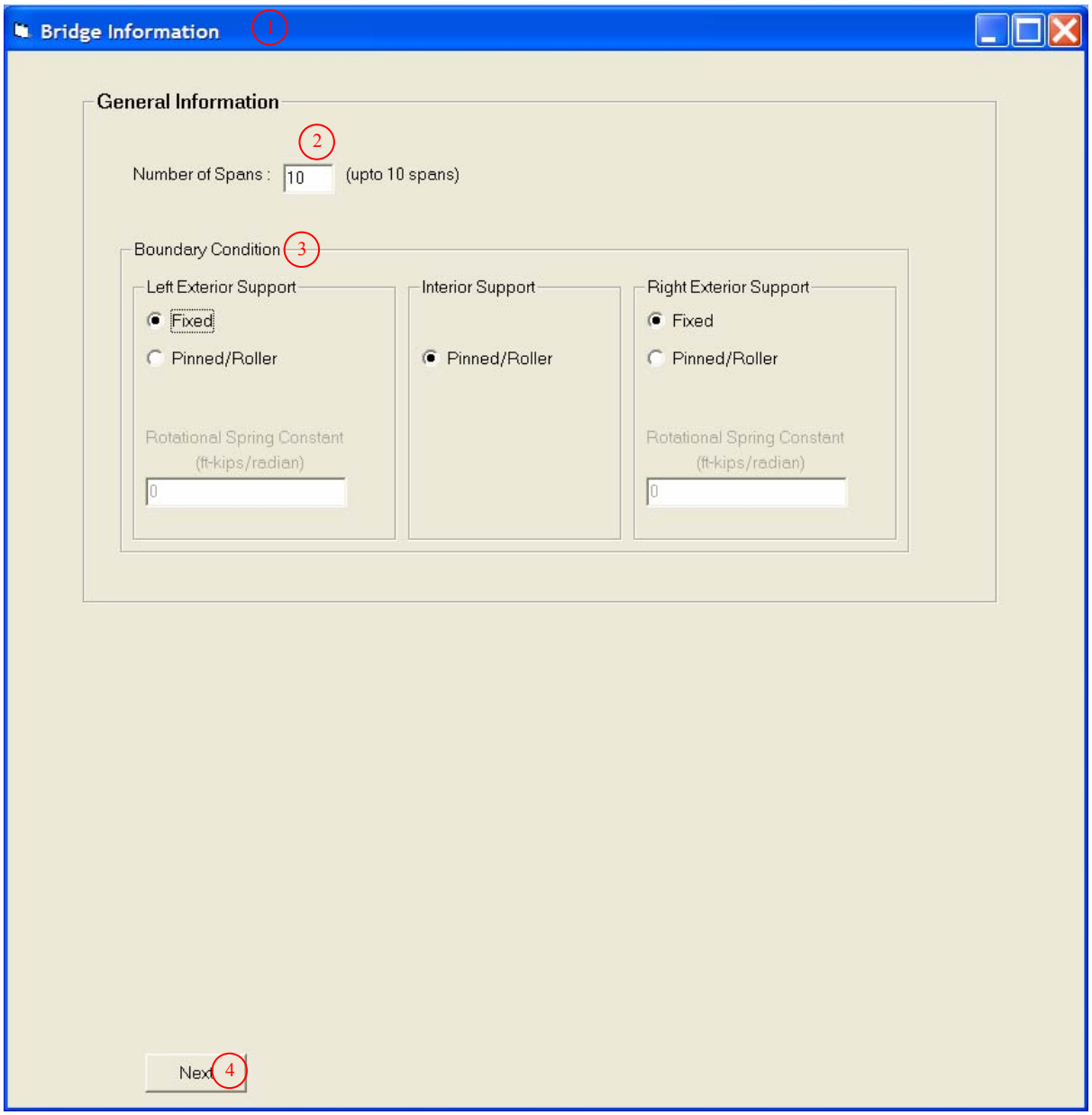

Figure 2-11. General information options.

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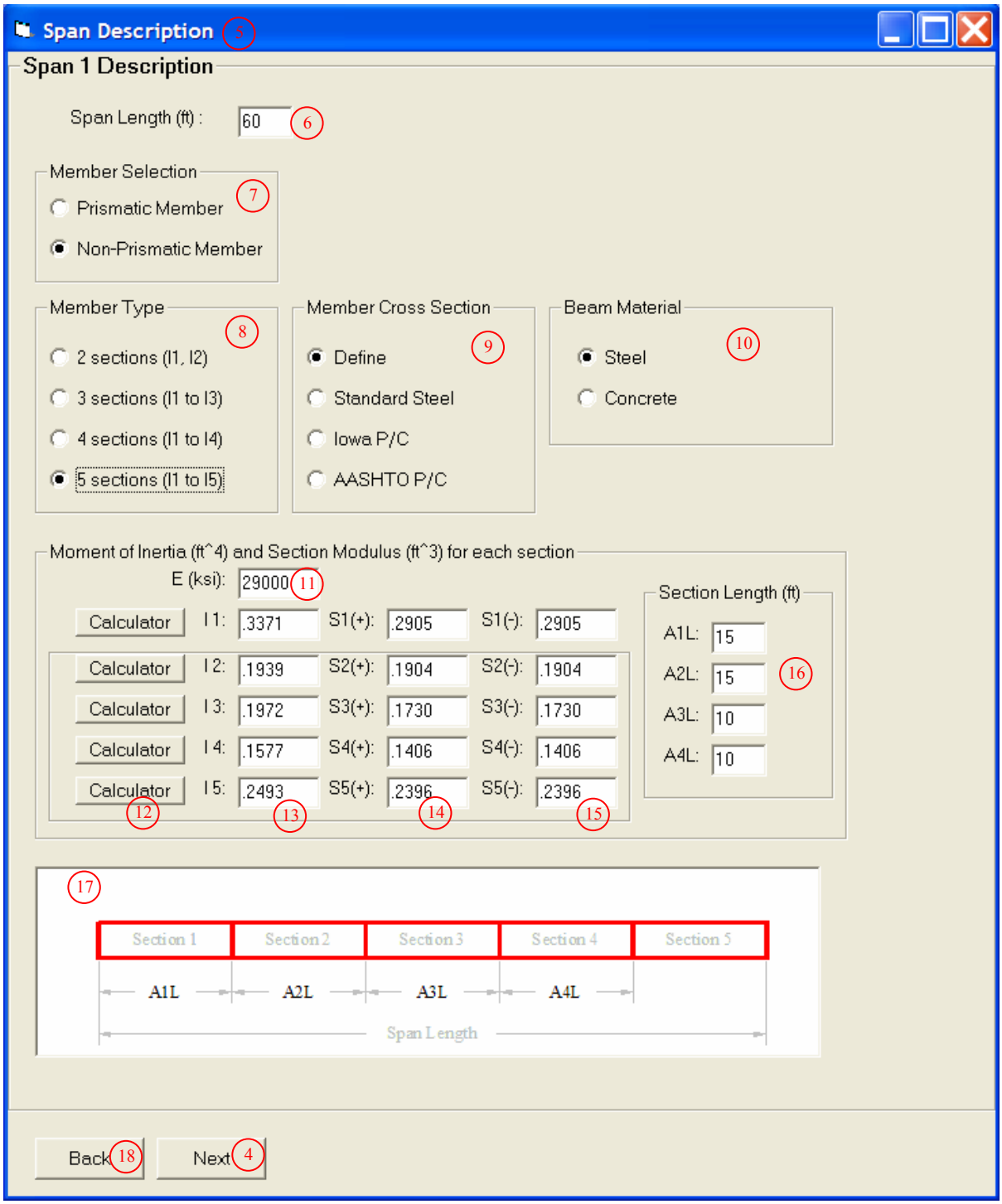

Figure 2-12. Span Description window.

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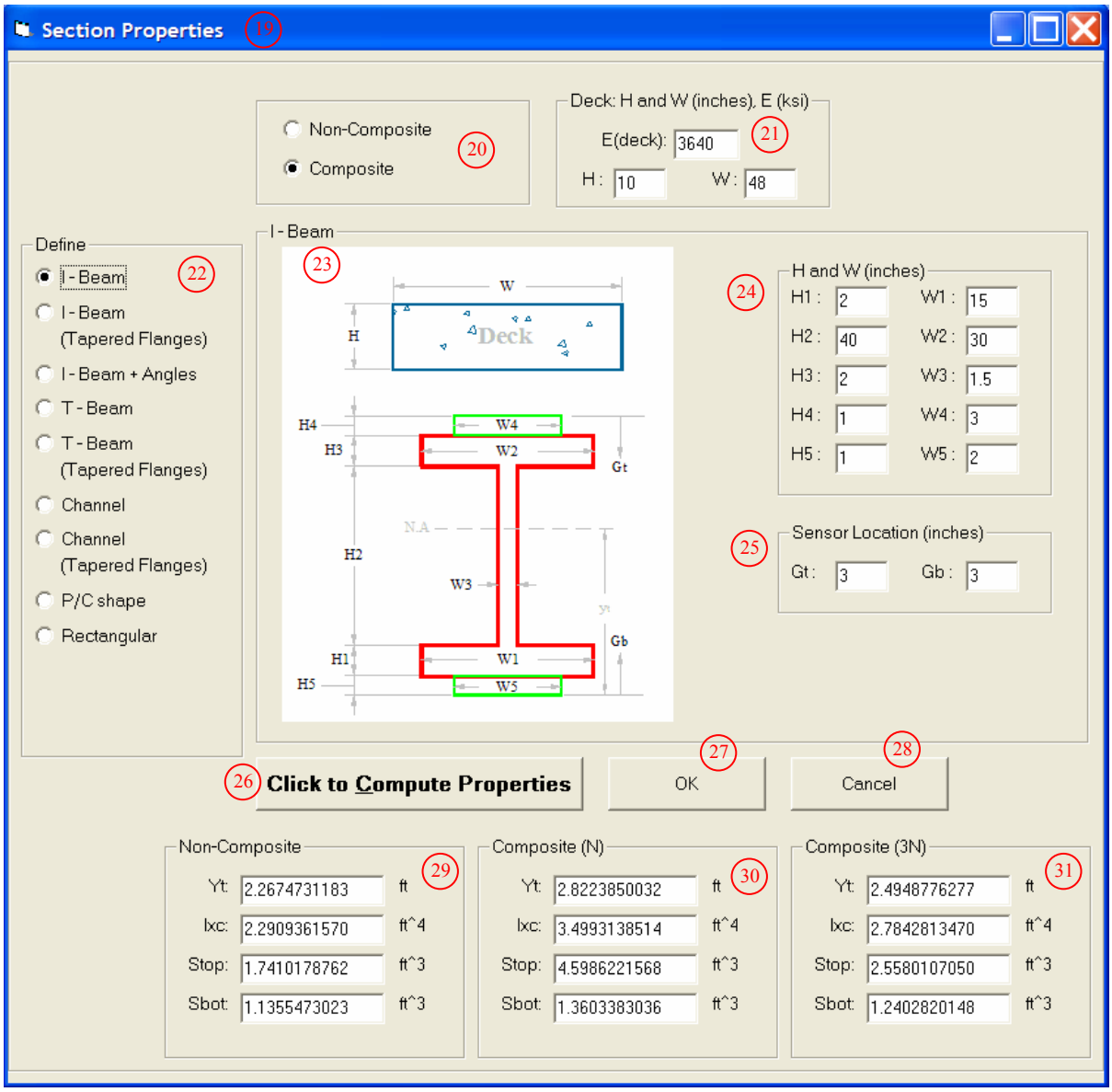

(a) Section properties for 'Define' option

Figure 2-13. Section Properties window.

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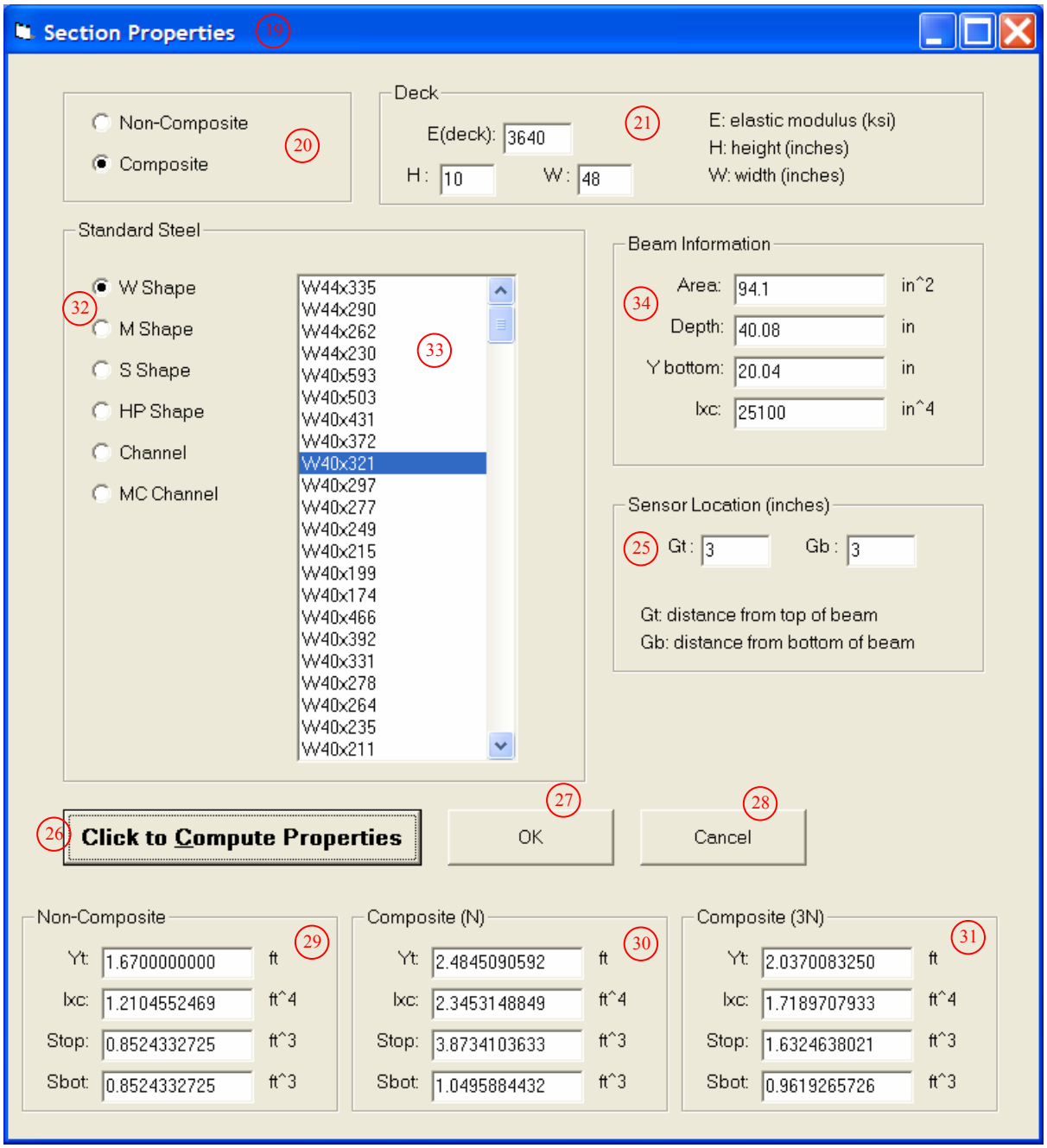

(b) Section properties for 'Standard Steel' option

Figure 2-13. (continued).

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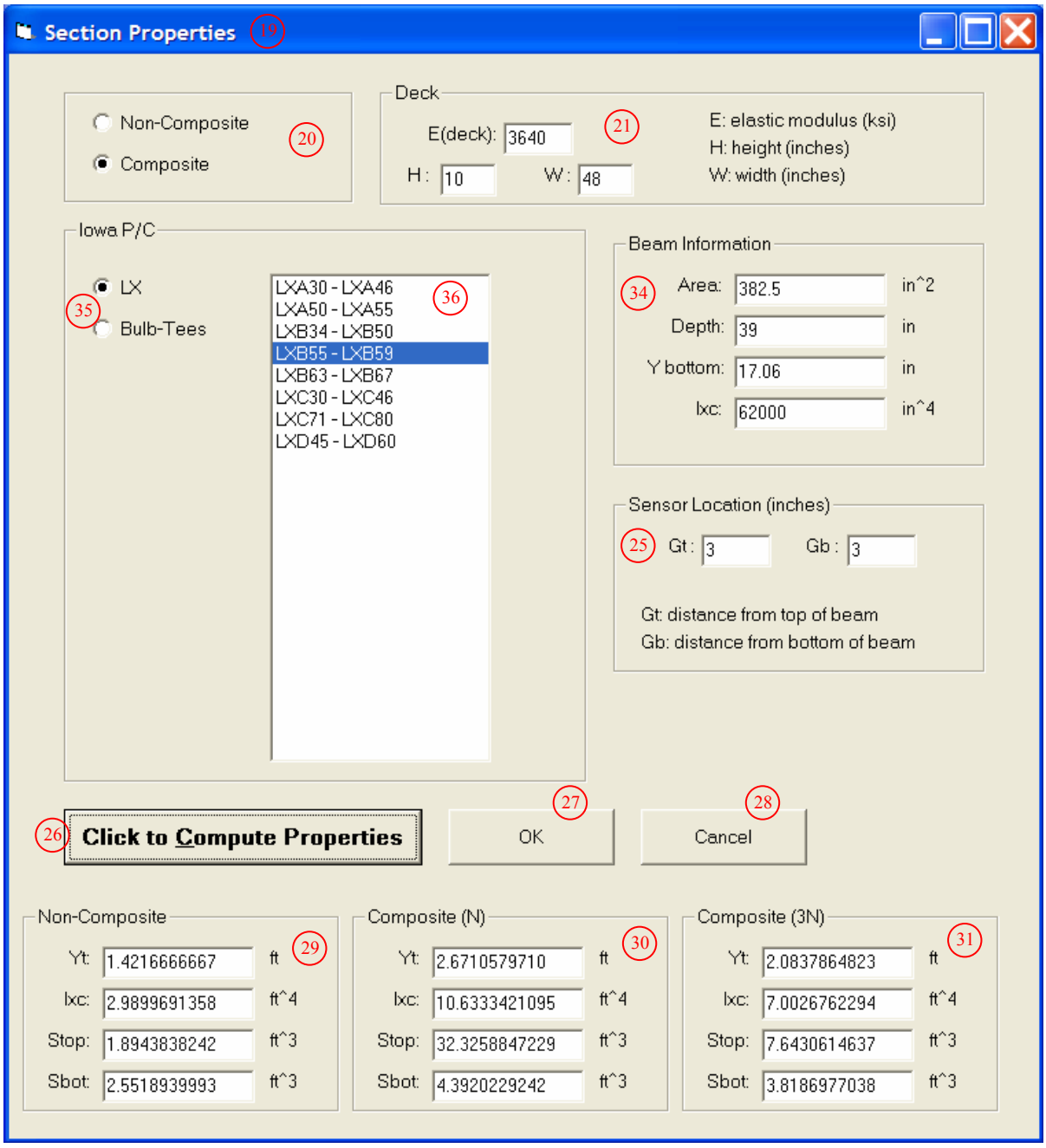

(c) Section properties for 'Iowa P/C' option

Figure 2-13. (continued).

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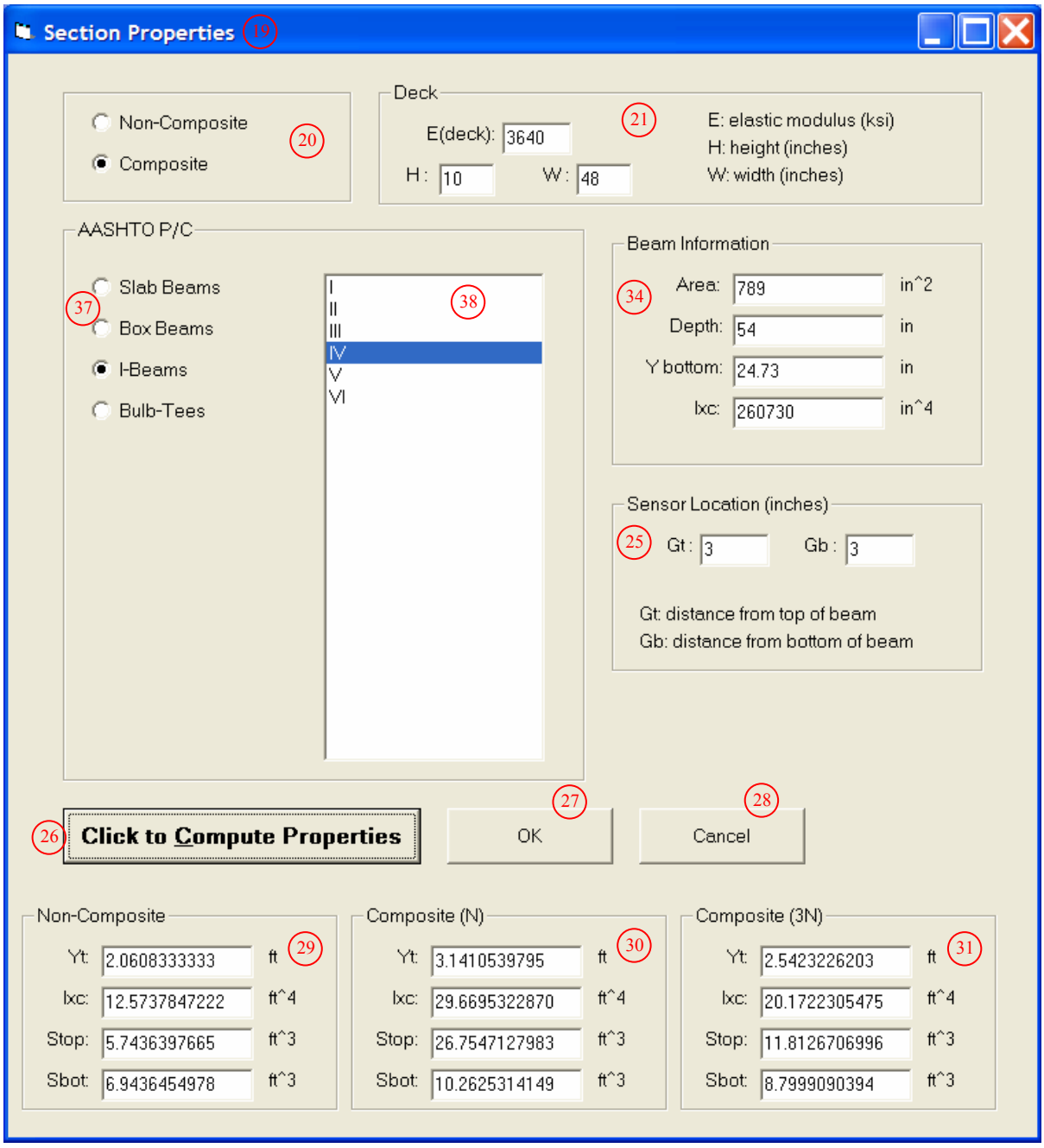

(d) Section properties for 'AASHTO P/C' option

Figure 2-13. (continued).

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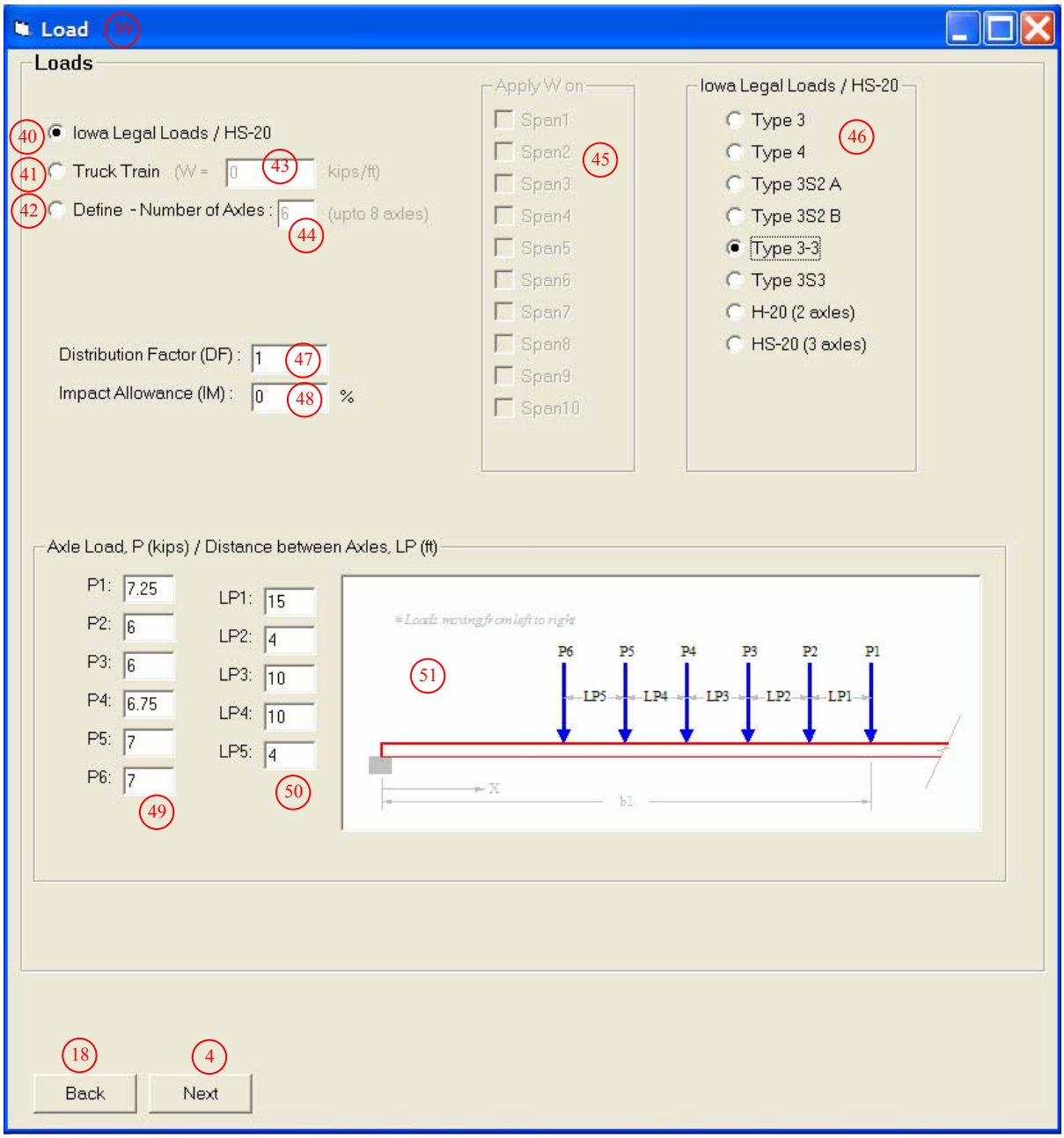

Figure 2-14. Load window.

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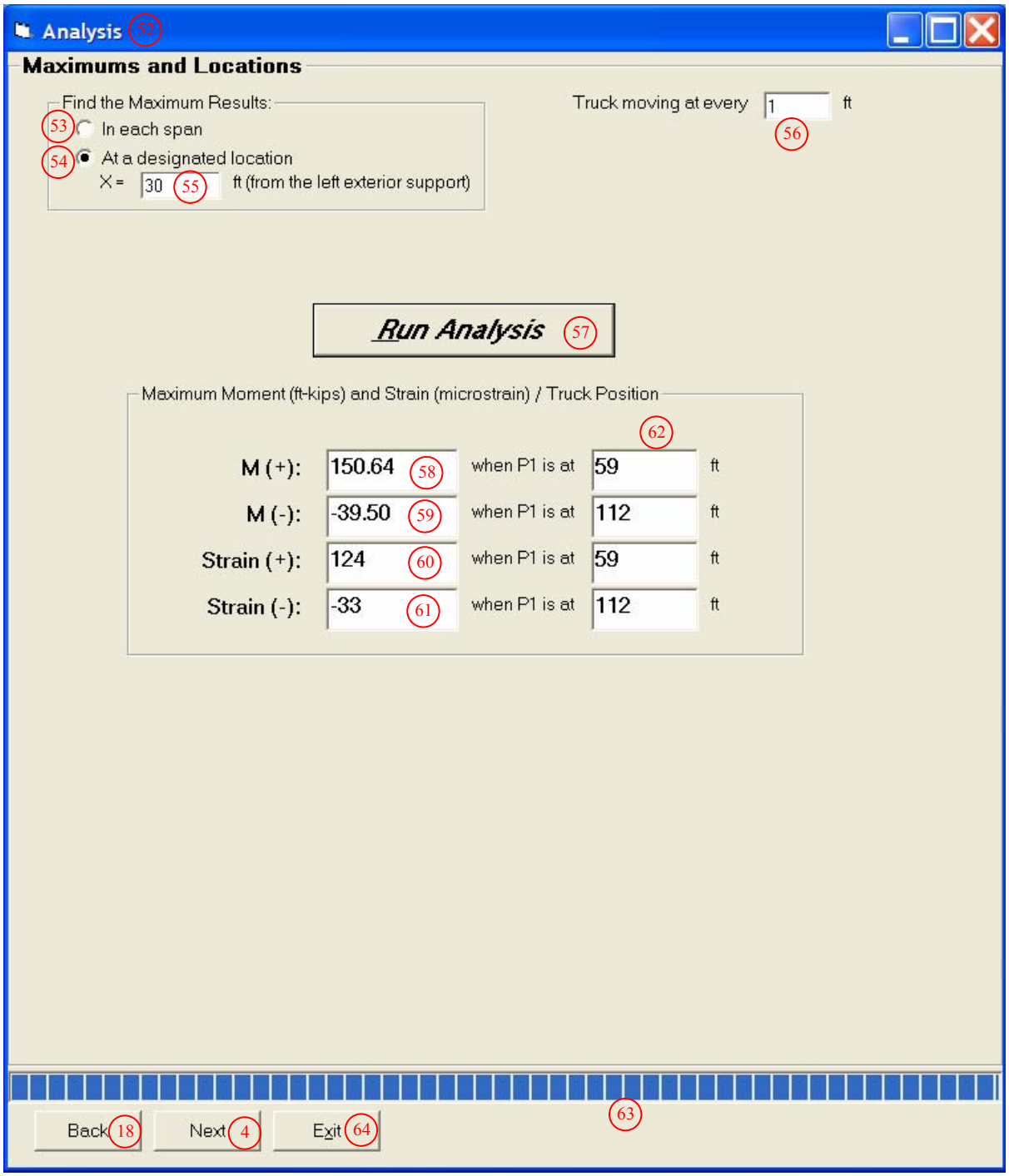

(a) 'At a designated location' option

Figure 2-15. Analysis window.

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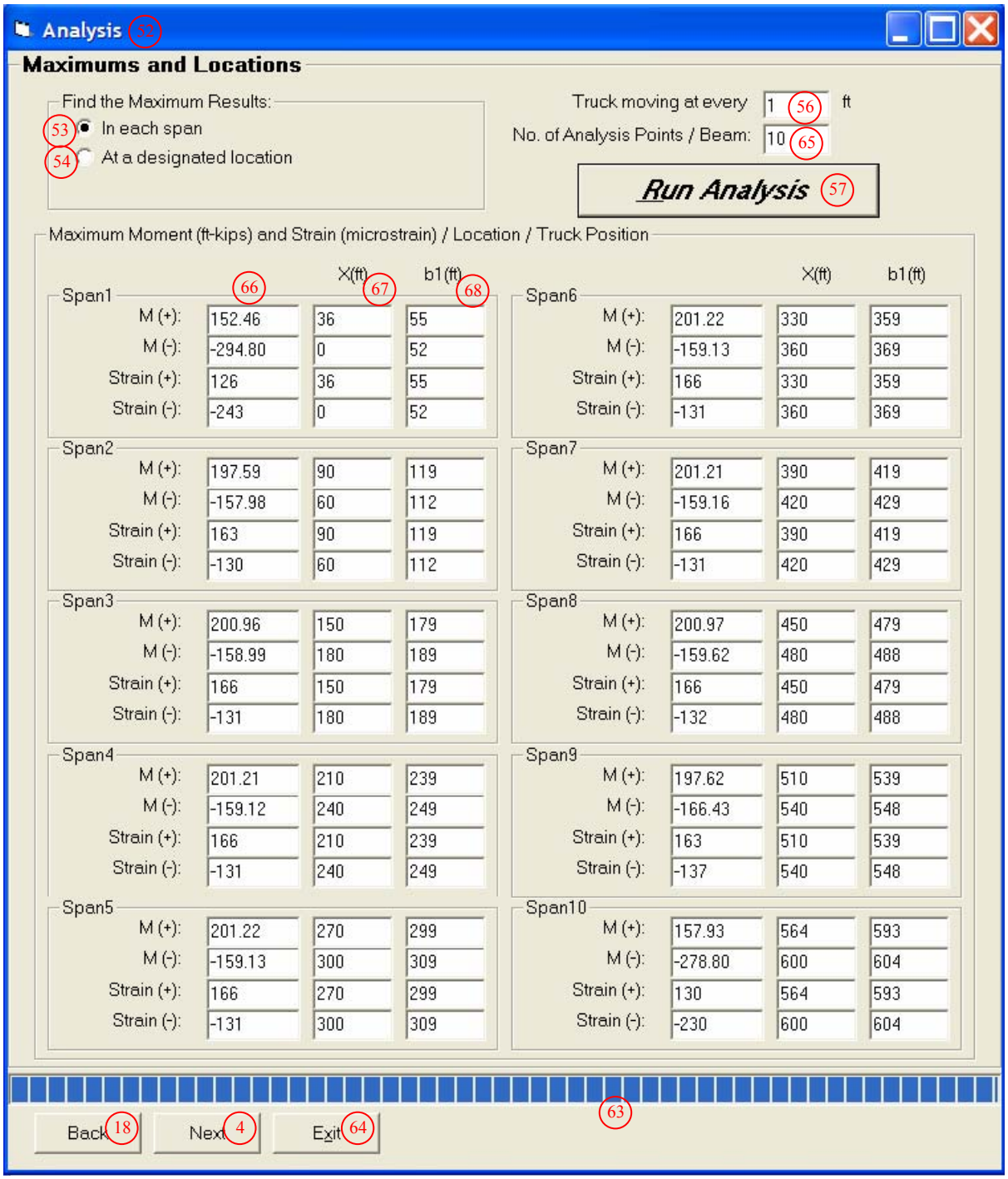

(b) 'In each span' option

Figure 2-15. (continued).

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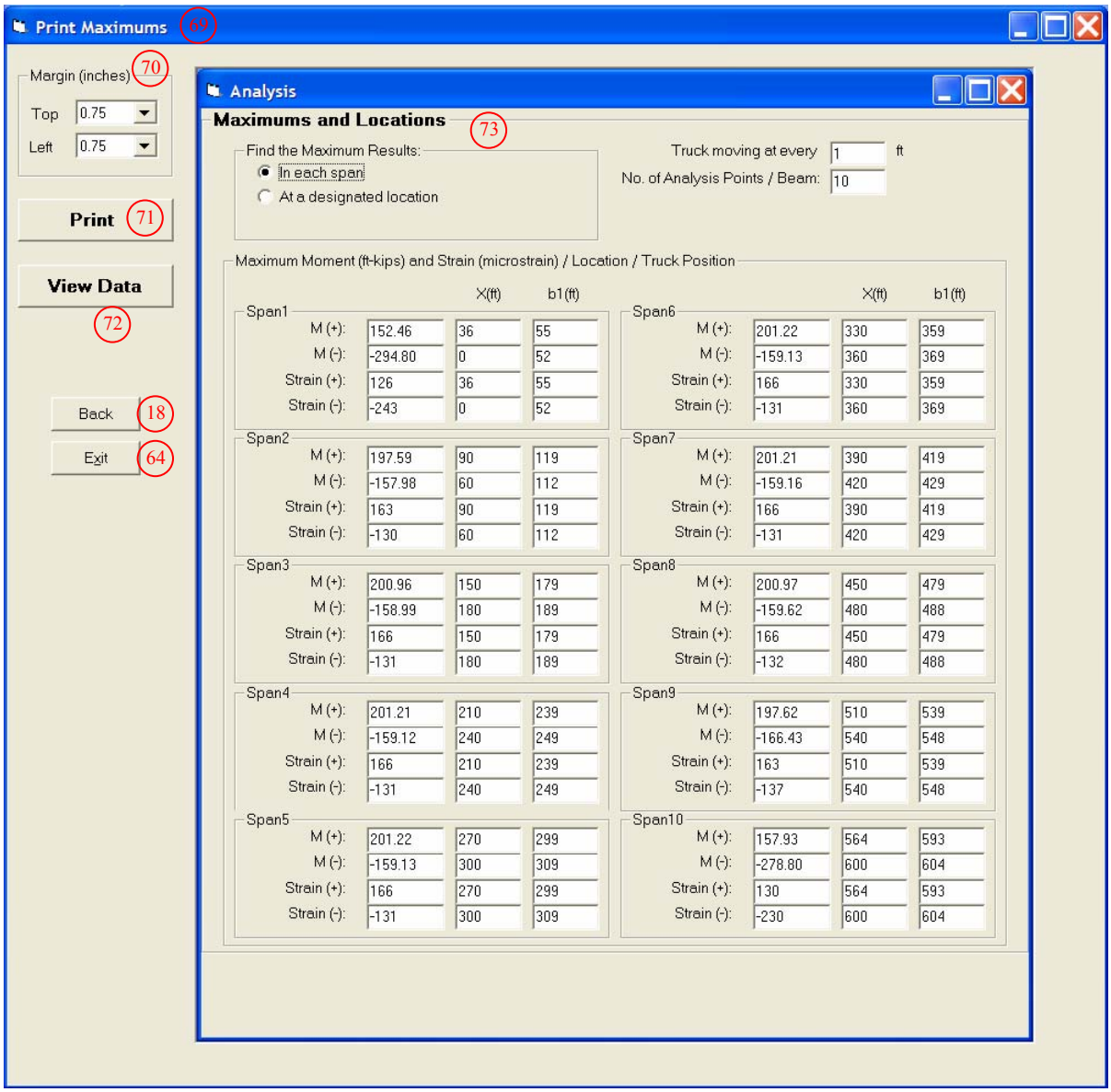

(a) When 'In each span' option is selected

Figure 2-16. Print Maximums Window.

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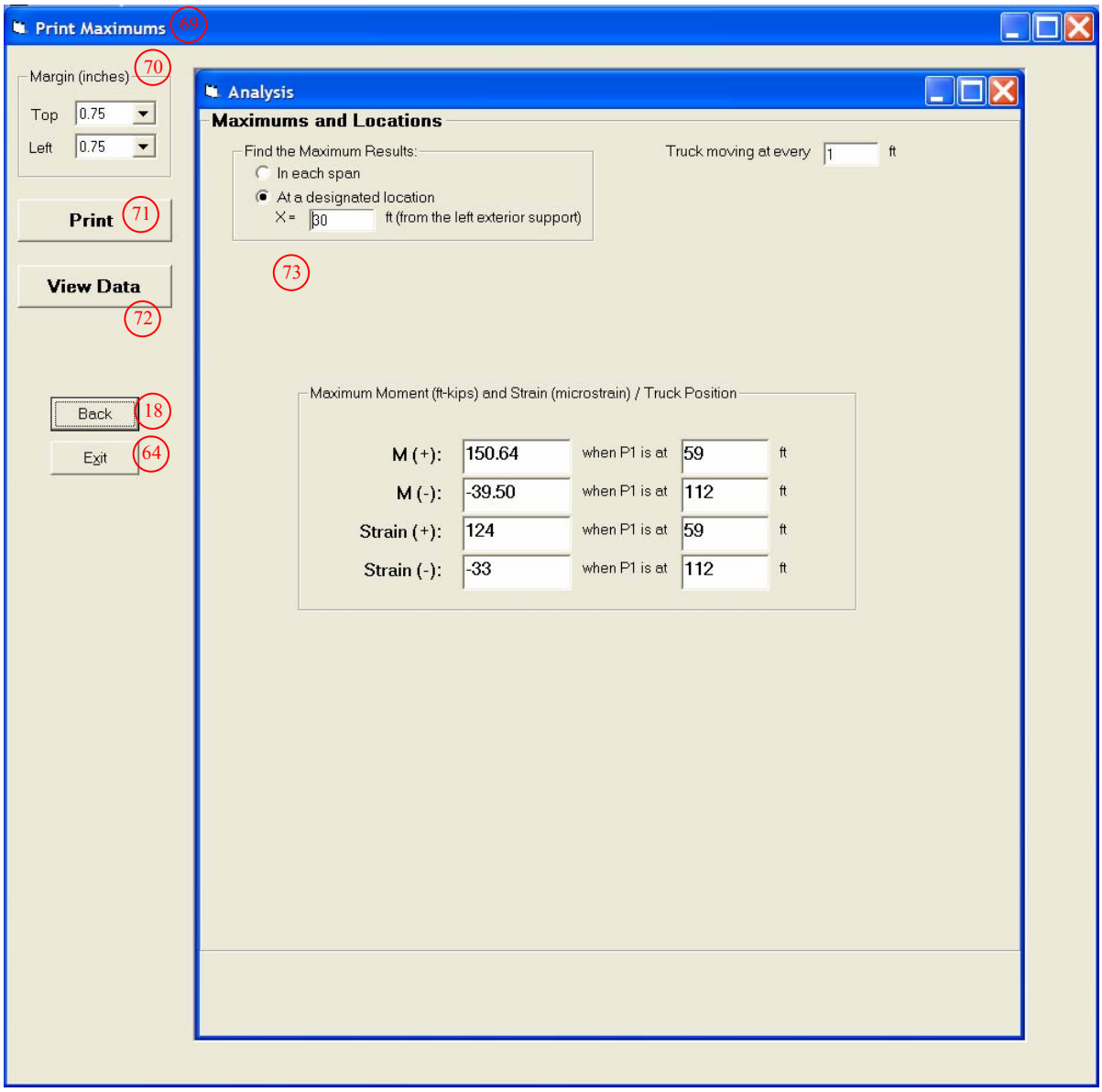

(b) When 'At a designated location' option is selected

Figure 2-16. (continued).

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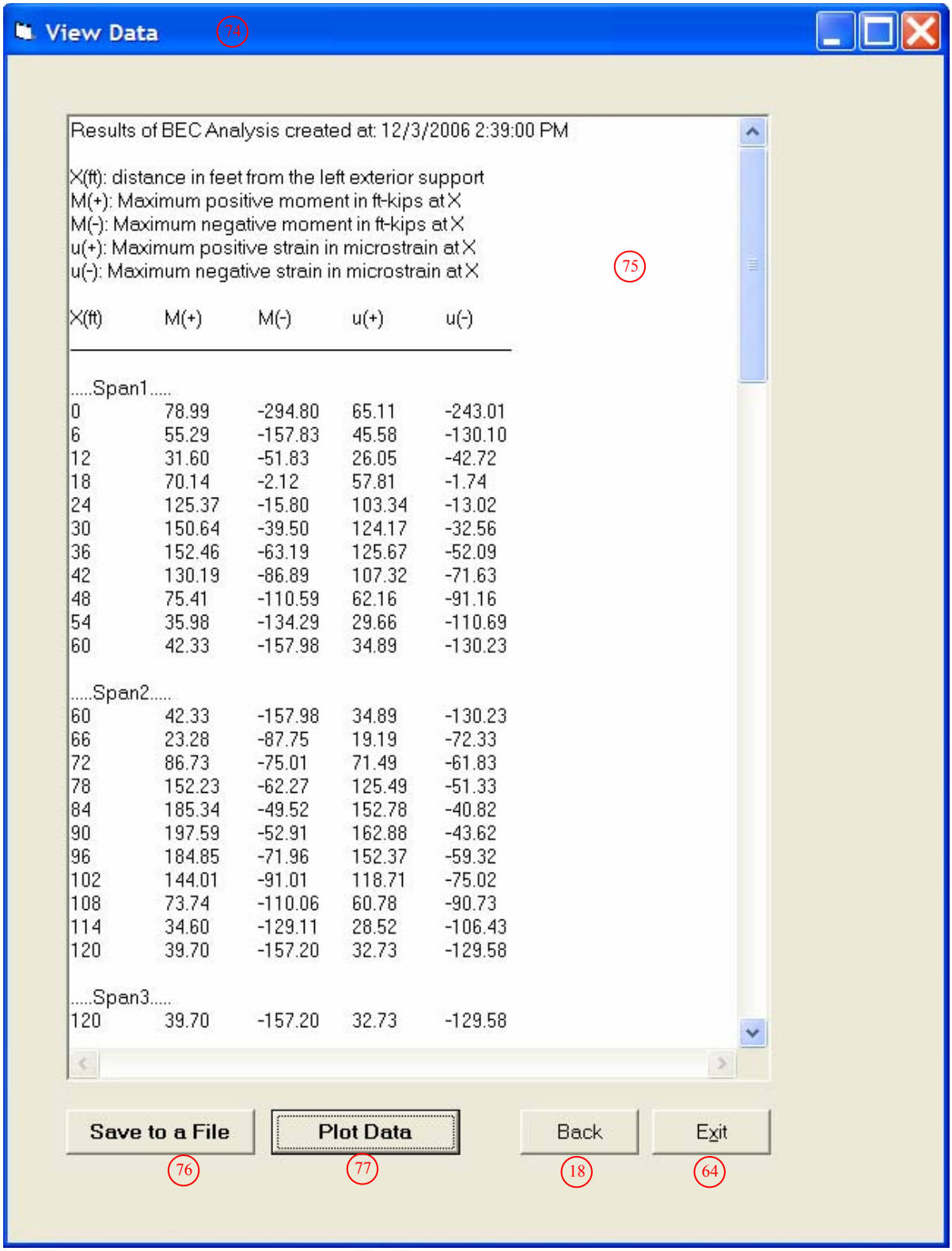

(a) When 'In each span' option is selected

Figure 2-17. View Data Window.

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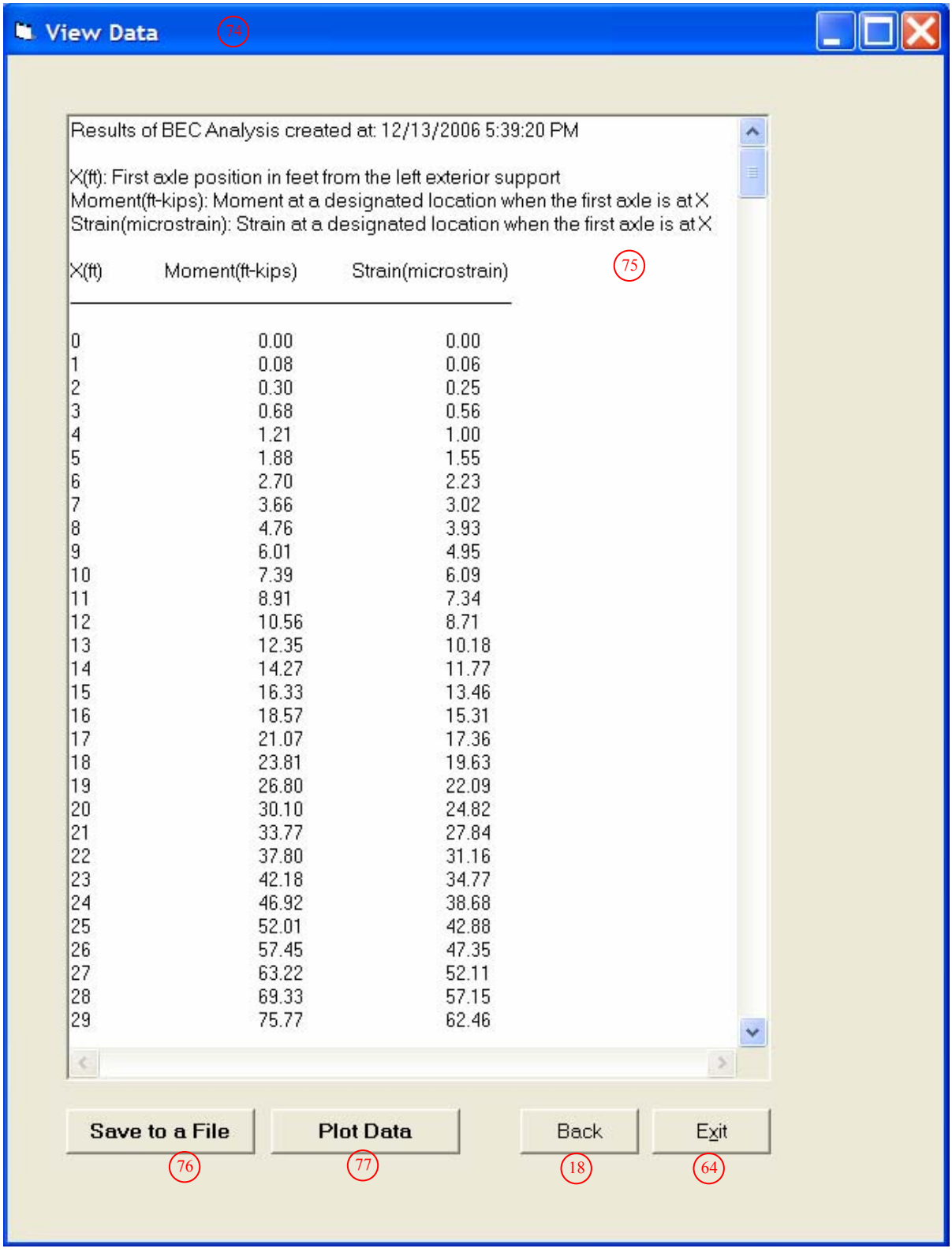

(b) When 'At a designated location' option is selected

Figure 2-17. (continued).

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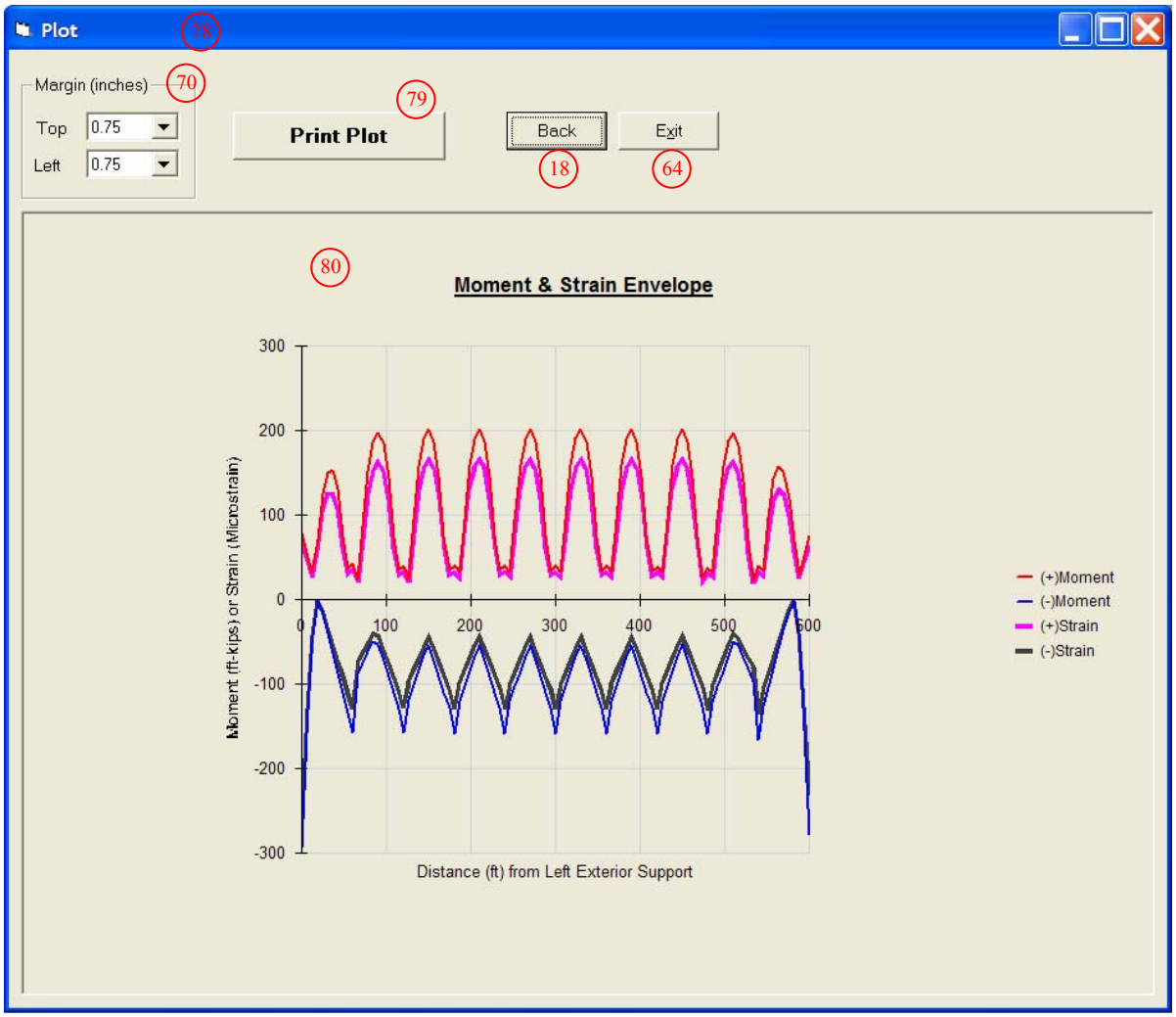

(a) When 'In each span' option is selected

Figure 2-18. Plot Window.

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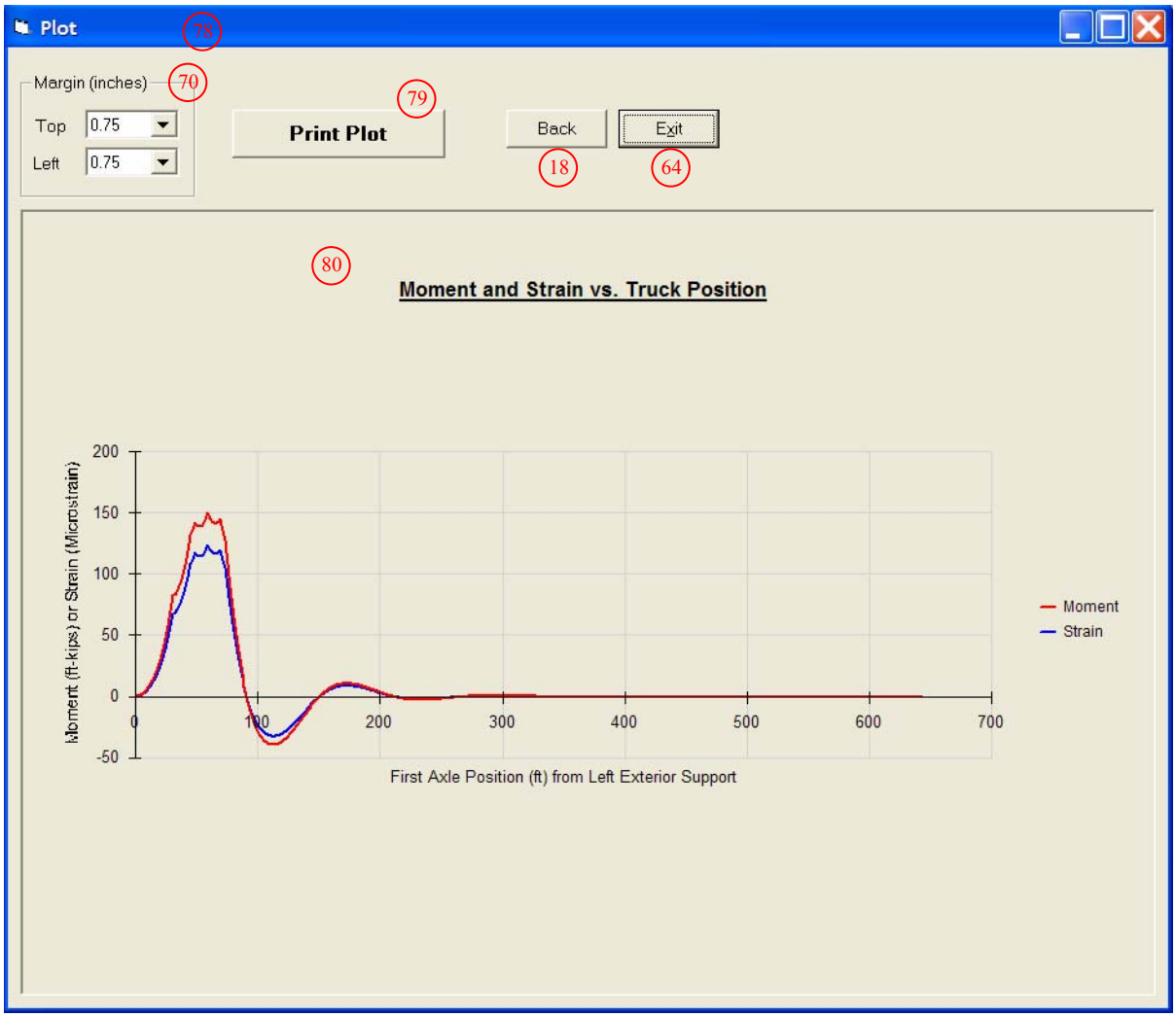

(b) When 'At a designated location' option is selected

Figure 2-18. (continued).

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Descriptions of 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.

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#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.

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#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.

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#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.

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#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.

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#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.

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 Fig. 2-10 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 Fig. 2-11. 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.

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- 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 Fig. 2-12; here, 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). Also note that these sensor locations can be

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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.

2.1.2.3. Section Properties Window

The 'Section Properties' window (#19) illustrated in Fig. 2-13 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).

A different window will be called depending upon the option selected in the 'Member Cross Section' frame (#9). Four scenarios can occur: 'Section Properties' window for (1) user definable general section types (2) standard steel (3) Iowa P/C and (4) AASHTO P/C.

Section Properties window for user definable cross sections

The window shown in Fig. 2-13a 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)

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- 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 Fig. 2-13b. 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. When 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 Fig. 2-13c 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 (either LX or Bulb-Tees), 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 Fig. 2-13d. 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.

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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 Fig. 2-14 allows the user to configure the 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, 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 Fig. 2-15. 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 (illustrated in Fig. 2.19) will appear indicating that the analysis was successfully completed. The results that will be displayed in the 'Analysis' window are as follows:

- Maximum positive and negative moments: #58, #59 or #66
- Maximum positive and negative strain: #60, #61 or #66
- Location(s) of maximum moments and strain: #55 or #67
- Location(s) of the first axle that generated the maximums: #62 or #68.

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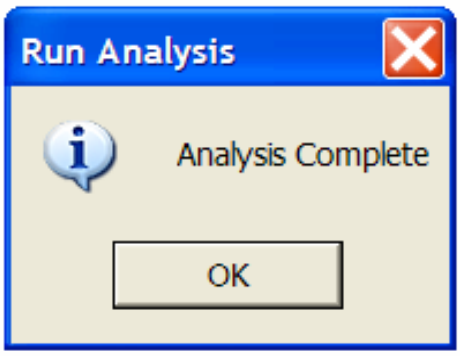

Figure 2-19. Prompt dialog box.

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 Fig. 2-15a 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 Fig. 2-15b. 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 Fig. 2-16 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

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numerical results. As illustrated in Fig. 2-17, 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 Fig. 2-17a; while it represents the first axle positions in the 'moment and strain vs. truck position' analysis results as shown in Fig. 2-17b. Also note that in Fig. 2-17a, the maximum results are displayed separately for each span for clarity. 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 (as illustrated in Fig. 2-20). *BEC Analysis* is programmed to save the text file in a temporary folder directory (e.g., C:\temp) by default. Therefore, if a 'temp' folder directory is not available in the PC in which *BEC Analysis* is run, users must create one before attempting to save the data to a file. An example of a text file saved in a temporary folder is presented in Fig. 2-21.

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 Fig. 2-18. The example provided in Fig. 2-18 is the result of analyzing a ten-span bridge, fixed at both exterior supports, loaded with a Iowa legal truck. The plot displayed can be printed if the 'Print Plot' command button (#79) is pressed.

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.

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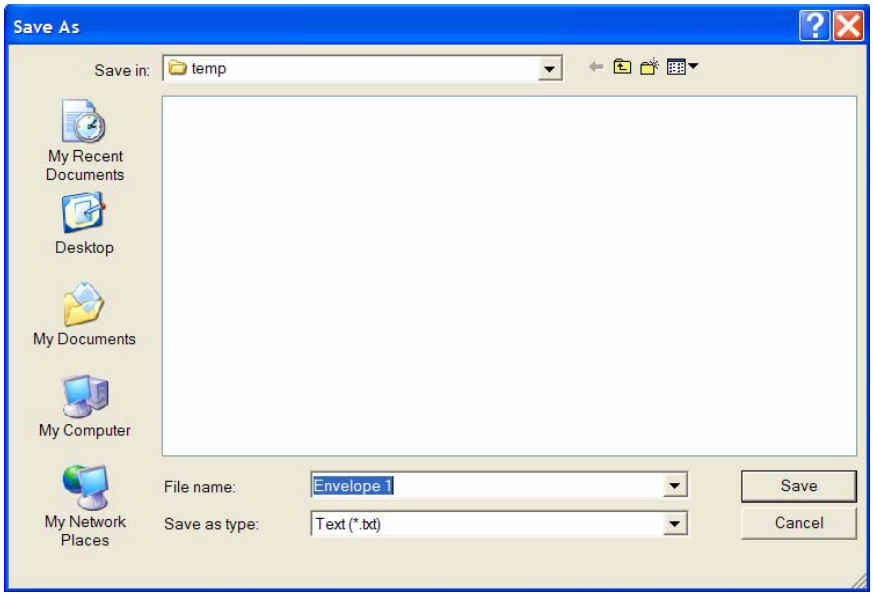

Figure 2-20. Prompt window for data saving.

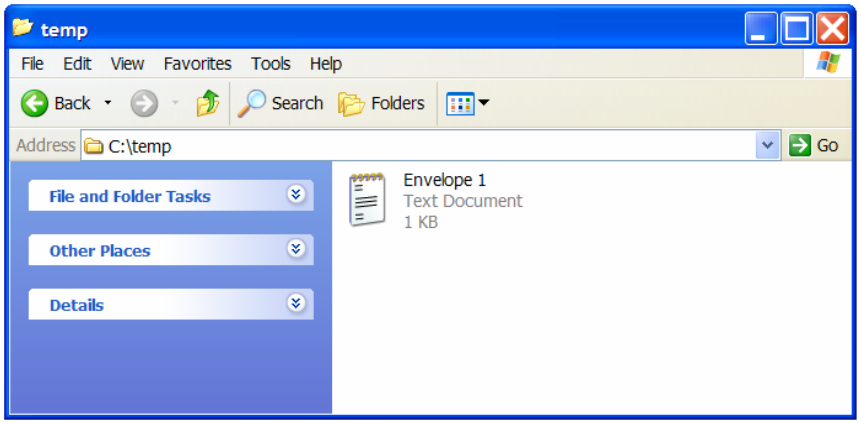

Figure 2-21. An example of a text file saved in a temporary folder.

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.

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- 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 Fig. 2-22, each parameter is expressed with b_i and y_i components, where b_i represents the time that the index or the event is recorded while y_i represents their magnitude in strain. These three parameters are used to find the slope within the strain record that contains the event. The slope of an event can be defined as the ratio of the absolute difference between the magnitude of an event and that of an event detection threshold with respect to the time difference between a start index and a peak index. The slope can be determined as

$$Slope = \frac{y_2 - y_1}{b_2 - b_1} \tag{2.125}$$

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.

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 from ambient traffic only. Therefore, eliminating or minimizing the unwanted elements is imperative.

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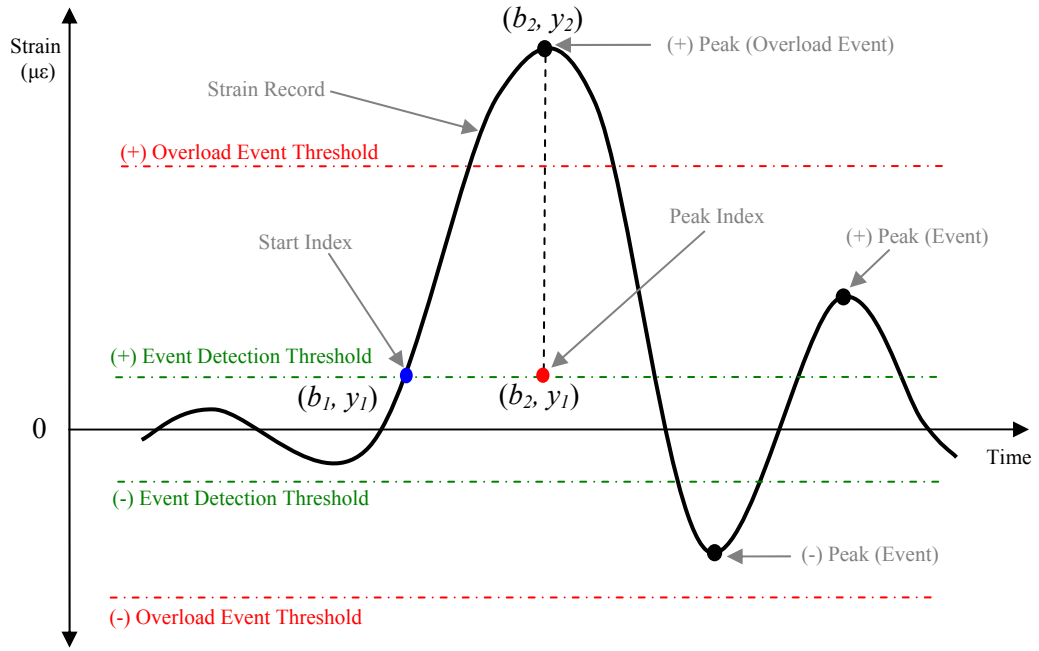

Figure 2-22. Parameters used to determine a slope in a strain record.

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,

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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 filer, therefore, can modify frequency contents of strain records by only allowing frequencies that are lower than a specified cutoff frequency. Among the commonly used digital filtering techniques, the Chebyshev filter is known to effectively minimize peak detection error with a relatively fast processing speed [42]. 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

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subsequently, the field monitoring software was developed to provide users with following information:

- Identifying and notifying alarm 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 Field Monitoring Software and Required Initial Setup

2.2.2.1. Components of 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

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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.

Each component of the field monitoring software was developed in LabView7.1. LabView utilizes a graphical programming language, G, to create programs with icons and strings in a flowchart-like form called a block diagram. The execution of a program in LabView is data driven, as opposed to an instruction driven execution in other commonly used programming systems that use text-based languages (e.g., C and C+) to create lines of code. A single LabView program is often referred to as a virtual instrument (VI) because its appearance and operation of interactive user interface, called a front panel, imitate an actual instrument. When a VI is used in another program, it is referred to as a subVI. During software development, significant effort was taken to ease and minimize user interaction. This task was accomplished by utilizing a series of GUI for each of operation. Each VI was designed to provide users with immediate feedback. A total of eight programs were created as are listed below:

- *1 Preliminary DAQ.VI*
- *2 FFT-PSD Analysis.VI*

(1) Preliminary Data Acquisition and Analysis

- *3 Input.VI*
- *4 MainDAQ815.VI*
- *5 View Strain History.VI*

(2) Main Data Acquisition and Processing

- *6 View Hourly File.VI*
- *7 Create Report (From Single File).VI*
- *8 Create Report (From Multiple Files).VI*

(3) Report Generation

The first two VIs (*1 Preliminary DAQ.VI* and *2 FFT-PSD Analysis.VI*) are designed for preliminary data acquisition and analysis while *3 Input.VI*, *4 MainDAQ815.VI* and *5 View Strain History.VI* are intended for use during main data acquisition and processing. The remaining VIs are used for viewing and generating reports. Included in the title of the first four VIs (1, 2, 3 and 4) is a number that indicates the order in which they should be executed. The other four VIs (5, 6, 7 and 8)

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can be executed only when needed and in any order. Each VI features a user interface and visualization command controls that are facilitated by tools contained in the program's graphical environment.

Presented in Fig. 2-23 is a general flowchart that illustrates the overall procedures undertaken by the field monitoring software. Screen shots of each VI are shown in Figs. 2-24 through 2-31. Note that the front panels of each VI 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 VI are presented in Tables 2-1 through 2-7.

Table 2-1. 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 B)
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.

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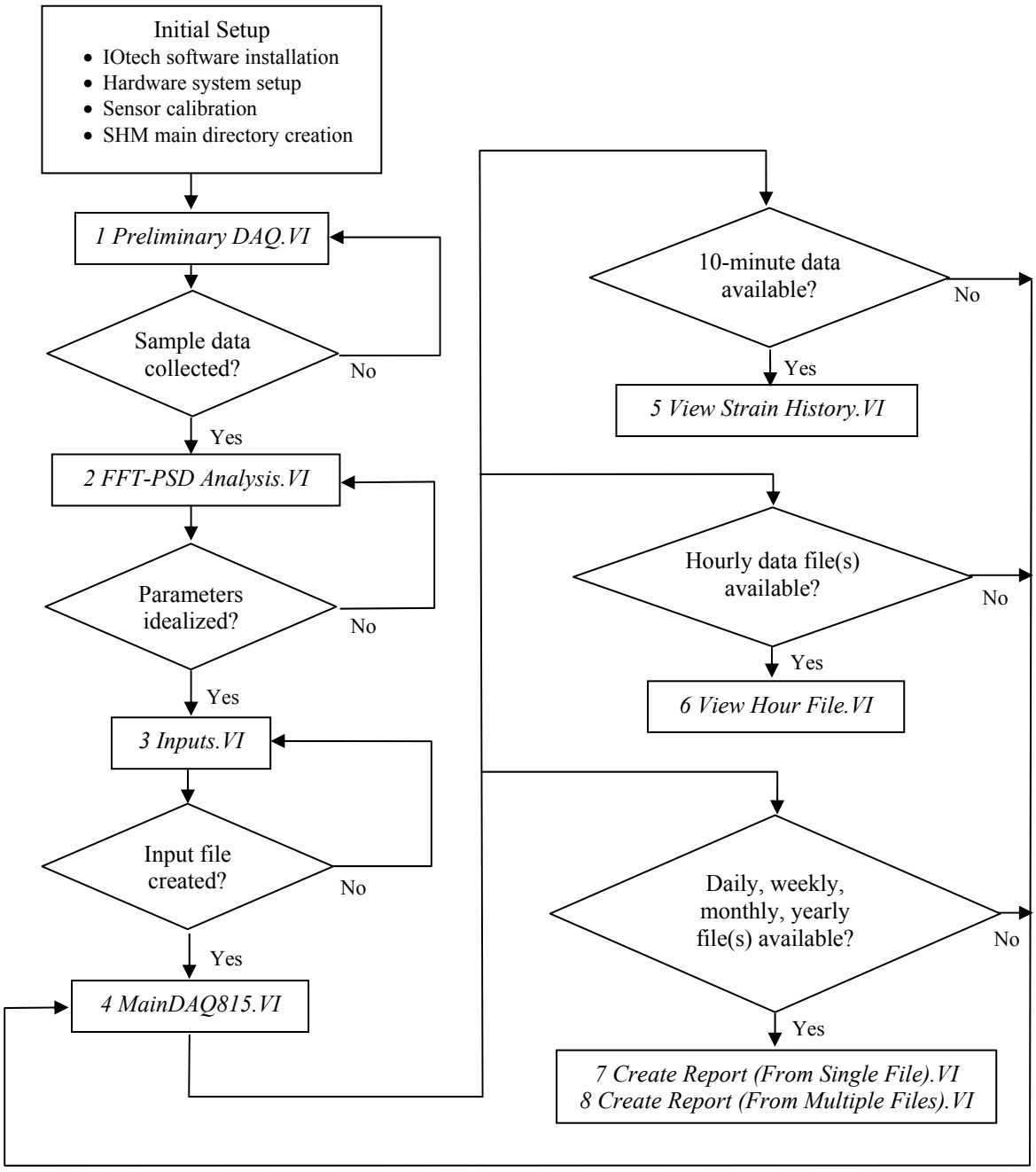

Figure 2-23. Illustration of overall procedures involved in the field monitoring software.

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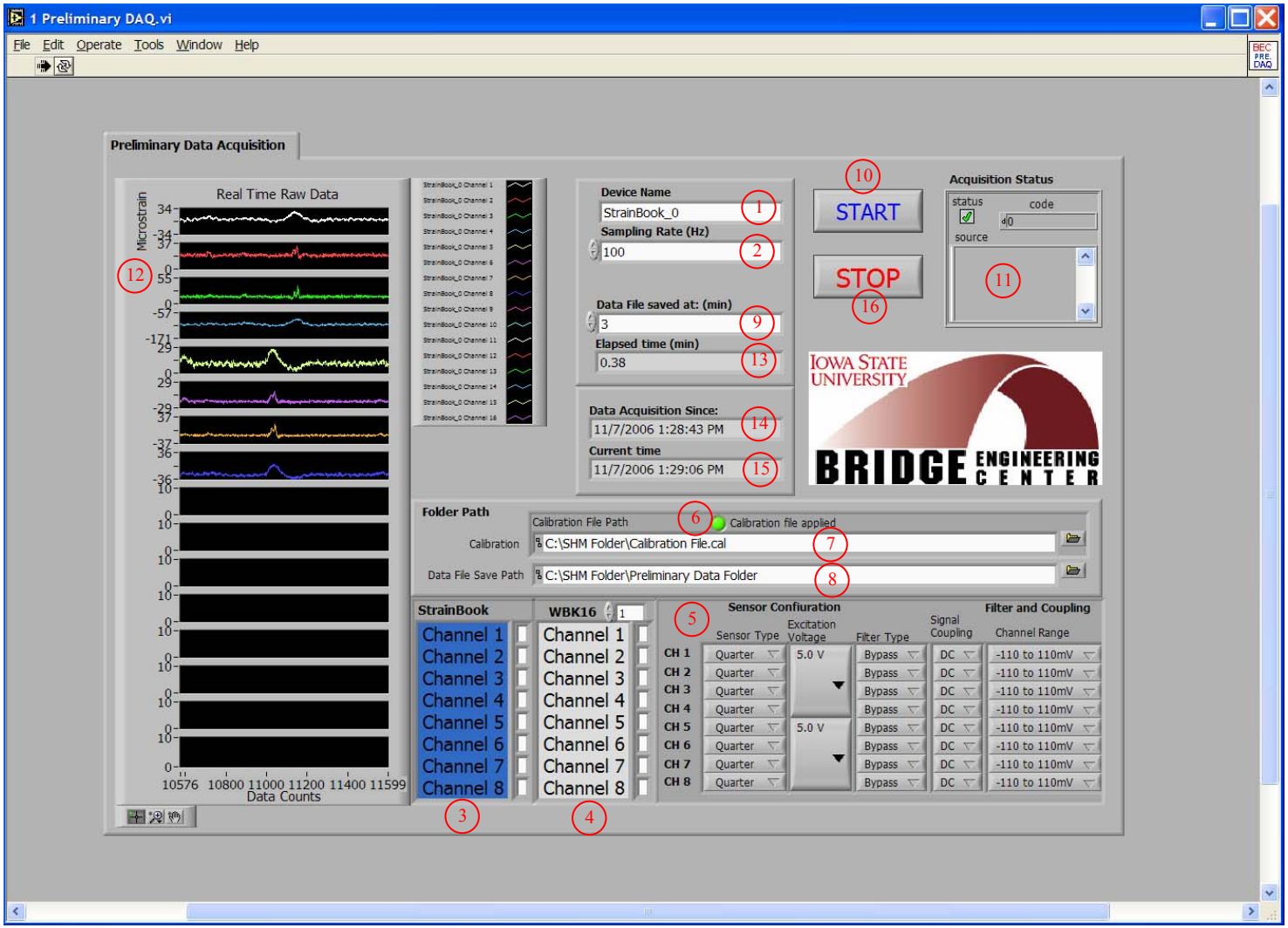

Figure 2-24. Screen shot of *1 Preliminary DAQ.VI* front panel.

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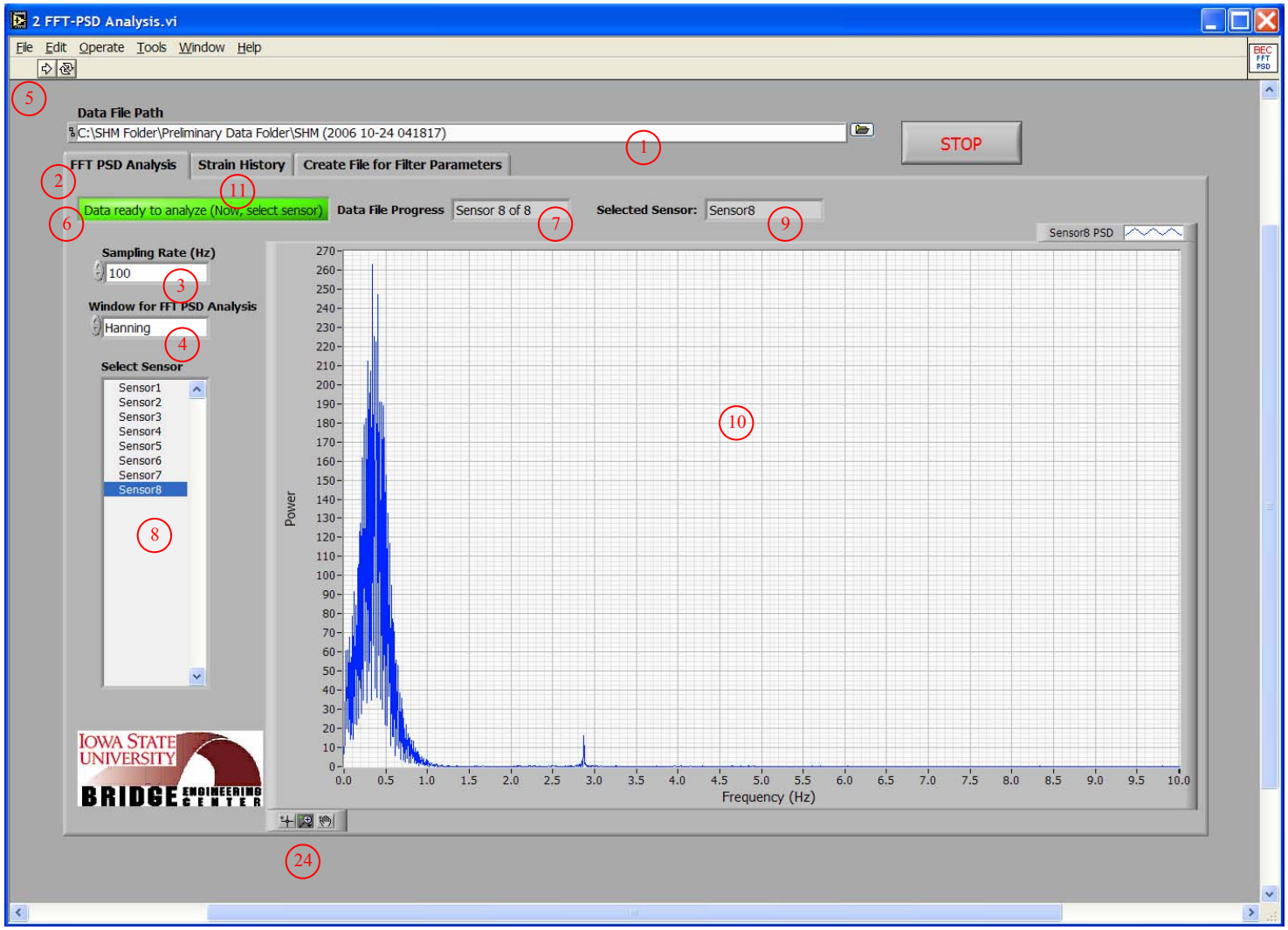

(a) FFT-PSD plot display for the selected sensor

Figure 2-25. Screen shot of *2 FFT-PSD Analysis.VI* front panel.

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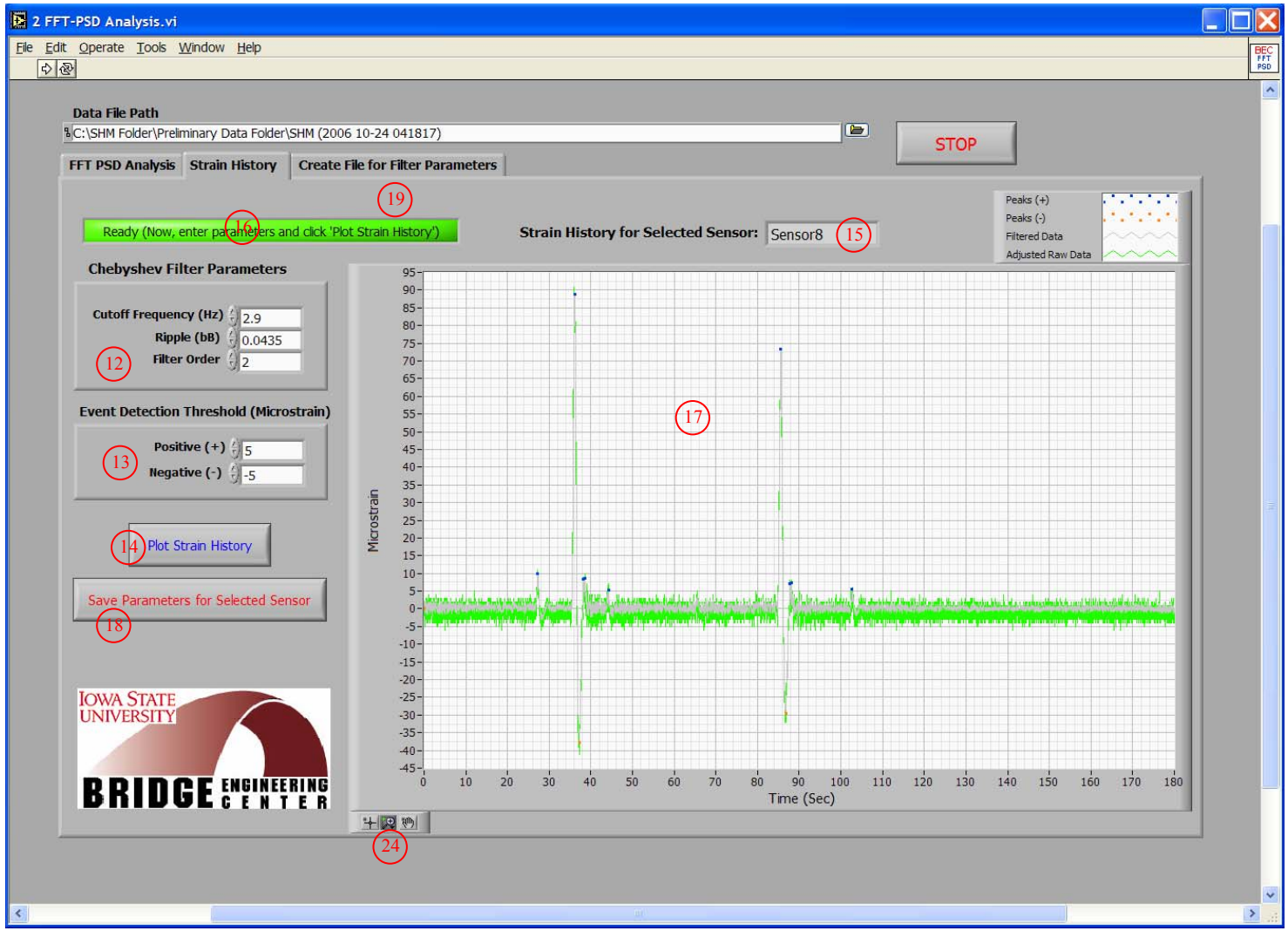

(b) Strain record display for the selected sensor

Figure 2-25. (continued).

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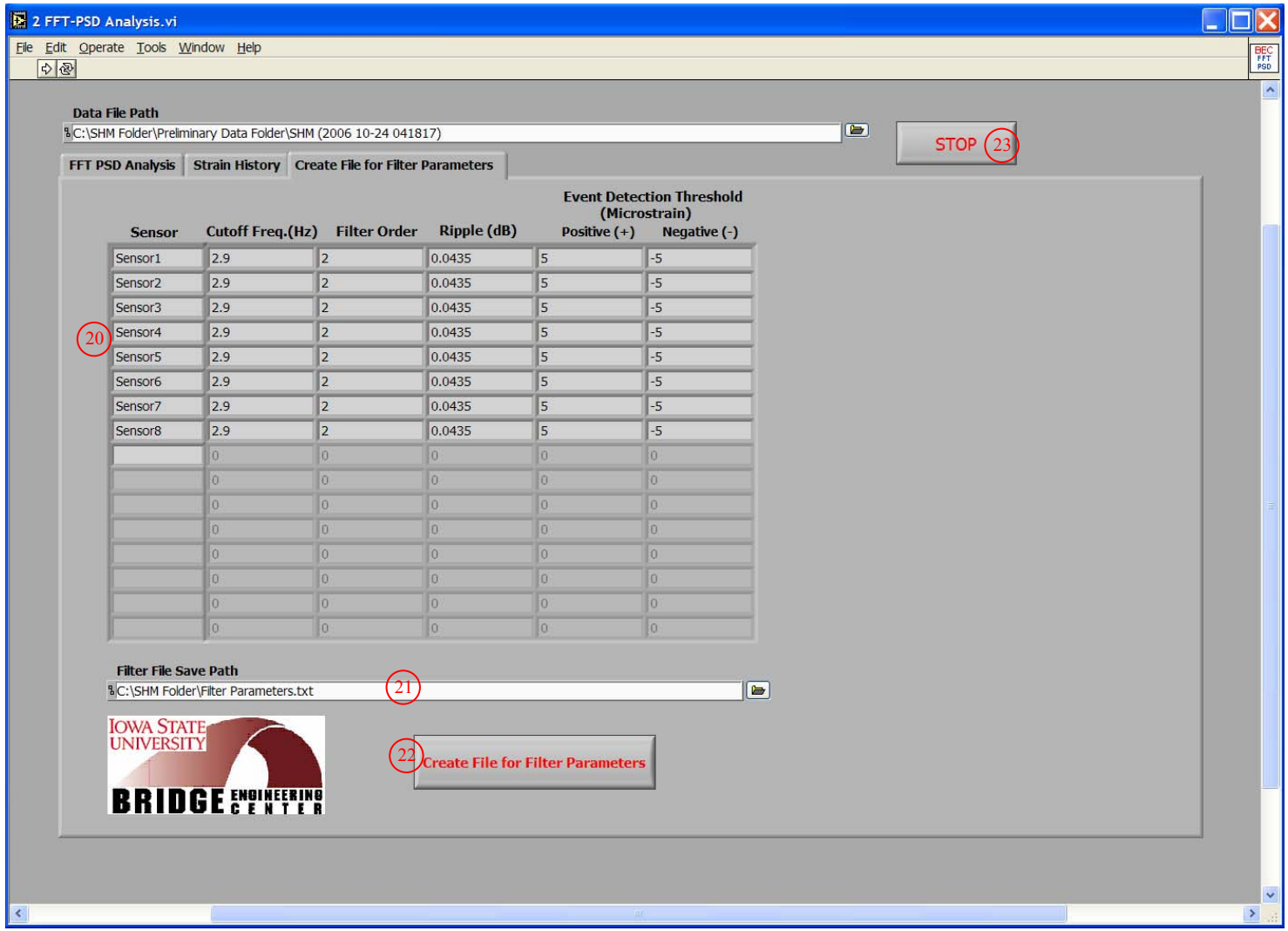

(c) Filter parameters display

Figure 2-25. (continued).

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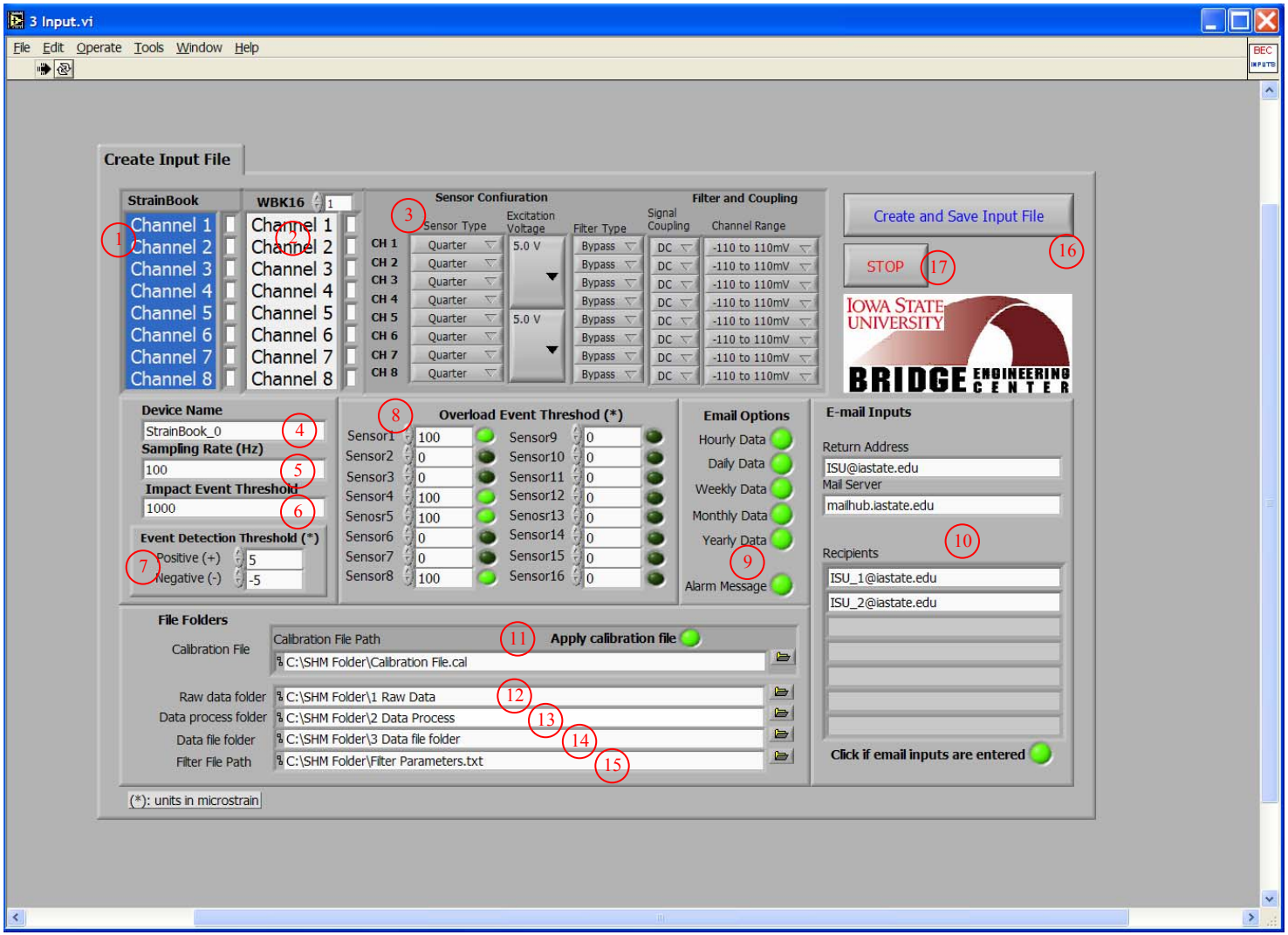

Figure 2-26. Screen shot of *3 Input.VI* front panel.

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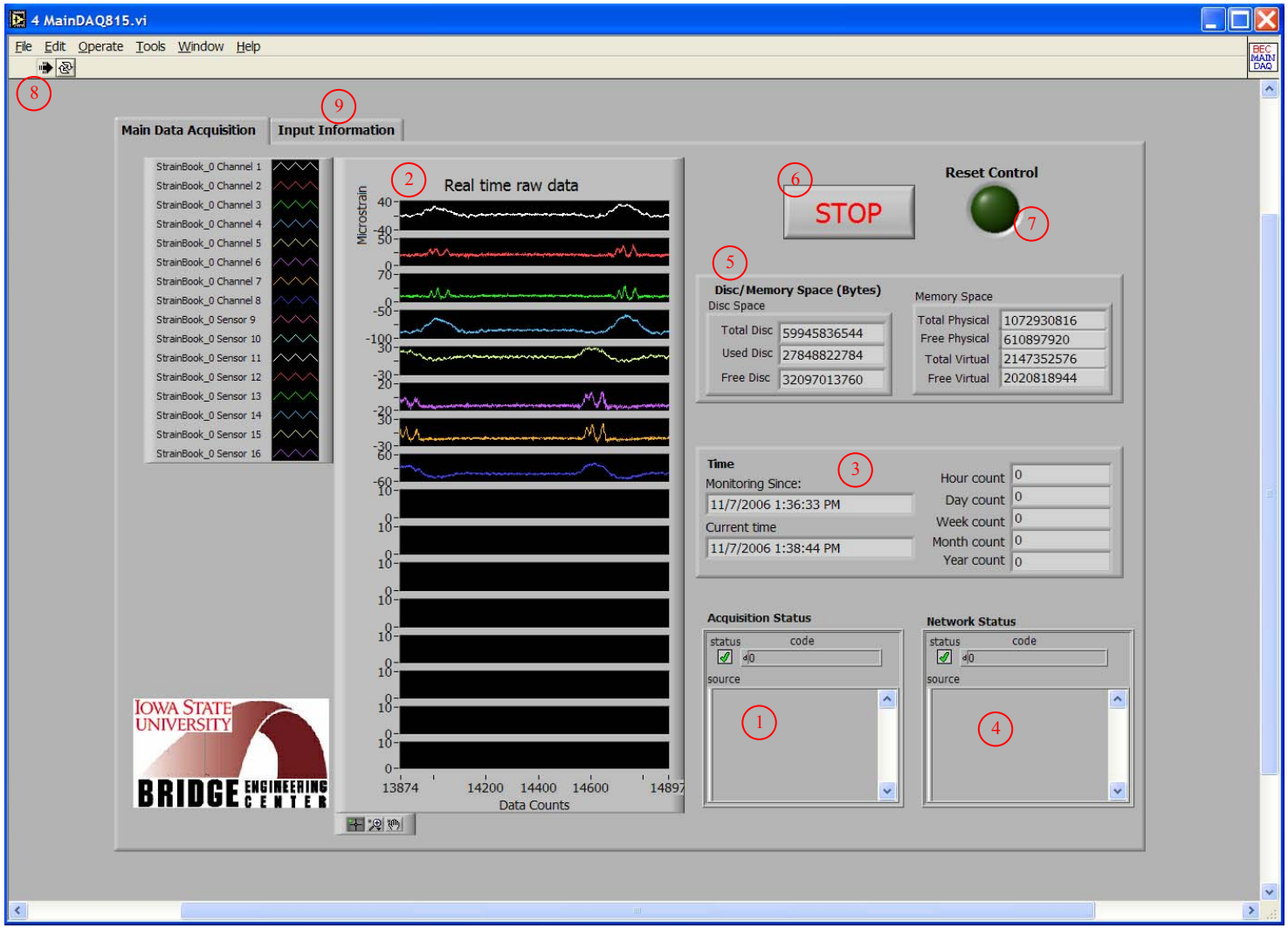

(a) Illustration of Main Data Acquisition tab

Figure 2-27. Screen shots of *4 MainDAQ815.VI* front panel.

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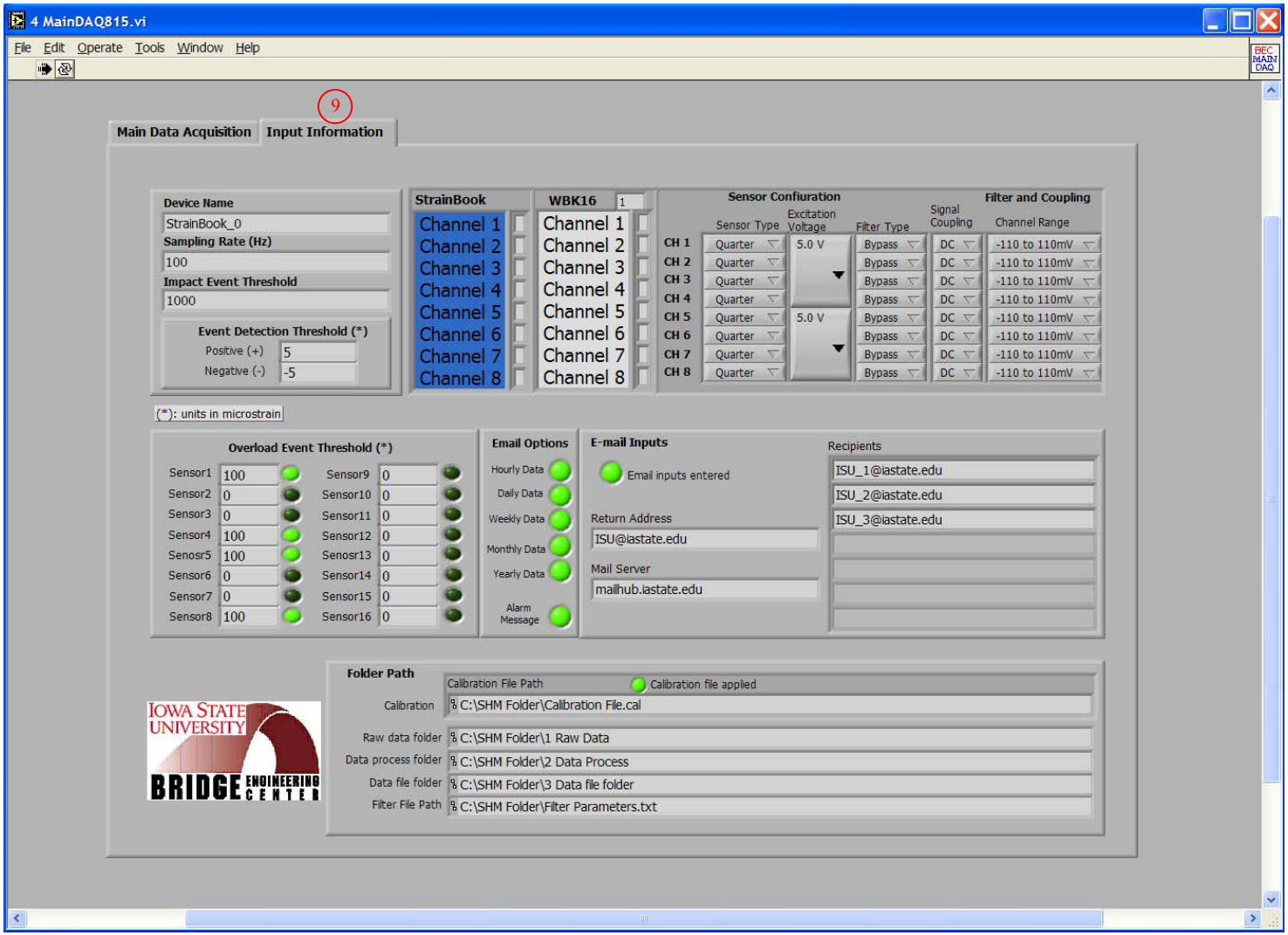

(b) Illustration of Input Information tab

Figure 2-27. (continued).

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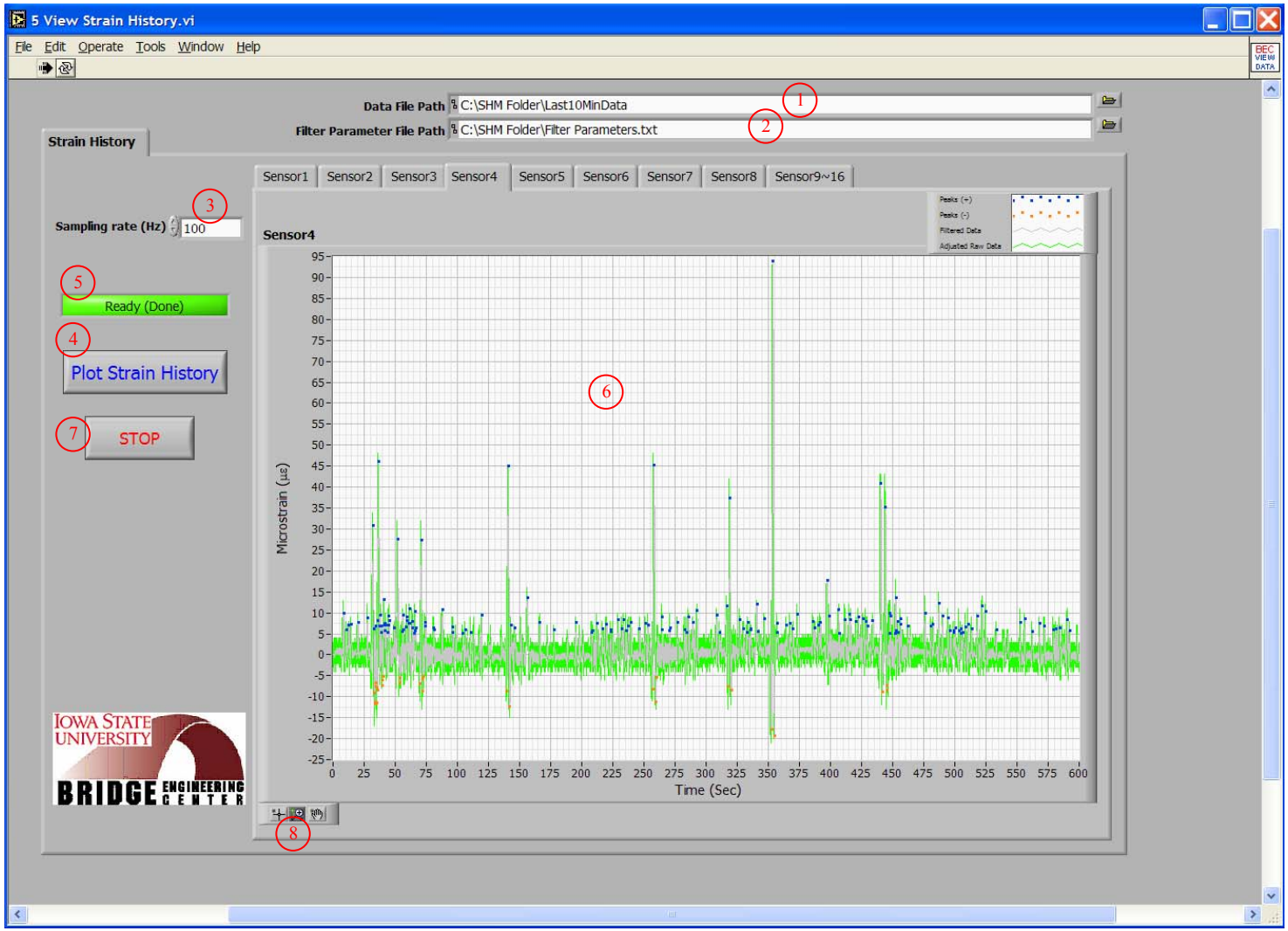

Figure 2-28. Screen shot of *5 View Strain History.VI* front panel.

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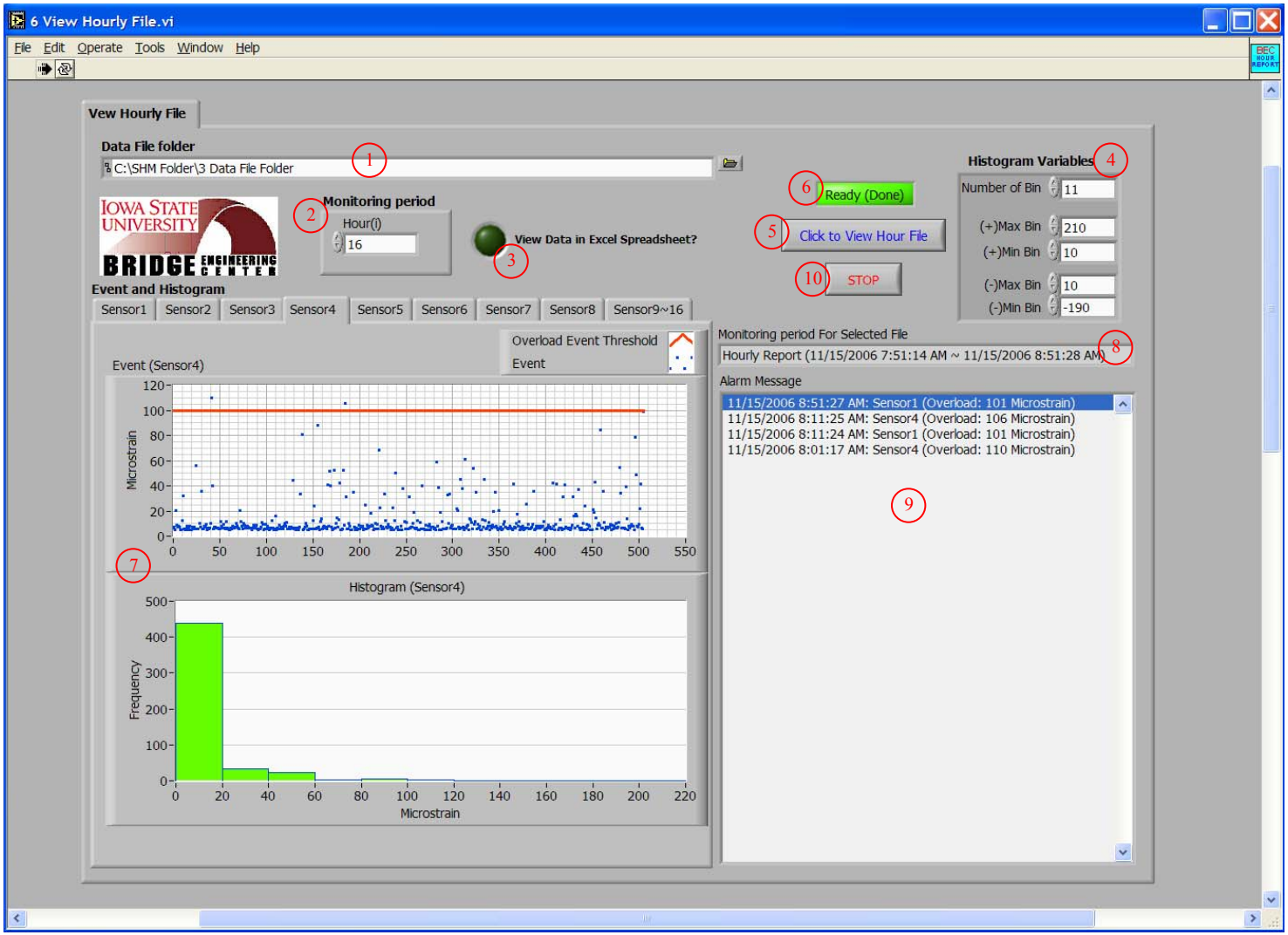

Figure 2-29. Screen shot of *6 View Hourly File.VI* front panel.

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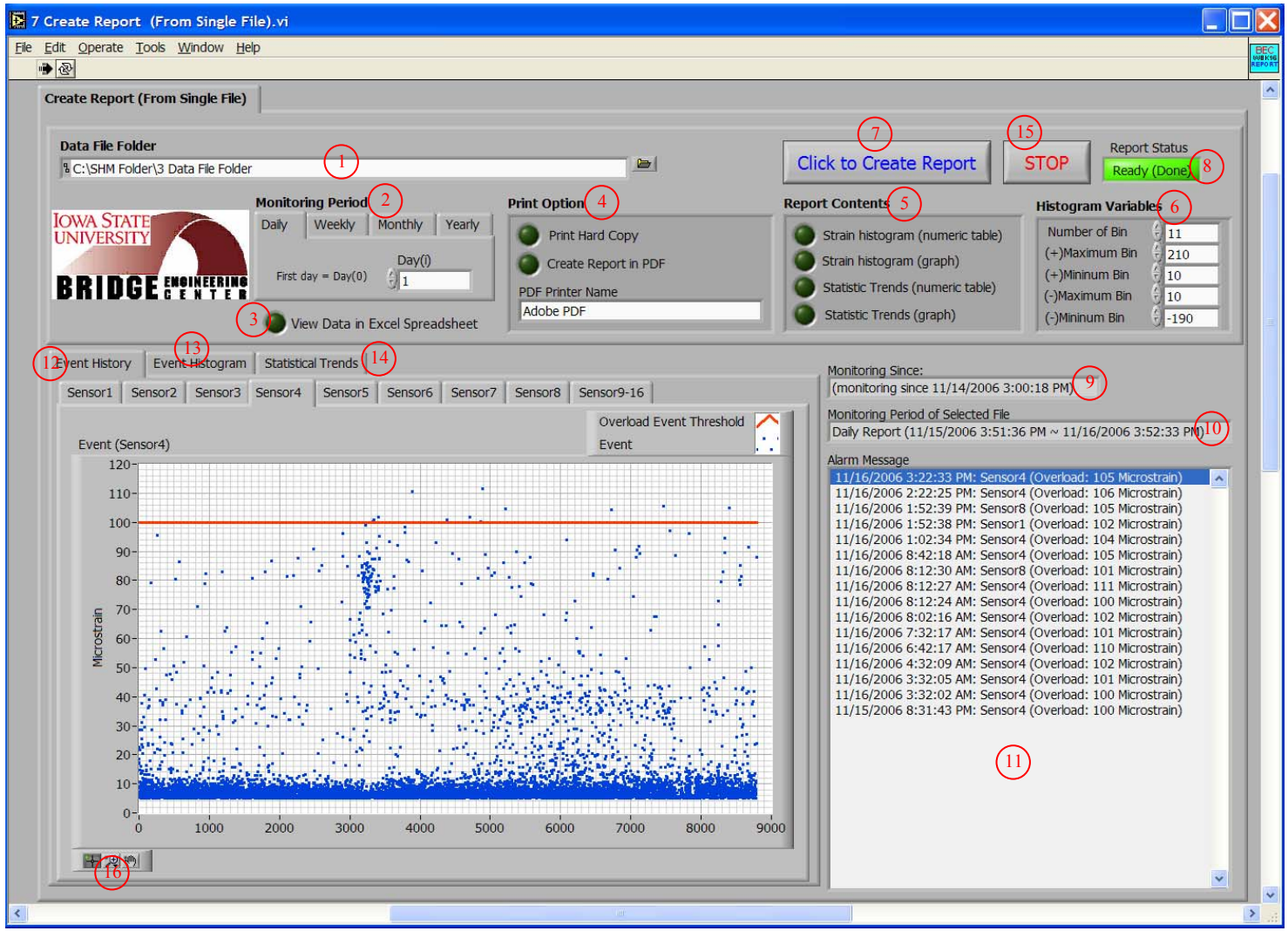

Figure 2-30. Screen shot of *7 Create Report (From Single File).VI* front panel.

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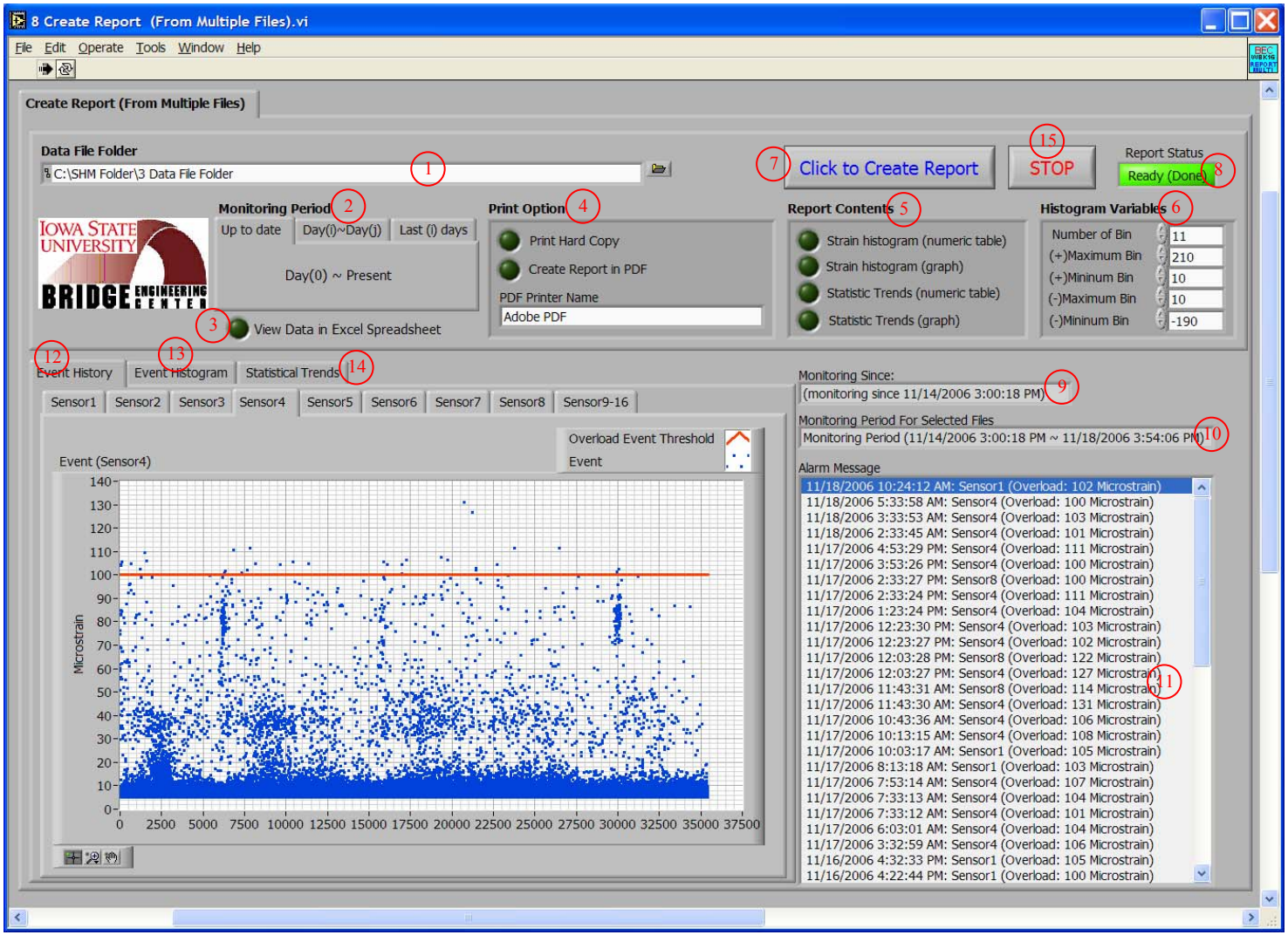

Figure 2-31. Screen shot of *8 Create Report (From Multiple Files).VI* front panel.

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

#	Control or Indicator	Description
1	**Data File Path Control**	Path to the sample 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 Threshold Control (Microstrain)**	Plus and minus event detection thresholds within which no peak (or event) will be detected.
14	**Plot Strain History Control**	When pressed, strain history will be displayed in graph indicator #17 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**	Temporarily stores the filter parameters and event detection

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	Indicator	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 2-3. 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 B) 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.

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Table 2-4. 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 2-5. 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).

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Table 2-6. 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 2-7. 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 Controls**	Allows users to change the format of histogram plot.
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

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		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).

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 B. The user must create a main directory entitled "SHM Folder" that contains the following four folders: "1 Raw Data", "2 Data Process", "3 Data File Folder", and "Preliminary Data Folder". Illustrated in Fig. 2-32 is the main directory 'SHM Folder' that contains four sub directories. In the following sections, overall procedures involved in running each VI (execution program) as well as select subVIs are described. In addition, step-by-step instructions on how to run each component are provided in Appendix C.

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.

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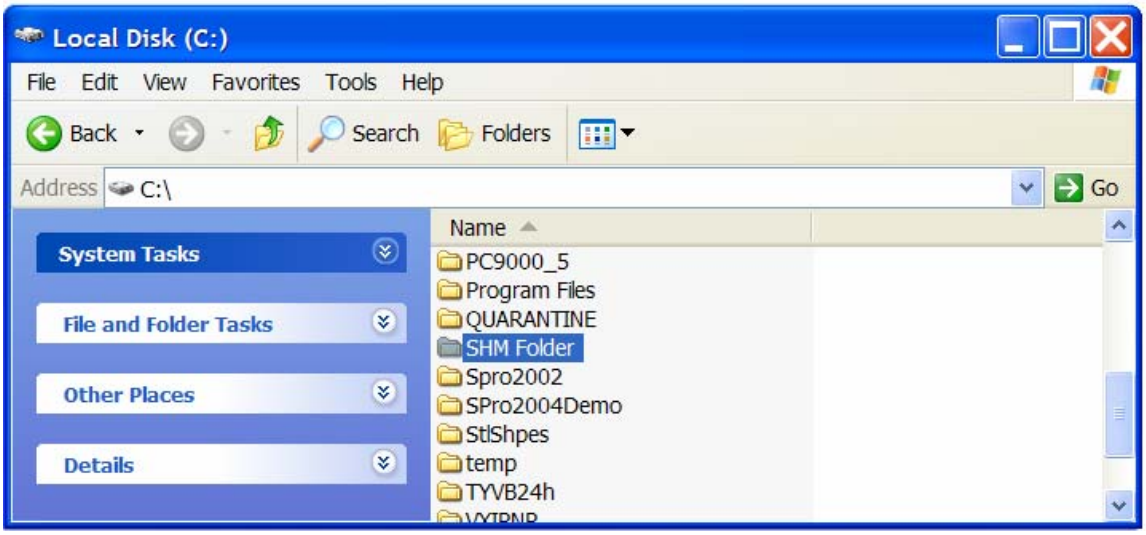
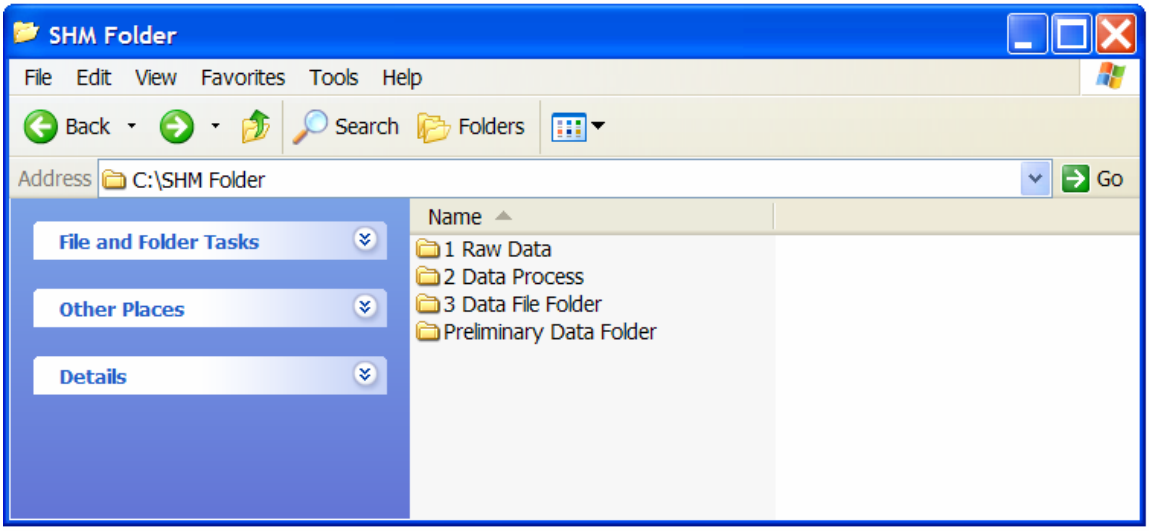


(a) SHM Folder main directory



(b) Sub directories

Figure 2-32. Illustration of 'SHM Folder' main directory with four sub directories created.

2.2.3.1. Preliminary Data Collection and Storage

1 Preliminary DAQ.VI allows users to acquire a small amount of data for immediate viewing, storage to the hard disk, and for use within *2 FFT-PSD Analysis.VI* to configure filter parameters. Illustrated in Fig. 2-24 is a typical setup for *1 Preliminary DAQ.VI*. Three steps – (a) basic setup on input parameters (b) VI execution, and (c) results verification – are involved in using this VI. The first step requires users to input parameters in controls #1 though #9 that are shown in Fig. 2-24 as follows:

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- 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 Fig. 2-24. 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 Fig. 2-24 – 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.

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- Once the data acquisition is completed, click the 'STOP' button (#16). This will terminate the program.

Illustrated in Fig. 2-33 are a series of data files like those that will be saved after running *1 Preliminary DAQ.VI*. As can be seen in Fig. 2-33, 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: second within the minute

Upon execution of the VI, data will be collected and written to a file with this file name. Note that with this file naming convention, users can see the absolute time at which each data was saved.

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.

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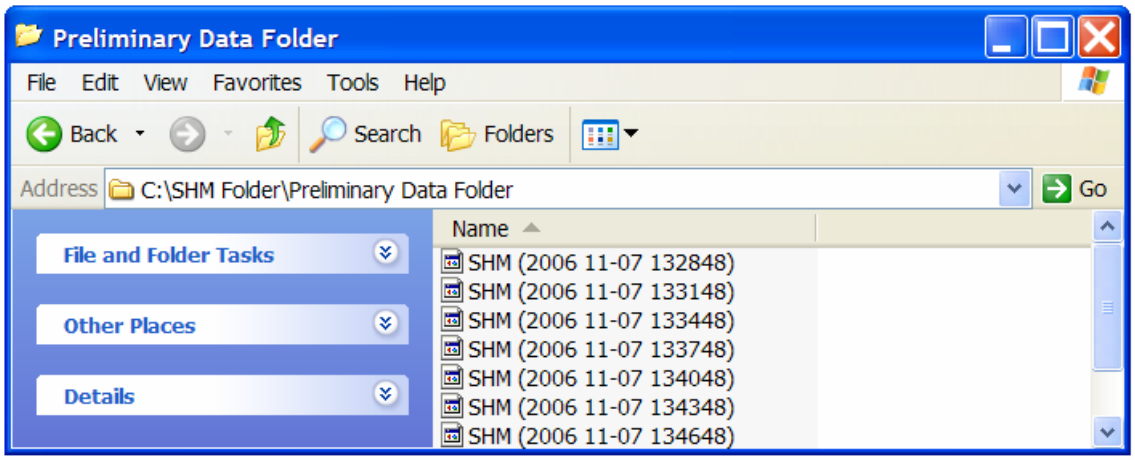

Figure 2-33. Illustration of data files saved upon execution of *1 Preliminary DAQ.VI*.

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 Preliminay 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 filer 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 following describes 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 Fig. 2-25, 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:

i. Select a data file from those that were saved in the 'Preliminary Data Folder' by using the browsing tool in control #1.

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ii. 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.

iii. 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.

iv. 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.

v. 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.

vi. 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.

vii. 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).

viii. Move to the Strain History' tab control (#11) and enter the cutoff frequency determined in step *vii*.

ix. Click the "Plot Strain History" control (#14) to see the effect of filtering for the selected sensor. Indicator #17 will display the strain history.

x. 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.

xi. 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:

xii. Perform the "step *i*" through "step *v*", but this time, select a data file that contains traffic plus noise induced strain.

xiii. Select a sensor with a mouse click within control #8 and move to the 'Strain History' tab (#11).

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xiv. Enter three filter parameters (#12) that will be applied to the selected strain data: cutoff frequency (Hz), ripple (dB), and filter order.

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 [42]. 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.

xv. 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.

xvi. 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.

xvii. 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.

xviii. 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:

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xix. 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'.

xx. Repeat "steps *xiii*" through "step *xix*" until the filter parameters and the event detection thresholds have been established for all sensors.

xxi. 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 Paremeters.txt'.

xxii. 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.

xxiii. 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 VIs: *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 VI 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:

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- 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.
- 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 an 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 any 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

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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 VI 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

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file. An example of this prompt dialog box is provided in Fig. 2-34. The last step is to stop the VI by pressing the 'STOP' control (#17).

When the *3 Input.VI* is executed, the user may want to verify that the input file is created in the main folder. For this verification, users then physically need to open the main directory and check the existence of the file. Also, the time at which the file is created can be checked by simply positioning a pointer with a mouse over the file as illustrated in Fig. 2-35.

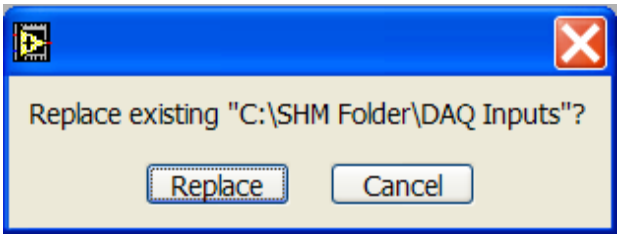

Figure 2-34. Prompt dialog box for an input text file.

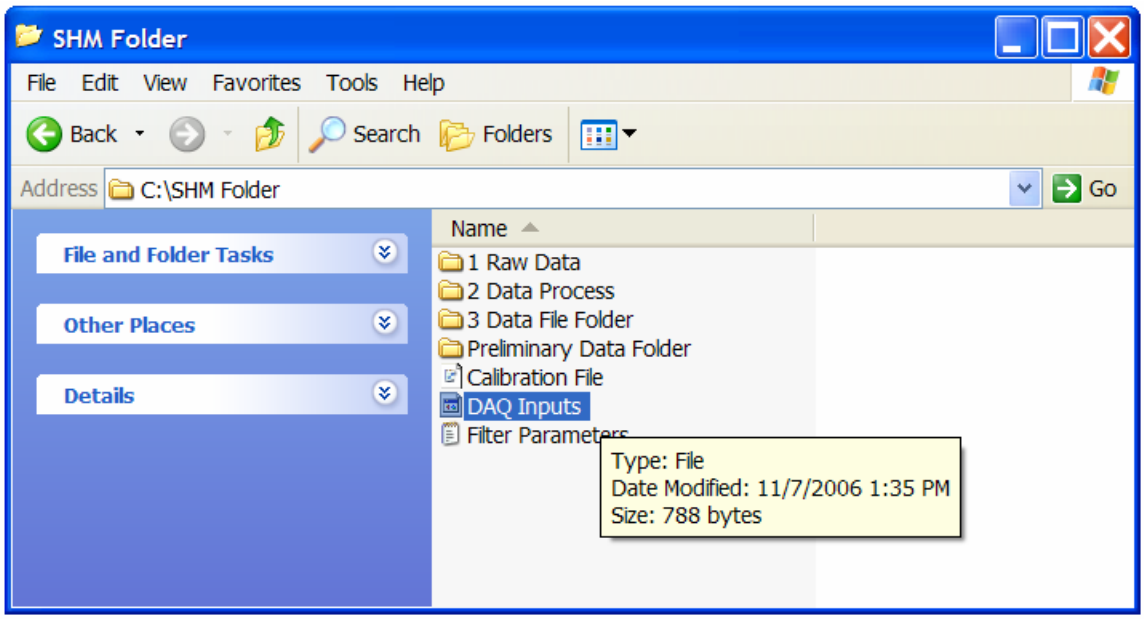

Figure 2-35. Illustration of a 'DAQ Inputs' file created in the 'SHM Folder' main directory.

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.

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Given that the data acquisition was successfully initialized, as depicted in Fig. 2-27, 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 VI is running, the following information will be displayed on the control panel of the VI shown in Fig. 2-27:

- 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 VI 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 (e.g., 2000, XP, NT, etc.) and virus scan software used, users may need to consult with a system analyst to resolve this. An example for changing security setting on virus scan software (McAfee VirusScan Enterprise) is provided in Appendix E.
    - 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 VI to stall or stop. All other functions except the email will still be functioning. The VI is programmed such that when an error related to network connection occurs, the VI will skip that step and carry on other tasks. Also note that since all data files created by the VI will be saved in '3 Data File Folder' in the main directory, users can always retrieve the data files manually.

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- 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 subVI, *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. Figure 2-36 illustrates a 'Last10MinData' file created in the main 'SHM Folder' directory.

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 subVI, *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: 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. An example of a text message is given below:

"11/6/2006 9:15:30 AM: Sensor4 (Overload: 153 Microstrain)"

The information generated by *Data Process.VI* will be temporarily stored within the subVI 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

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

As mentioned, *4 MainDAQ.VI* must be installed as a service on the local host PC so that if there is a power outage, the program will autonomously resume when the power comes back on. Additional efforts were taken during the software development phase to minimize data loss due to power outage. To this end, the program was designed to internally operate in a loop and a binary file, 'DAQ Time', in which numeric information on elapsed time (displayed in #3 in Fig. 2-27) are saved is created or updated every hour. With this configuration, every time the program is restarted, it pauses for 60 seconds during which the data acquisition instrument is initialized, retrieve information from the DAQ Time file and resumes data collection. An illustration of a 'DAQ Time' file created in the main directory is presented in Fig. 2-37.

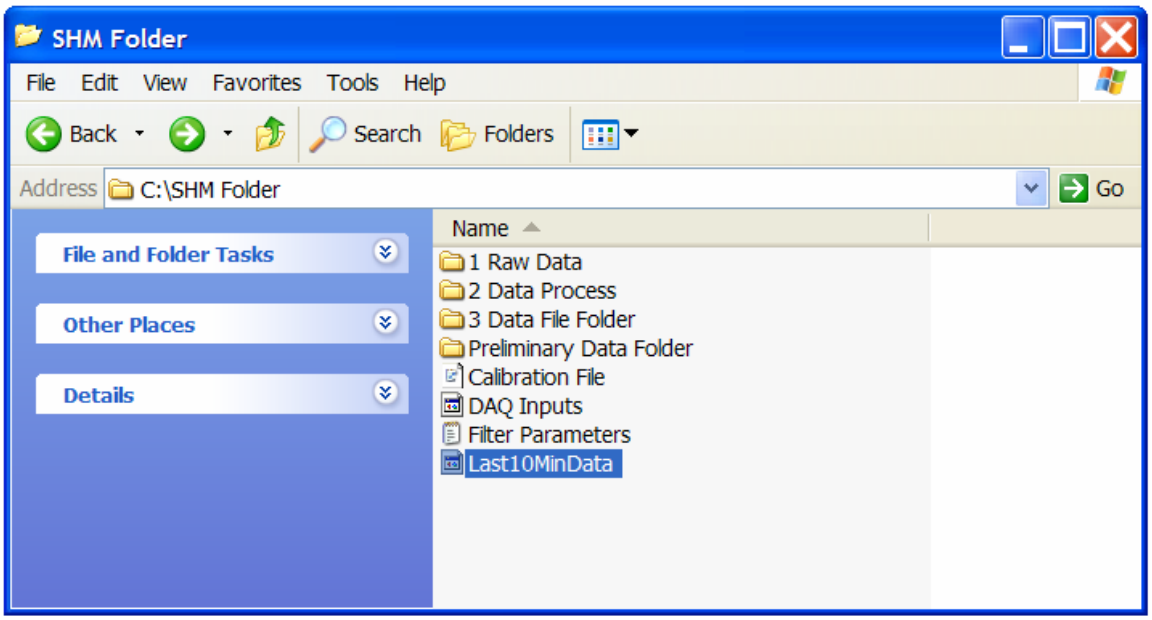

Figure 2-36. Illustration of a 'Last10MinData' file created in the main directory.

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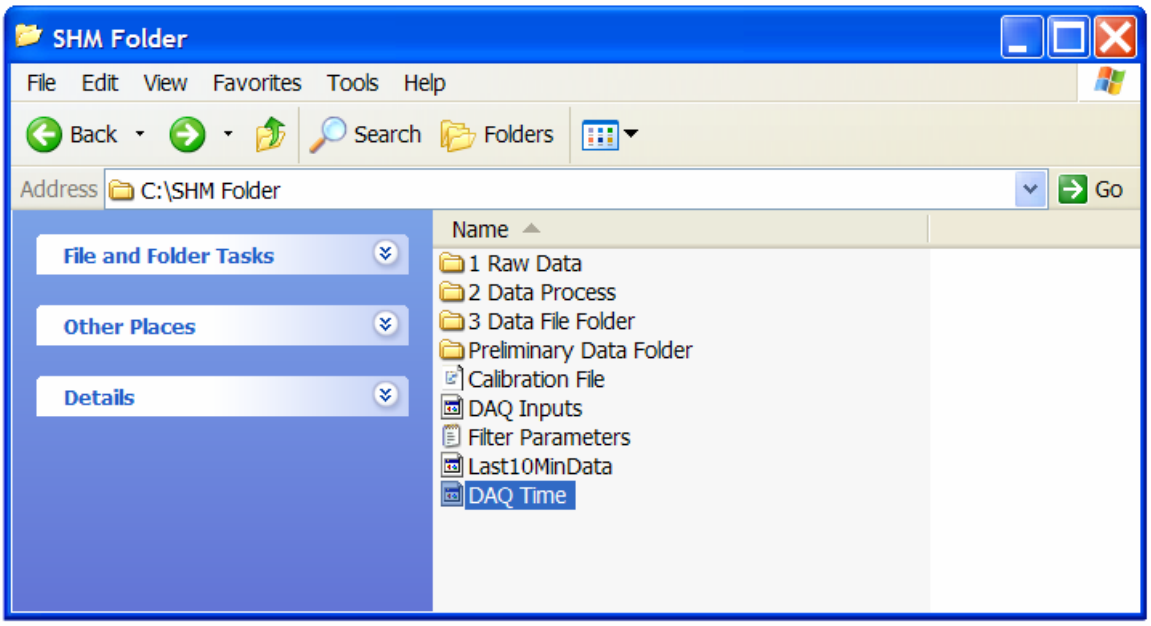

Figure 2-37. Illustration of a 'DAQ Time' file created in the main directory.

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 VI 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. This will allow the user to keep the old data files saved in a different directory so that they can be retrieved if necessary. If the user does not feel the need to keep these old data files, the user can simply delete the old data file folder. Note that creating a new 'Old Data File Folder' will take place only when the 'Reset' option is selected and the execution program is started. 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'. An illustration of two 'Old Data File Folder' directories created in the main directory is presented in Fig. 2-38.

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. The data files created here will be used for the application of viewing and generating reports, which are described in Section 2.2.5.

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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 the user to view what has recently been collected. *5 View Strain History.VI* as shown in Fig. 2-28 was developed to allow the user to easily view these data. The following procedures are involved in running the VI:

- 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 VI. 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 VI by pressing STOP button control (#7).

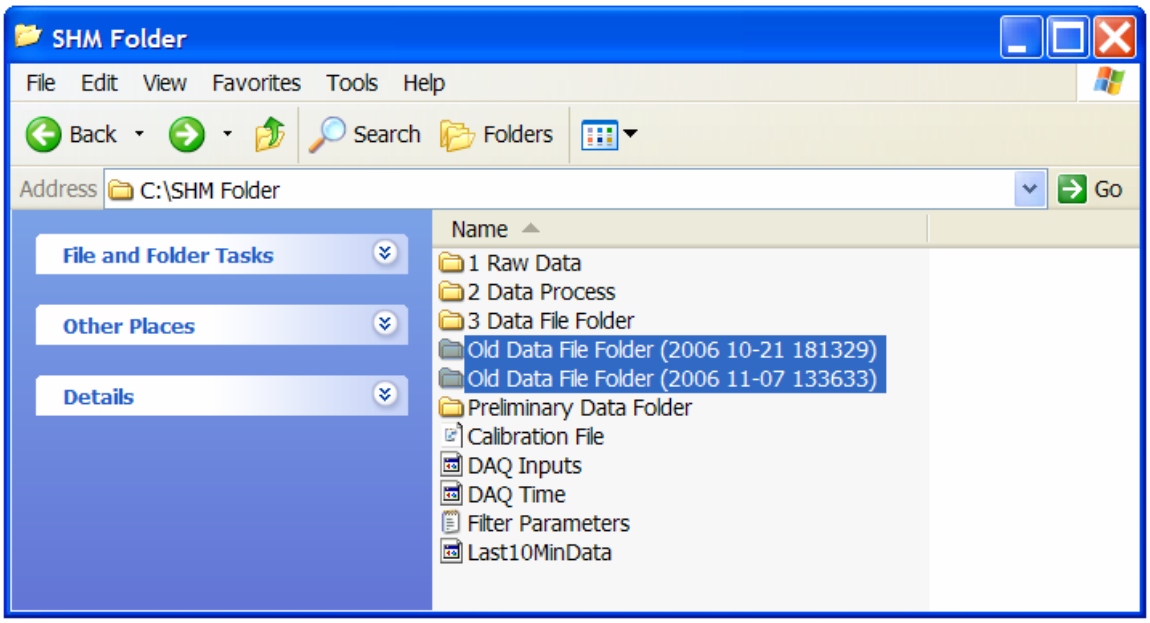

Figure 2-38. Illustration of 'Old Data File Folder' directories created in the main directory.

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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 as more data files will be archived over time. In order to address this issue, these VIs were programmed to find the correct file or files specified by user inputs. The procedures involved in executing each of these VIs 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 Fig. 2-29 is an example setting for *6 View Hourly File.VI*. The following procedures are involved in running the VI:

- 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 VI by pressing STOP control (#9).

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2.2.5.2. Creating Reports

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 VIs are the same as shown in Figs. 2-30 and 2-31. 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

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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).

- Stop the VI by pressing STOP control (#15).

Note-1: As can be seen in Figs. 2-30 and 2-31, 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 Fig. 2-39. 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' 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 (Fig. 2-40a)
b. Day (i) ~ Day (j): allows to access multiple daily data files created during user specified time period (Fig. 2-40b)
c. Last (i) days: allows to access multiple daily files created during the last user specified days (Fig. 2-40c)

Note that, except in the 'Up to date' tab shown in Fig. 2-40a, 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.

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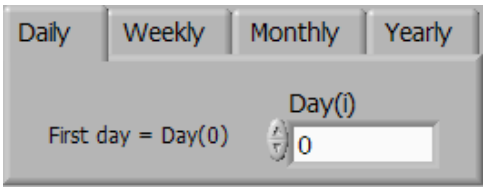
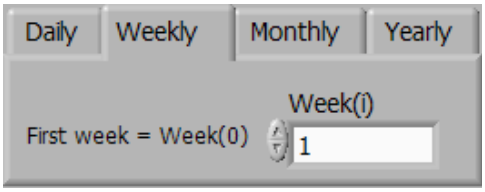
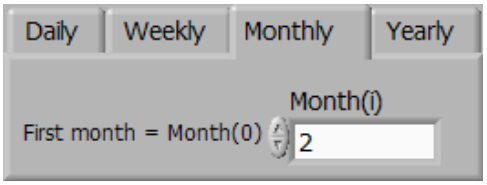


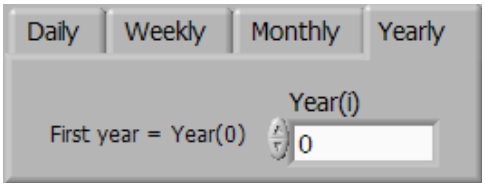
(a) Daily data file



(b) Weekly data file

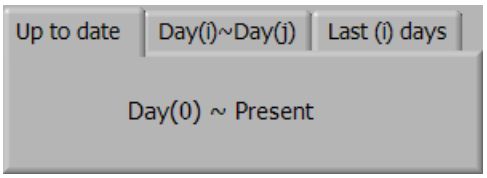


(c) Monthly data file

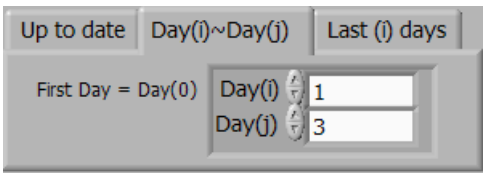


(d) Yearly data file

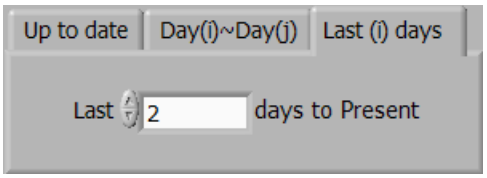
Figure 2-39. Data file selection option for *7 Create Report (From Single File).VI.*



(a) Up to date



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



(c) Last (i) days to present

Figure 2-40. Data file selection option for *8 Create Report (From Multiple Files).VI.*

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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 VI 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 Figs. 2-30 and 2-31 while examples of graphical representation of an event histogram and statistical trends are presented in Fig. 2-41. 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 Fig. 2-30. 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 Fig. 2-41b. 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 Fig. 2-41c.

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.

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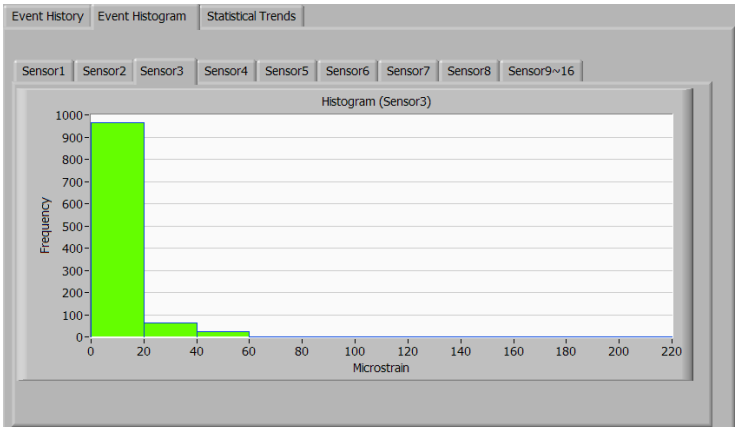
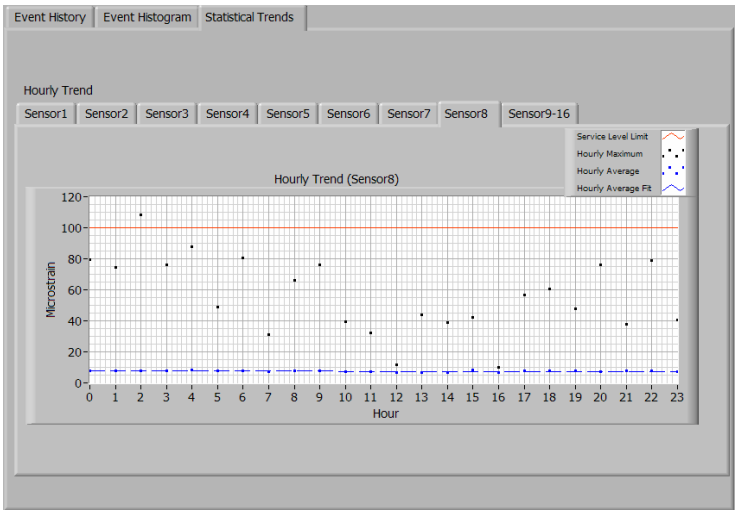


(a) Event Histogram



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

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

Figure 2-41. Examples of event histogram and statistical trends.

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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 (see Appendix F for a detailed drawing of the Hitec Products weldable strain gage). 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., ¼, 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 Fig. 2-42. 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. More information regarding specifications of StrainBook/616 and WBK16 is provided in Appendix G. The prices (in 2006) of the StrainBook/616 and the WBK16 expansion module are $6,000 and $4,000 per unit, respectively.

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 Figs. 2-43a and 2-43b are the two possible communication schematics. The StrainBook/616 is

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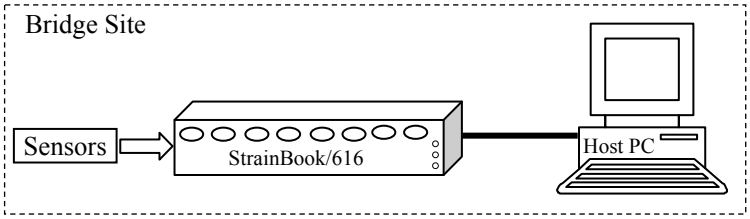
capable of connecting both directly to an Ethernet port on the host PC or to a network hub or router via its built-in 10/100BaseT Ethernet interface. Note that either a straight-through or a cross-over cable can be used to connect between instruments. For the first case, the communication between the 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.

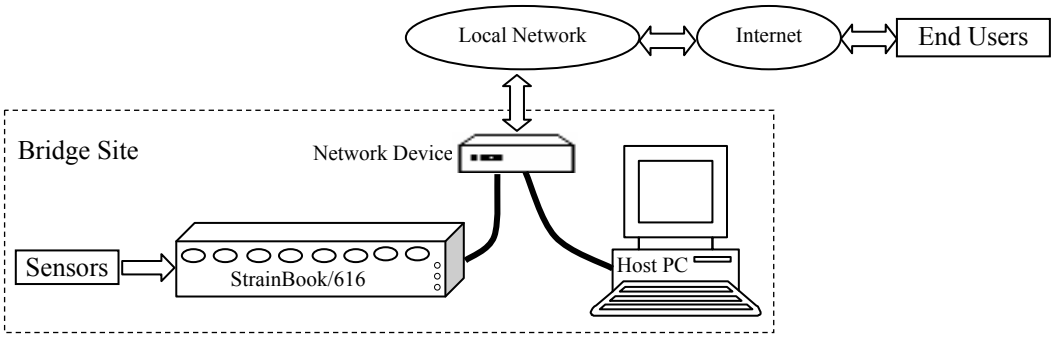
Courtesy of IOtech

(a) StrainBook/616 with 8 built-in strain channels (b) WBK16 8-channel expansion module

Figure 2-42. IOtech instrument hardware.



(a) Direct connection from the host PC to the Device



(b) Connection with a network device

Figure 2-43. Communication schematics.

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3. SYSTEM DEMONSTRATION

The developed SHM system was tested and implemented on a US30 highway bridge in order to demonstrate and verify its general usage. The following sections summarize this demonstration.

In general, Section 3.1 describes the bridge selected for the demonstration of the SHM system while the hardware installation processes are illustrated in Section 3.2. The required procedures for using *BEC Analysis* as well as the field monitoring software are given in Sections 3.3 and 3.4. In order to demonstrate the accuracy of the SHM system, validation tests were performed for *BEC Analysis* and for the hardware system. These validations are summarized throughout this chapter. Also included in Sections 3.3 and 3.4 are select results generated from each software.

3.1. BRIDGE DESCRIPTION

The bridge selected for demonstrating the developed SHM system is the 320 ft x 30 ft, three-span continuous, welded steel girder bridge shown in Fig. 3-1. The bridge is located in central Iowa in Story County, IA carrying US Highway 30 (US30) 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 ¼-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 Fig. 3-2. The sizes of the plate girder flanges are variable as shown in Fig. 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˚.

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 US30 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.

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(a) End view (looking east)

(b) Side view (looking south east)

(c) Bottom view (looking east)

Figure 3-1. Overall bridge photographs.

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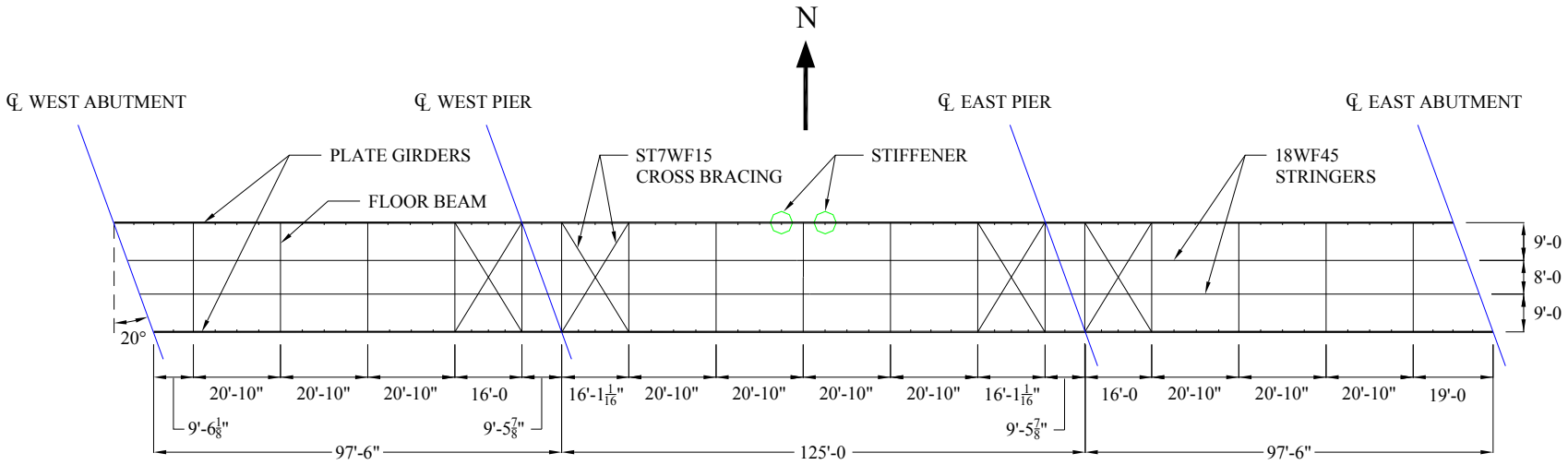
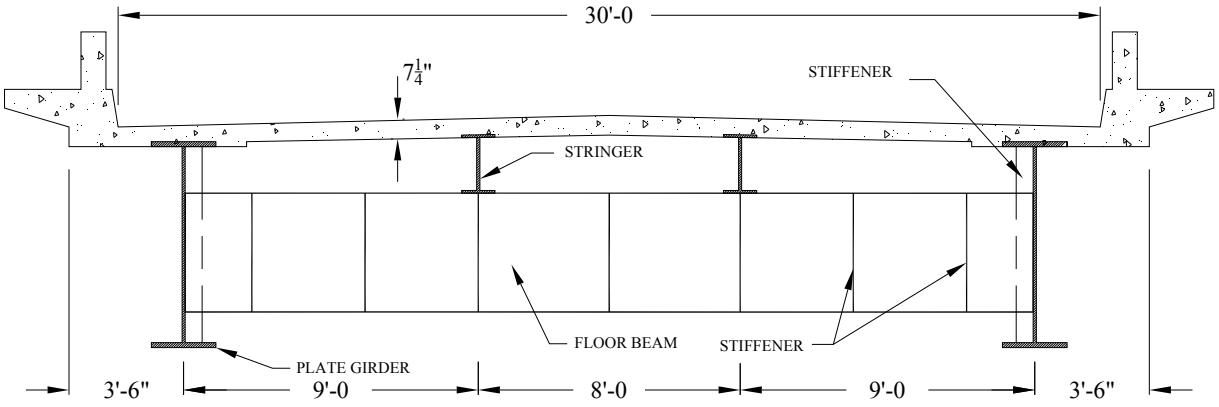


(a) Framing plan.



(b) Typical cross section

Figure 3-2. Framing plan and typical cross section of the bridge.

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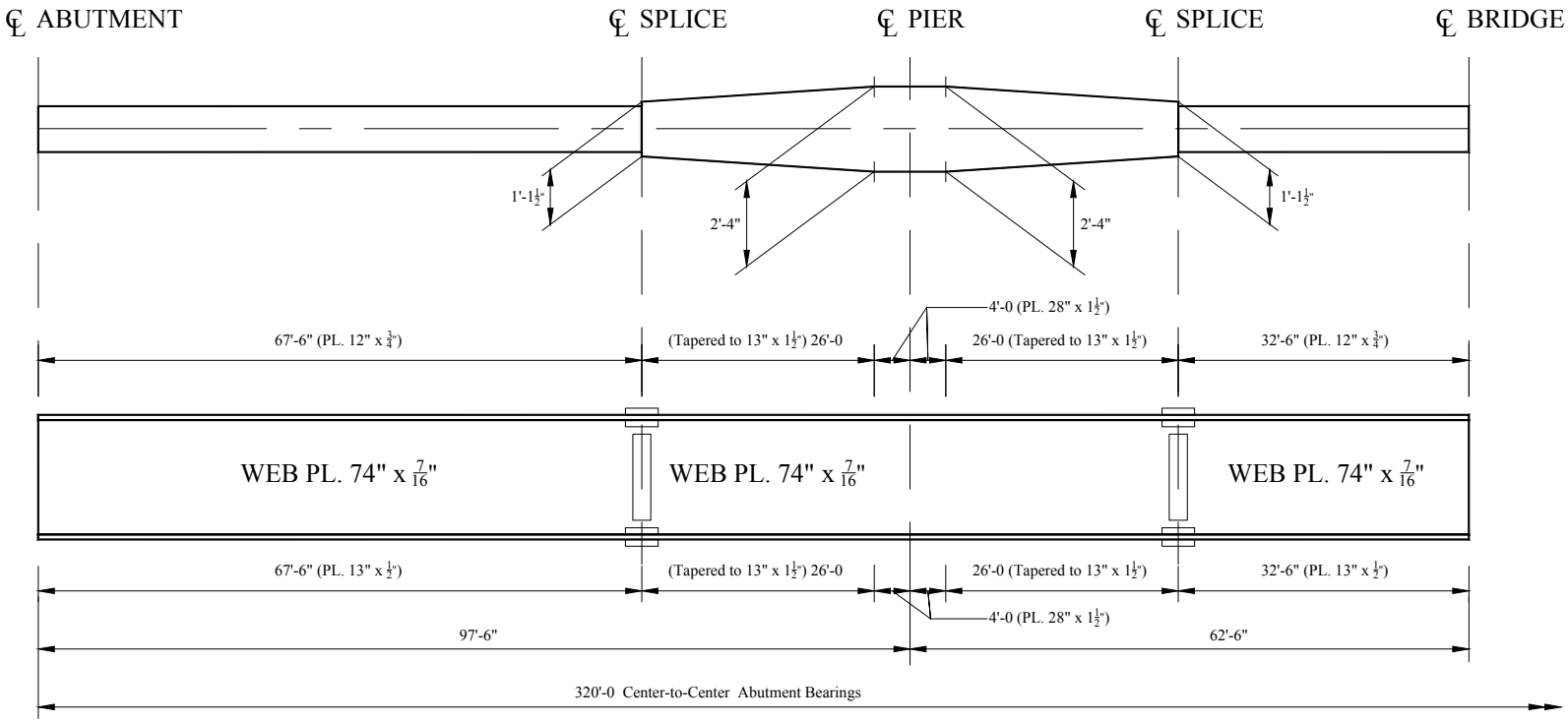

Figure 3-3. Plate girder detail.

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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 though 8) were installed in the positive moment region of the plate girders and stringers in the center span and four sensors (Sensors 1 though 4) in the West end span as shown in Fig. 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 as shown in Figs. 3-5 and 3-6. Surface preparation and welding tasks were performed following the manufacturer's recommendations. More information about the general instruction on the surface preparation is provided in Appendix F.

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 as shown in Fig. 3-7c to protect them from surrounding moisture. In addition, numerous cable ties were used to intermittently secure the entire length of the strain gage cables.

The installation of the strain gages and 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 Linksys wireless router. These hardware components were installed in an environmentally controlled aluminum cabinet, shown in Fig. 3-8, 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

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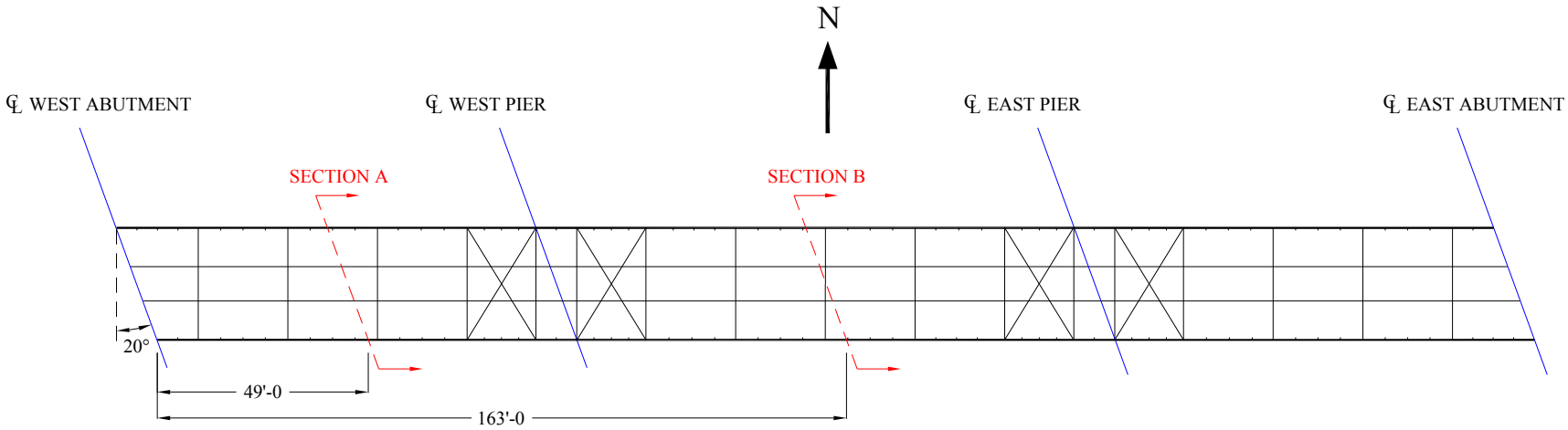
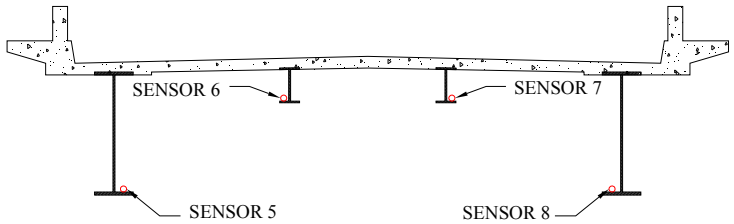
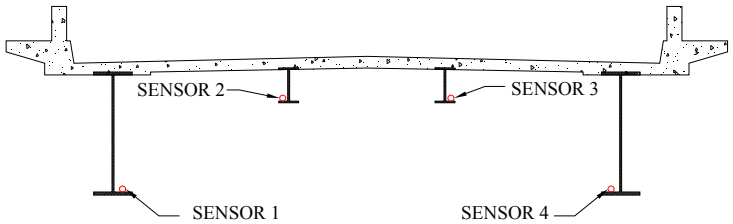


(a) Plan view with sections A and B



(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.

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Courtesy of Measurements Group

Figure 3-5. Low capacity discharge spot welder.

Figure 3-6. Control panel of low capacity discharge spot welder.

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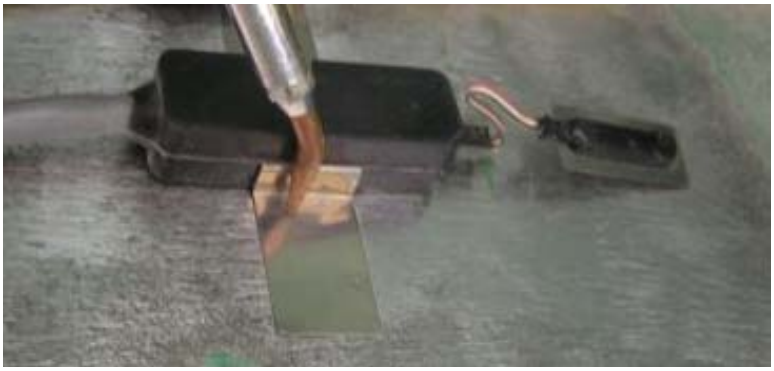

(a) Welding transition tab

(b) Welding gage

(c) Strain gage protected with butyl rubber underneath aluminum foil tape and primer

Figure 3-7. Installation photographs of strain gage.

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

(b) Hardware components inside the cabinet

Figure 3-8. Environmentally controlled cabinet containing the monitoring equipments.

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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 B. The StrainBook/616 data acquisition instrument and the host PC were both connected to the Linksys router with Ethernet cables, creating a local area network that allows direct communication among the hardware components. The network at the bridge site was then, due to fortunate proximity, connected to Iowa State University (ISU) network via wireless communication. For wireless communication between the bridge site and the ISU network, an antenna was mounted on an overhead sign frame that is located at the west end of the bridge as shown in Fig. 3-9 (Note: connection to a network like this is not required). With an Internet connection available, users are able to:

- Access the host PC and operate the SHM system from anywhere in the world.
- Receive processed and reduced data files and/or to be notified of any alarm events via email.

Figure 3-9. Wireless communication equipment installed at the west end of the bridge.

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

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stringers are monitored for changes in behavior. This section demonstrates how overload 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 Fig. 3-10. 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

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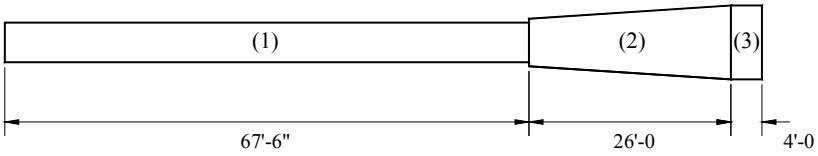
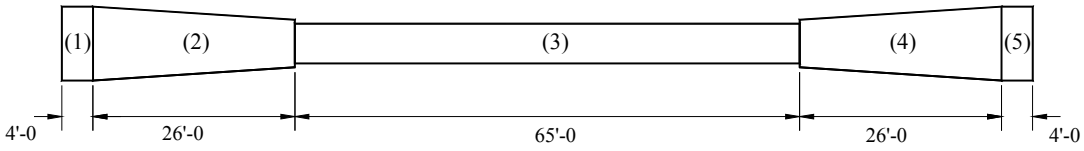
- Plate girder cross section dimensions in the east end span (Span 3)

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

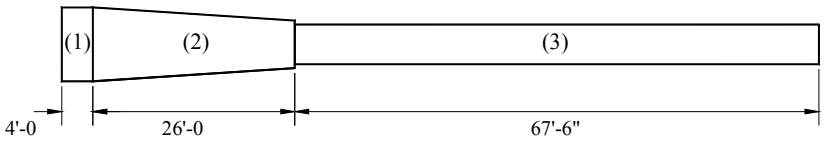
- Distribution factor (DF) and impact allowance (IM) were determined in accordance with the AASHTO Standard Specifications for Highway Bridges, 16th edition [39] to be
  - DF = 2.769
  - IM = 22% for the west end span and 20% for the center span



(a) Span 1



(b) Span 2



(c) Span 3

Figure 3-10. 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

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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 US30 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. As shown in Fig. 3-11, 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 [39]. 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.

Figures 3-12 through 3-24 present the theoretical response of the bridge due to each loading case. The moments and strains for each loading case are plotted as functions of moving truck position (i.e., moment and strain vs. first axle position measured from the left exterior support). Also, 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. Note that, for the HS 20 truck with 3 axles, a notation was utilized to specify the rear axles spacing as shown below:

"HS 20 Truck (3 axles – rear axles spacing)"

where, rear axles spacing ranges from 14 ft to 30 ft.

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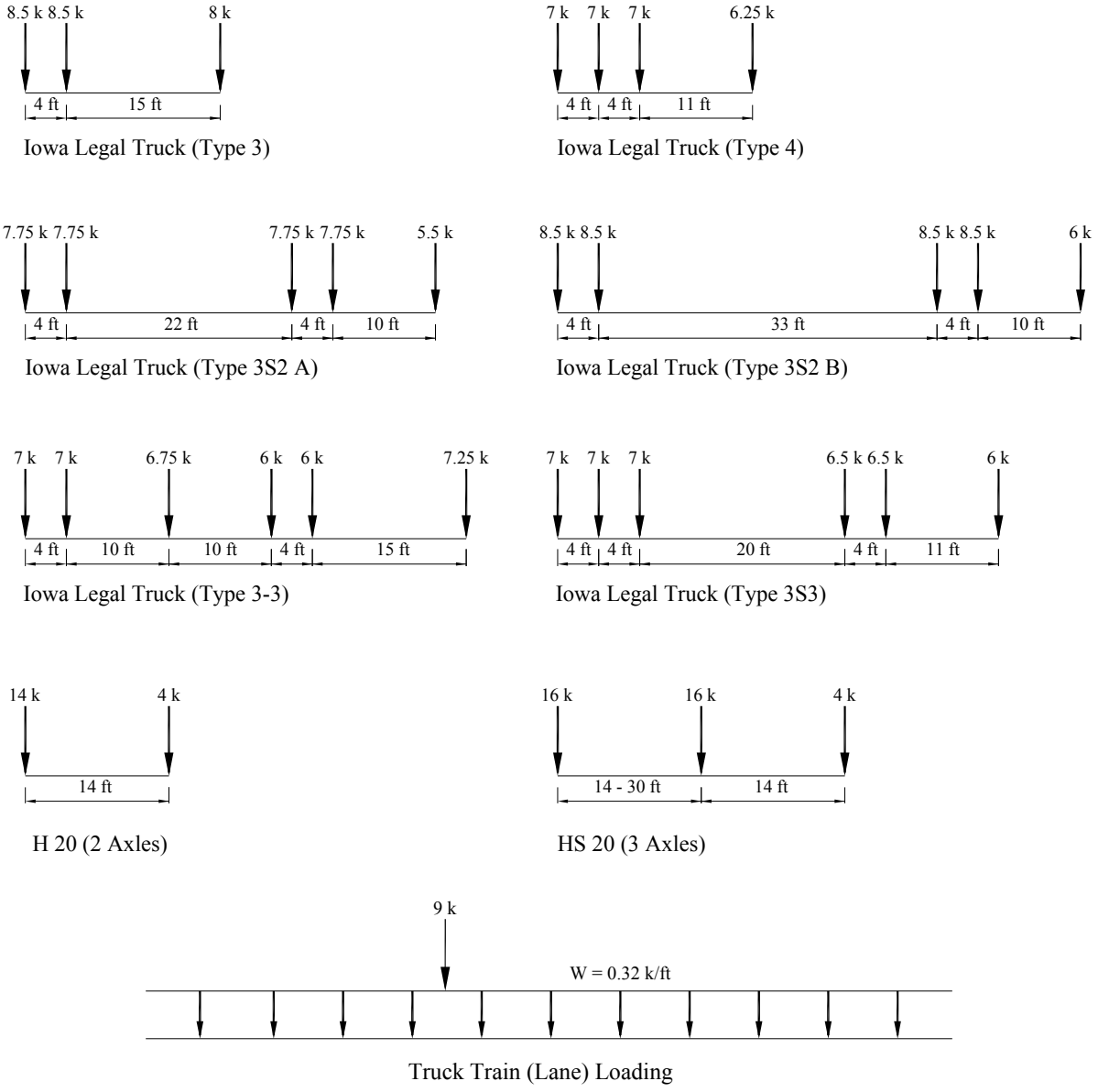

Figure 3-11. Iowa legal, H-20 and HS-20 trucks and truck train loading (wheel line load).

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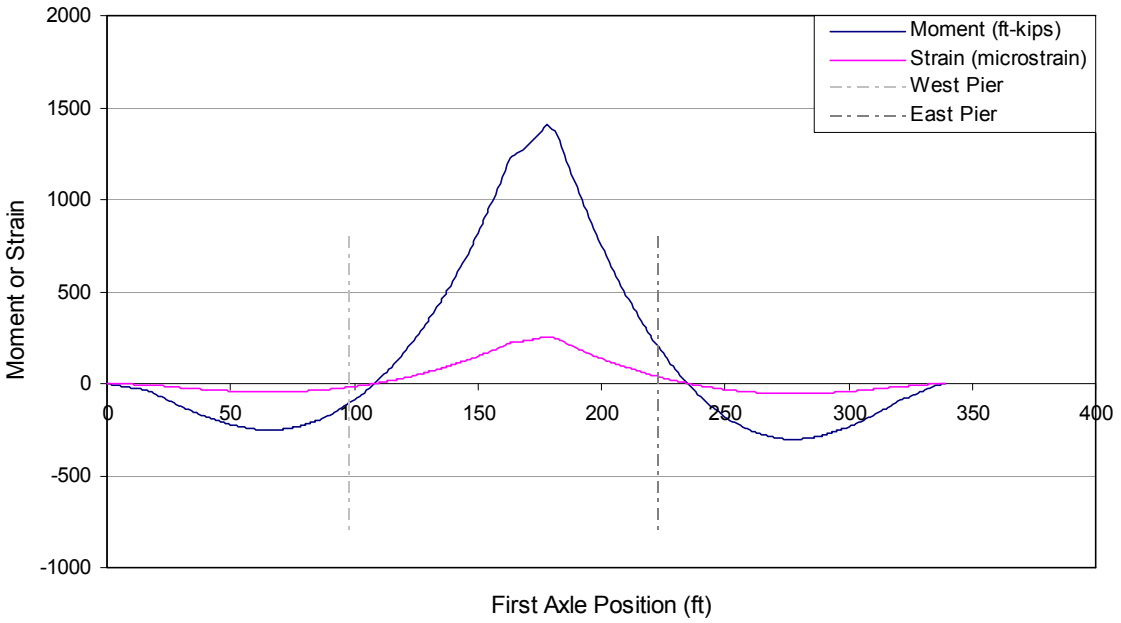
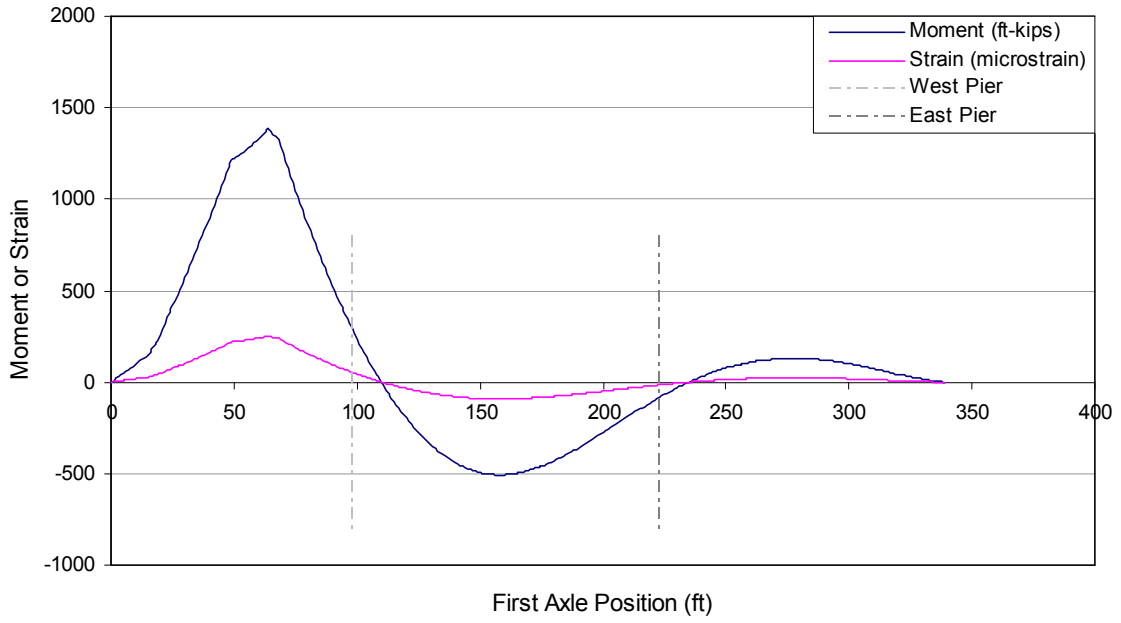


(a) Sensors 1 and 4 in the center span



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

Figure 3-12. Moments and strain due to Iowa legal truck (Type 3) at the sensor locations with respect to the first axle position.

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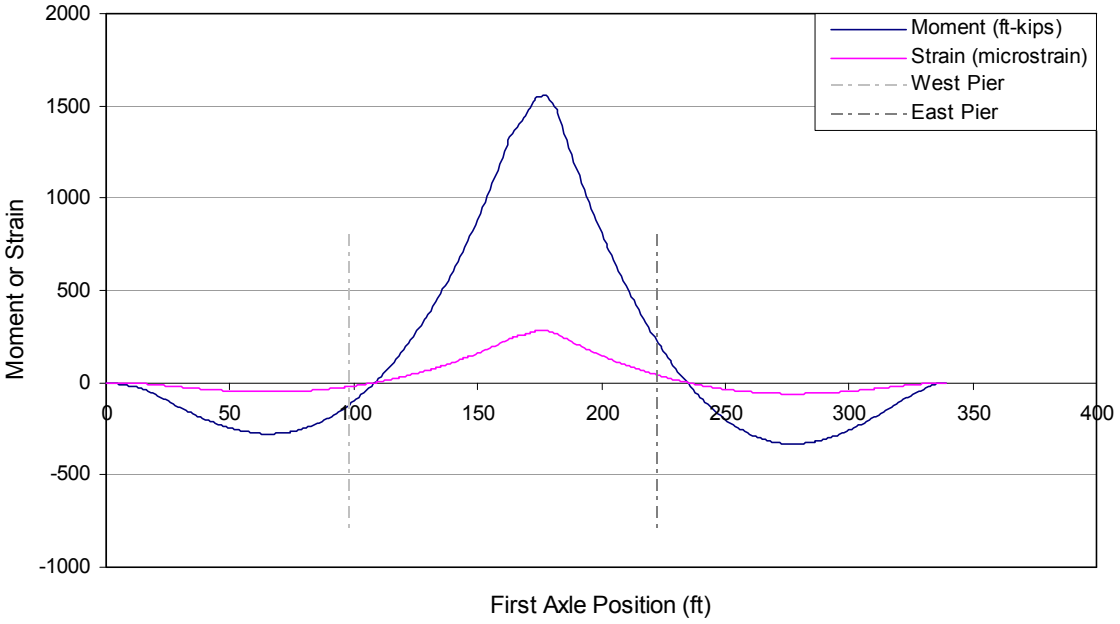
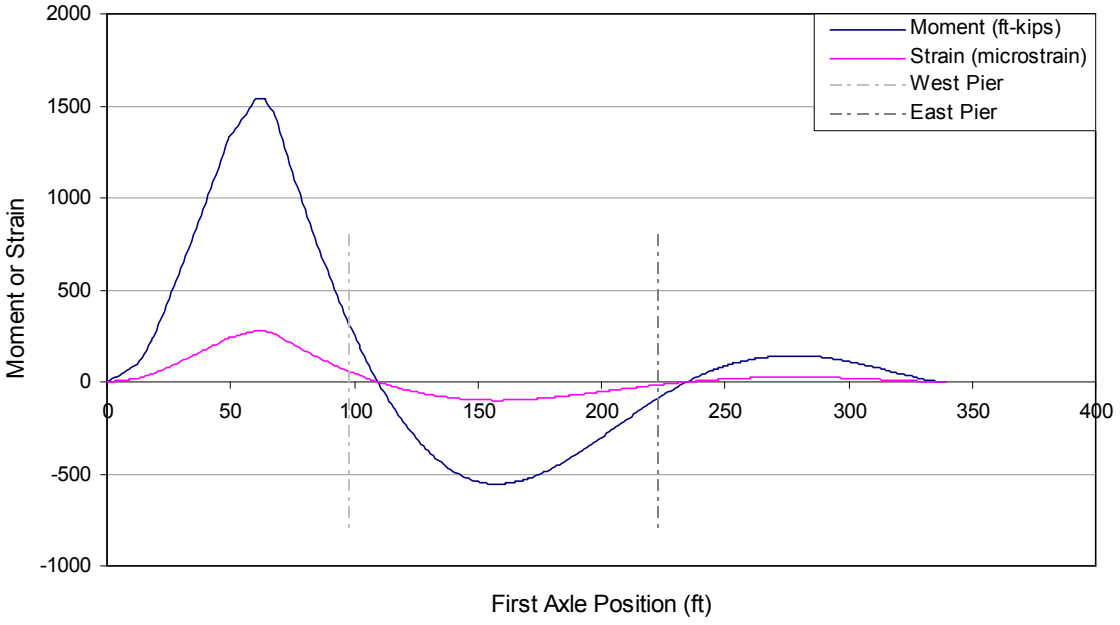


(a) Sensors 1 and 4 in the center span



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

Figure 3-13. Moments and strain due to Iowa legal truck (Type 4) at the sensor locations with respect to the first axle position.

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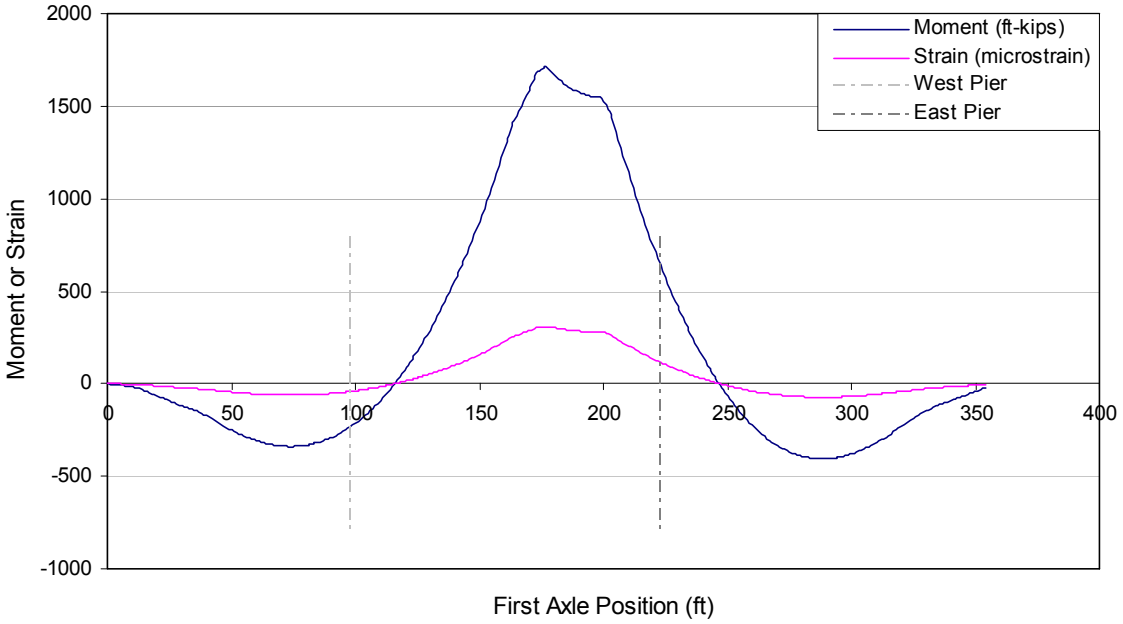
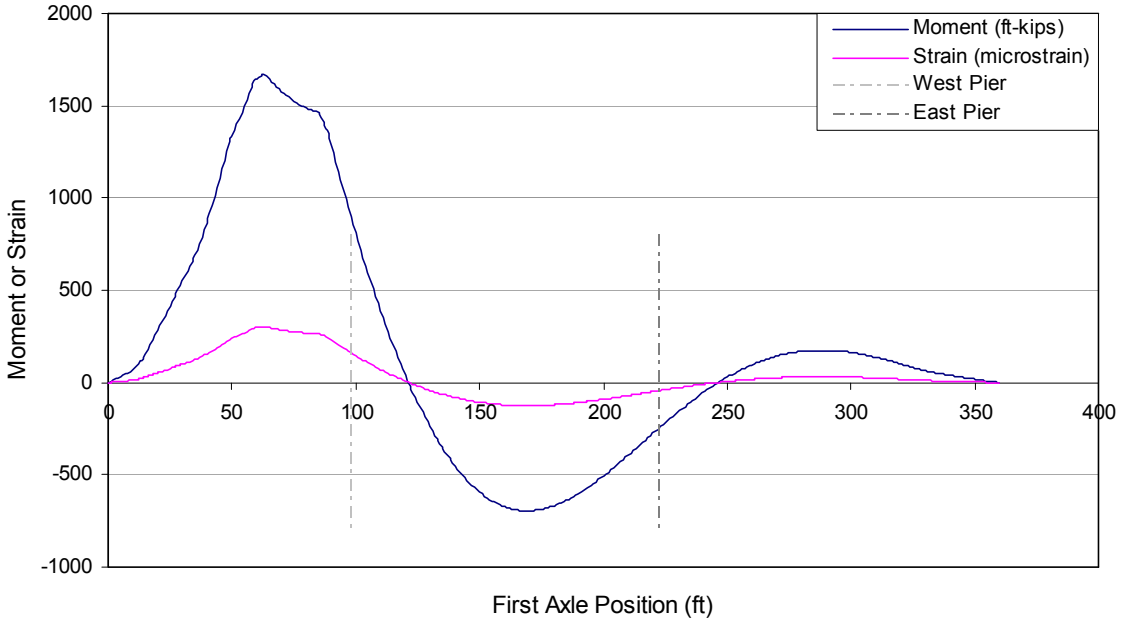


(a) Sensors 1 and 4 in the center span



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

Figure 3-14. Moments and strain due to Iowa legal truck (Type 3S2 A) at the sensor locations with respect to the first axle position.

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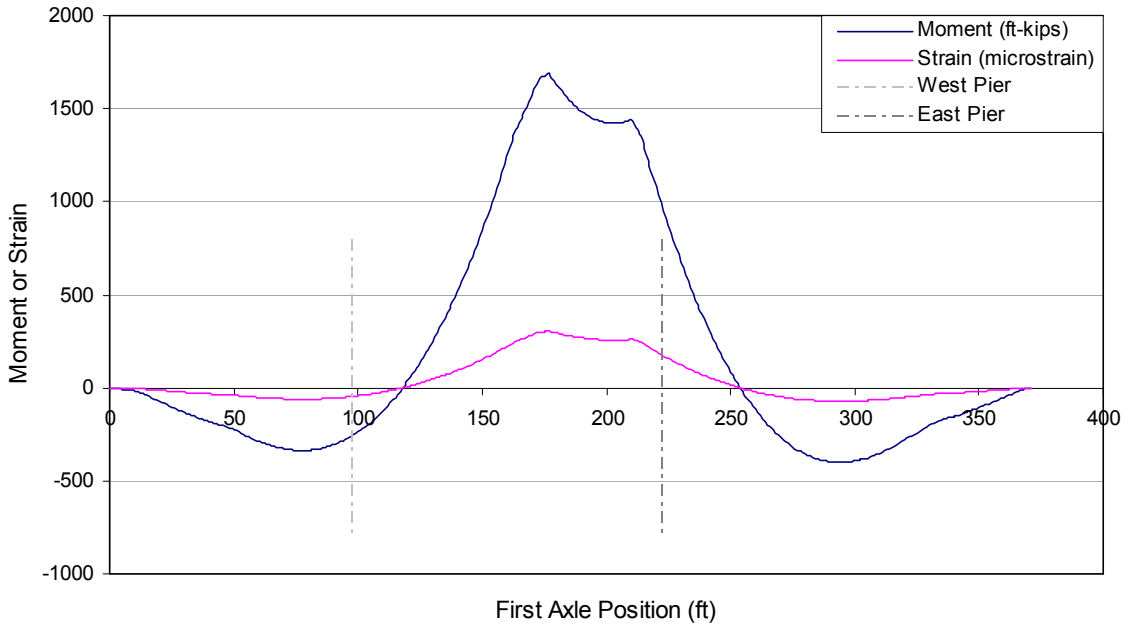
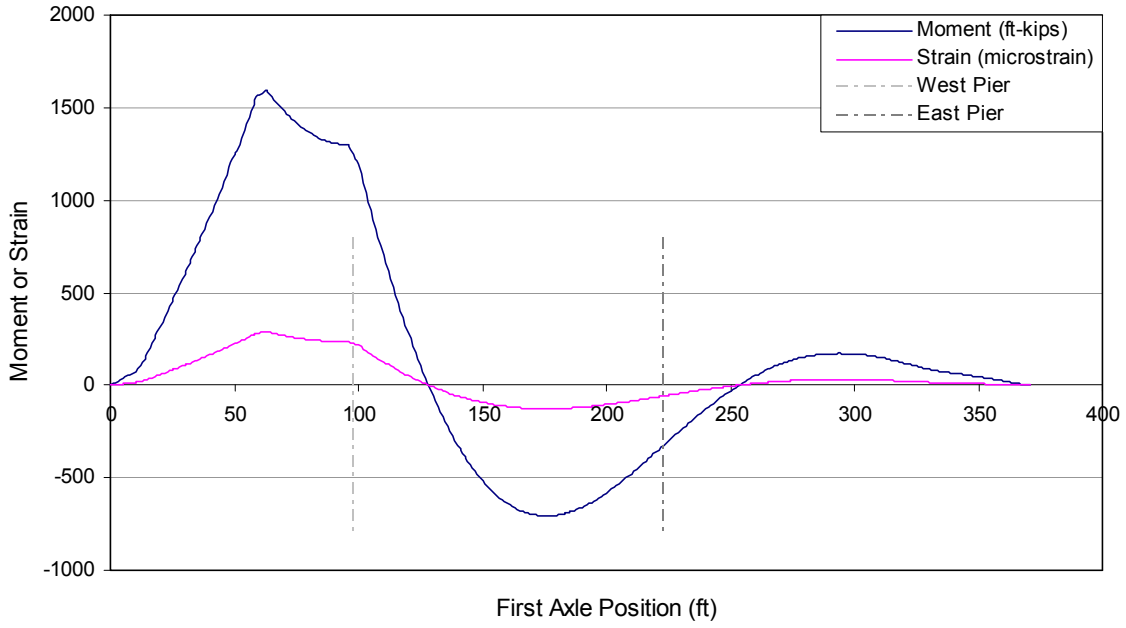


(a) Sensors 1 and 4 in the center span



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

Figure 3-15. Moments and strain due to Iowa legal truck (Type 3S3 B) at the sensor locations with respect to the first axle position.

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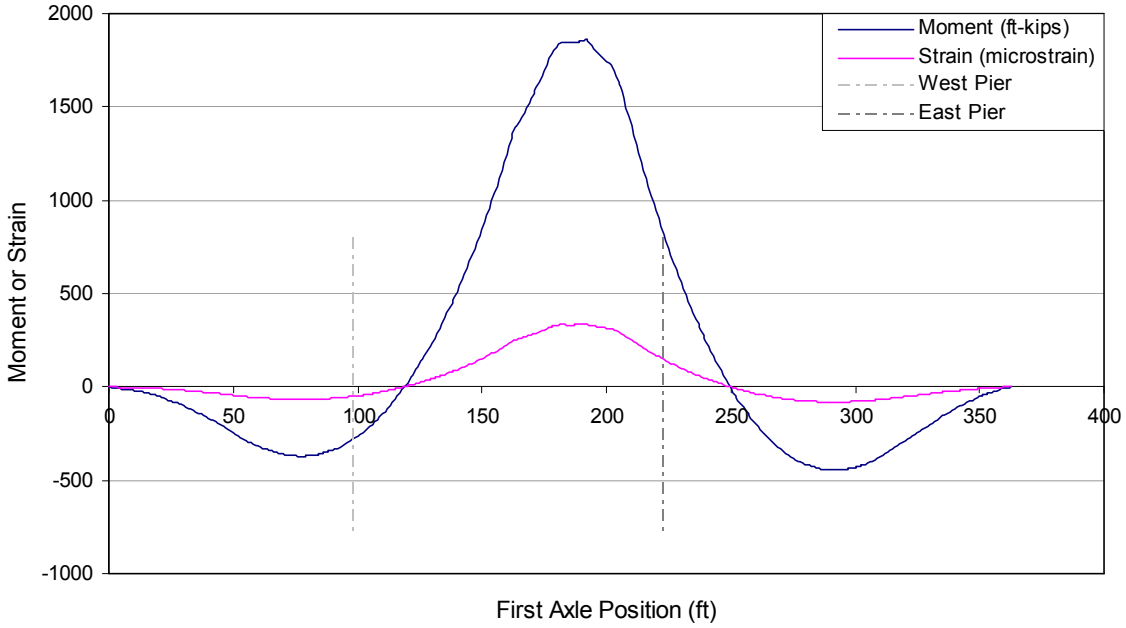
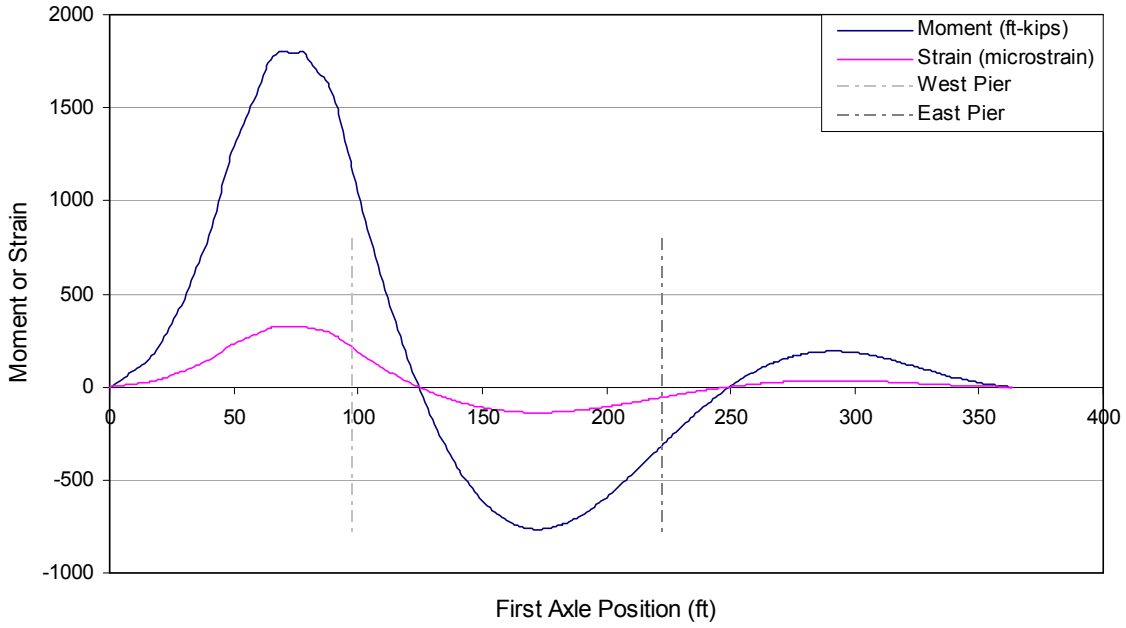


(a) Sensors 1 and 4 in the center span



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

Figure 3-16. Moments and strain due to Iowa legal truck (Type 3-3) at the sensor locations with respect to the first axle position.

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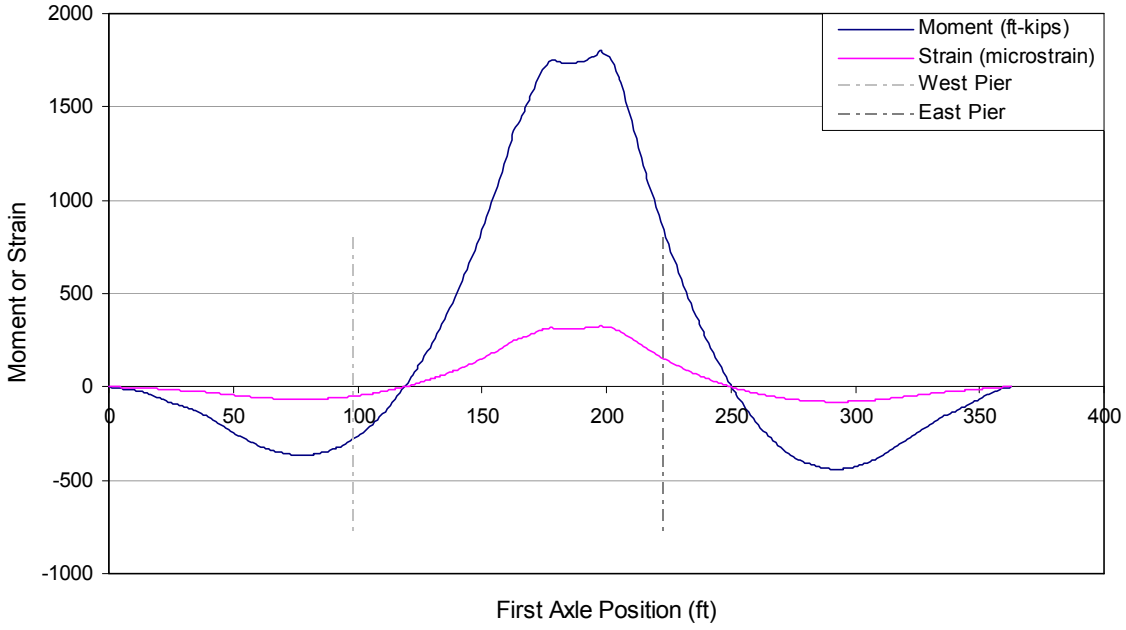
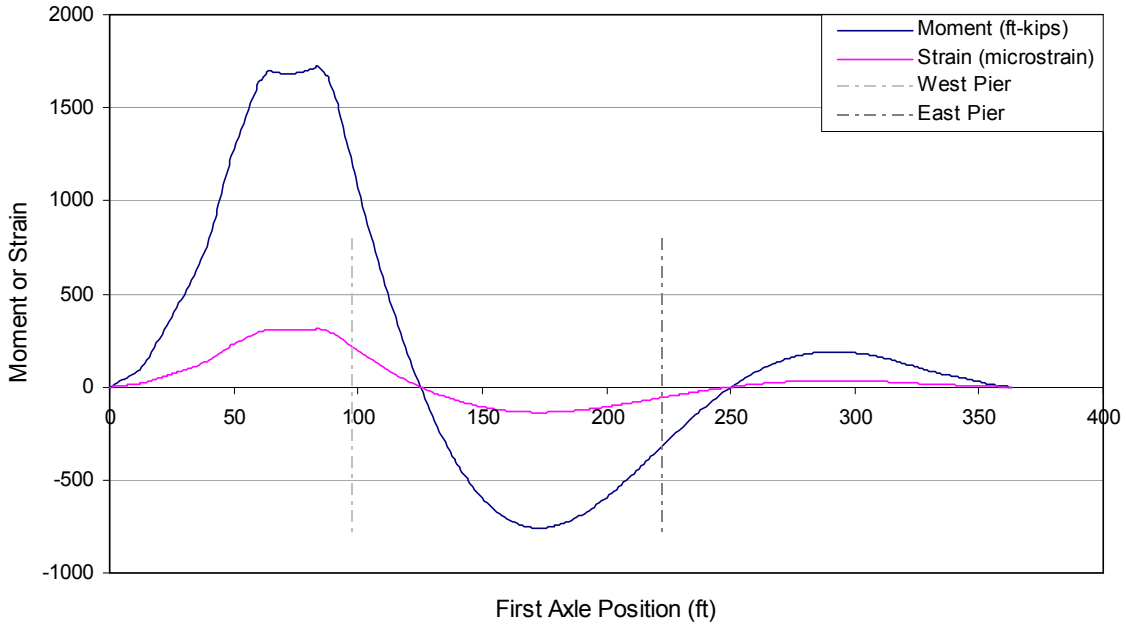


(a) Sensors 1 and 4 in the center span



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

Figure 3-17. Moments and strain due to Iowa legal truck (Type 3S3) at the sensor locations with respect to the first axle position.

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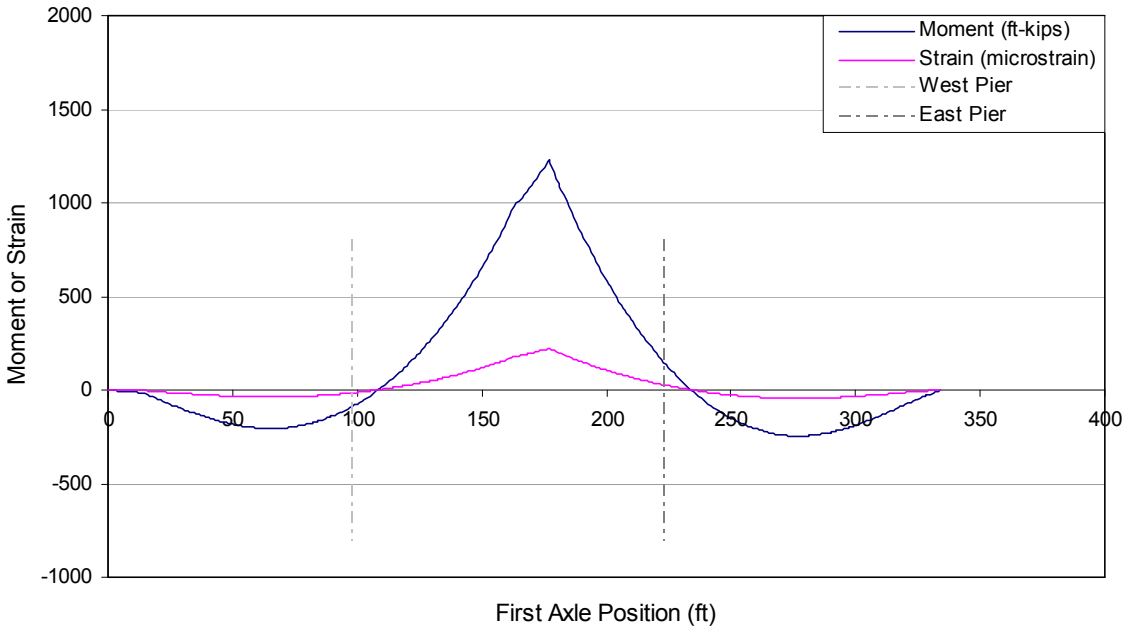
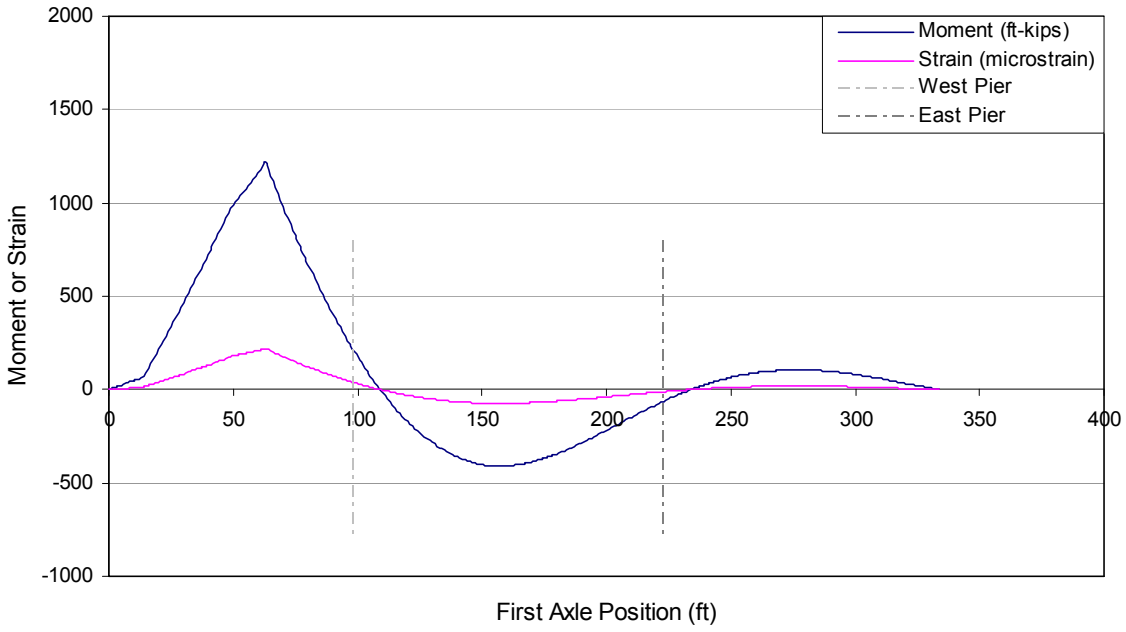


(a) Sensors 1 and 4 in the center span



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

Figure 3-18. Moments and strain due to H 20 truck (2 axles) at the sensor locations with respect to the first axle position.

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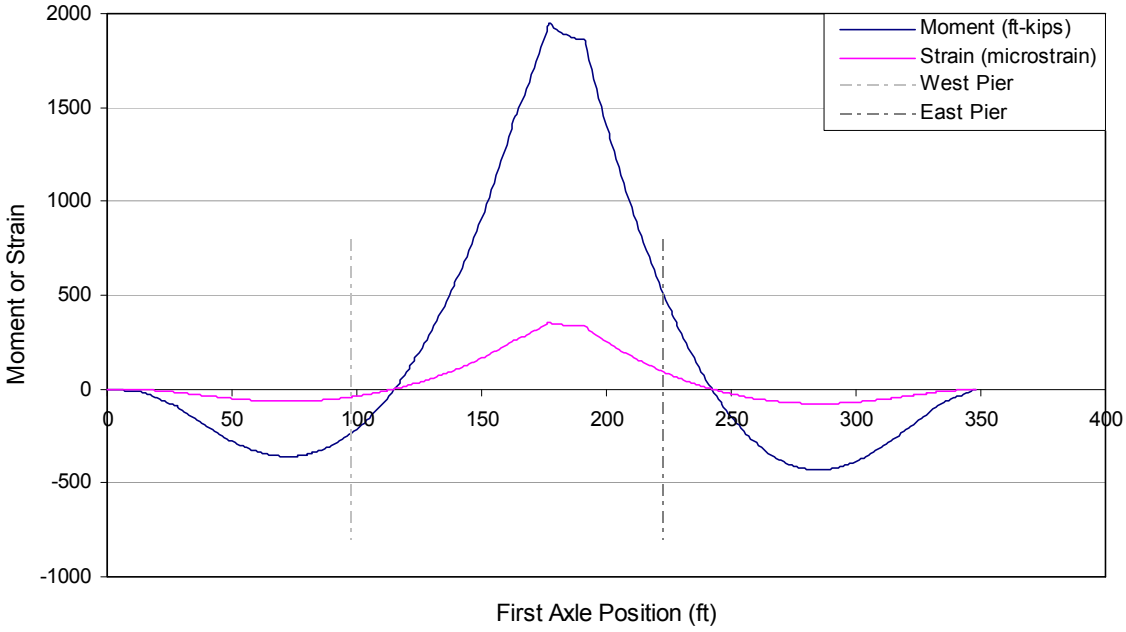
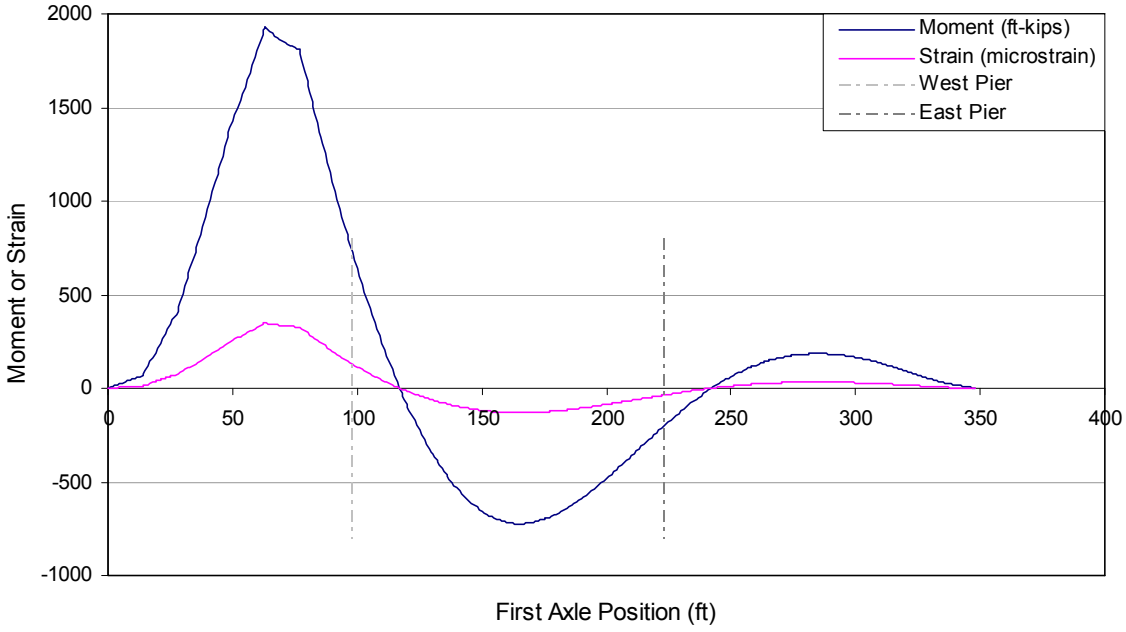


(a) Sensors 1 and 4 in the center span



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

Figure 3-19. Moments and strain due to HS 20 truck (3 axles – 14 ft) at the sensor locations with respect to the first axle position.

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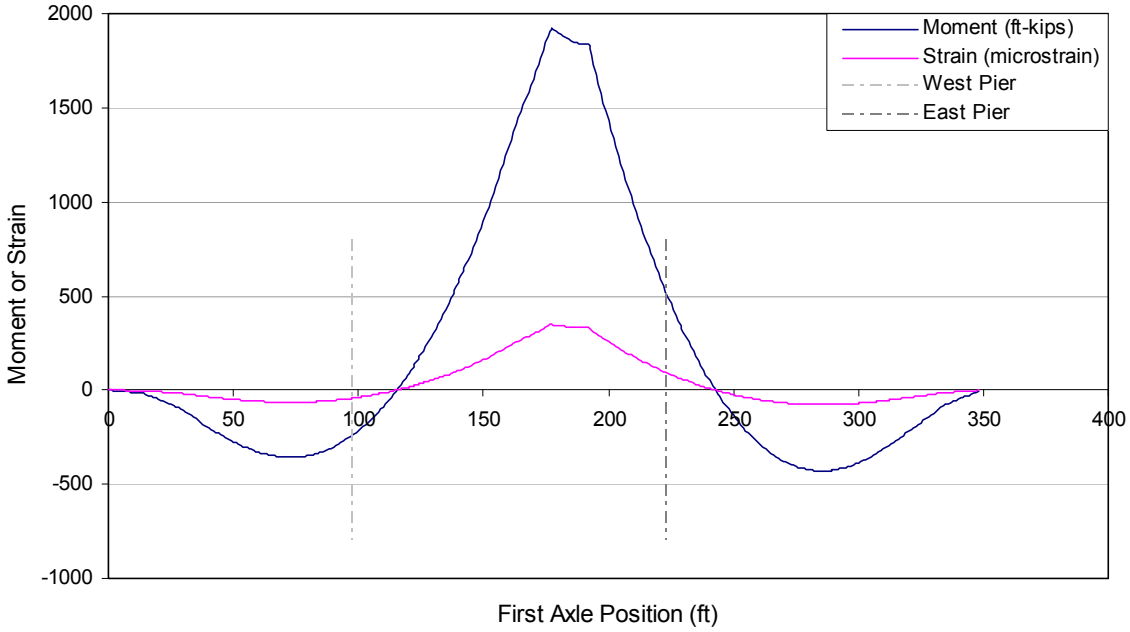
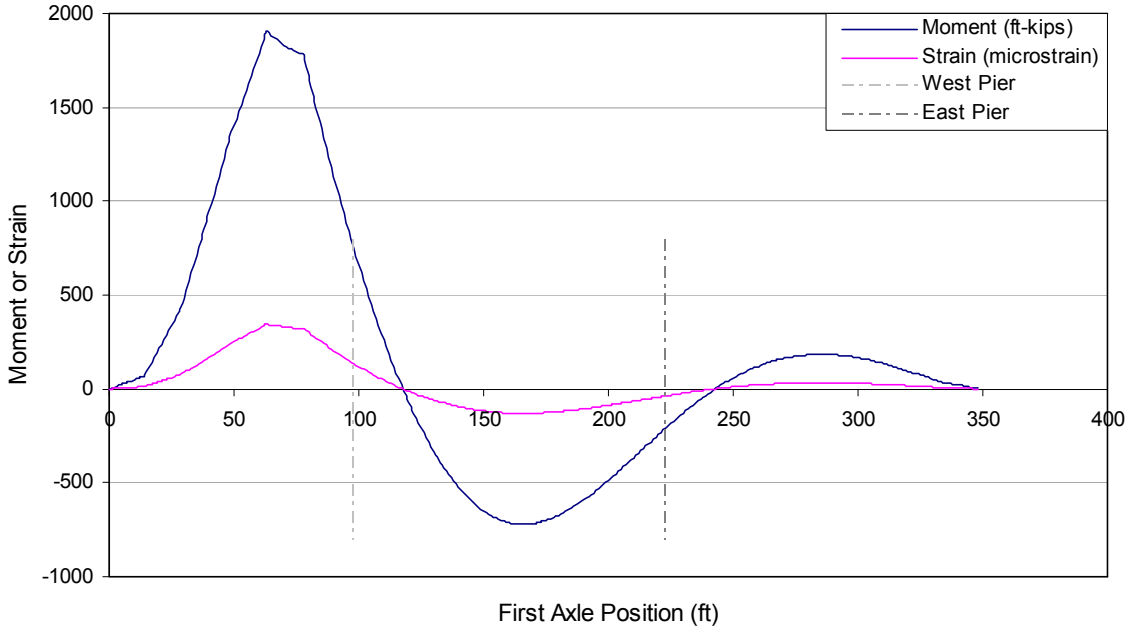


(a) Sensors 1 and 4 in the center span



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

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

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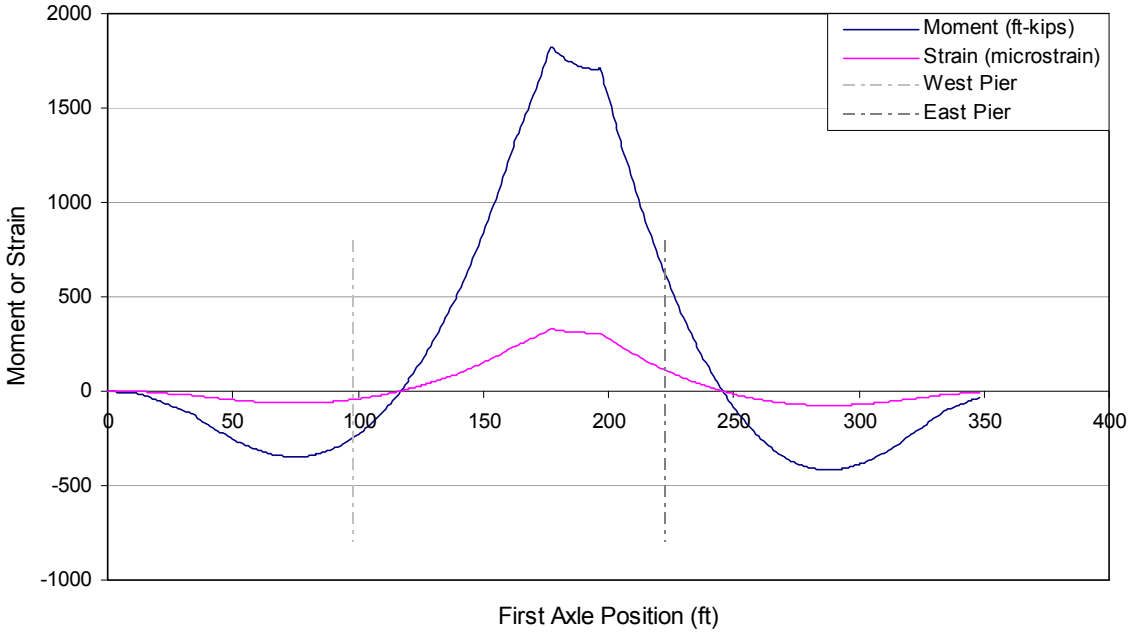
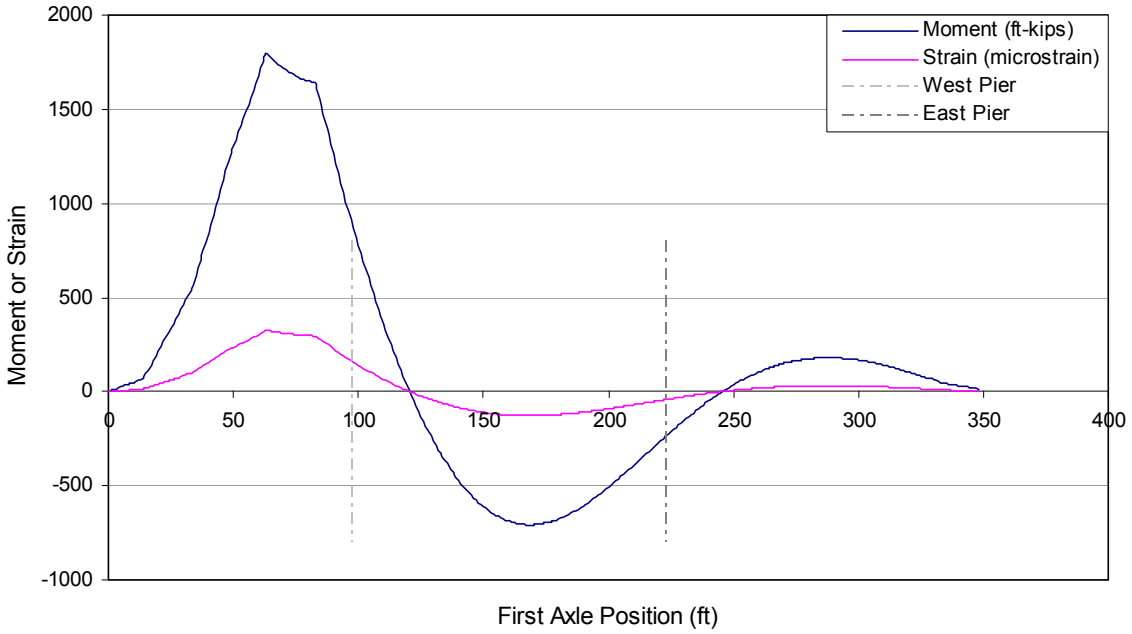


(a) Sensors 1 and 4 in the center span



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

Figure 3-21. Moments and strain due to HS 20 truck (3 axles – 20 ft) at the sensor locations with respect to the first axle position.

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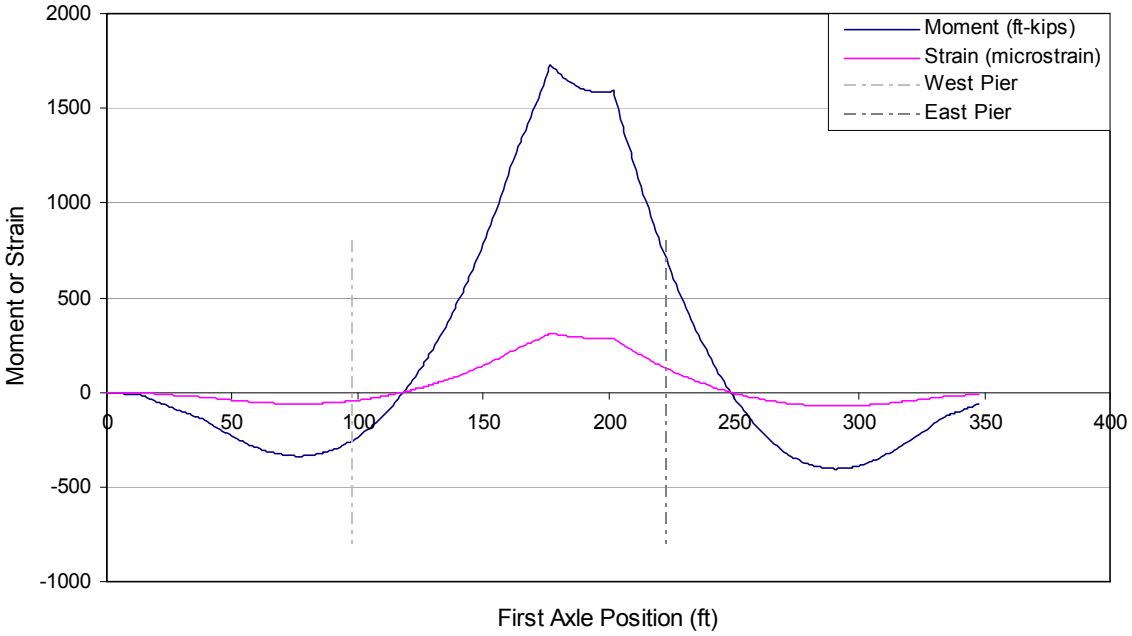
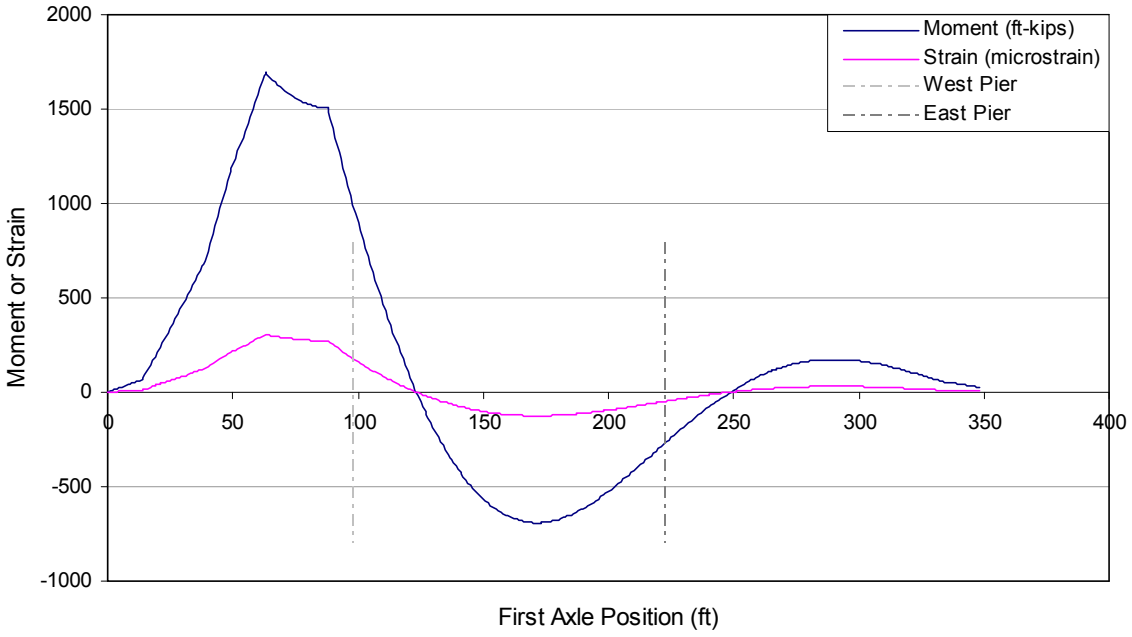


(a) Sensors 1 and 4 in the center span



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

Figure 3-22. Moments and strain due to HS 20 truck (3 axles – 25 ft) at the sensor locations with respect to the first axle position.

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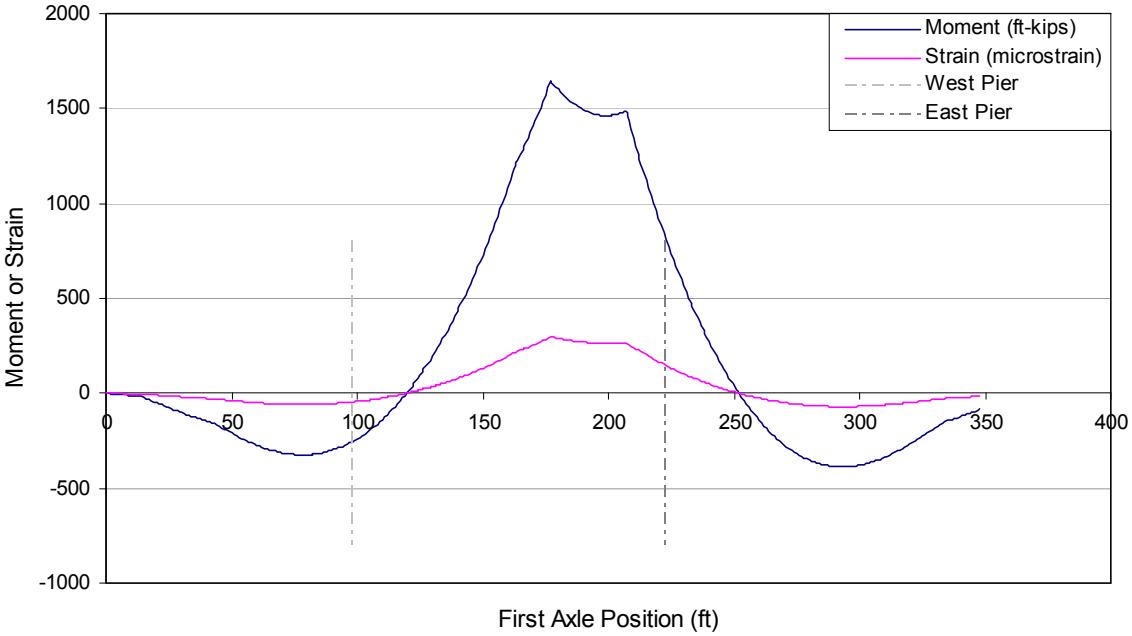
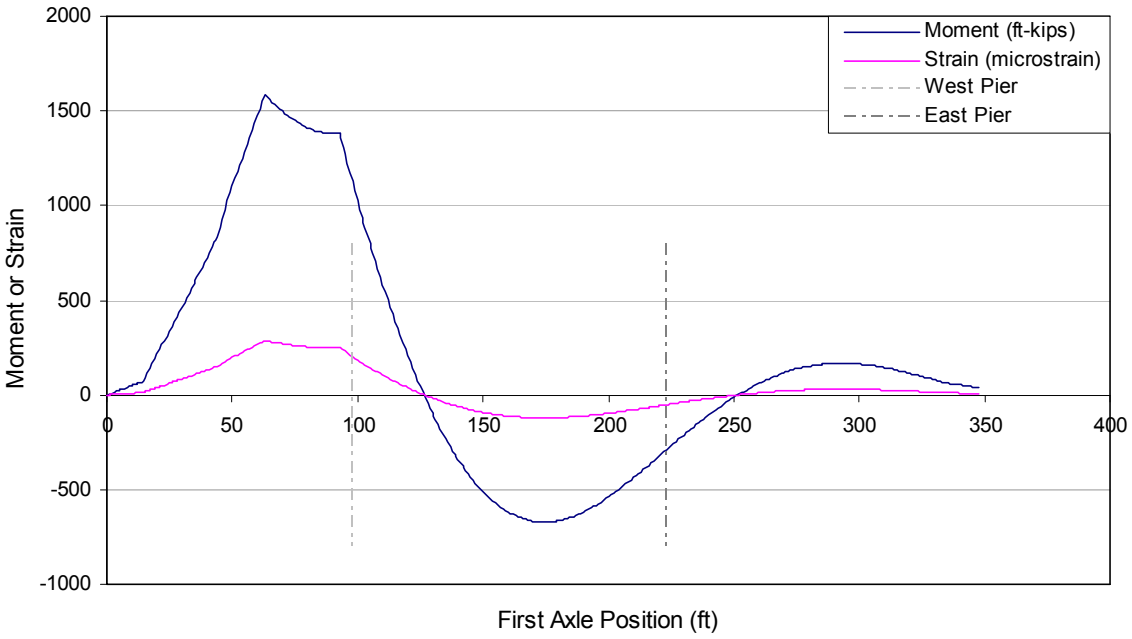


(a) Sensors 1 and 4 in the center span



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

Figure 3-23. Moments and strain due to HS 20 truck (3 axles – 30 ft) at the sensor locations with respect to the first axle position.

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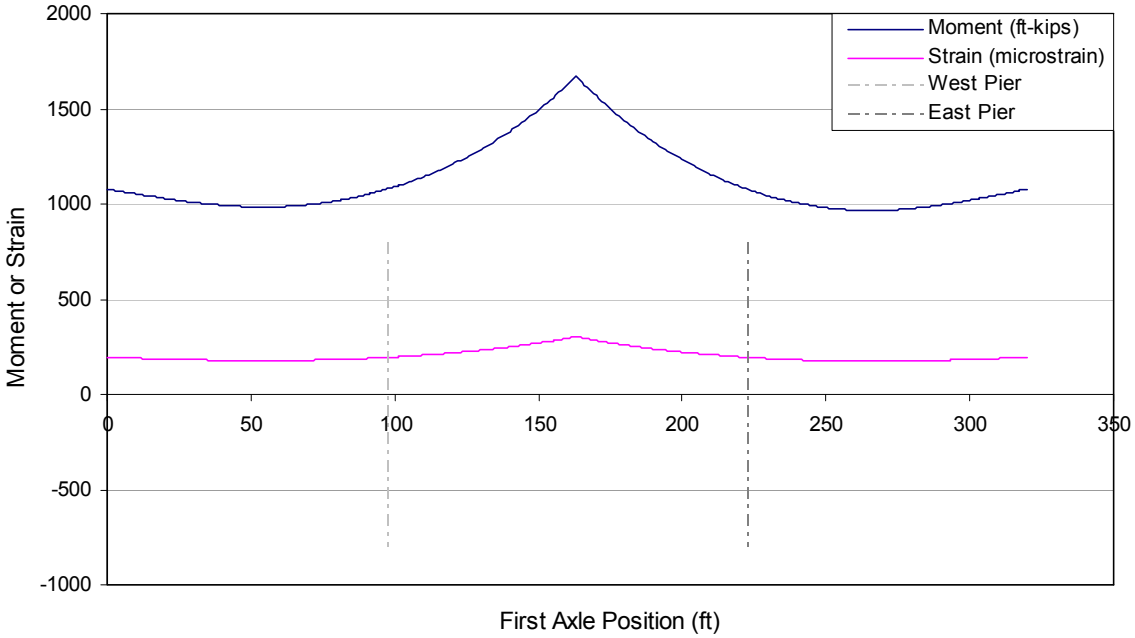
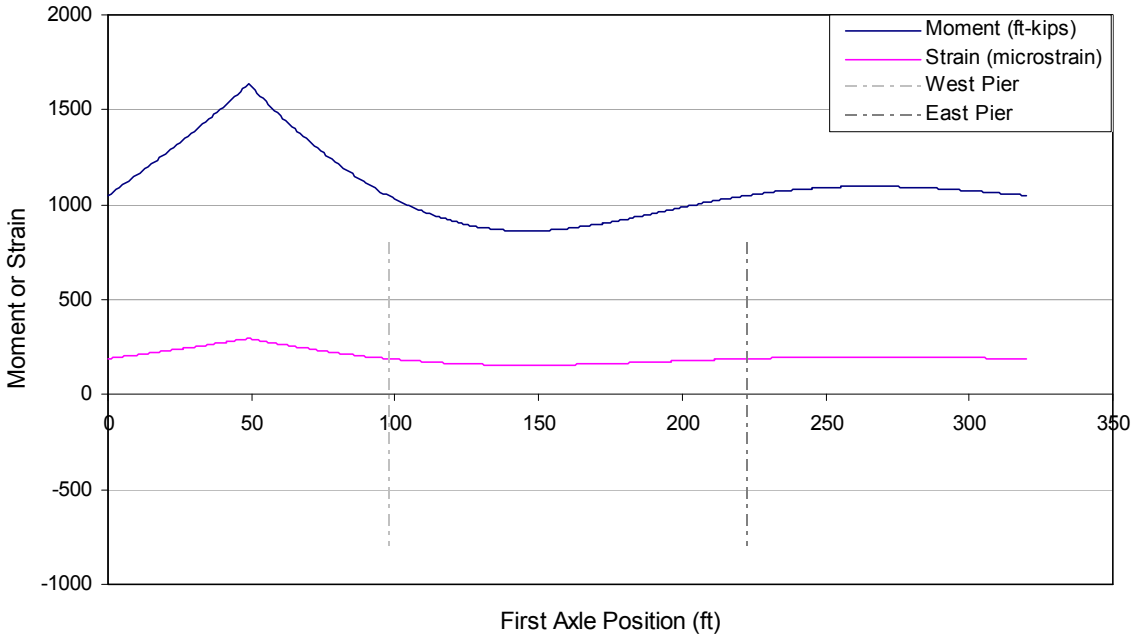


(a) Sensors 1 and 4 in the center span



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

Figure 3-24. Moments and strain due to truck train (lane) loading at the sensor locations with respect to the first axle position.

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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

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After the moment and strain plots were generated for each load case with *BEC Analysis*, general observations were made. When comparing the load cases with the same gross weight but different overall distance within the moving trucks (i.e., HS 20 trucks (3 axles – 14 ft) vs. (3 axles – 30 ft); Iowa legal trucks Types 3S2 B vs. 3-3), larger absolute maximum moments and strains were generated from the trucks with shorter overall lengths. This indicates that the vehicles with essentially identical gross weight but different axle configuration could generate different strain measurements. Note that the response in the moment and strain history for the lane load does not start/end from/to zero while all other cases do. This can be attributed to the effect of the uniformly distributed loads that are applied in span(s) of the bridge.

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 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.

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 computation as well as other structural analysis software such as QConBridge and STAAD.Pro. Only the validation checks performed with STAAD.Pro, in which the US30 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 Fig. 3-10.

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

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generated by *BEC Analysis*. The input files used in STAAD.Pro for the validation checks are presented in Appendix H.

The graphical representations of the results obtained by running *BEC Analysis* and those by STAAD.Pro are shown in Figs. 3-25 through 3-30. 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*.

3.4. FIELD MONITORING SOFTWARE DEMONSTRATION

This section summarizes how the field monitoring software was set up and used for the US30 bridge. Additionally, sample evaluation reports for the US30 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 are those resulting from ambient traffic only. The effect of the 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 Figs. 3-31 and 3-32 are the resulting PSD plots that illustrated frequency contents within the measured strain recorded with and without traffic, respectively.

From Fig. 3-31, 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 Fig. 3-32, 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.

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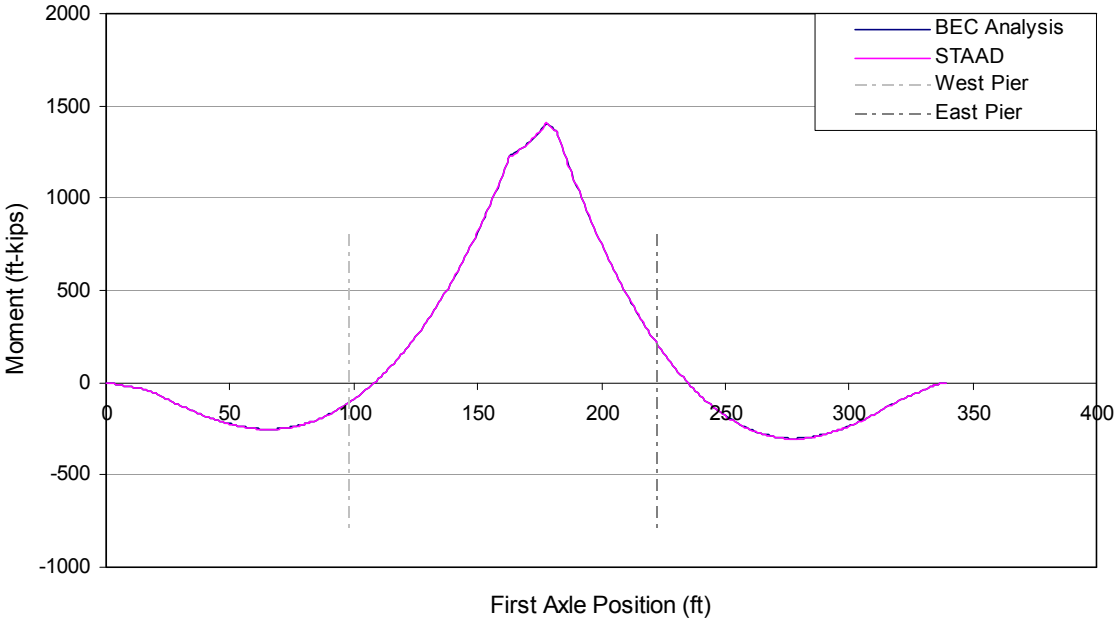
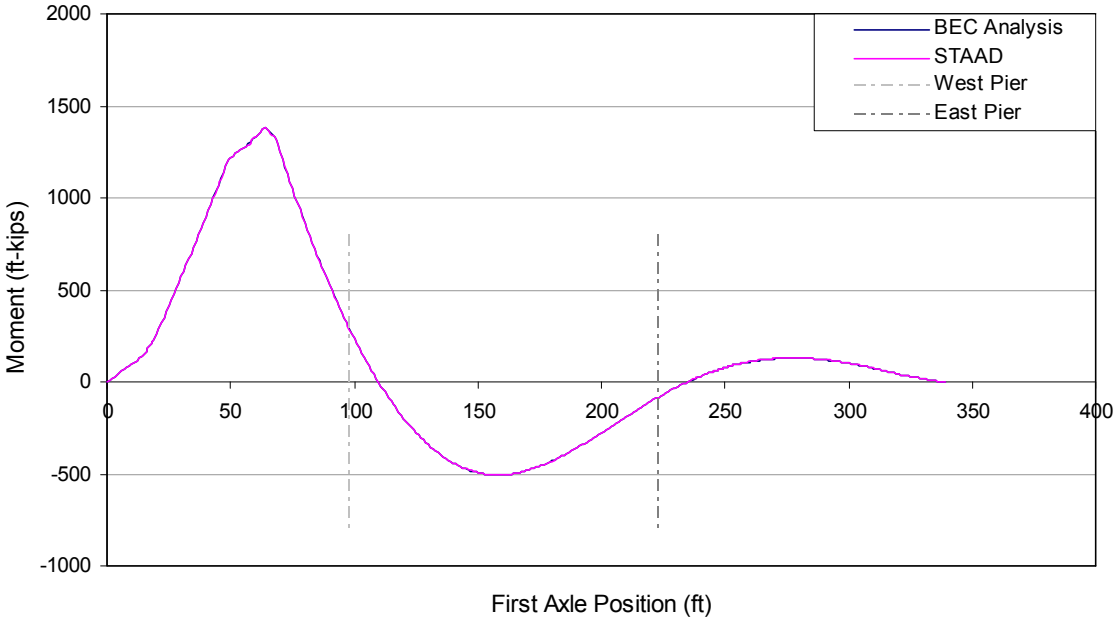


(a) Sensors 1 and 4 in the center span



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

Figure 3-25. Analytical moments due to Iowa legal truck (Type 3) at the sensor locations with respect to the first axle position.

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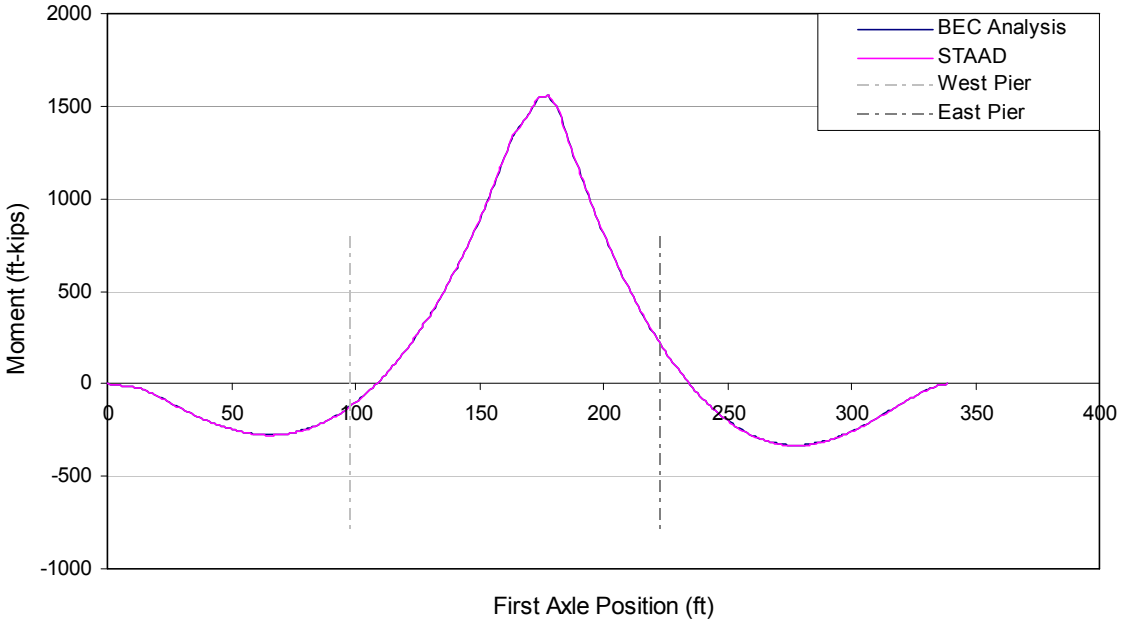
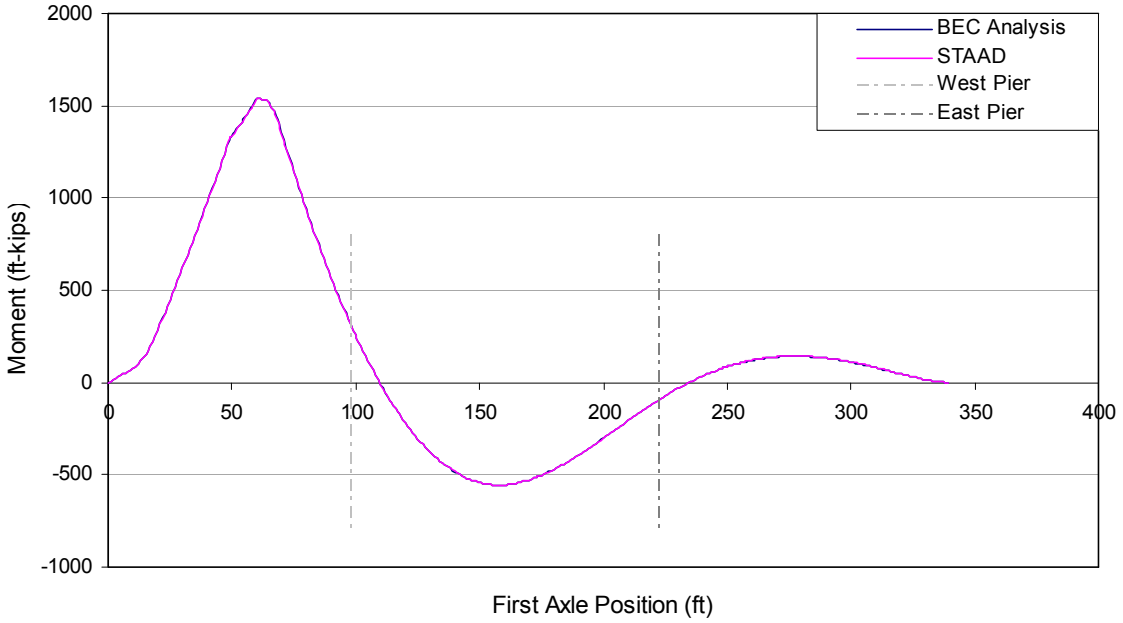


(a) Sensors 1 and 4 in the center span



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

Figure 3-26. Analytical moments due to Iowa legal truck (Type 4) at the sensor locations with respect to the first axle position.

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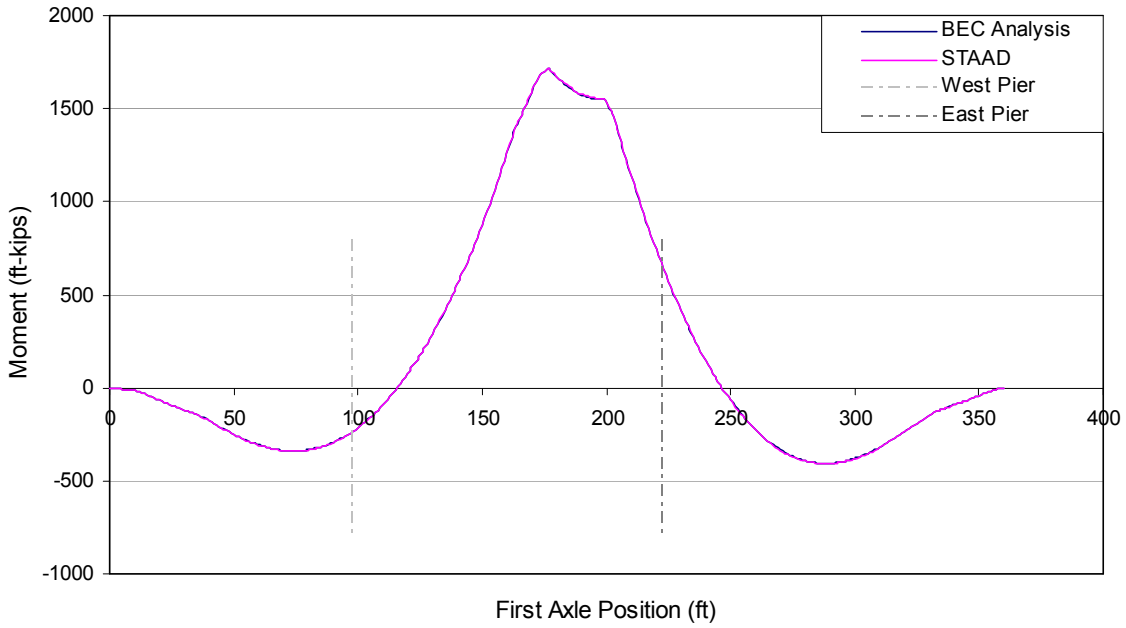
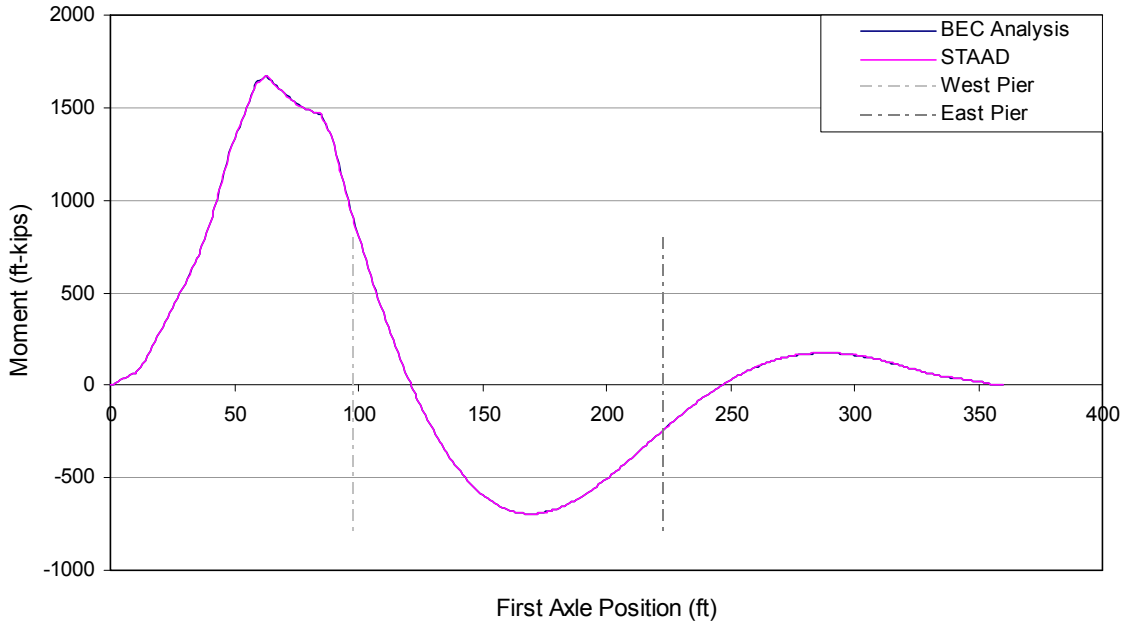


(a) Sensors 1 and 4 in the center span



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

Figure 3-27. Analytical moments due to Iowa legal truck (Type 3S2 A) at the sensor locations with respect to the first axle position.

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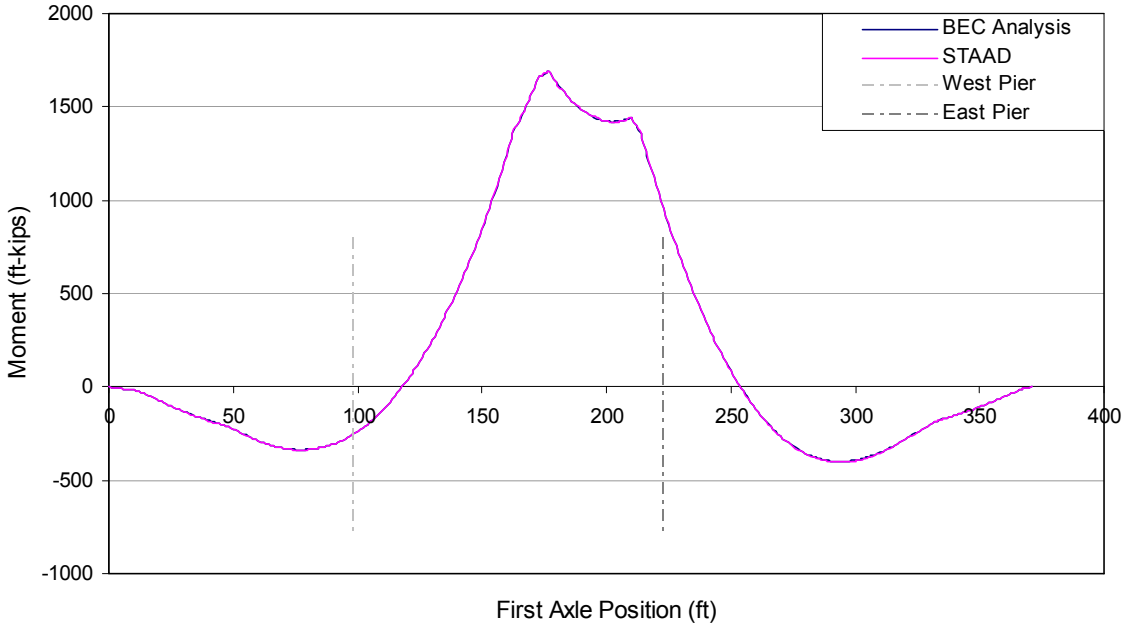
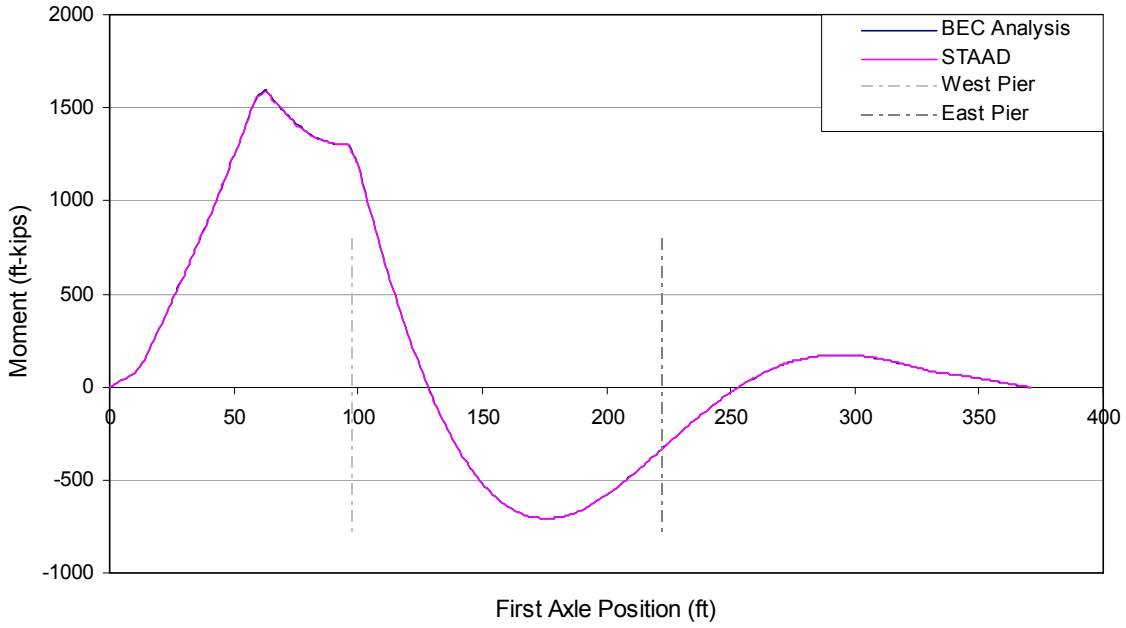


(a) Sensors 1 and 4 in the center span



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

Figure 3-28. Analytical moments due to Iowa legal truck (Type 3S2 B) at the sensor locations with respect to the first axle position.

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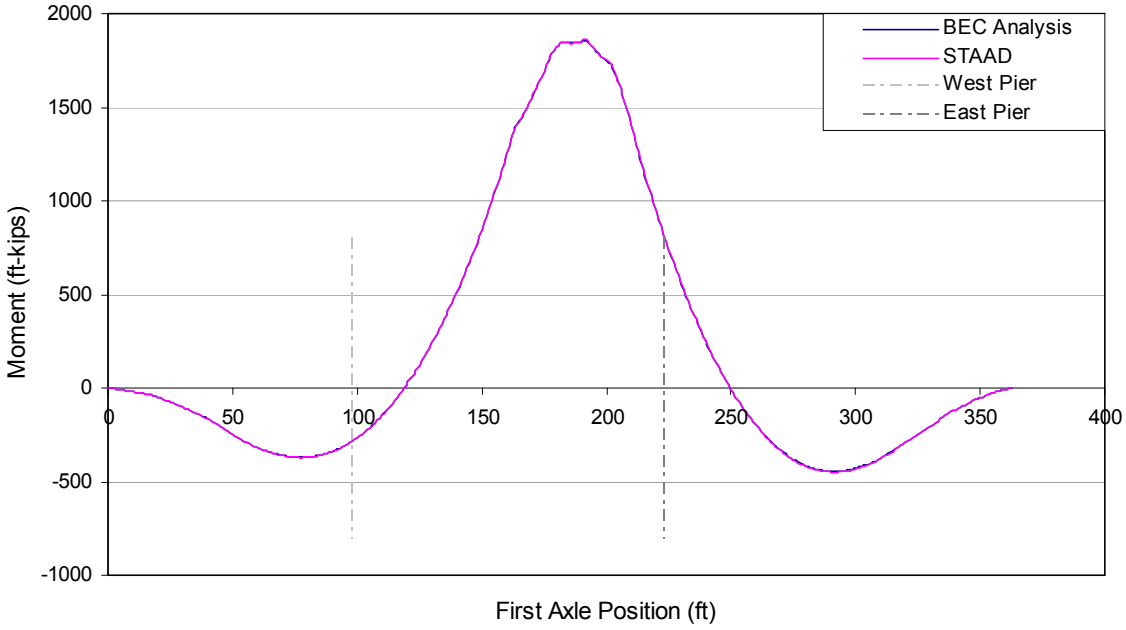
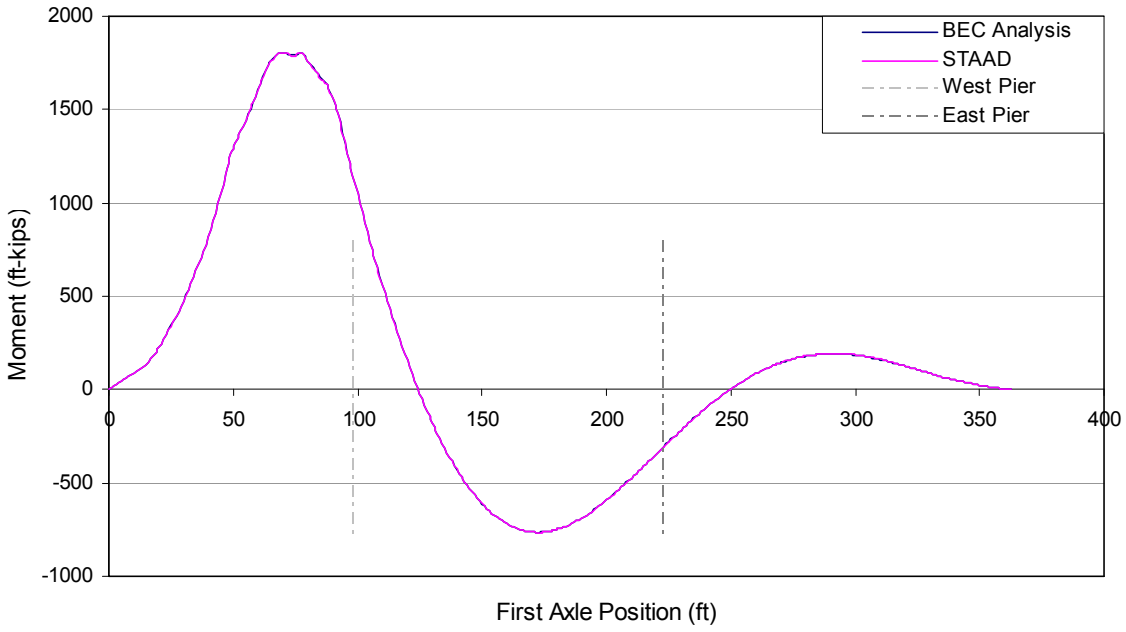


(a) Sensors 1 and 4 in the center span



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

Figure 3-29. Analytical moments due to Iowa legal truck (Type 3-3) at the sensor locations with respect to the first axle position.

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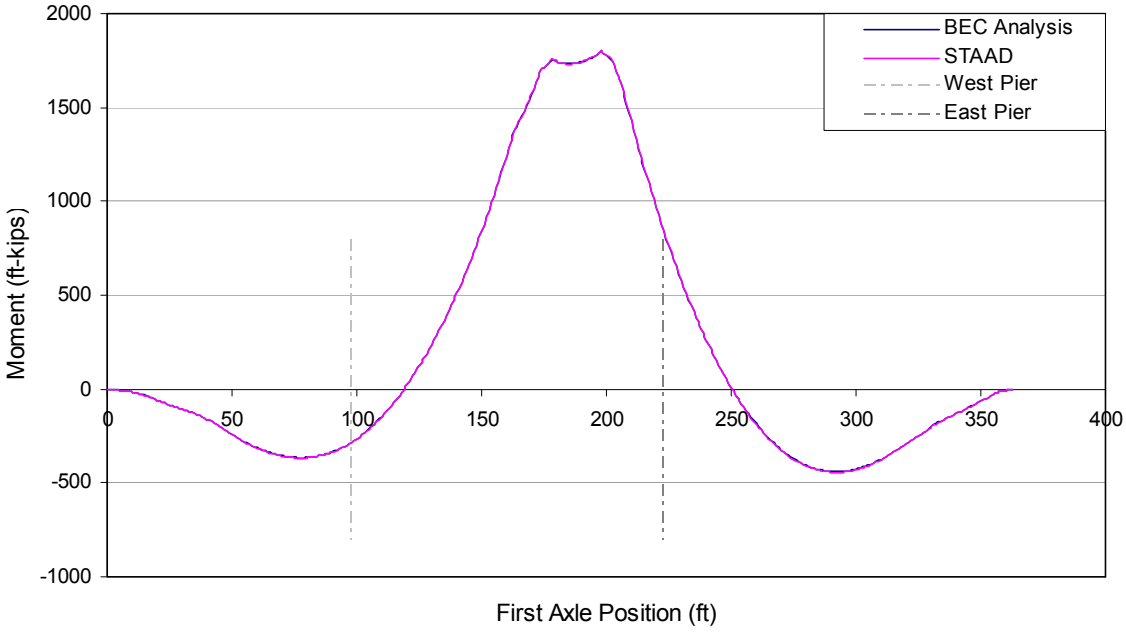
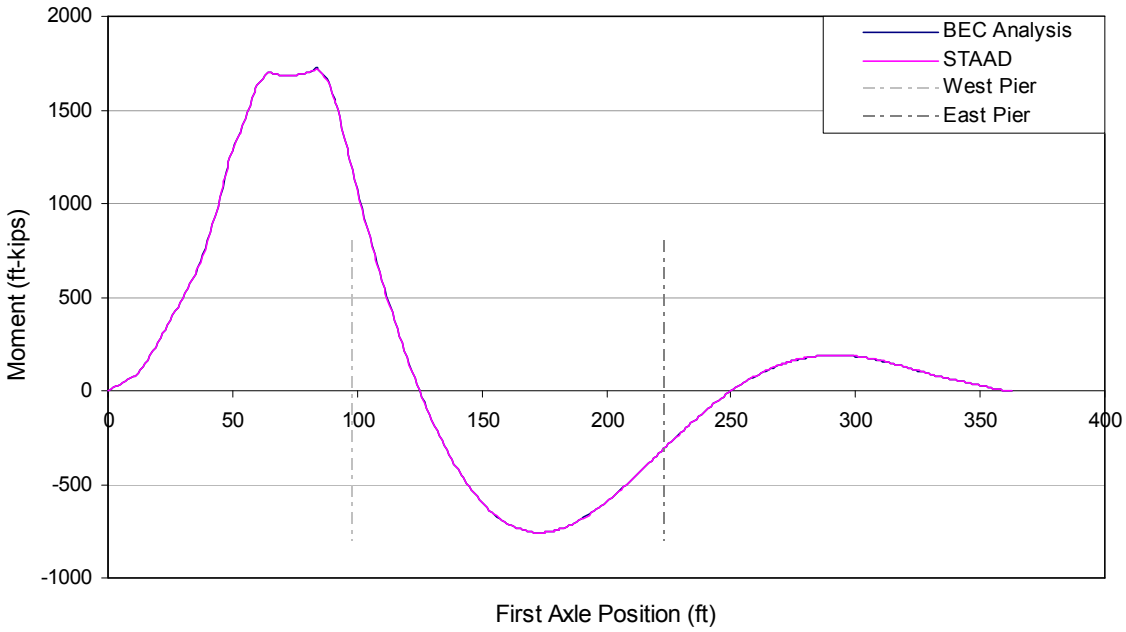


(a) Sensors 1 and 4 in the center span



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

Figure 3-30. Analytical moments due to Iowa legal truck (Type 3S3) at the sensor locations with respect to the first axle position.

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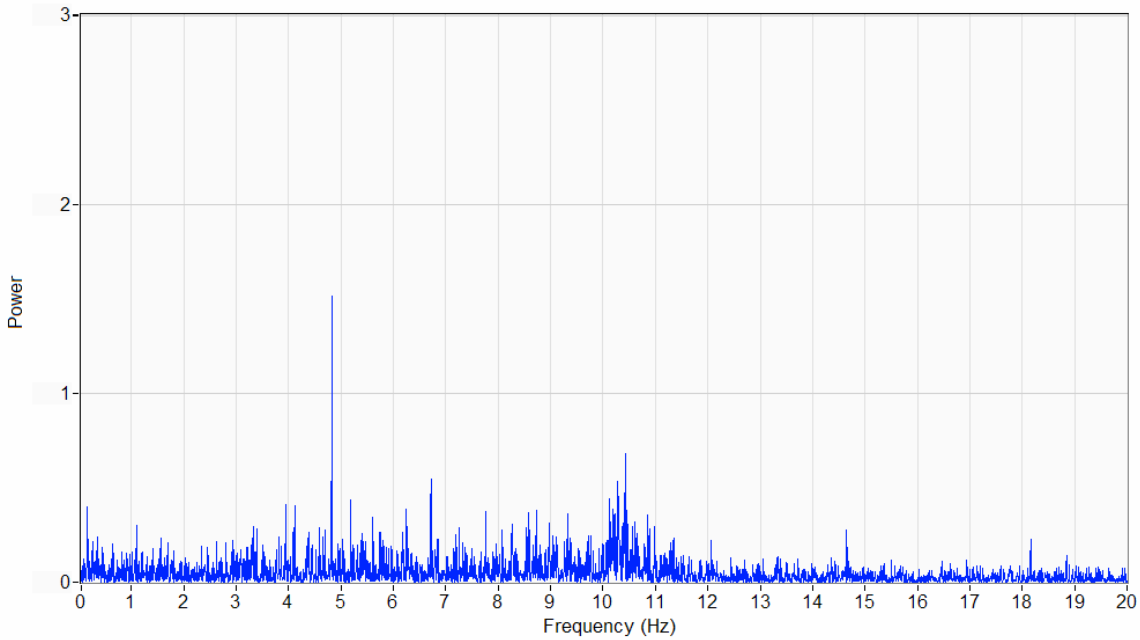
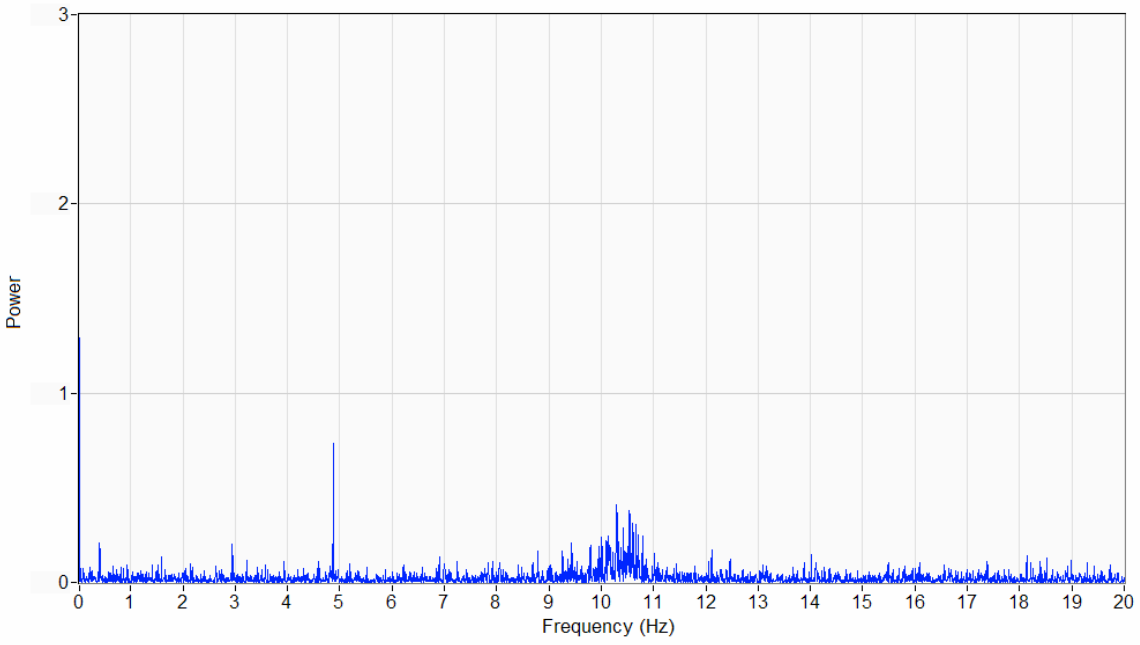


(a) Sensor 1



(b) Sensor 2

Figure 3-31. PSD plot from sample data with no traffic on the bridge.

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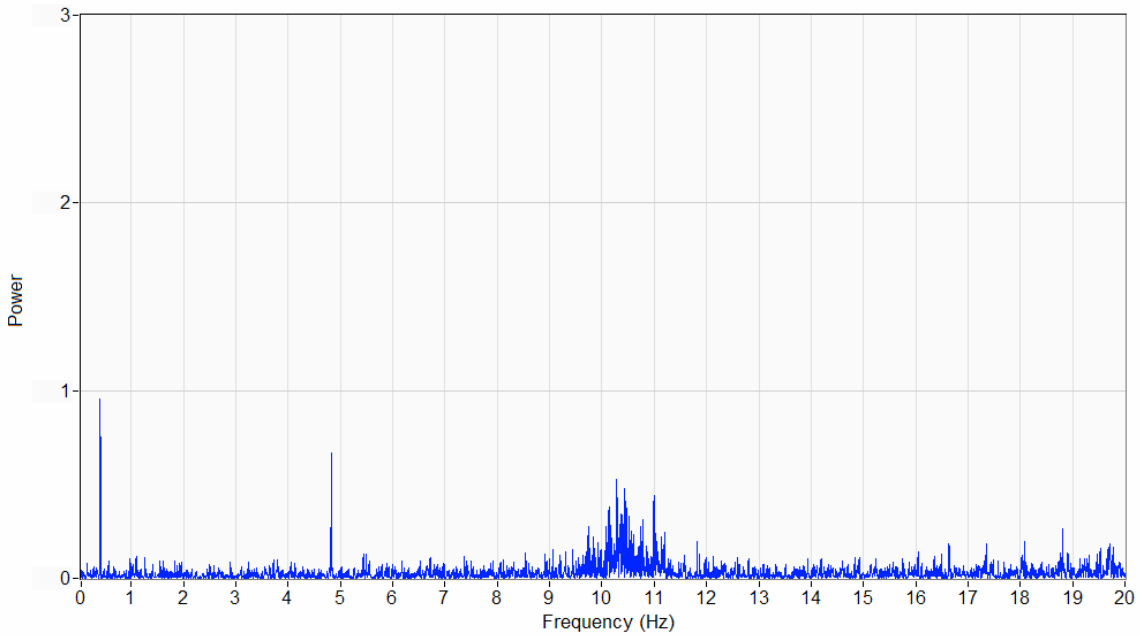
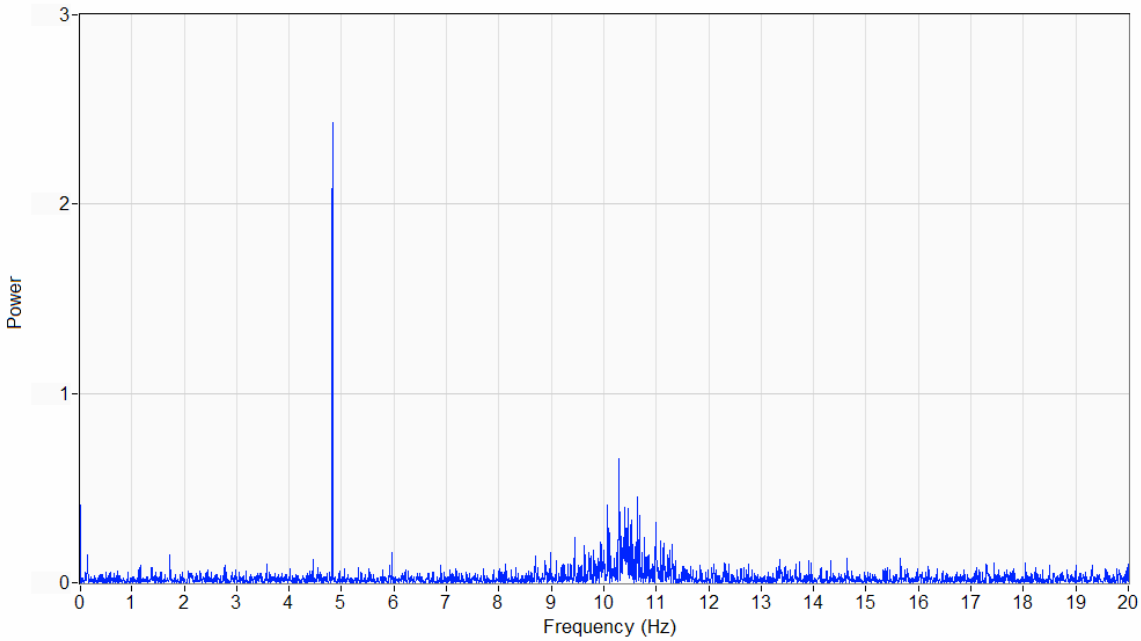


(c) Sensor 3



(d) Sensor 4

Figure 3-31. (continued).

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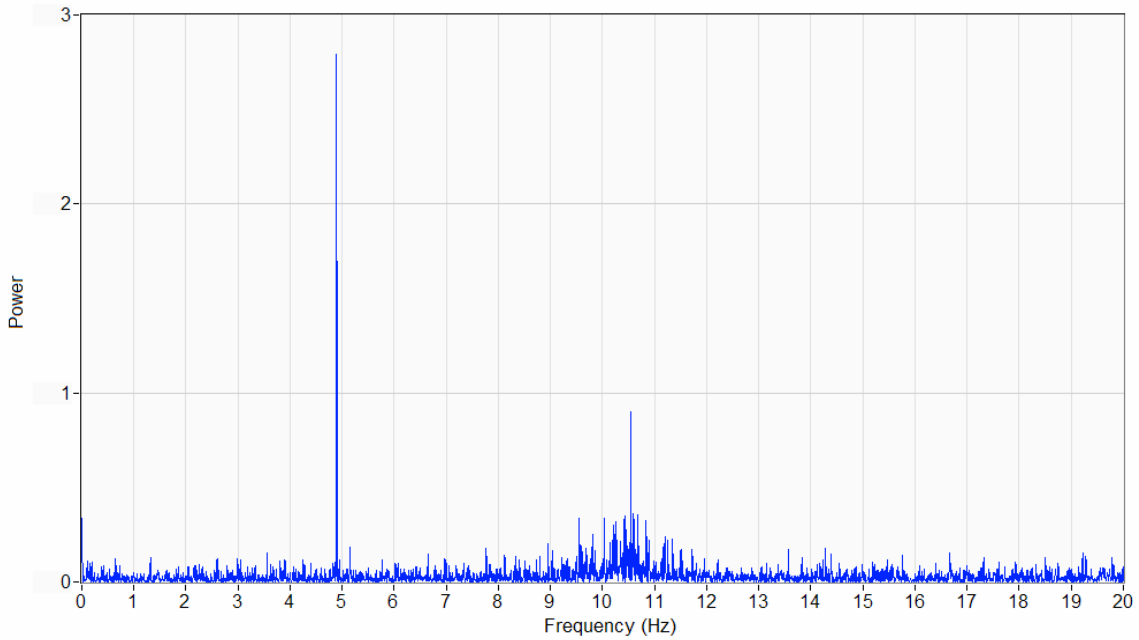
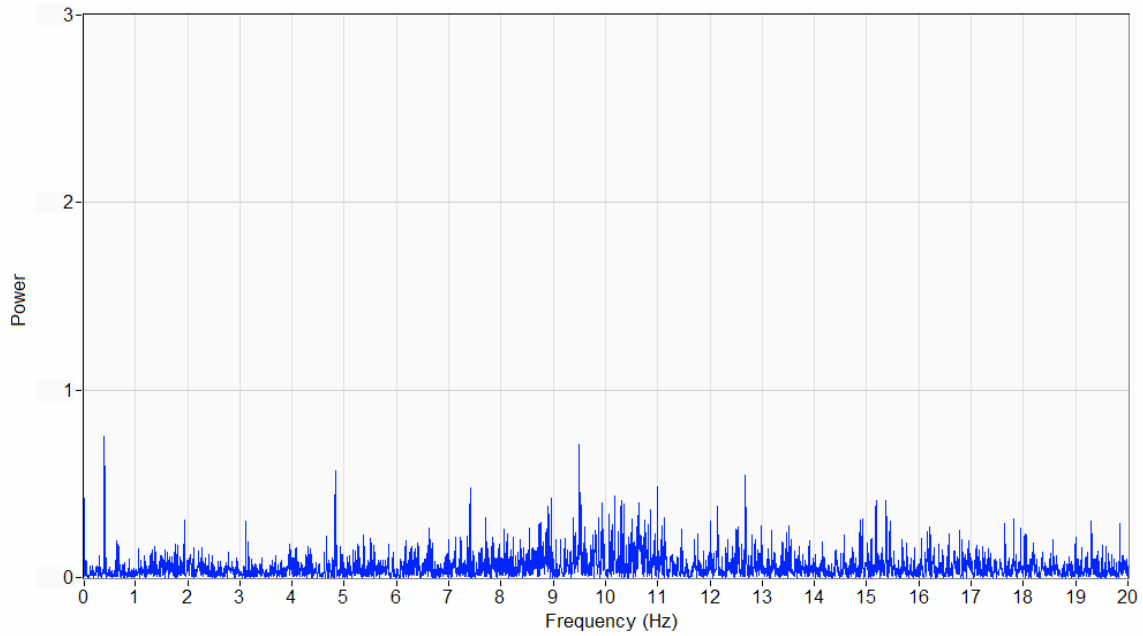


(e) Sensor 5



(f) Sensor 6

Figure 3-31. (continued).

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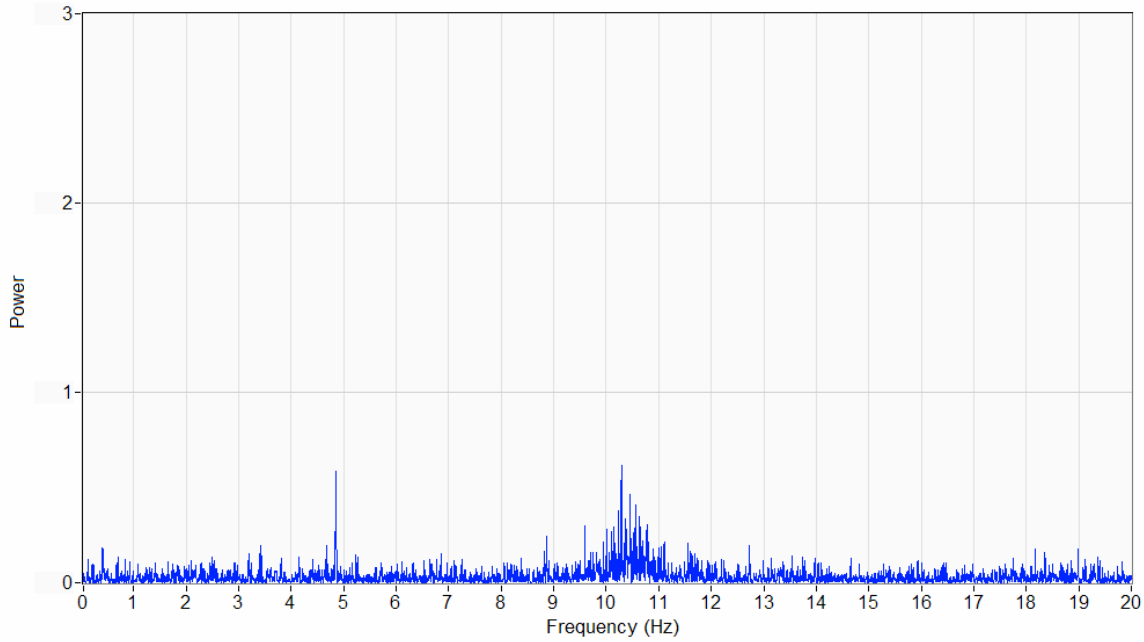
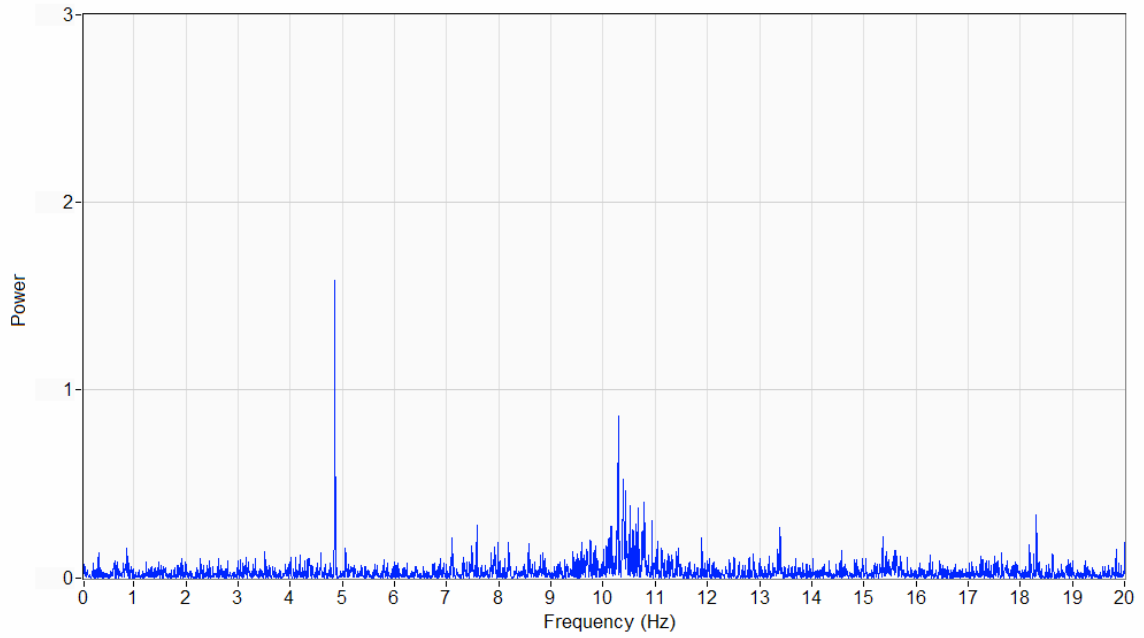


(g) Sensor 7



(h) Sensor 8

Figure 3-31. (continued).

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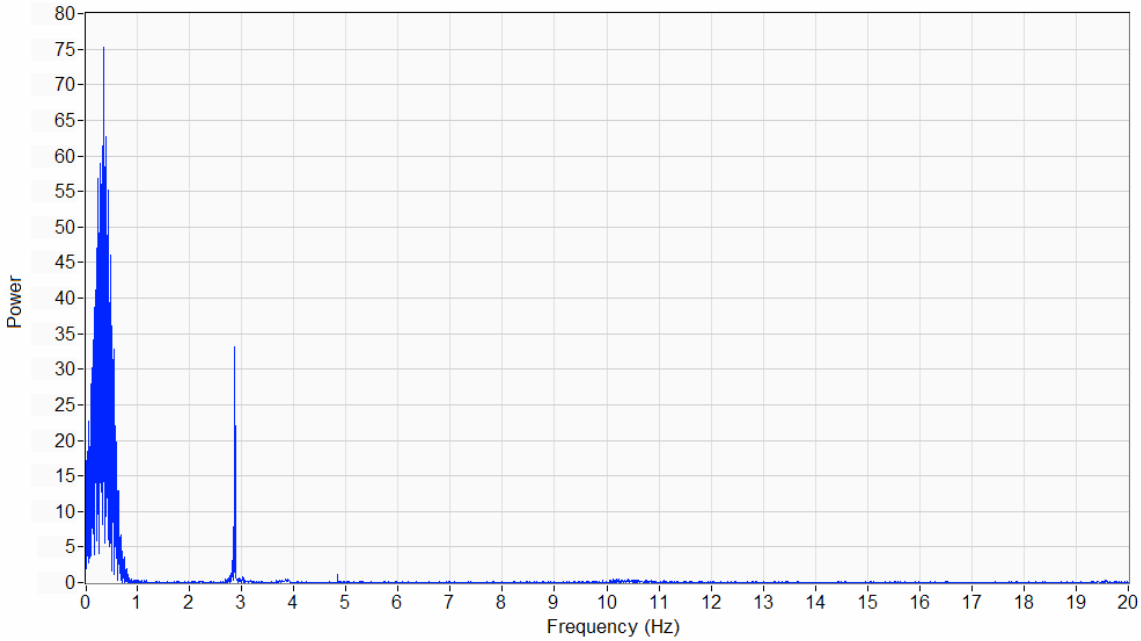
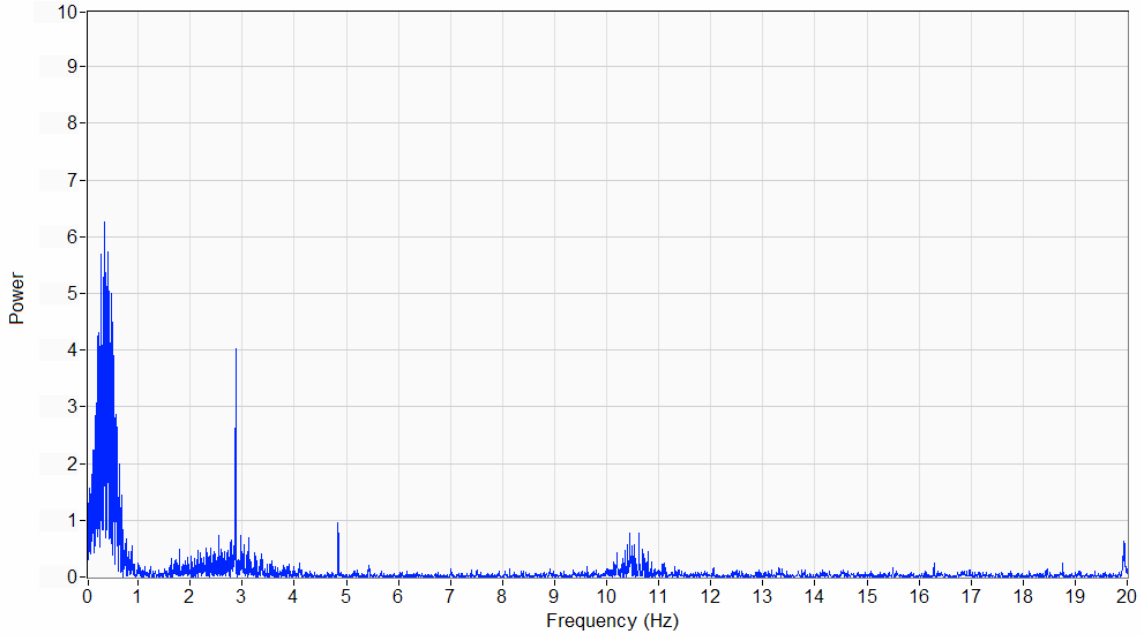


(a) Sensor 1



(b) Sensor 2

Figure 3-32. PSD plot from sample data with traffic on the bridge.

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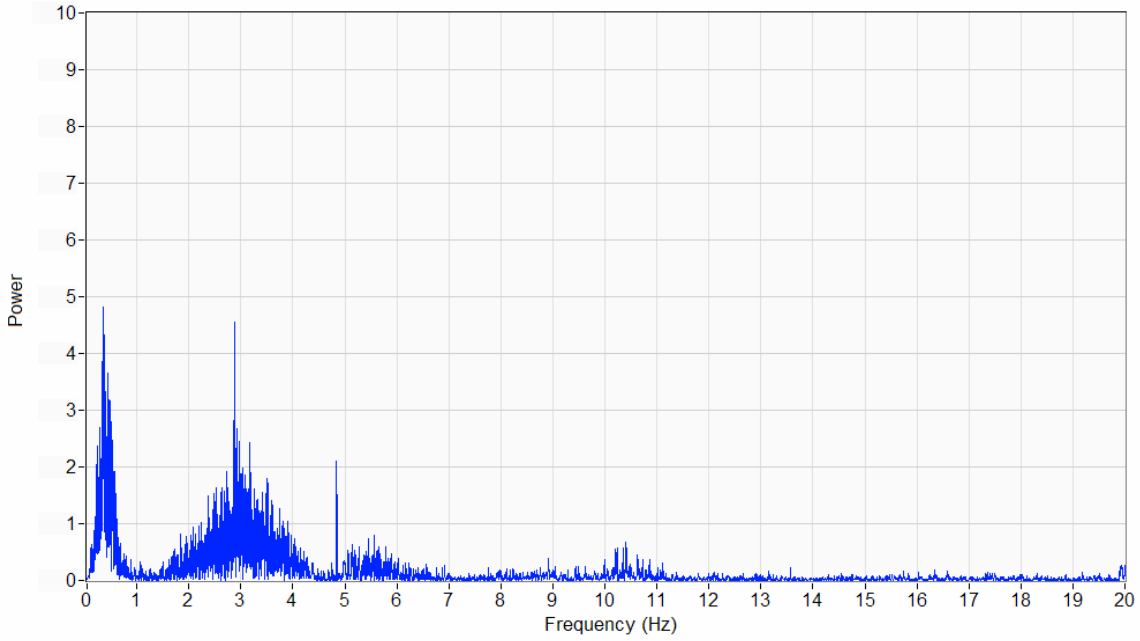
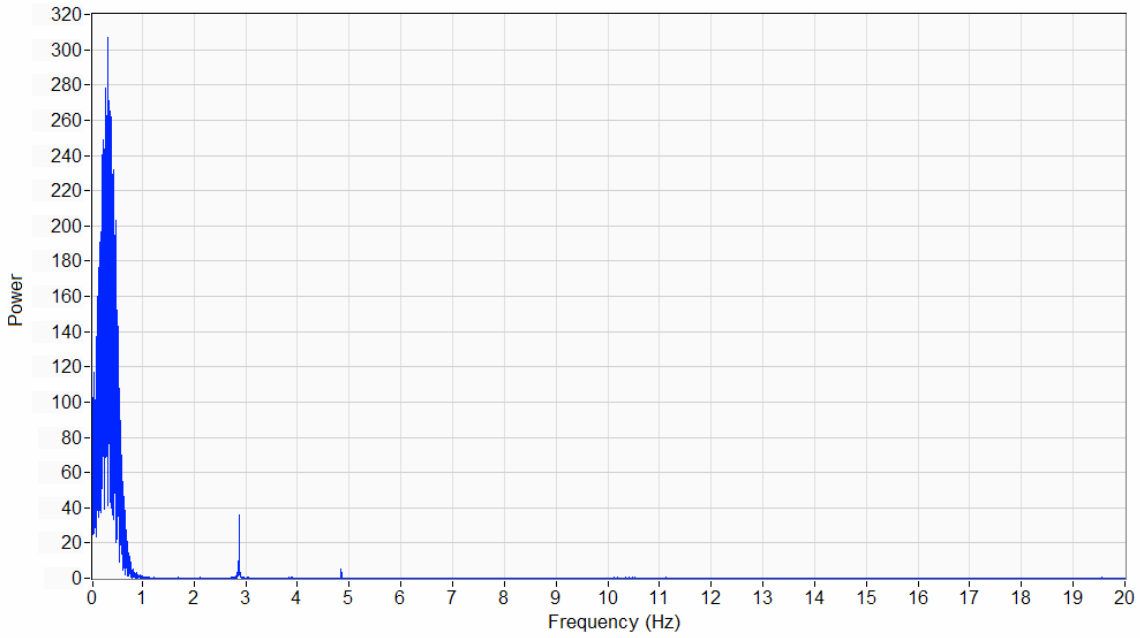


(c) Sensor 3



(d) Sensor 4

Figure 3-32. (continued).

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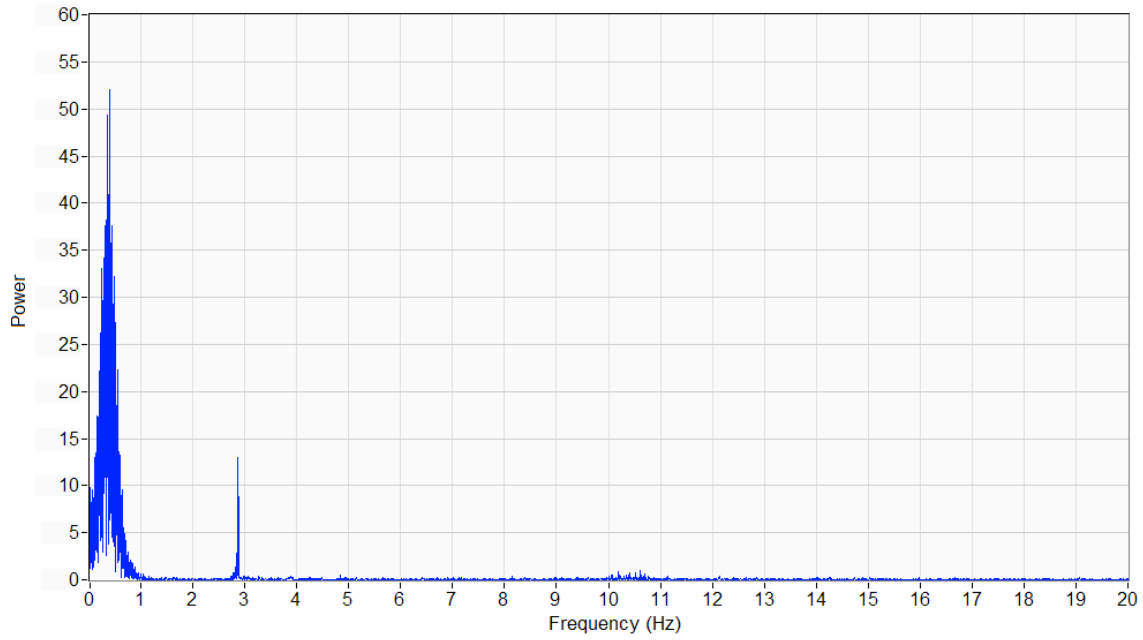
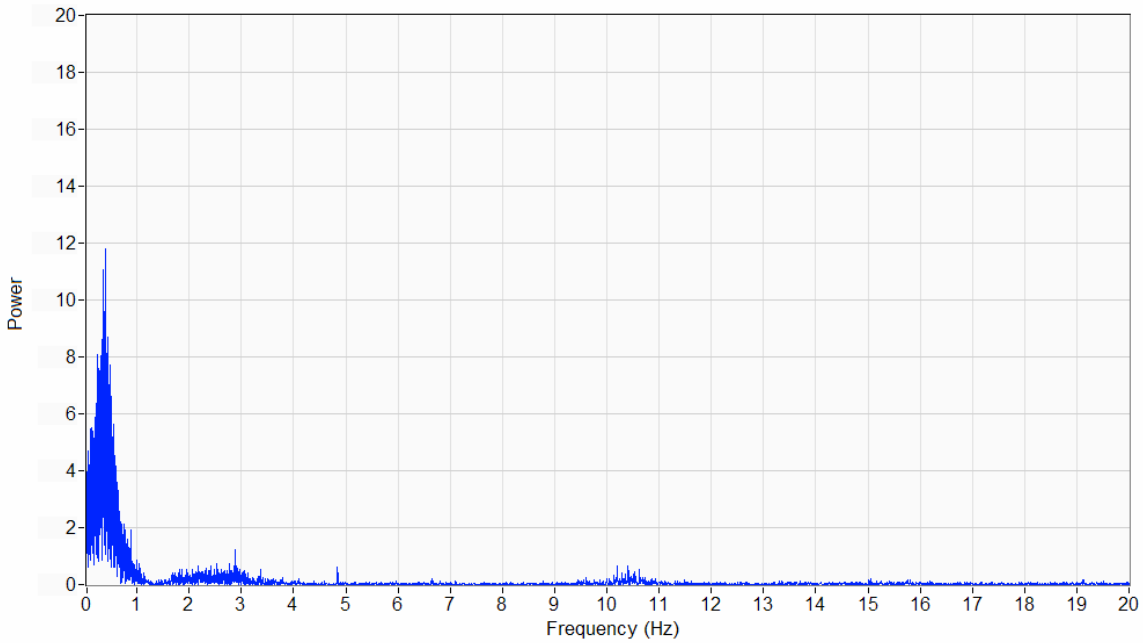


(e) Sensor 5



(f) Sensor 6

Figure 3-32. (continued).

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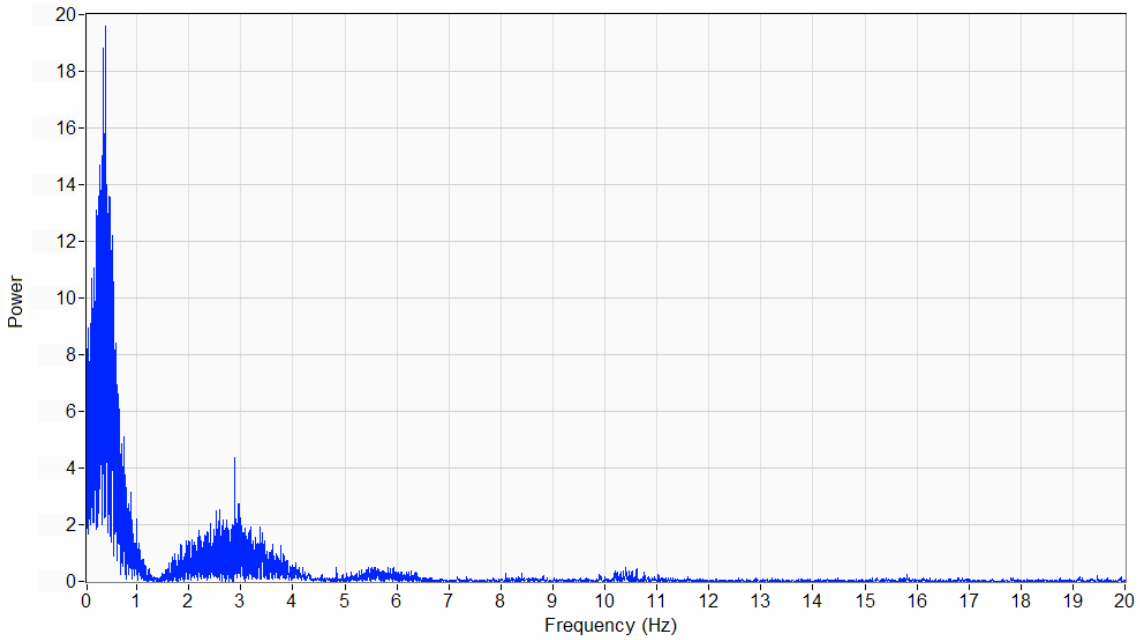
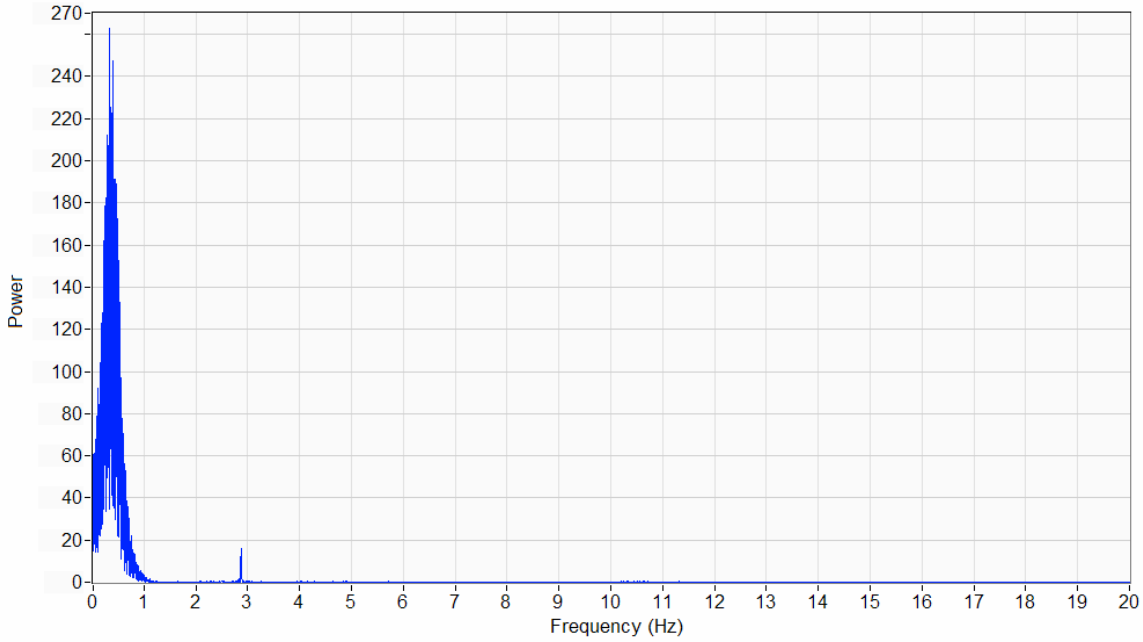


(g) Sensor 7



(h) Sensor 8

Figure 3-32. (continued).

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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 event 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 Engineers's Guide to Digital Signal Filter Processing* [42] and *LabVIEW Analysis Concepts* [43]. The event 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 event detection thresholds are presented in Fig. 3-33.

Figs. 3-33a and 3-33b 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 event detection thresholds are presented in Figs. 3-33c through 33e. As shown in Figs. 3-33c through 3-33e, 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 event 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 event detection thresholds for each sensor are presented in Table 3-3.

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).

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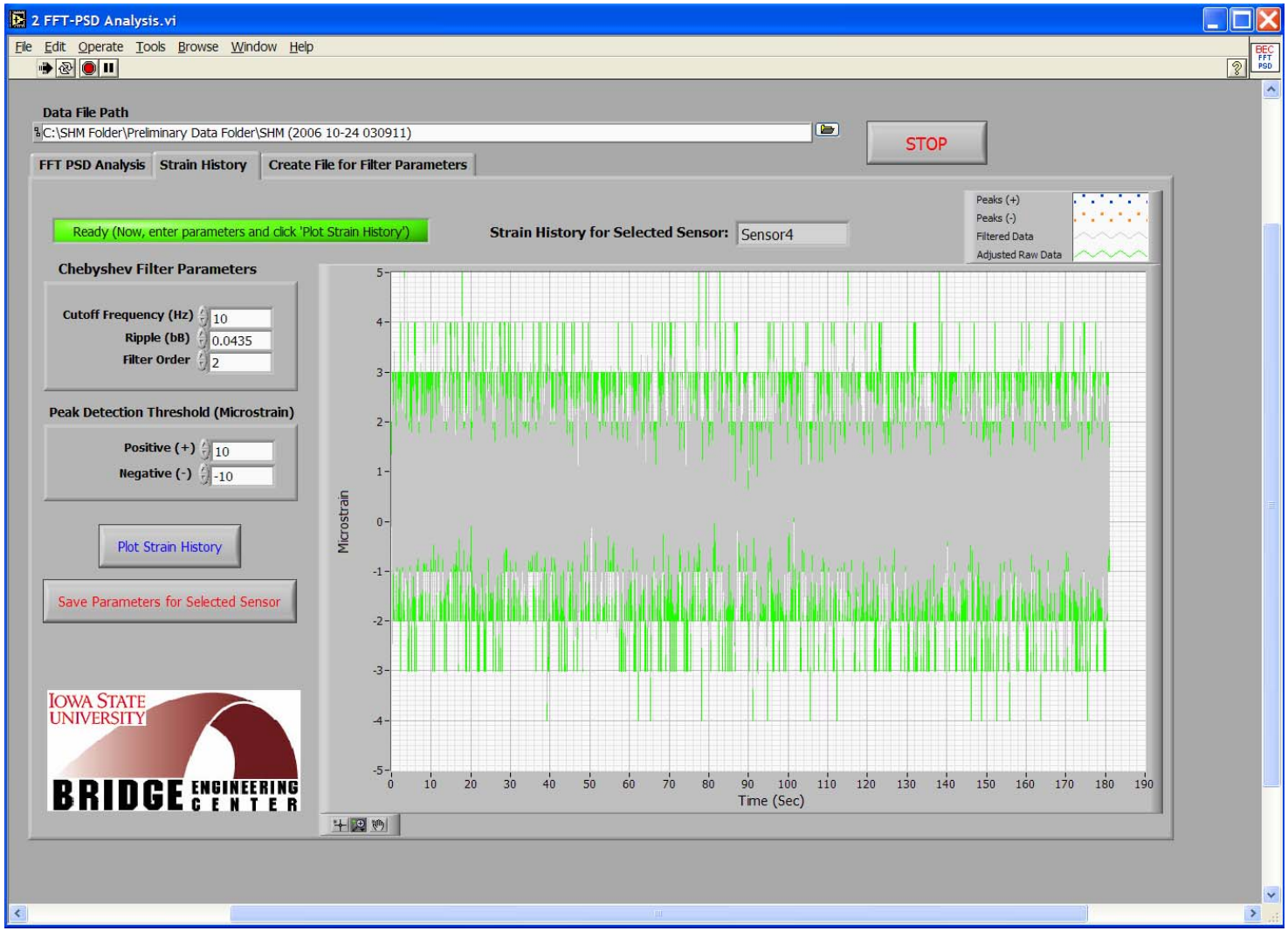

(a) Noise induced strain history with cutoff frequency set at 10 Hz (3-minute sample data)

Figure 3-33. Illustration of effect on filter parameters and event detection thresholds.

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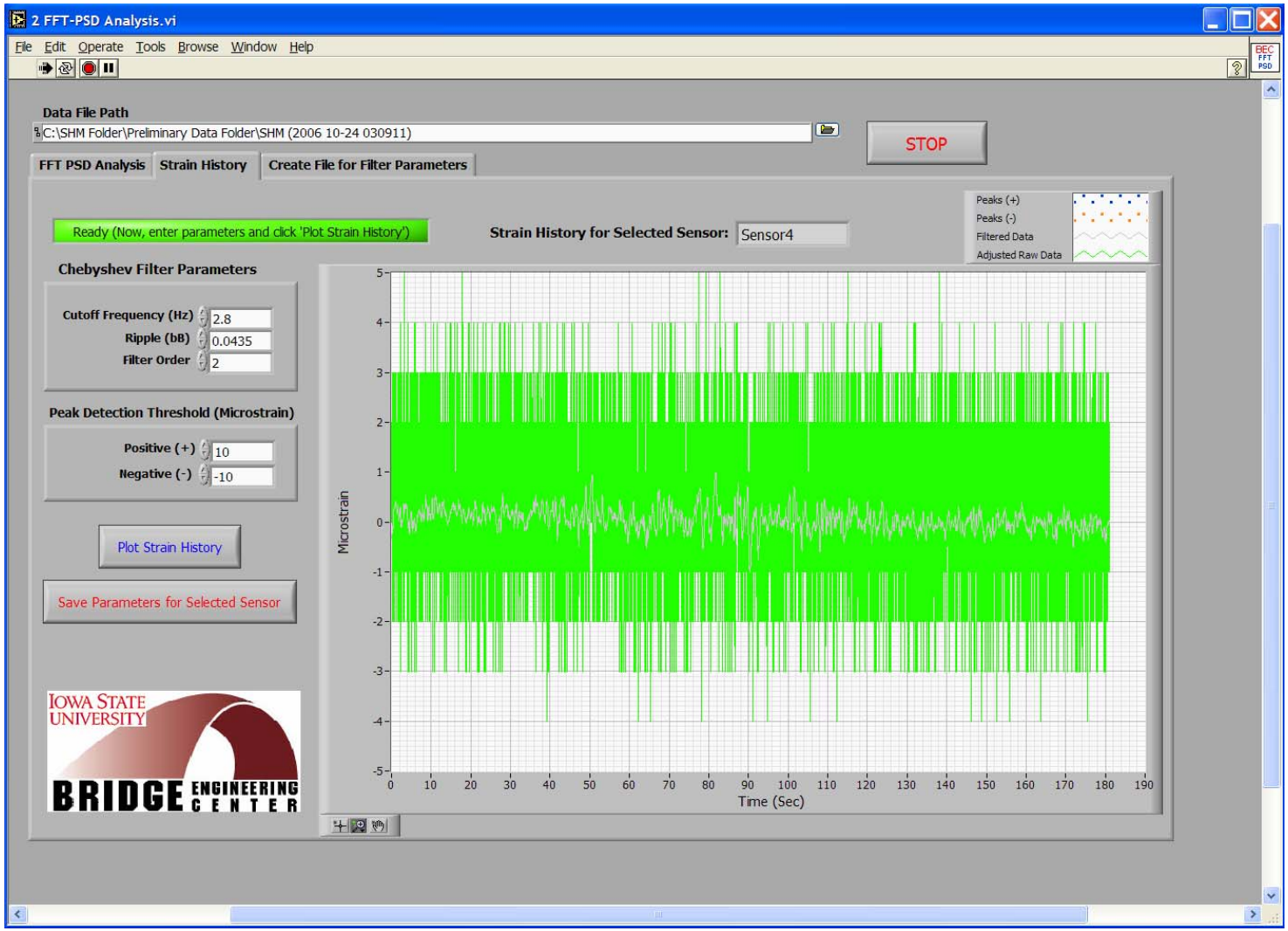

(b) Noise induced strain history with cutoff frequency set at 2.8 Hz (3-minute sample data)

Figure 3-33. (continued).

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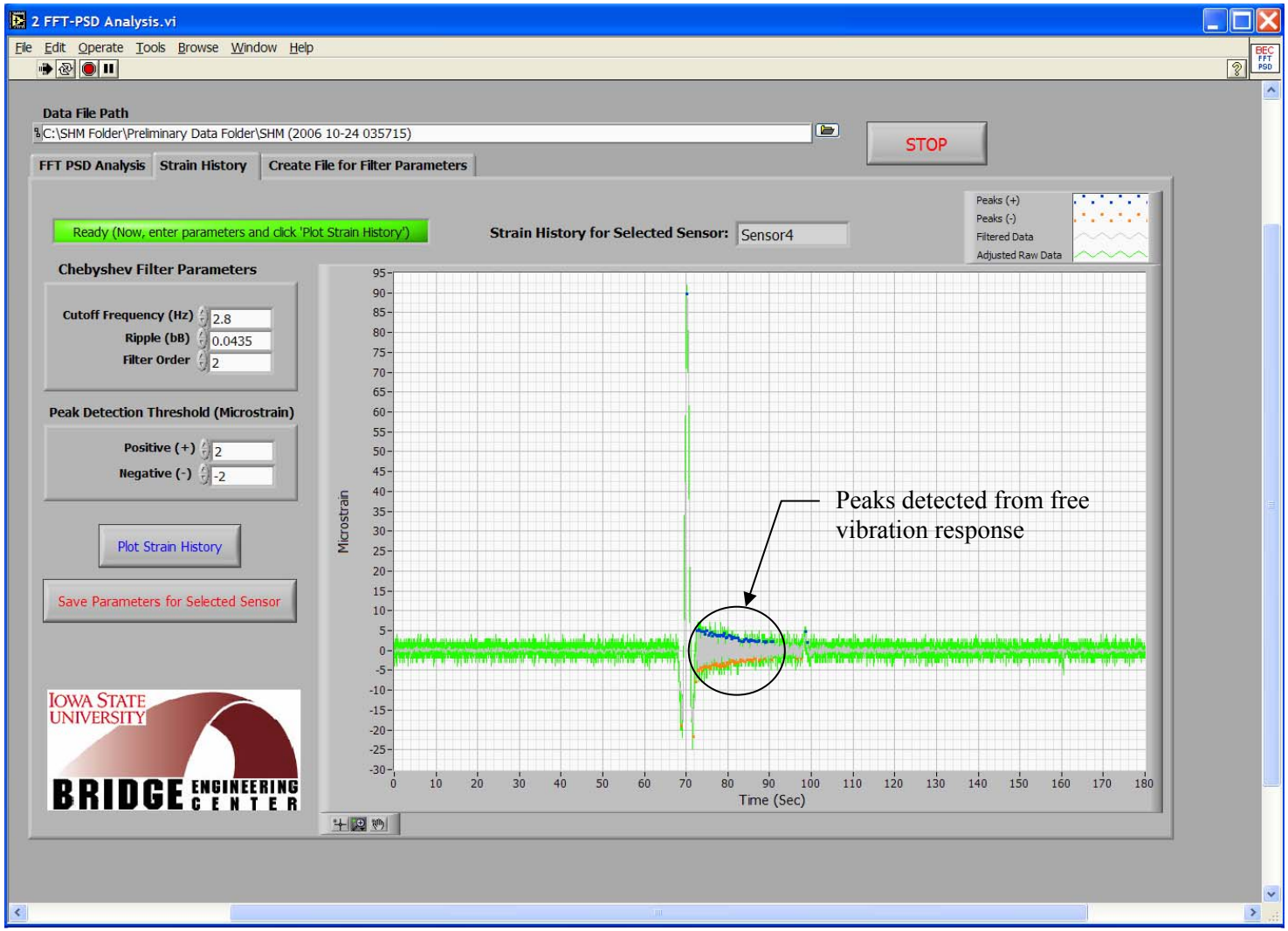

(c) Semi-truck induced strain history with event detection thresholds set at ±2 microstrain (3-minute sample data)

Figure 3-33. (continued).

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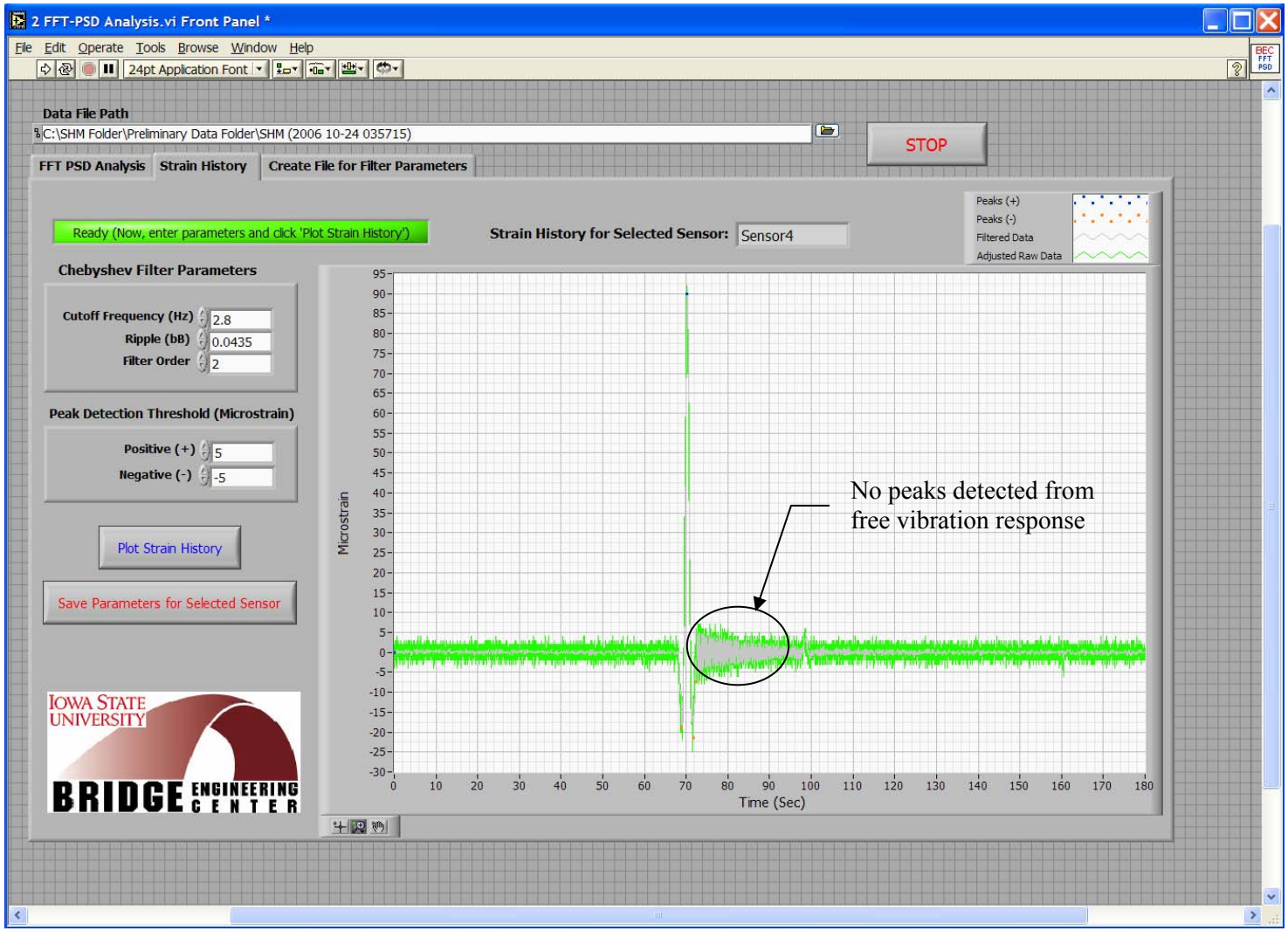

(d) Semi-truck induced strain history with event detection thresholds set at ±5 microstrain (3-minute sample data)

Figure 3-33. (continued).

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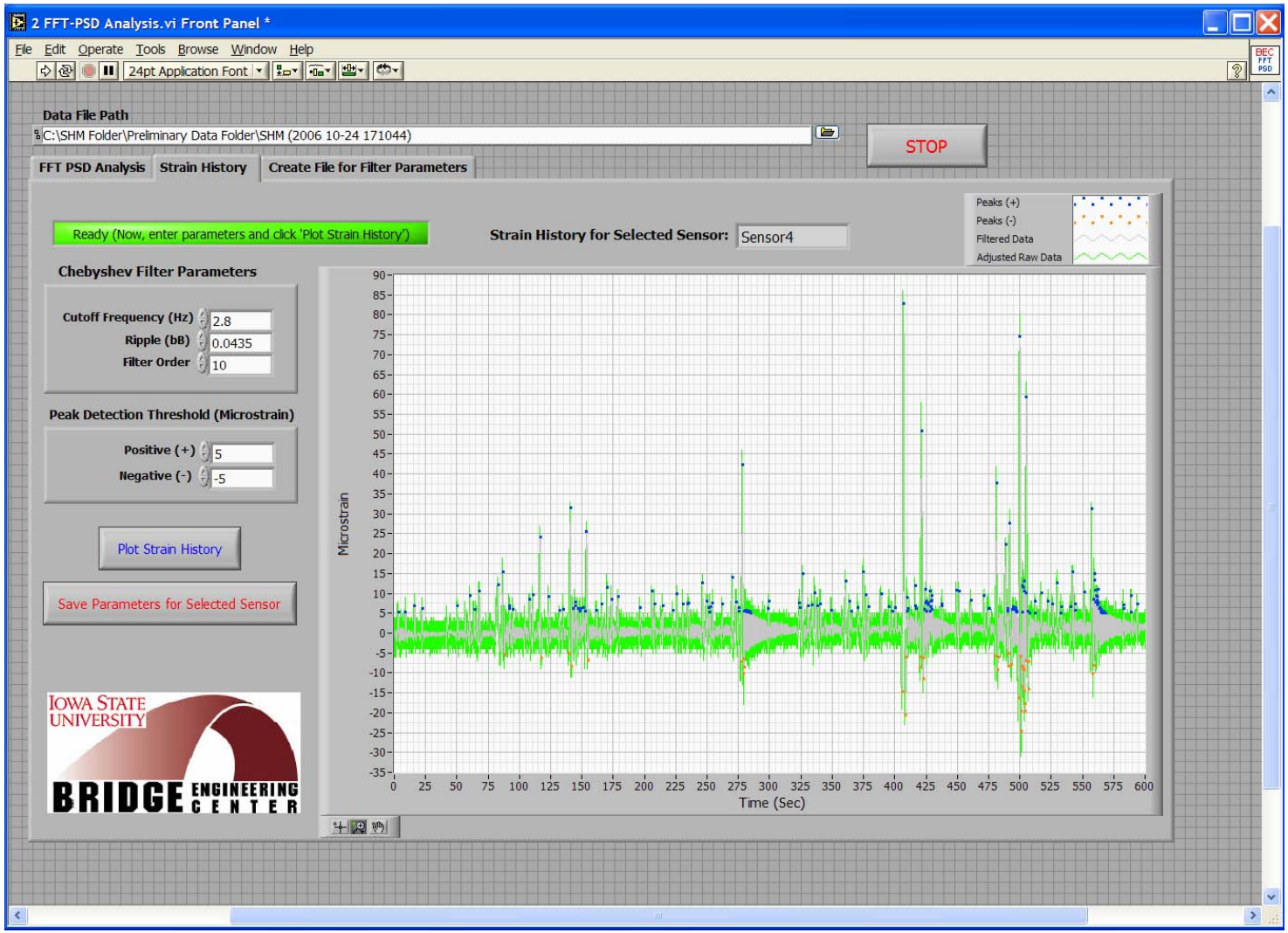

(e) Strain history with event detection thresholds set at ±5 microstrain (10-minute sample data)

Figure 3-33. (continued).

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Table 3-3. Filter parameters and event detection thresholds.

Sensor	Cutoff Frequency (Hz)	Filter Order	Ripple (dB)	Event 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

Photographs of a typical BDI system setup and a strain transducer installed are presented in Fig. 3-34. 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 3-35 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 με and, therefore, the SHM system was thought to be performing accurately.

3.4.3. Input Settings and Main Data Acquisition/Processing

After the hardware components had been installed and the filter parameters and event 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 Fig. 2-26 except the magnitude of the overload event thresholds for the select sensors and the email address information.

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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 in the '3 Data File Folder' within the main directory as shown in Fig. 3-36.

(a) BDI system setup

(b) BDI strain transducer installed next to the weldable strain gage

Figure 3-34. Photographs of a typical BDI system setup and a strain transducer.

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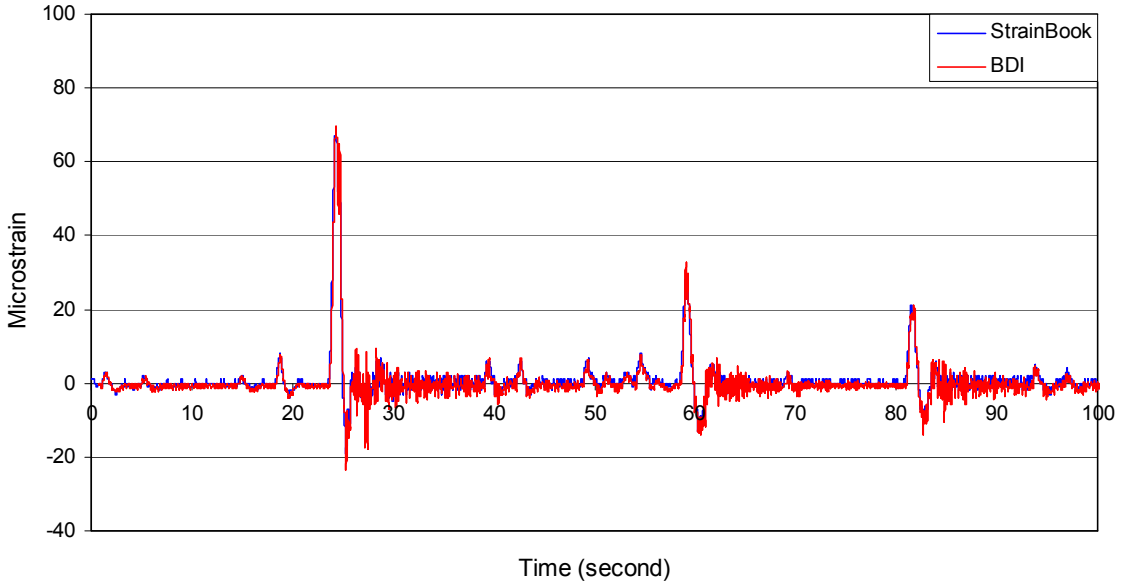
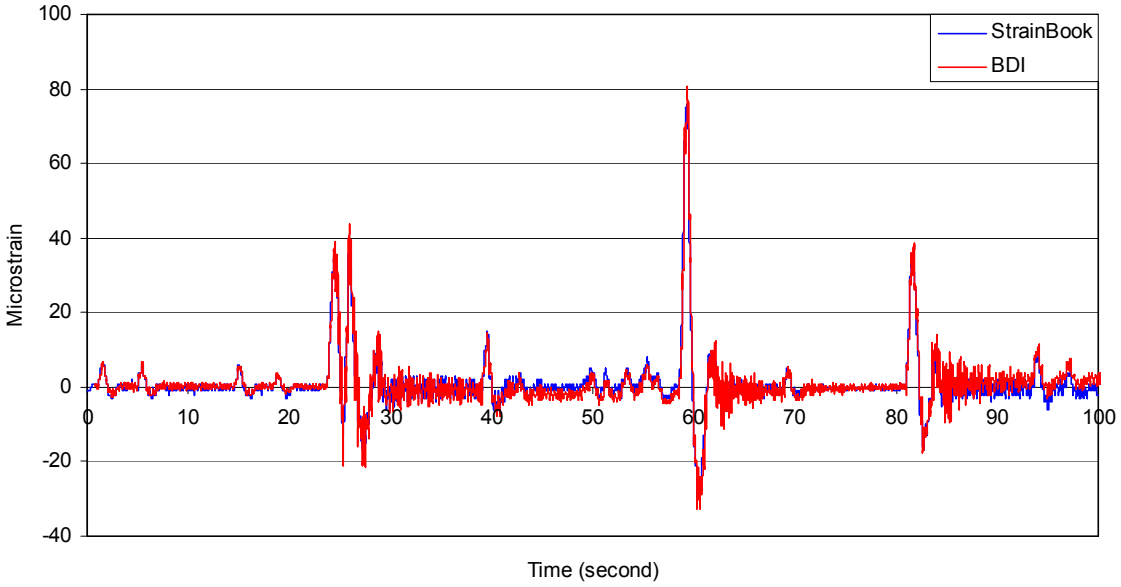


(a) Sensor 5



(b) Sensor 8

Figure 3-35. Examples of in-service validation testing (comparison of measured strains collected by the BDI system and the SHM system).

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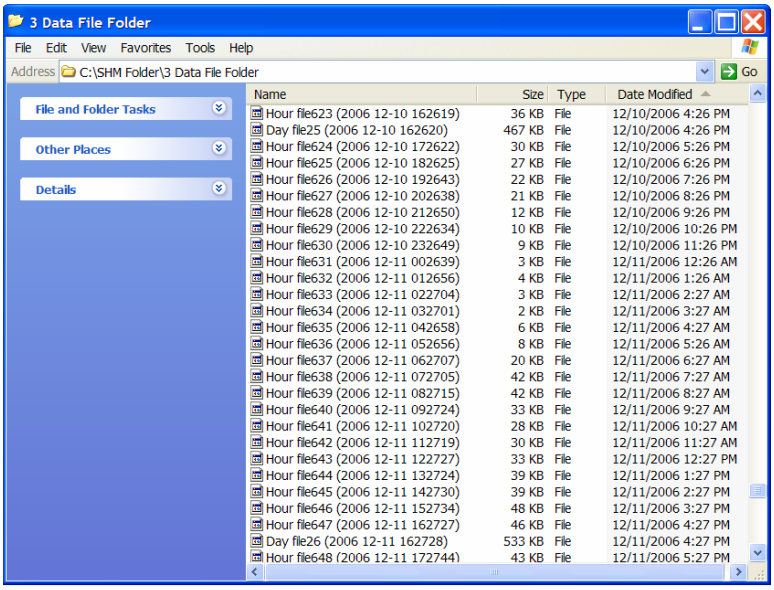

Figure 3-36. Data files archived in '3 Data File Folder' within the main directory.

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 Fig. 3-37 while an example of a complete evaluation report generated by *8 Create Report (From Multiple Files).VI* is provided in Appendix I.

Each data point in any of the event history plot in Fig. 3-37 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 follow:

- No alarm event had occurred for the monitored period. The field monitoring software was programmed to list those events, if any, that exceed the overload and/or impact event thresholds for each sensor and as can be seen in Tables 3-4 and 3-5 as well as in Fig. 3-37, no

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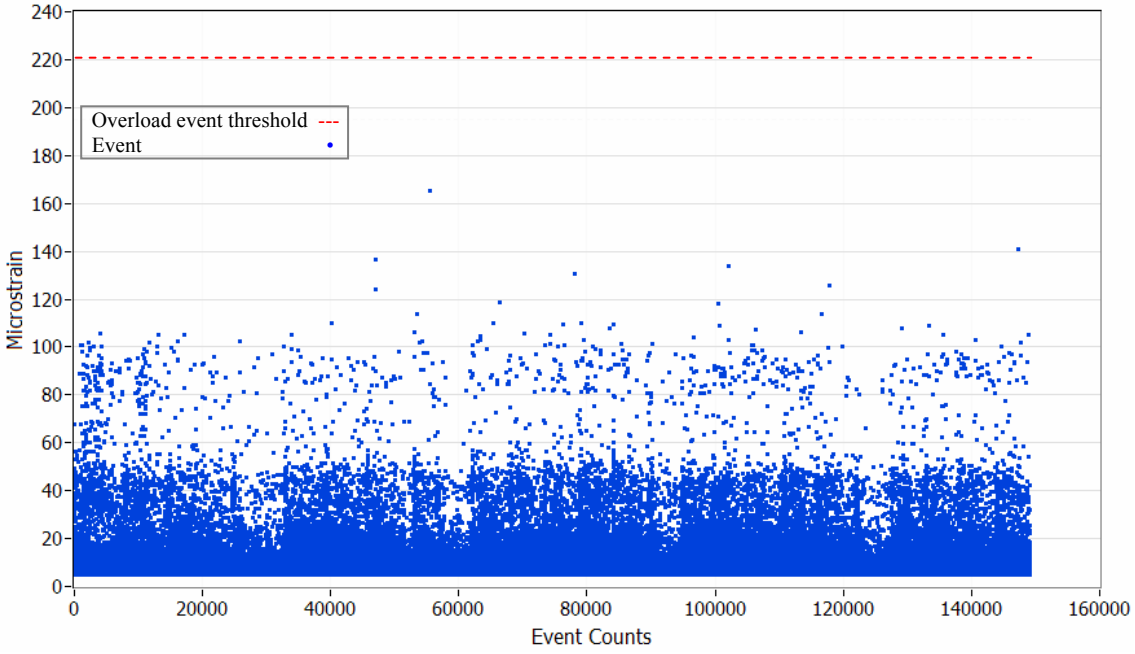
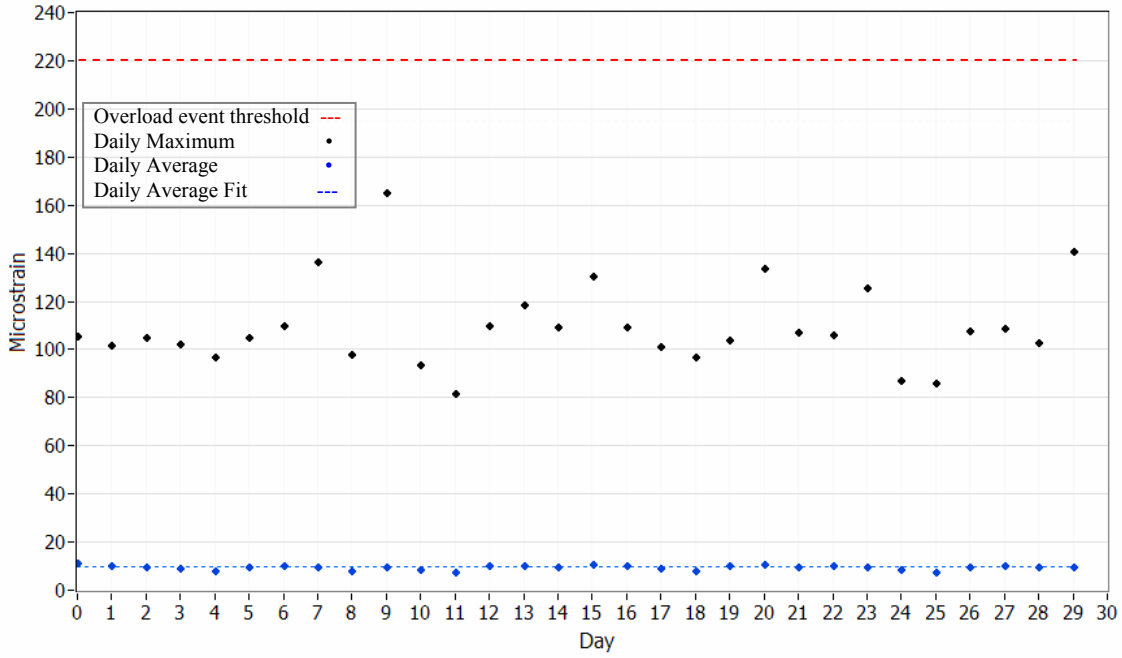


(a) 30-day event history for Sensor 1



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

Figure 3-37. Monthly evaluation from on Nov. 14th through Dec. 14th of 2006.

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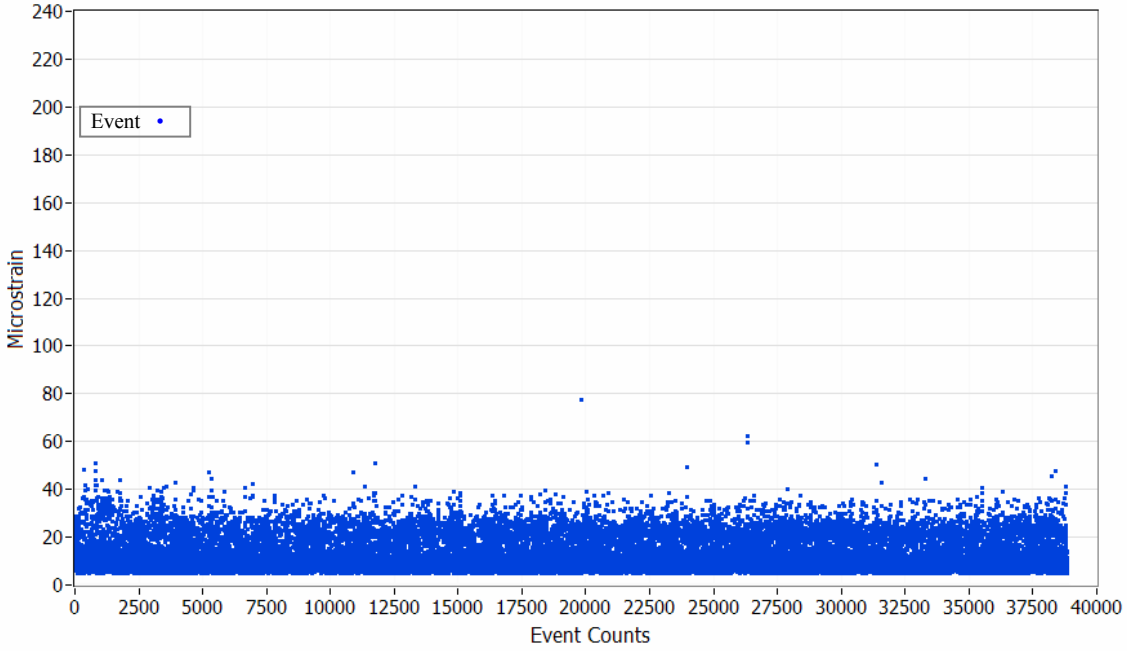
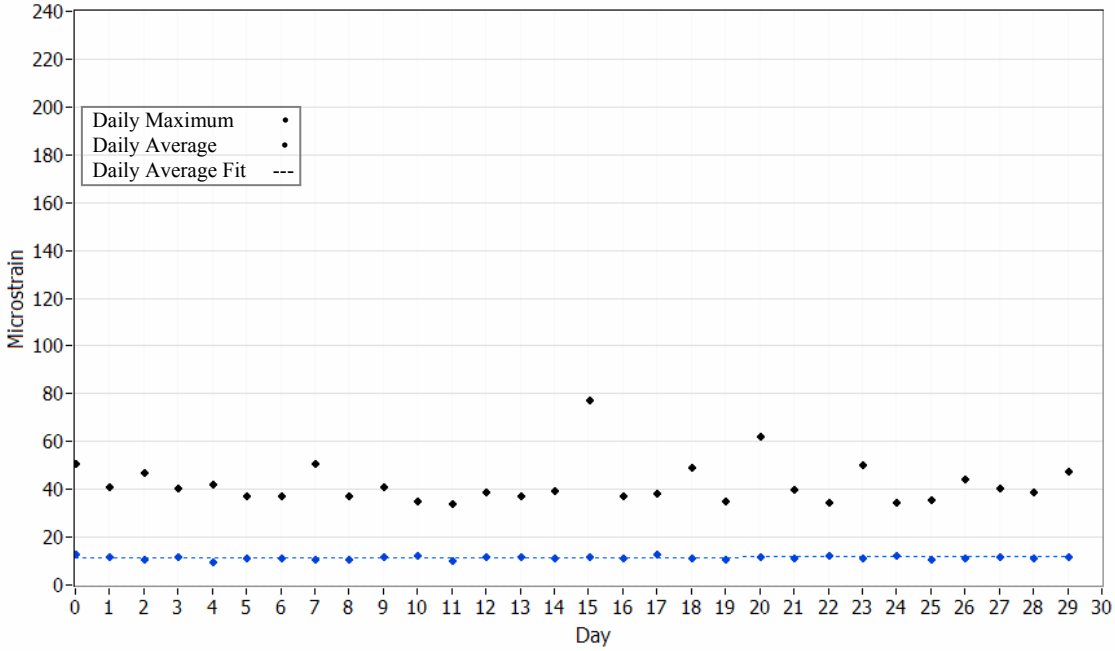


(c) 30-day event history for Sensor 2



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

Figure 3-37. (continued).

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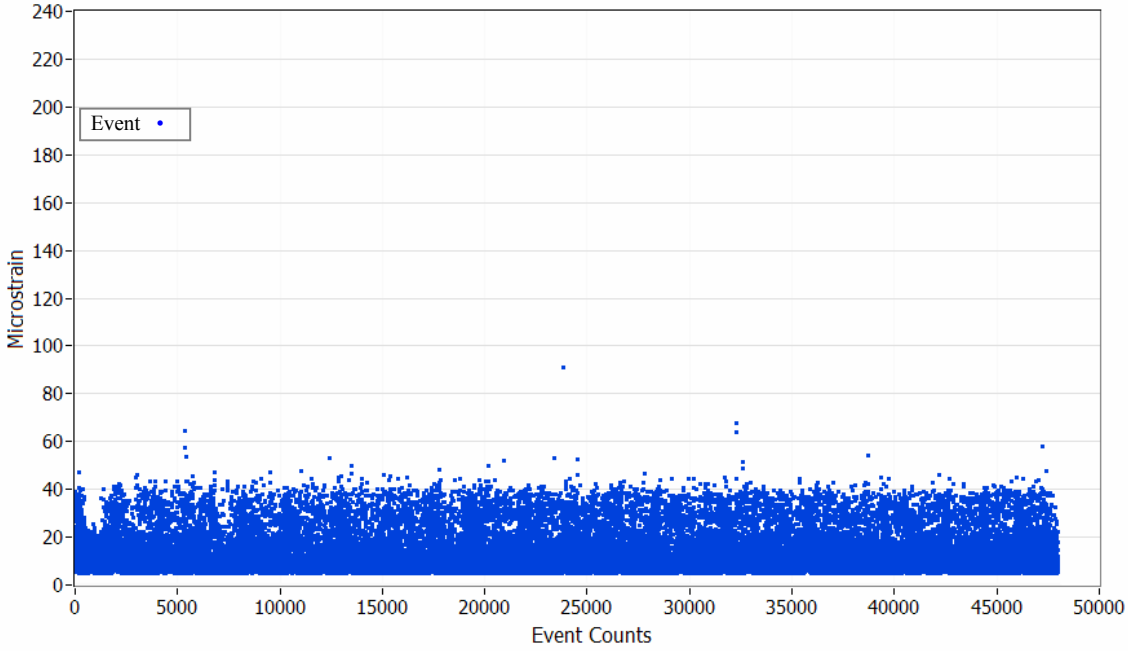
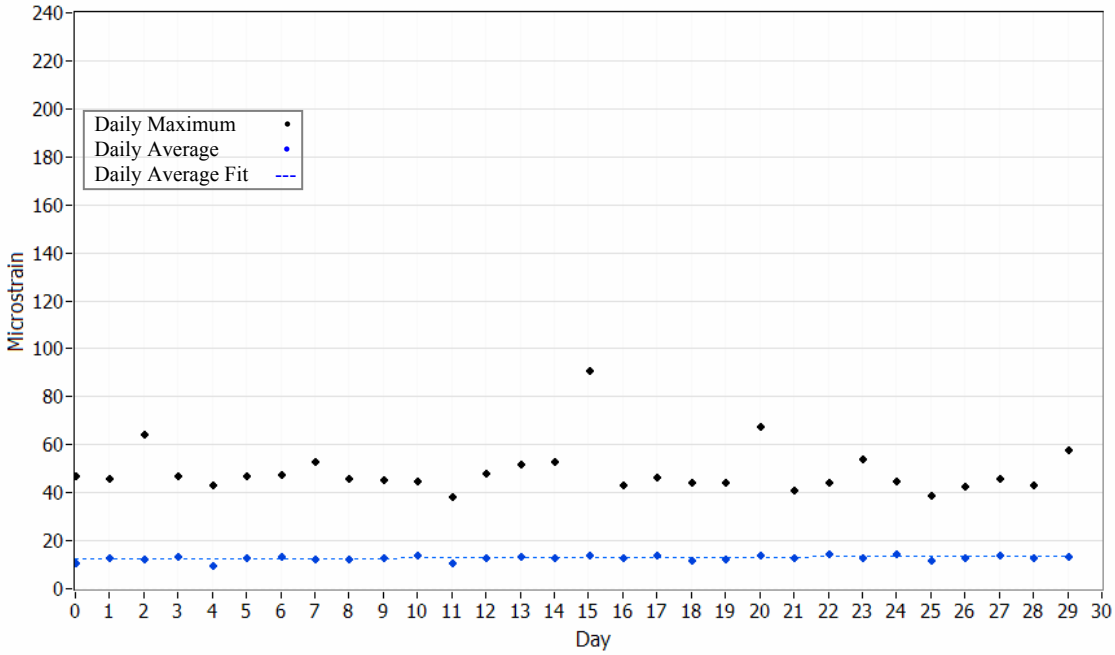


(e) 30-day event history for Sensor 3



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

Figure 3-37. (continued).

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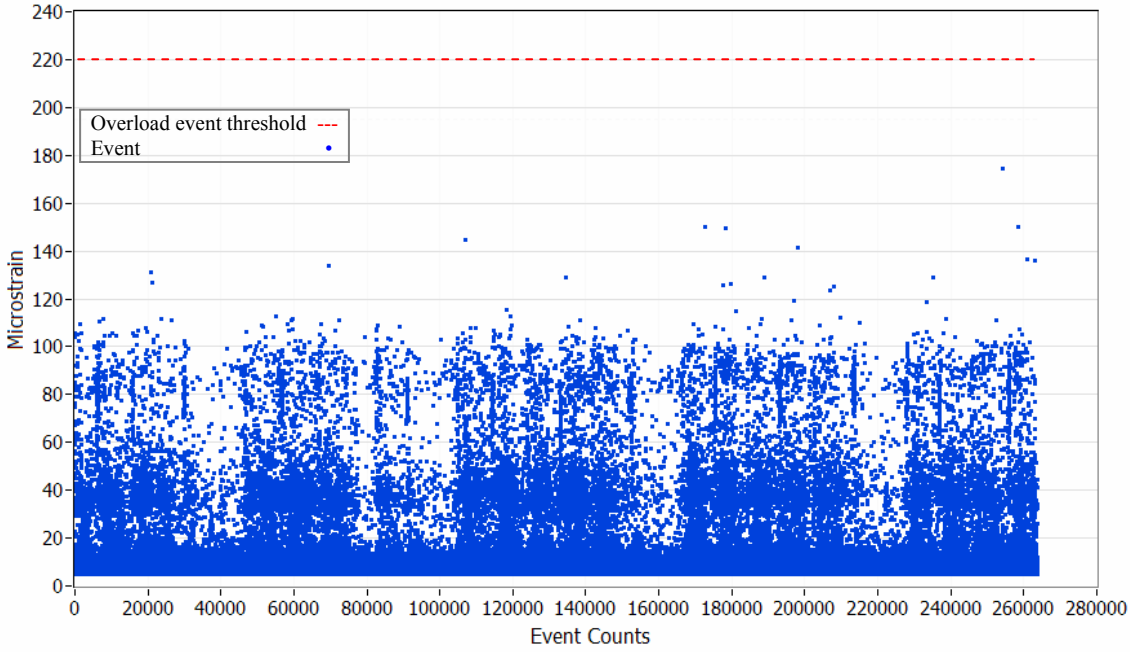
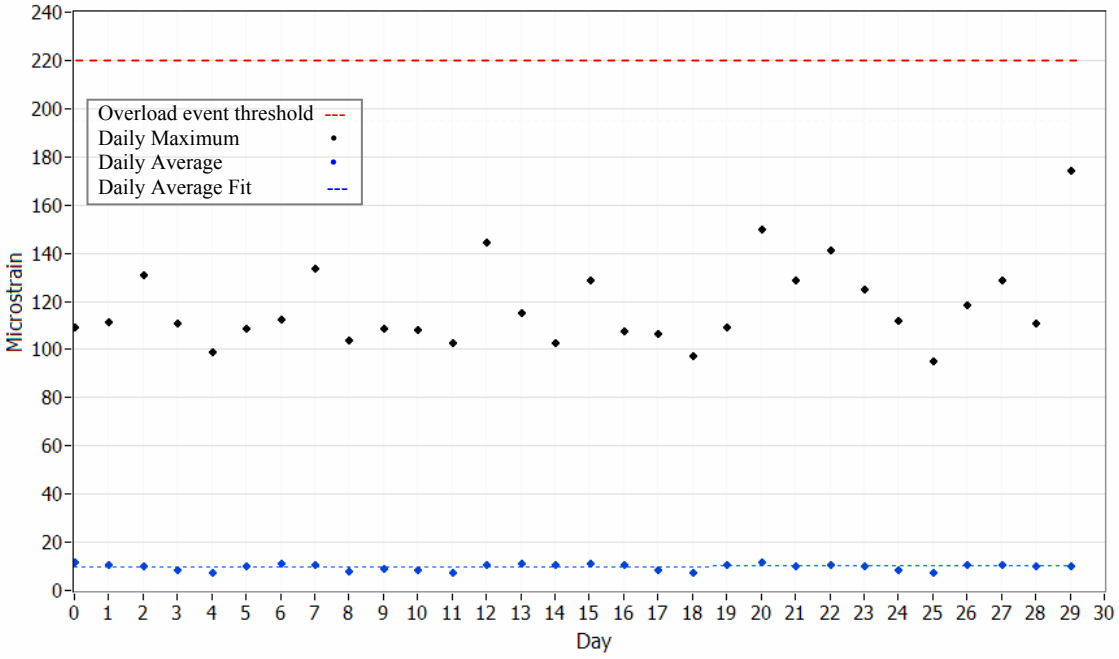


(g) 30-day event history for Sensor 4



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

Figure 3-37. (continued).

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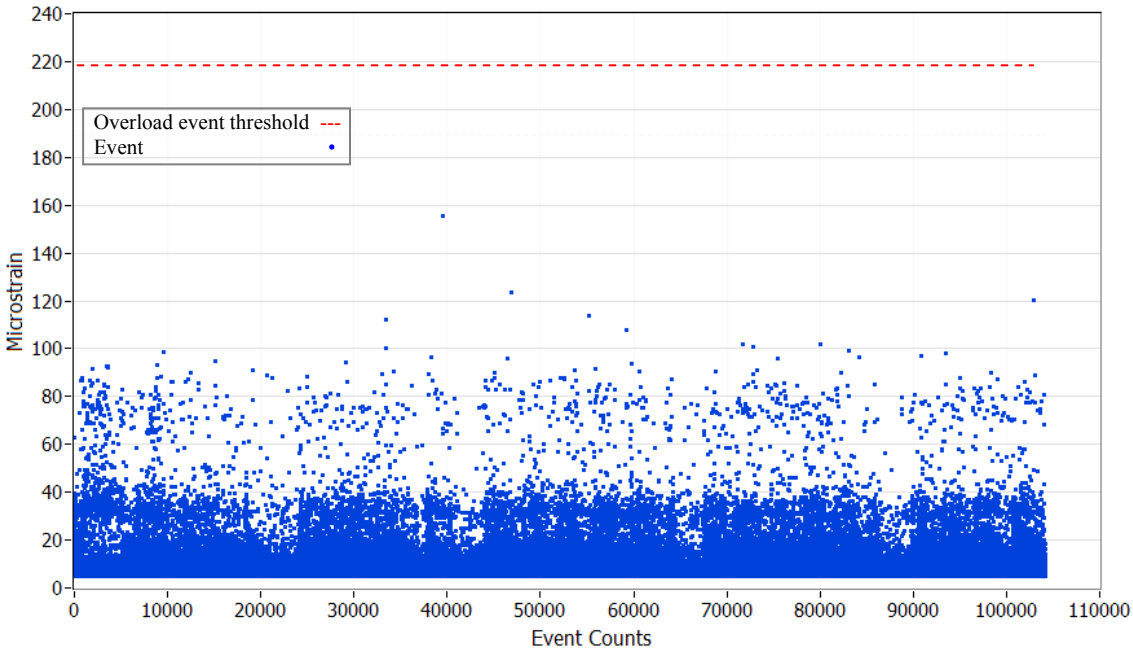
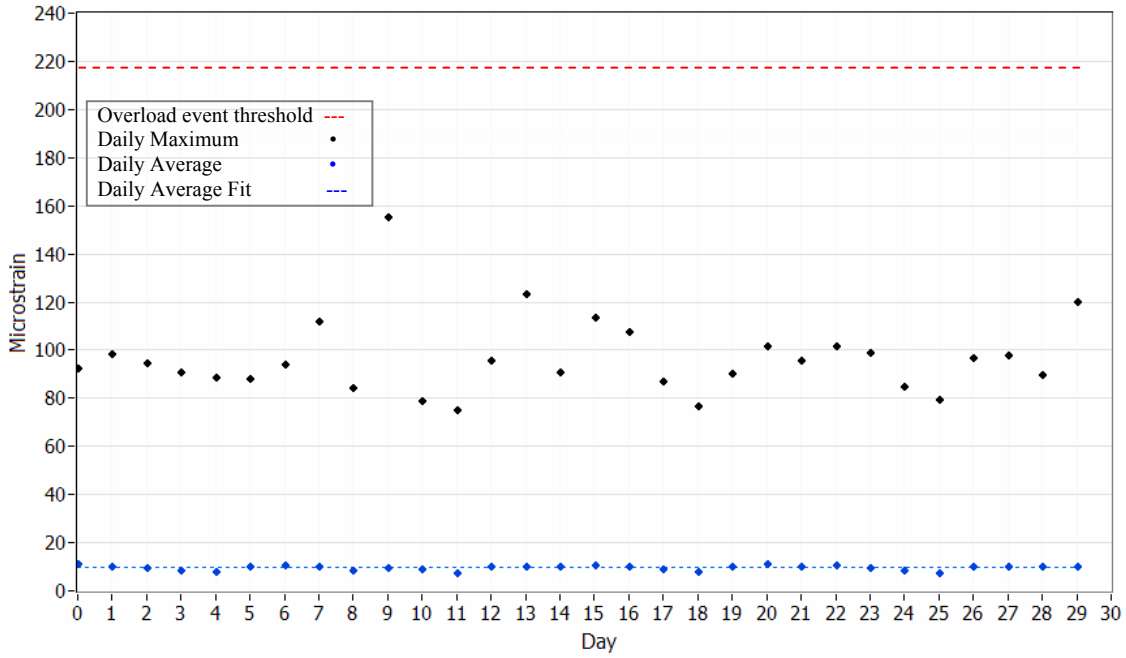


(i) 30-day event history for Sensor 5



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

Figure 3-37. (continued).

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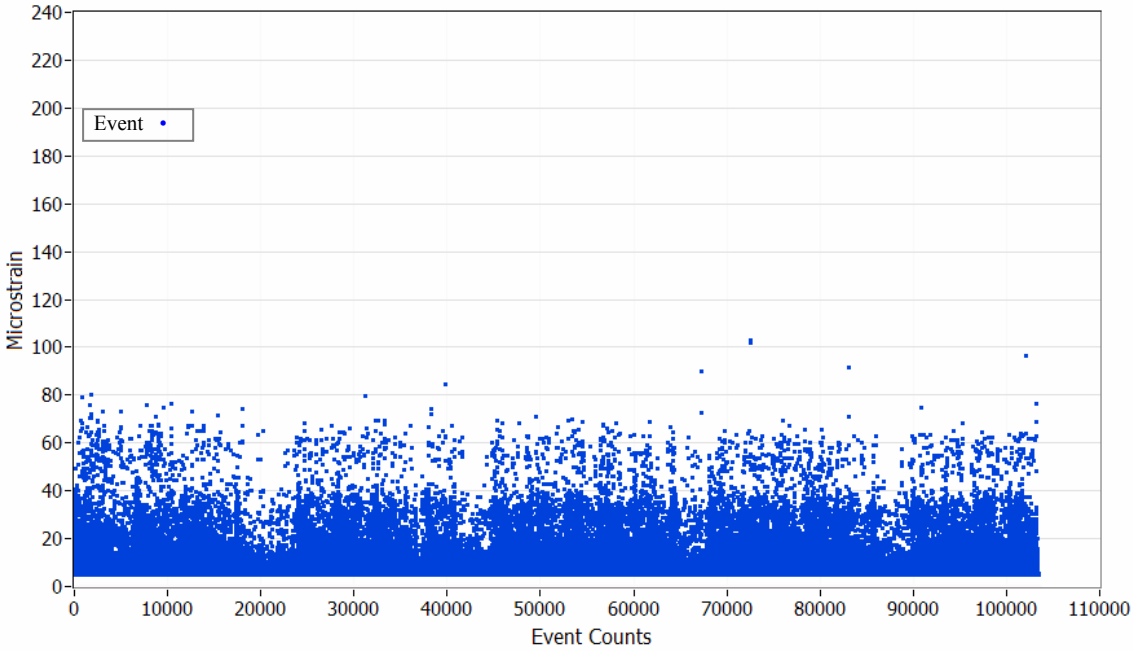
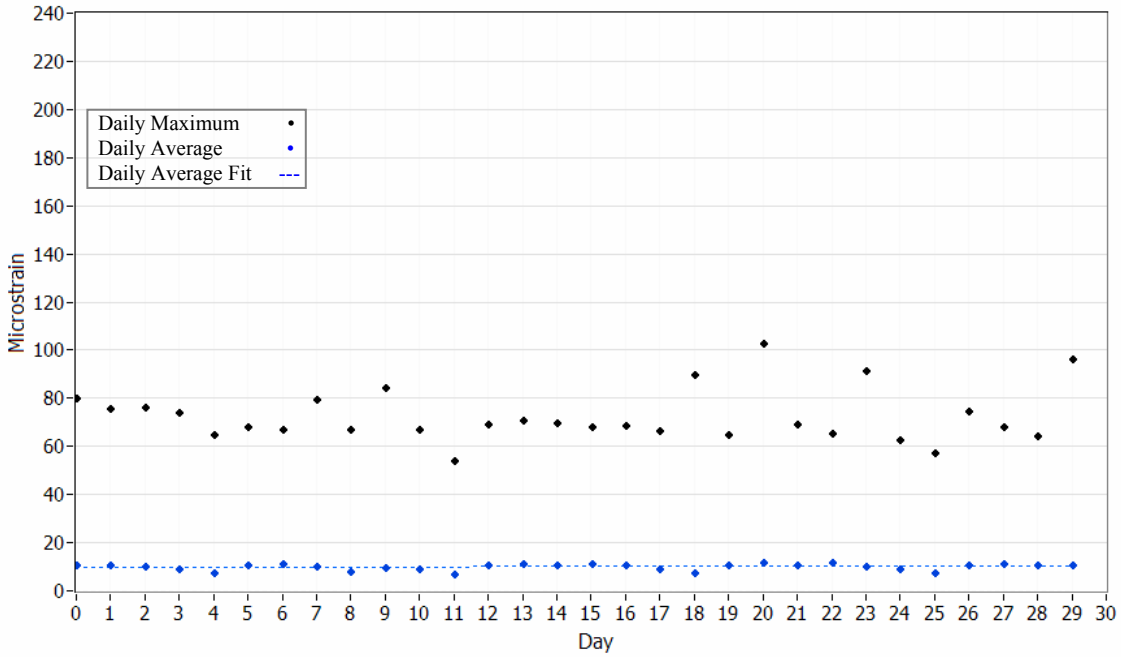


(k) 30-day event history for Sensor 6



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

Figure 3-37. (continued).

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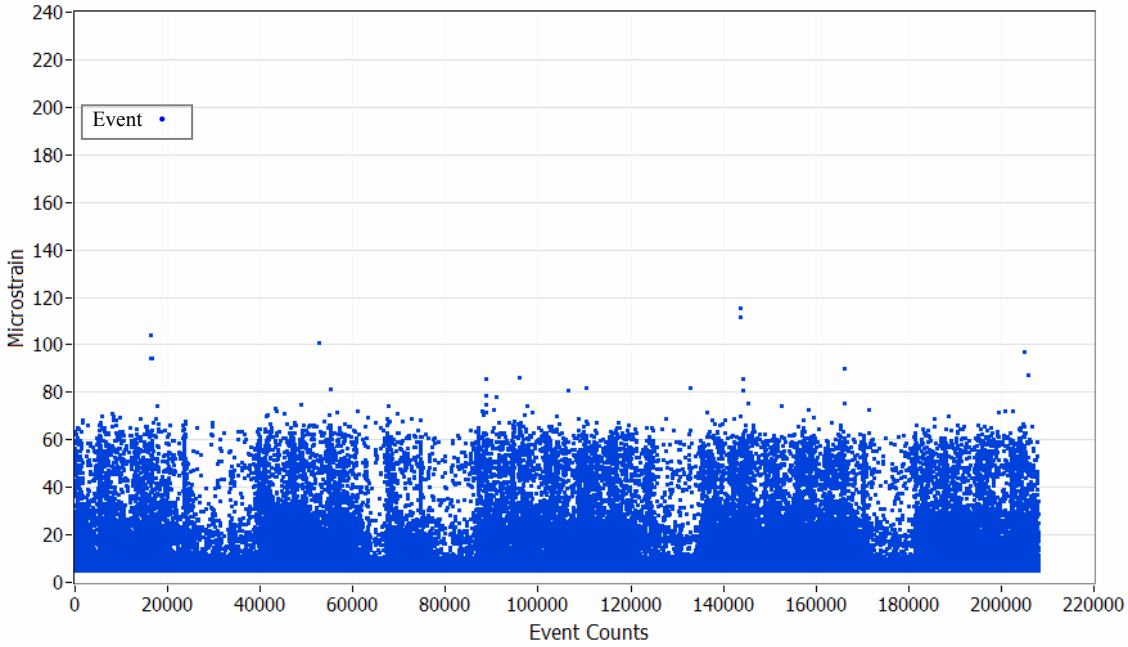
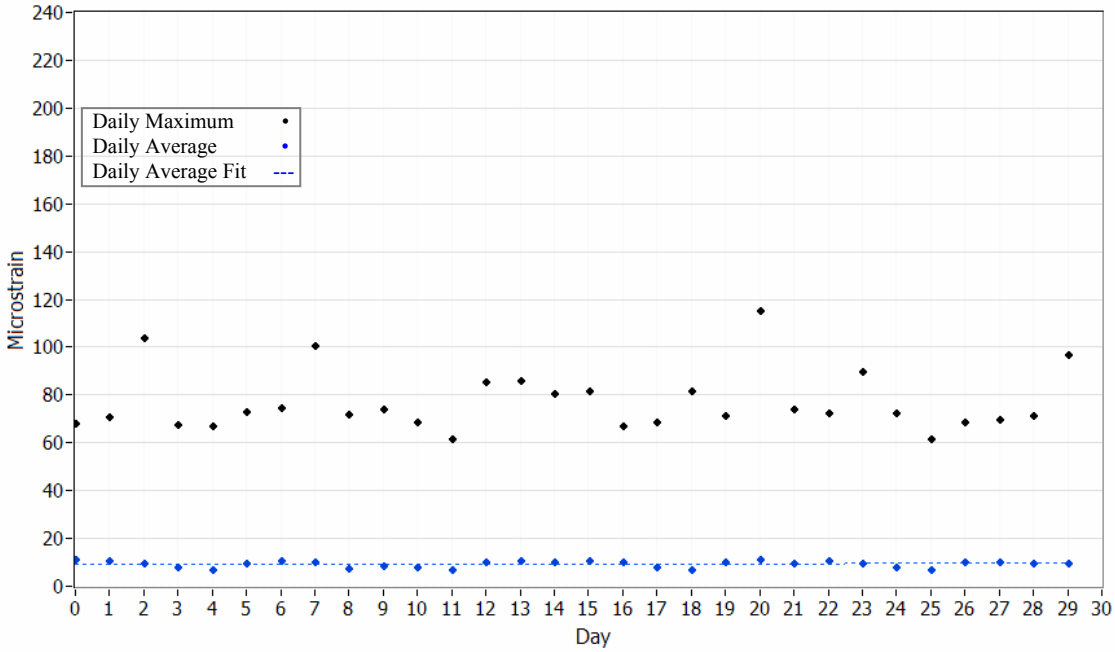


(m) 30-day event history for Sensor 7



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

Figure 3-37. (continued).

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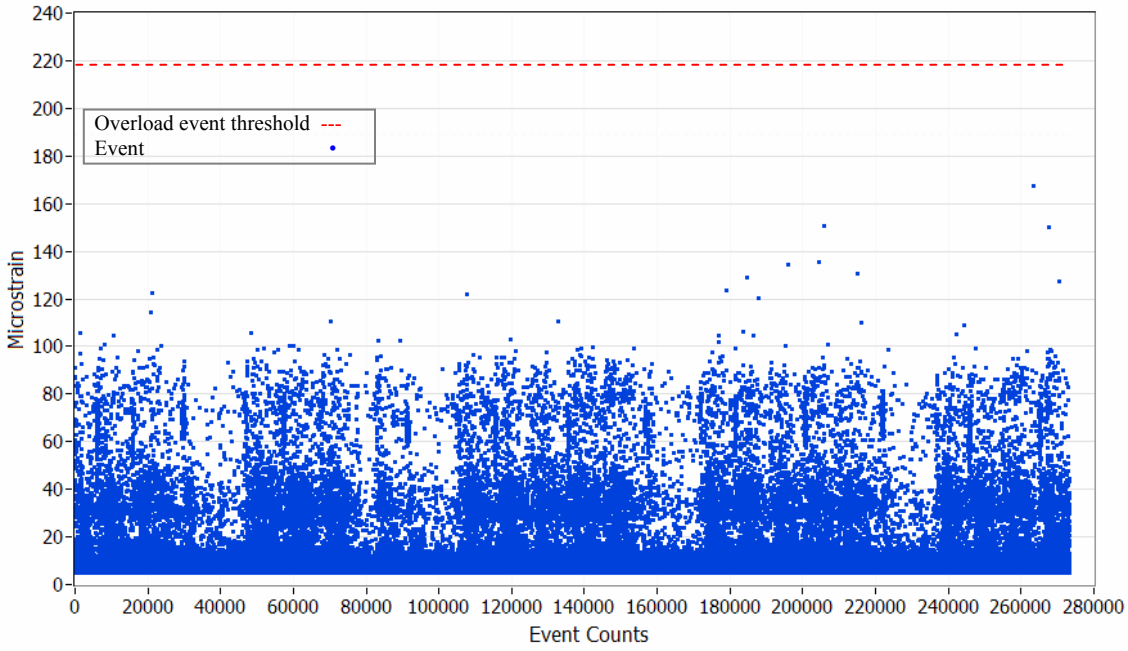
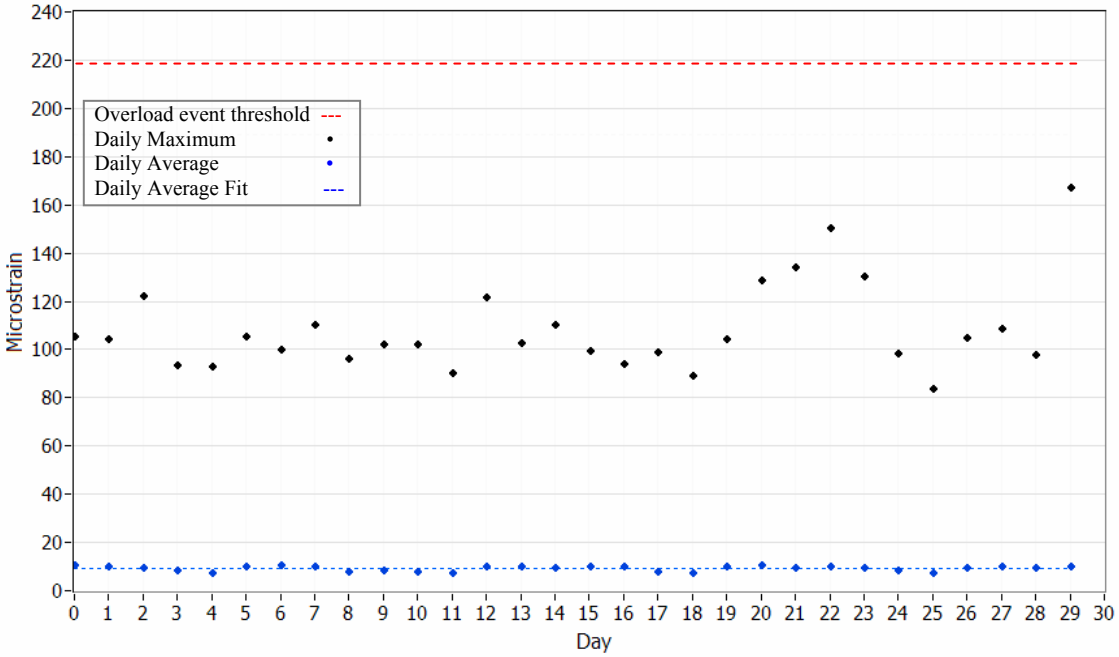


(o) 30-day event history for Sensor 8



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

Figure 3-37. (continued).

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identified events exceeded the overload and/or impact event thresholds that were set. Therefore, no alarm event is listed in the evaluation report (see Appendix I).

- The magnitudes of the daily maximum events, as presented in Table 3-5 and Fig. 3-37, fluctuate 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 events. 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 Fig. 3-37, 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. For reliable estimation or prediction of change in bridge performance, the bridge should be monitored for sufficient period of time and the contents in the evaluation reports should be thoroughly investigated and correctly interpreted.
- 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); fewer events were identified in the north stringers than those in the south stringers.
- From reviewing the number of identified events in Table 3-6 and Fig. 3-37, relatively fewer events were identified from the sensors installed on the stringers than on the plate girders. One possible reason could be the event 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.
- Comparing the numerical counts of identified events in the stringers, fewer events were identified in the center span (Sensor 2 and 3) than in the west end span (Sensor 6 and 7). This

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may be due to the fact that the sensors installed on the stringers in the west end span are close to the floor beam as previously shown. As mentioned before, the stringers are intermittently supported by the transversely placed floor beams which are then supported by the longitudinal plate girders. It appears as though these floor beams provide additional stiffness in the vicinity and/or support-like resistance (like elastic vertical springs) to the stringers. Consequently, measured strains in the stringers (Sensors 2 and 3) in the center span are smaller than those in the west end span and less likely exceed the event detection thresholds. Therefore, fewer events were identified.

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 Figs. 3-38 and 3-39. After reviewing and comparing the histograms, several observations were made as follow:

- 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 night time.
    - 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.

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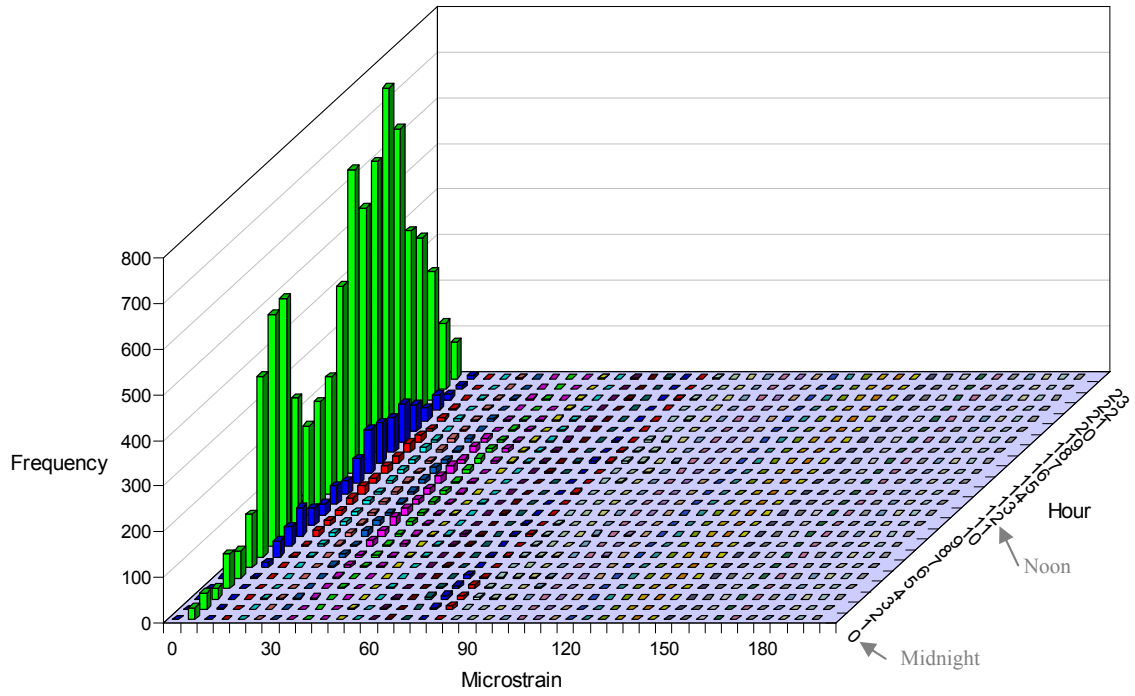
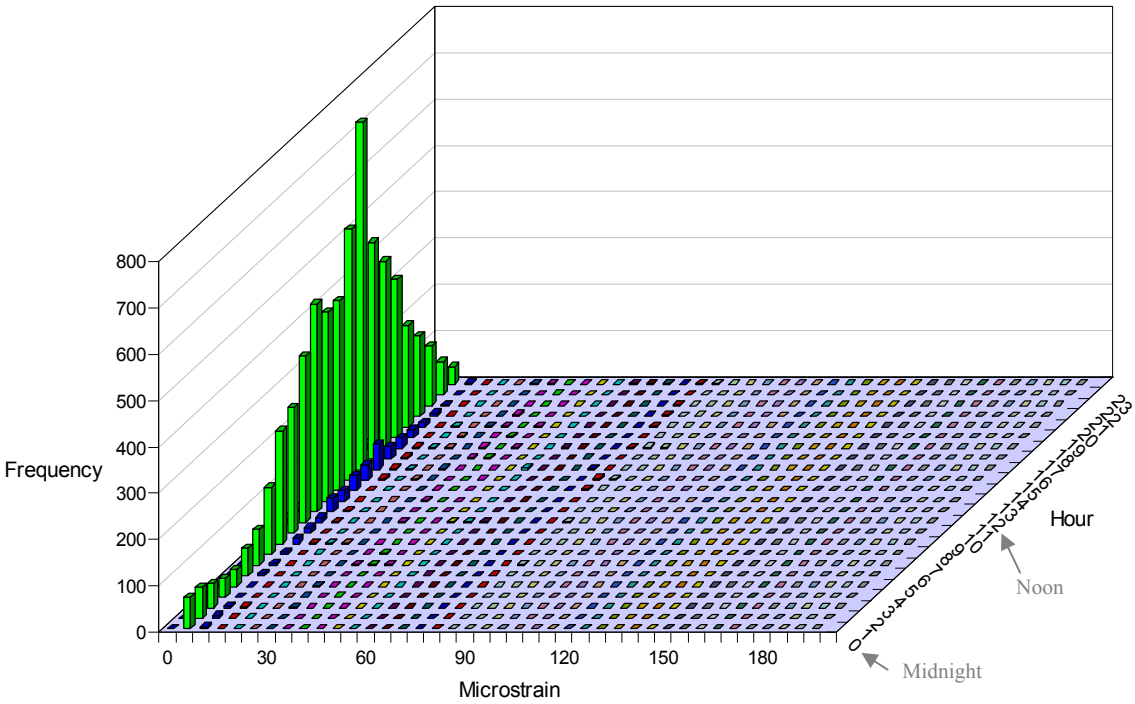


(a) Hourly event histogram for Nov. 16th (Thursday), 2006



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

Figure 3-38. Hourly event histograms of typical weekday and weekend day for Sensor 4 (bin width: 5 microstrain).

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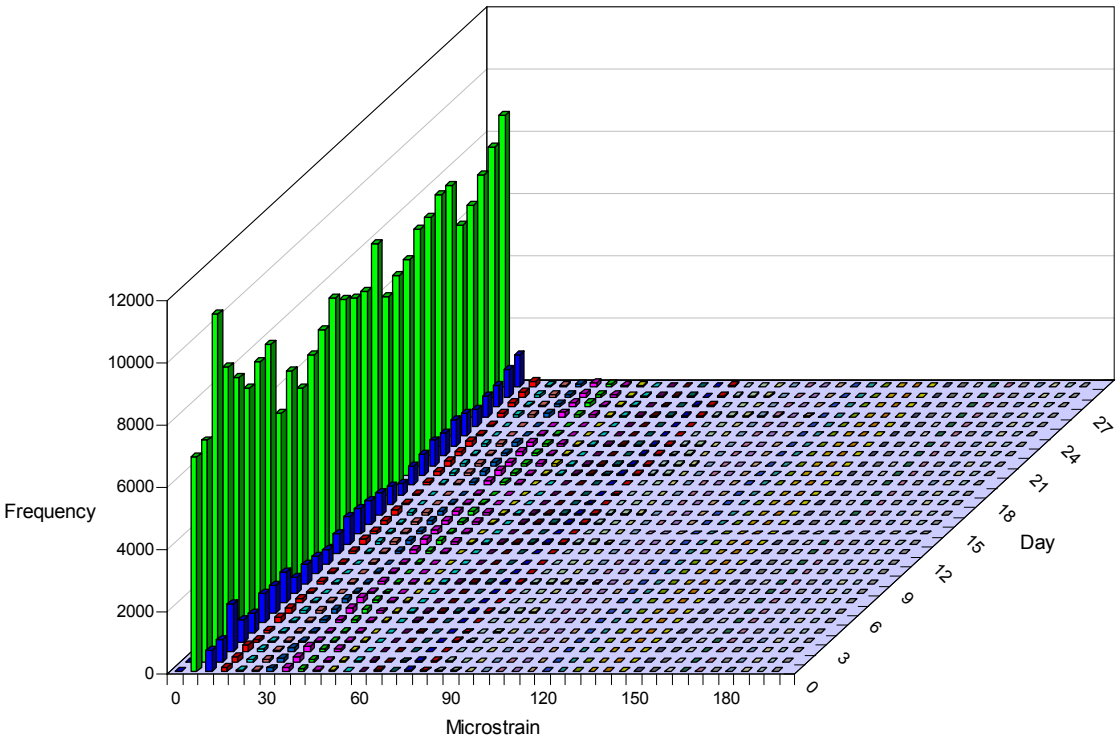
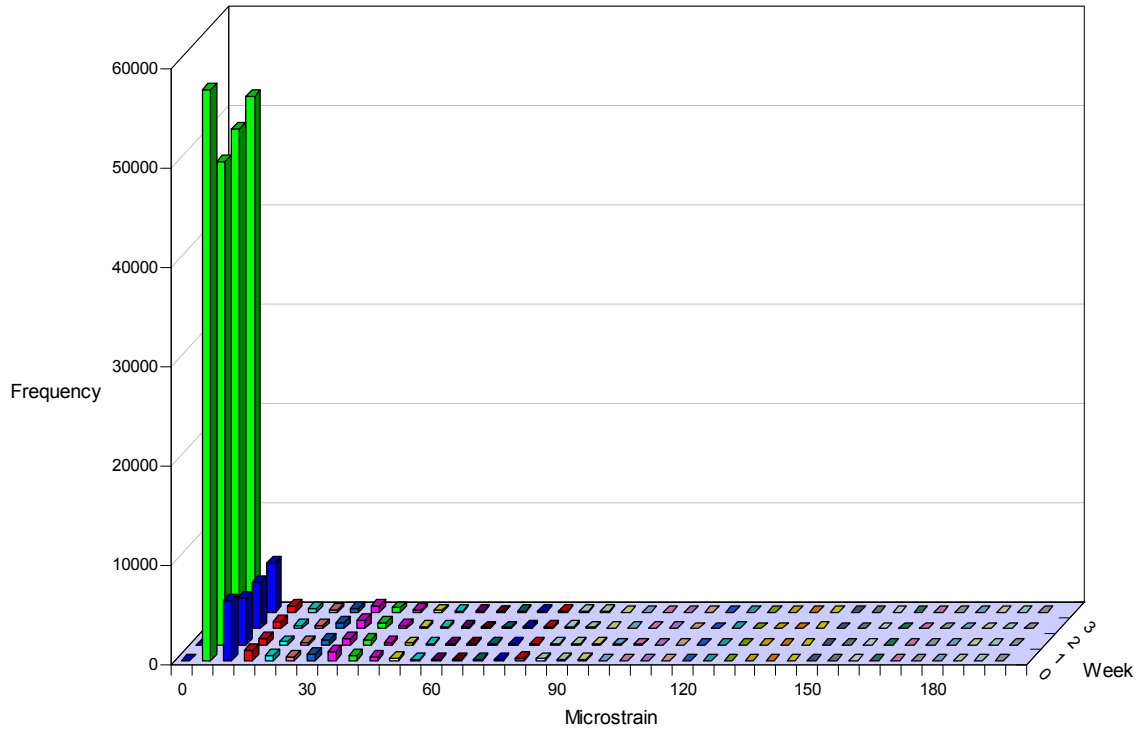


(a) Daily event histograms (Nov. 14th 3 pm through Dec. 14th 3 pm, 2006)



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

Figure 3-39. Daily and weekly event histograms for Sensor 4 (bin width: 5 microstrain).

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

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

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Table 3-6. Number of identified events (bin width – 20 microstrain).

Sensor\ Min. bin	0	20	40	60	80	100	120	140	160	180	200	Total
1	137849	8093	2456	271	452	56	5	1	1	0	0	149184
2	32836	5971	34	2	0	0	0	0	0	0	0	38843
3	38967	8773	223	3	1	0	0	0	0	0	0	47967
4	245901	8469	4899	2018	2133	199	12	5	1	0	0	263637
5	95521	7369	630	500	163	7	2	1	0	0	0	104193
6	92610	9170	1331	296	5	2	0	0	0	0	0	103414
7	191547	10198	5769	594	13	4	0	0	0	0	0	208125
8	256114	10187	3603	2600	919	22	9	2	1	0	0	273457

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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

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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 are 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

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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 cost, development, installation, and the overall performance of the SHM system:

- The developed low-cost SHM system is suitable for implementation of typical girder bridges. Excluding the communication and power equipments and 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.

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- 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: DESCRIPTION ON CONTROLS AND INDICATORS AND PRINCIPLE PROCEDURES IN *BEC ANALYSIS*

A1. Description on Controls and Indicators in *BEC Analysis* **200**
A2. Principle Procedures in *BEC Analysis* **206**

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A1. Descriptions on controls and indicators 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.

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#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.

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#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.

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#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.

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#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.

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#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.

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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.

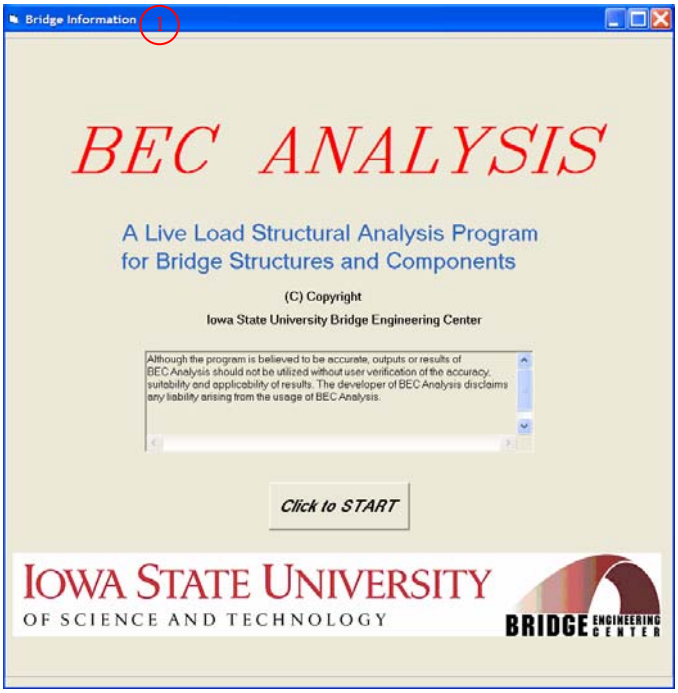

Figure A-1. *BEC Analysis* title screen on Bridge Information window.

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.

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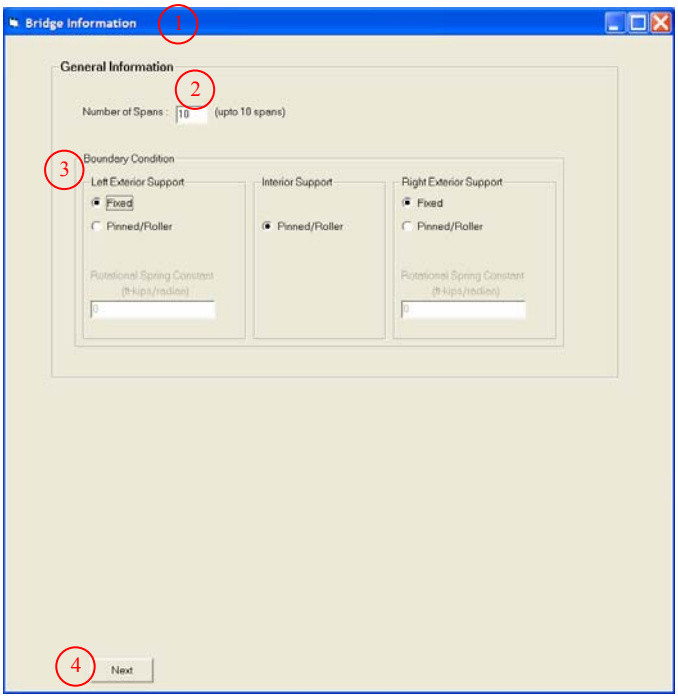

Figure A-2. General information options on Bridge Information window.

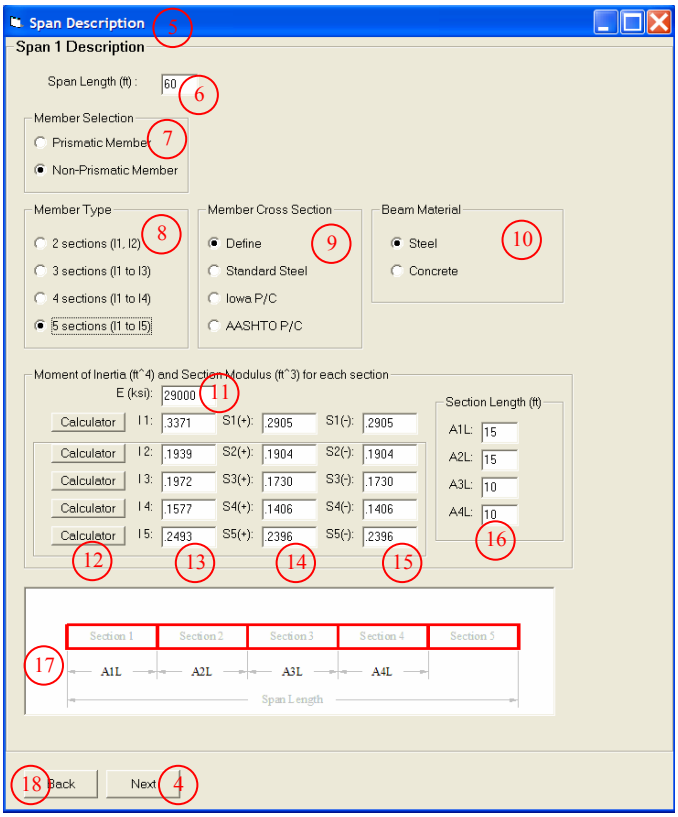

Figure A-3. Span Description window.

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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*.

- 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.

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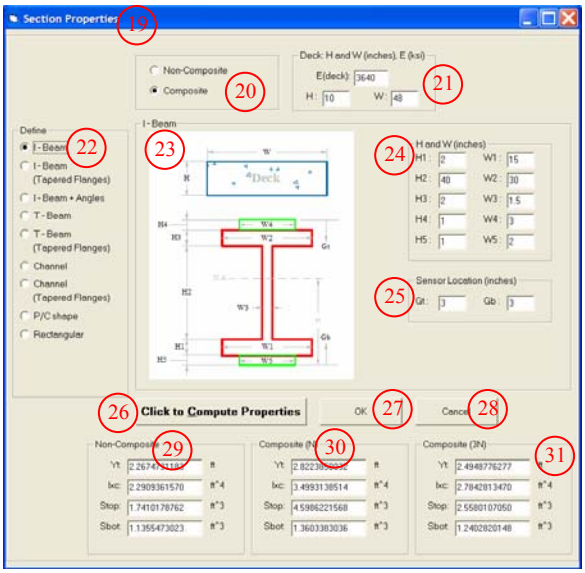
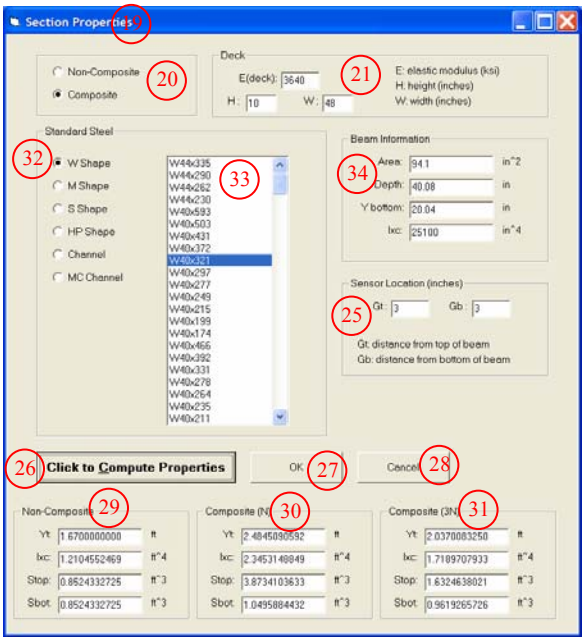


(a) Section properties for 'Define' option



(b) Section properties for 'Standard Steel' option

Figure A-4. Section Properties window.

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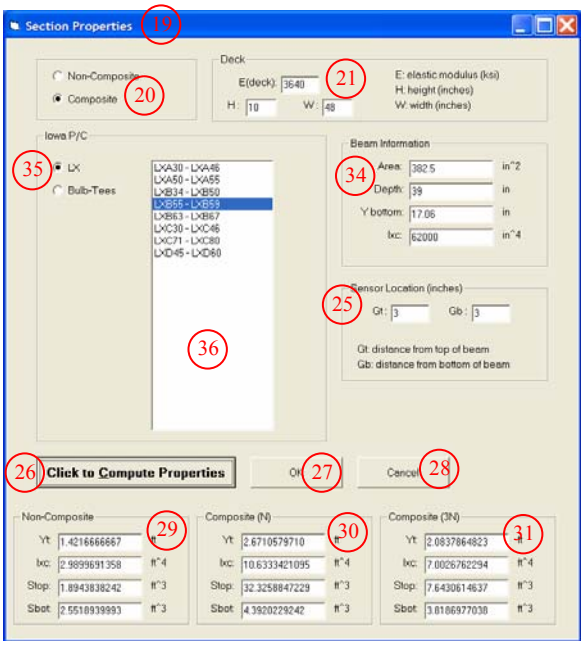
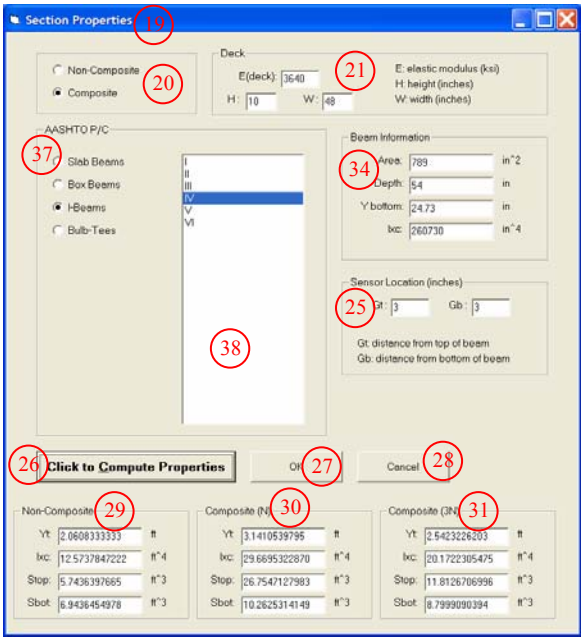


(c) Section properties for 'Iowa P/C' option



(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.

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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).

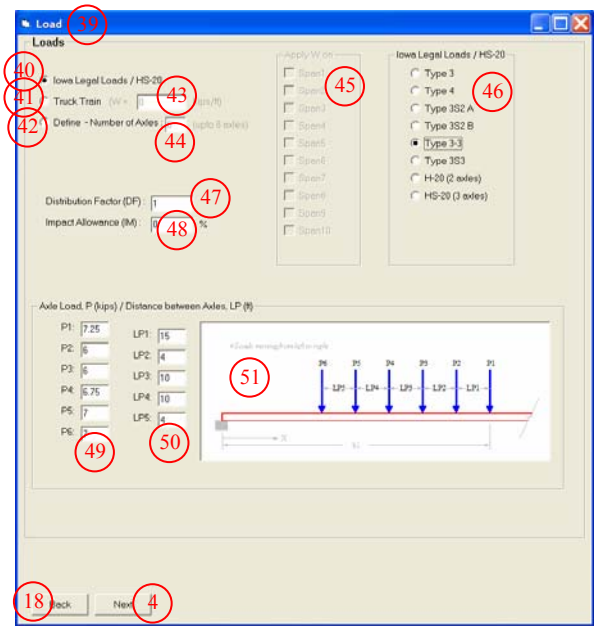

Figure A-5. Load window.

- 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).

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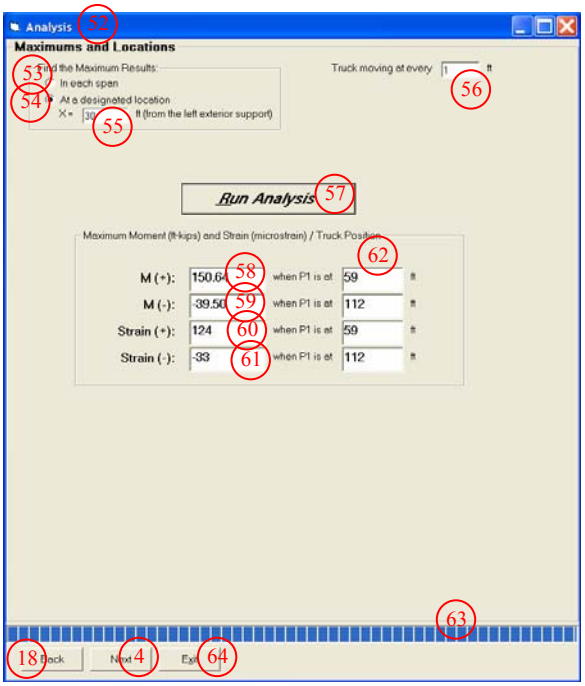
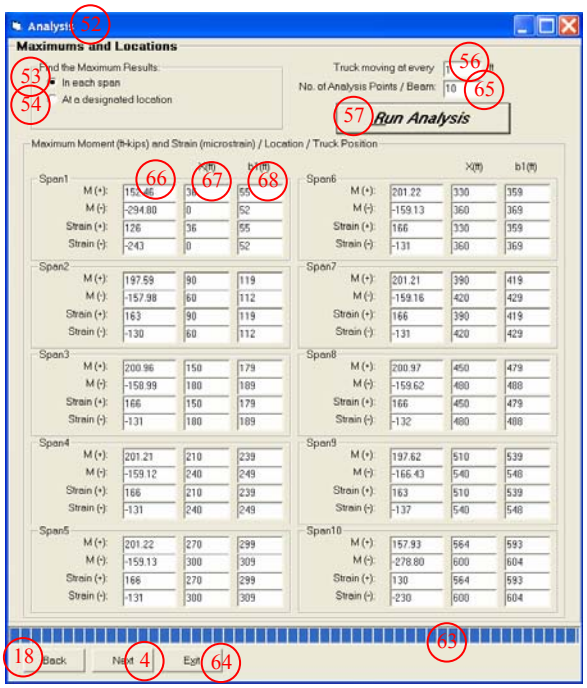


(a) 'At a designated location' option



(b) 'In each span' option

Figure A-6. Analysis window.

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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 envelops.

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.

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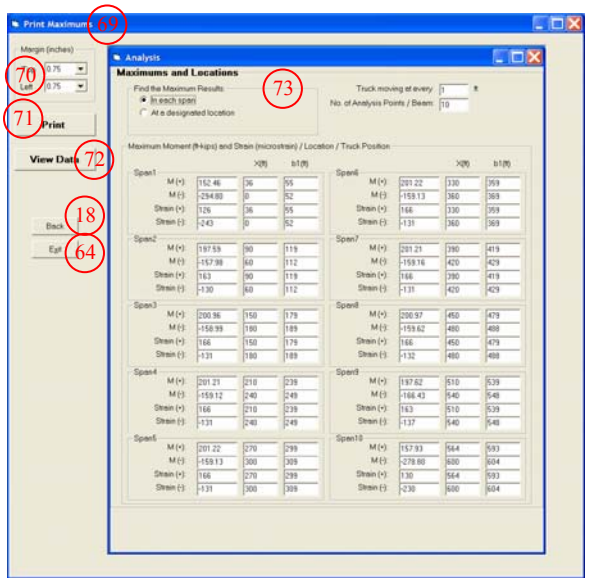
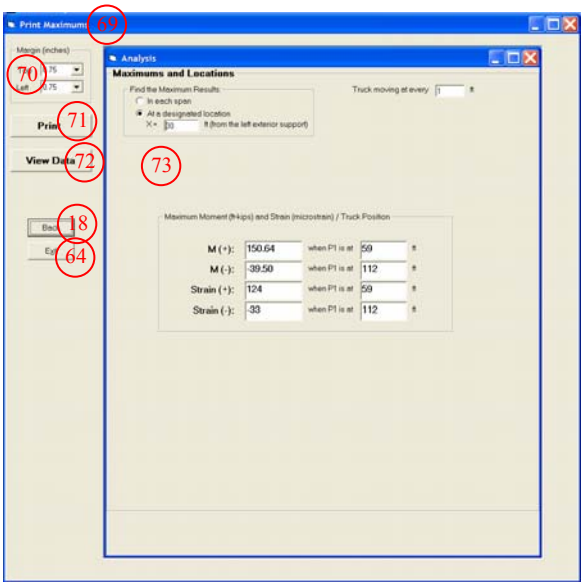


(a) When 'In each span' option is selected



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

Figure A-7. Print Maximums Window.

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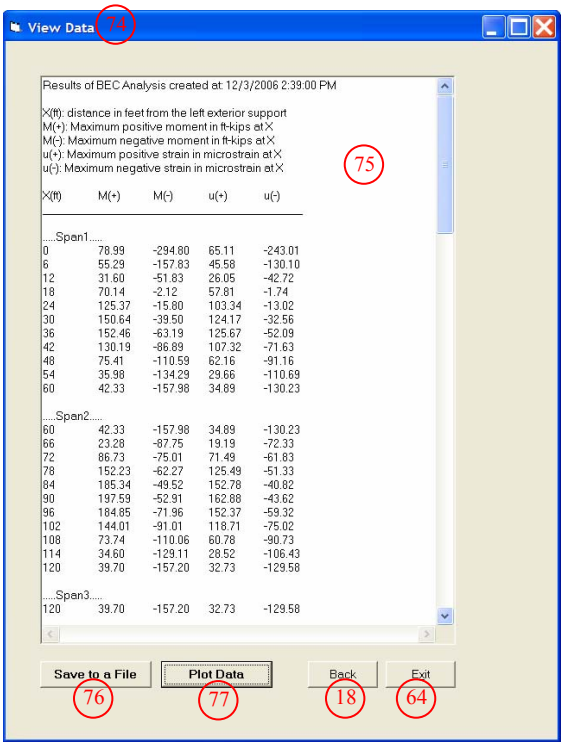
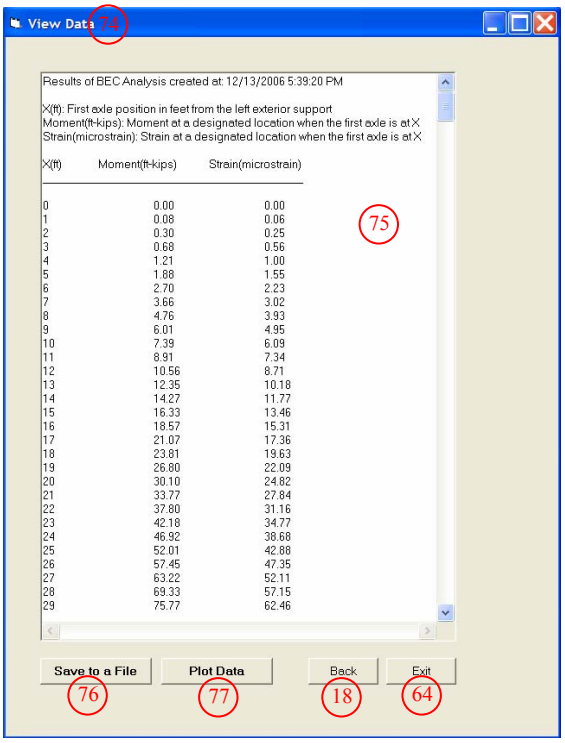


(a) When 'In each span' option is selected



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

Figure A-8. View Data Window.

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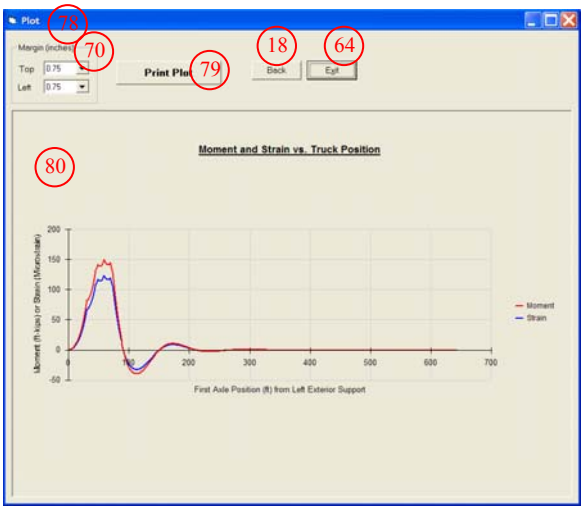
(a) When 'In each span' option is selected



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

Figure A-9. Plot Window.

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APPENDIX B: SYSTEM REQUIREMENTS, *IOtech* SOFTWARE INSTALLATION, HARDWARE SYSTEM SETUP, BRIDGE CONFIGURATION AND SENSOR CALIBRATION

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B1.1 System Requirement 218

B1.2. IOtech Software Installation 219

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B2. Bridge Configuration (*) 231

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B3a. Sensor Calibration Example 246

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

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B1. Setup and Connecting to the Ethernet

B1.1. 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**

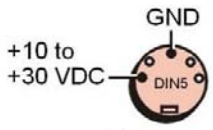
In addition, verify that your computer meets the following **minimum** requirements.

- **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.



Power Input
DIN5 Connector

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.

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B1.2. 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*.

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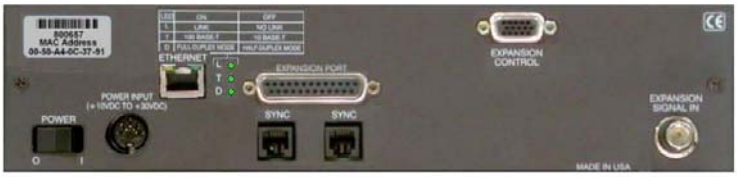
B.1.3. Ethernet Connection and System Power-up

Ethernet Connection and System Power-up

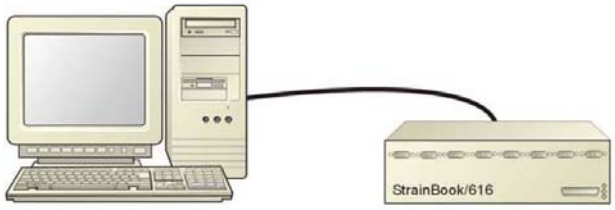
Ethernet connectivity can only be used with Windows NT, Windows 2000, or Windows XP operating systems.

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.)

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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.

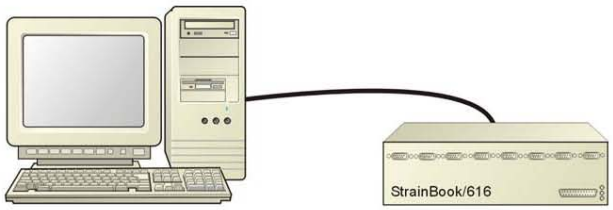
The four network types are as follows:

- **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

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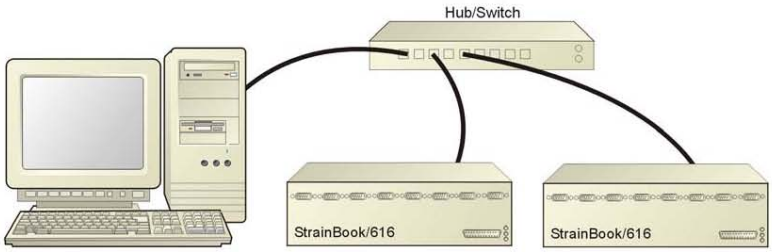
Dedicated Network - making use of a network hub or switch

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.

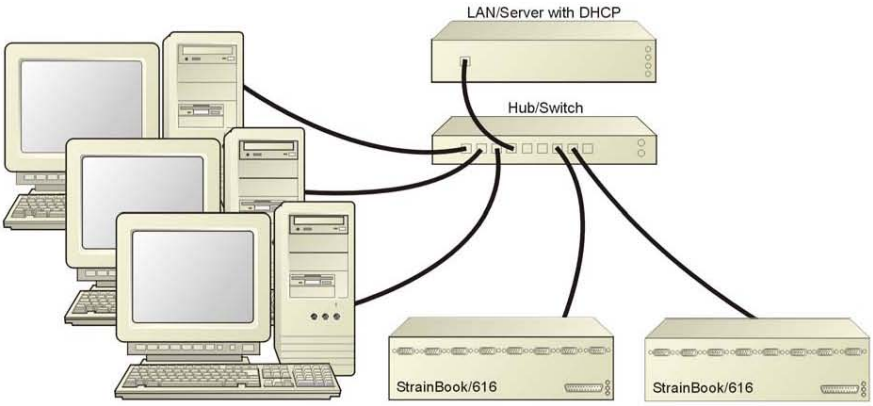


Dedicated Network using a Hub/Switch

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.

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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.

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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.

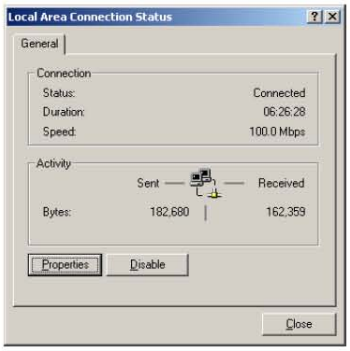
STEP 5 - Configure the Computer's Network Settings [Applies to "dedicated networks" only]

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

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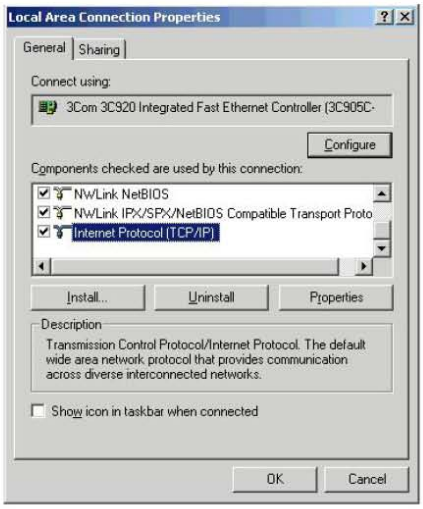
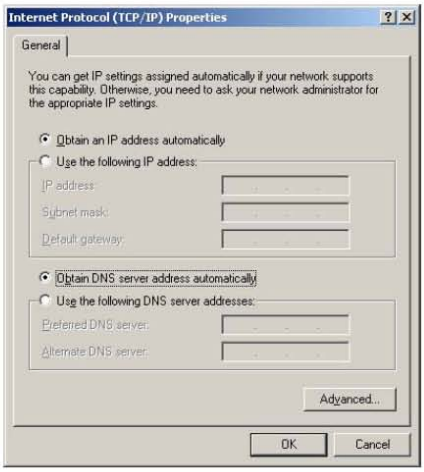
4. In the "Local Area Connection Status" box (previous figure), click on the <**Properties**> button. The "Local Area Connection Properties" box will appear (following figure).



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

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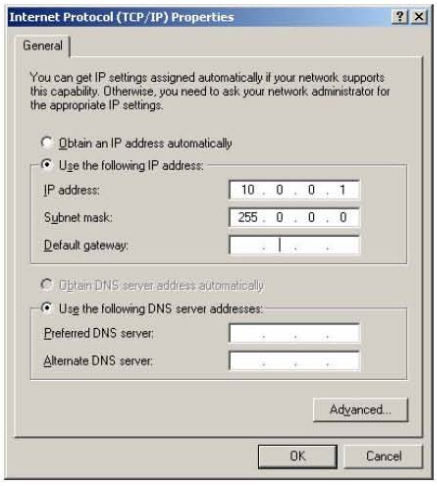
Configure the Computer's TCP/IP settings as follows.



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.

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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.***

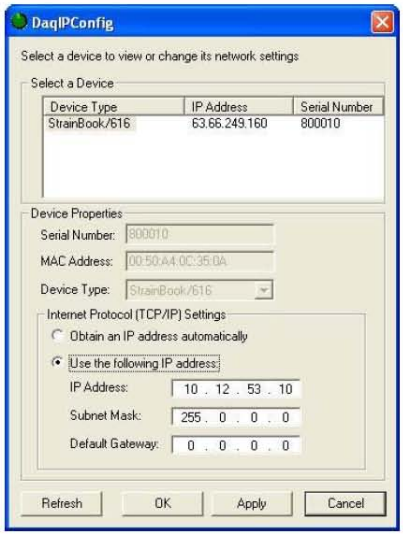
   Note: In the above figure there is only one device to select, i.e., StrainBook/616.

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.

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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.

a. Open the Control Panel by navigating from the Windows' Desktop as follows:
Start Menu ⇒ Settings ⇒ Control Panel

b. From the Control Panel, double-click the ***Daq Configuration*** icon.

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

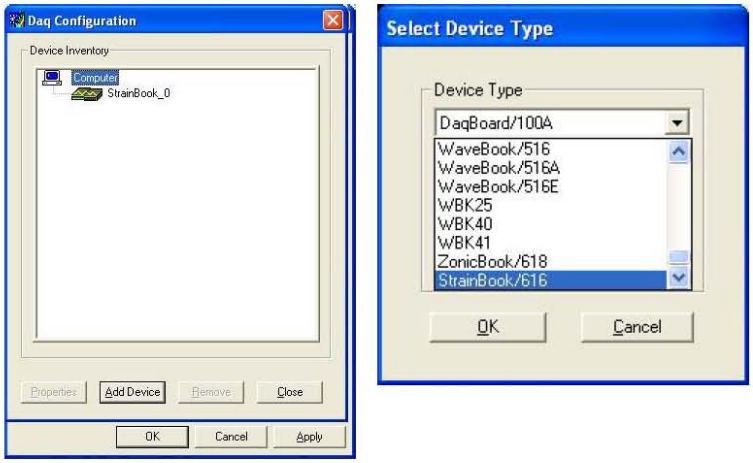
The first-level device is the device that will be connected directly to the Ethernet, via a host computer's Ethernet jack or a jack on a network hub. The StrainBook/616 is an example of a first-level device.

a. Select the Computer image in the Device Inventory configuration tree (following figure).

b. Click the <**Add Device**> button. The "Select Device Type" box will appear.

c. Select the StrainBook/616 from the list of devices, as applicable.

d. 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

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

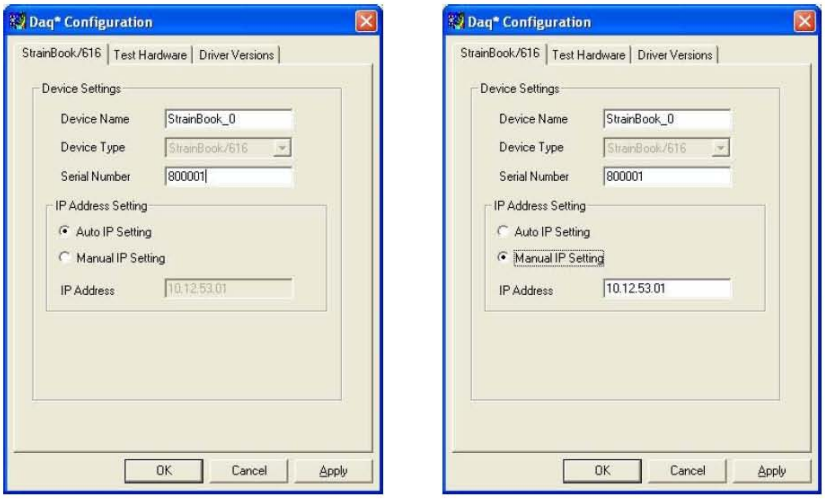
In this step you will set the device properties according to one of the following two methods, depending on whether you have a "Dedicated Network" or a "LAN with DHCP Server Network."

Users of Dedicated Networks follow these 2 steps.

a. Enter the **Serial Number** of the first-level device (StrainBook/616). In the following screen shots the Serial Number is 800000.

b. 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.

c. 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.

a. Enter the base 10 version of the **Serial Number** of the StrainBook/616.

b. Select the "**Manual IP Setting**" radio button.

c. In the **IP Address** field, enter the IP address.

d. 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.

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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.

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B2. Bridge Configuration

Bridge Configurations 6

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Three-Wire Quarter-Bridge 6-10
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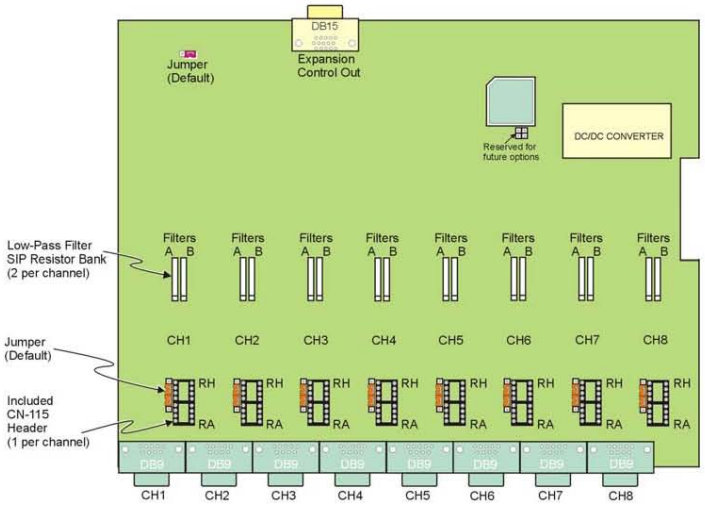
CA-177 Strain Gage Cable 6-12
CA-189, DB9 Adapter Option 6-13
WBK16/LC Load Cell Shunt Cal Internal Option 6-15
CN-115-1 User-Configurable Plug-In Card Option 6-20

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

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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

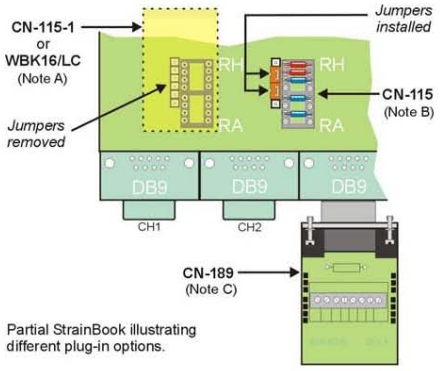
Each channel has a CN-115 2x8 resistor socket header and two associated jumpers (JP101 and JP102) located on the StrainBook's main board. The jumpers, associated with a given channel, must be installed if a CN-115 will be used for that channel. The associated jumpers must be removed if a CN-115-1 or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

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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.

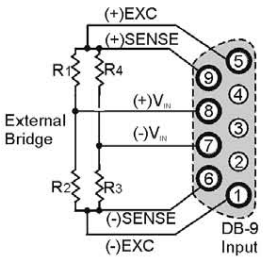
Each of the 8 input channels has locations for five bridge-completion resistors. These BCR's are for use with *quarter* and *half-bridge* strain gages. The resistors make up the fixed values necessary to complete the 4-element bridge design.

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 KΩ, and 0.25-watt resistors. Lower values will dissipate more power and add heat. Values >1KΩ 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 MΩ 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.

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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.

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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 MΩ resistors are also connected where the jumpers would be located to prevent circuit discontinuities. These 1 MΩ 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 kΩ; 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:

$$R_{Shunt} = R_{Bridge\ Arm} \left[\left(V_{Excitation} / 4\,(V_{out}) \right) - 0.5 \right]$$

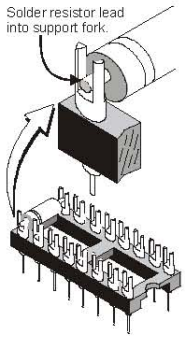
$$R_{Shunt} = 350 \left[\left(10 / 4(0.020) \right) - 0.5 \right] = 43{,}575\Omega$$

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 2×8 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.

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



Soldering Resistors to Adapter Plug

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.

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Installing a CN-115

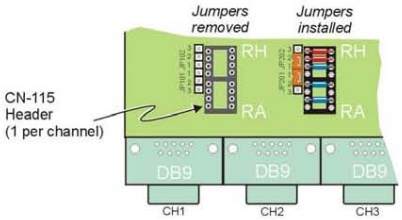
CAUTION
Remove the StrainBook from power and disconnect the unit from the host PC and from all externally connected equipment prior to connecting cables, signal lines, and/or removing the cover to install or remove components. Electric shock or damage to equipment can result even under low-voltage conditions.
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.

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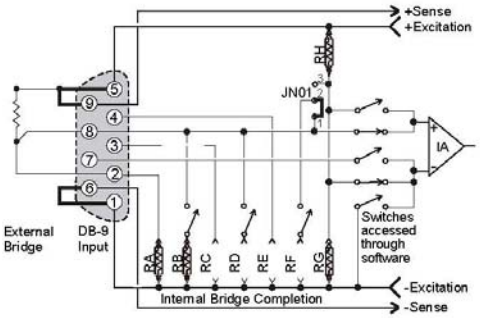
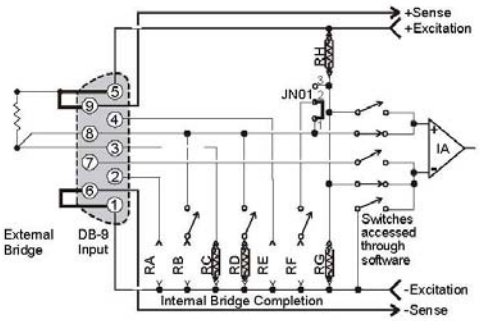
Three-Wire Quarter-Bridge Configurations

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.



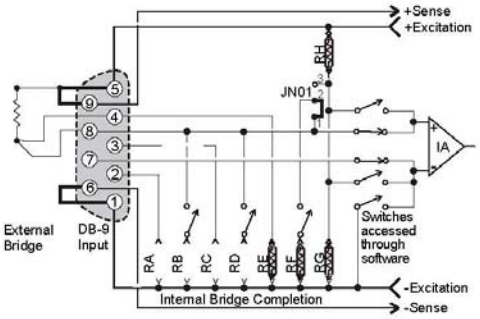
Three-Wire Quarter-Bridge (+), Using RA (120-Ohm nominal), B Shunt Resistor

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.

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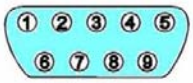

*Cable Pinout**

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 1	Brown wire		
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.

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.

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.

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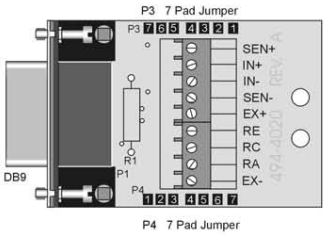
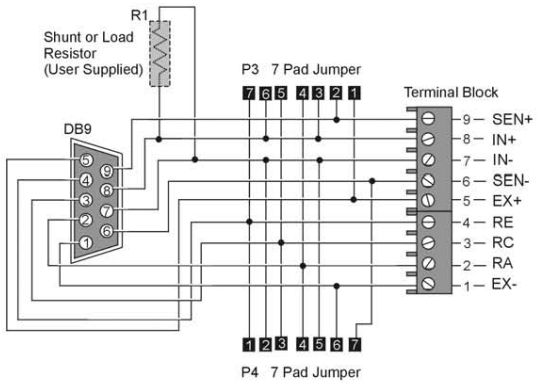


CN-189 DB-9 Adapter Option

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 .

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B3. Sensor Calibration

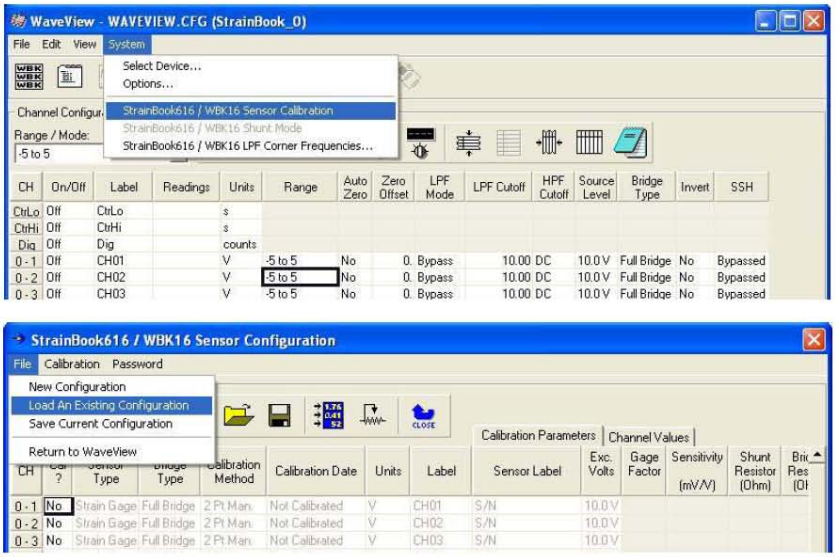
Sensor Calibration

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)

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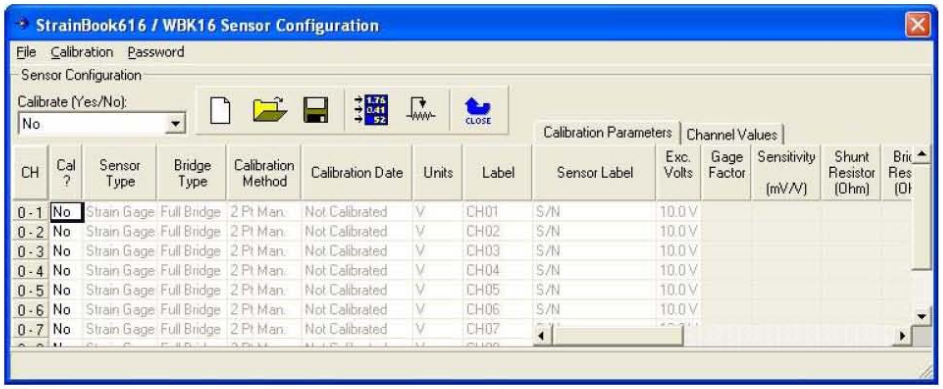
To open the Sensor Configuration [Calibration] window, click on WaveView's **Sensor Calibration button**. The button is depicted at the left and pointed out in the upper portion of the previous figure. You can also open the window from WaveView's **System pull-down menu**.

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.

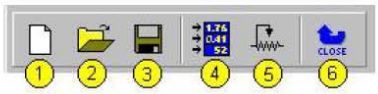
Sensor Configuration Main Components



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

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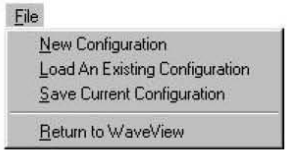
File

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 *Sensor Configuration* 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 *Sensor Configuration* 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.

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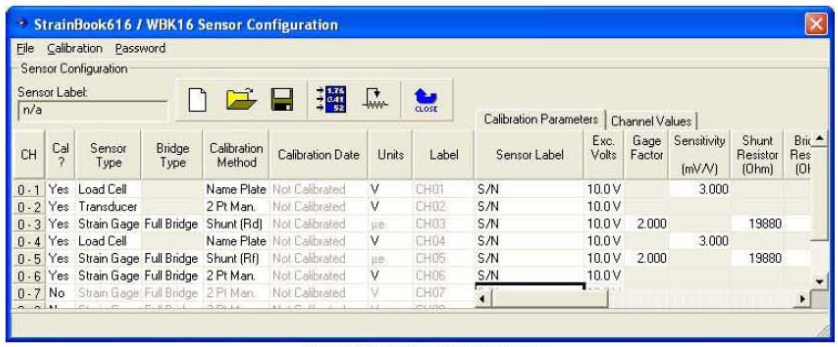
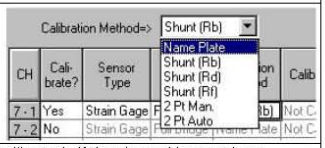
Calibration Parameters Tab Selected



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 *Sensor Configuration* 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. 
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 *WaveView Configuration* 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).

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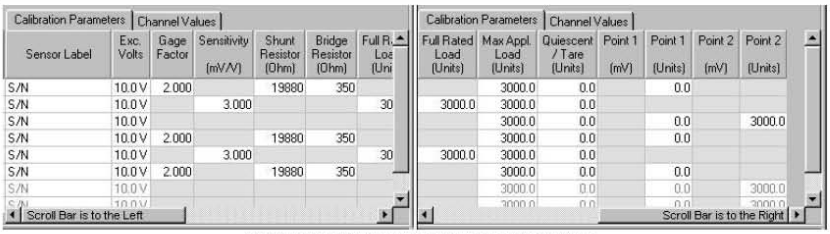

Calibration Parameters Section of Window
Two Views Obtained by Scroll Bar Movement

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).

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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 με is connected to a StrainBook [or WBK16 channel]. The gage will be used in an environment were the expected range of measurement is limited to -200 to +1000 με. This gage [in its quiescent state] has a 500 με 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:

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

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B3a. 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. B-1 and B-2 are as follows:

i. 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.

ii. Go to 'File' and select 'New'.

iii. Under 'On/Off' column (#1), select channels to be activated (i.e., switch to 'On').

iv. Click 'Hide Inactive Channel Rows' (#2) to have only activated channels displayed.

v. Select 'mV' (#3), '-30.3 to 30.3' (#4), '5V' (#5), and '1/4 Bridge' (#6) for all activated channels as illustrated in Fig. B-1.

vi. Click 'Calibration' (#7) which will open up a window, 'StrainBook616/WBK16 Sensor Configuration' shown in Fig. B-2.

vii. 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): ¼ 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

viii. Click 'Calibration Enabled Channel' (#18) to calibrate the selected channels.

ix. Once the calibration is completed, click 'Close' (#19) and save the calibration file.

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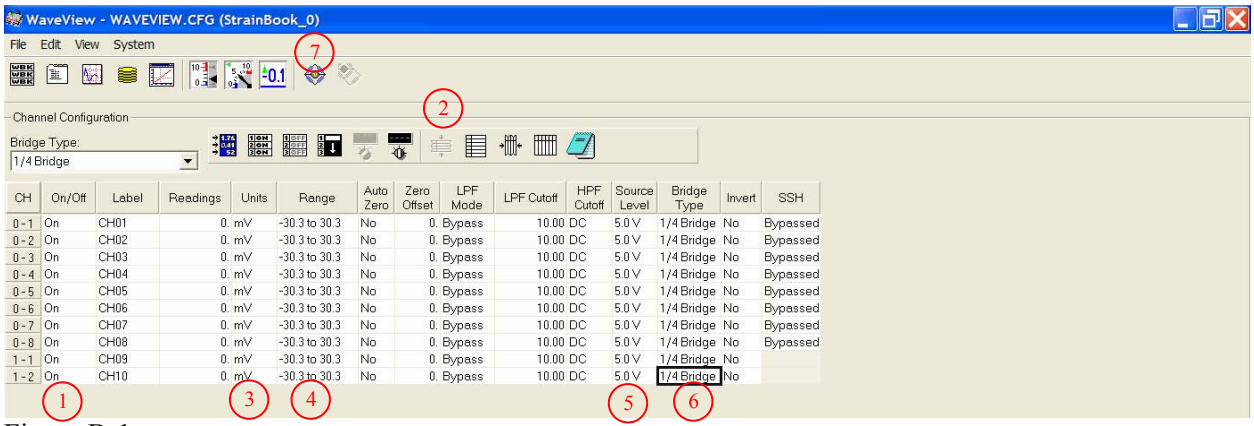

Figure B-1.

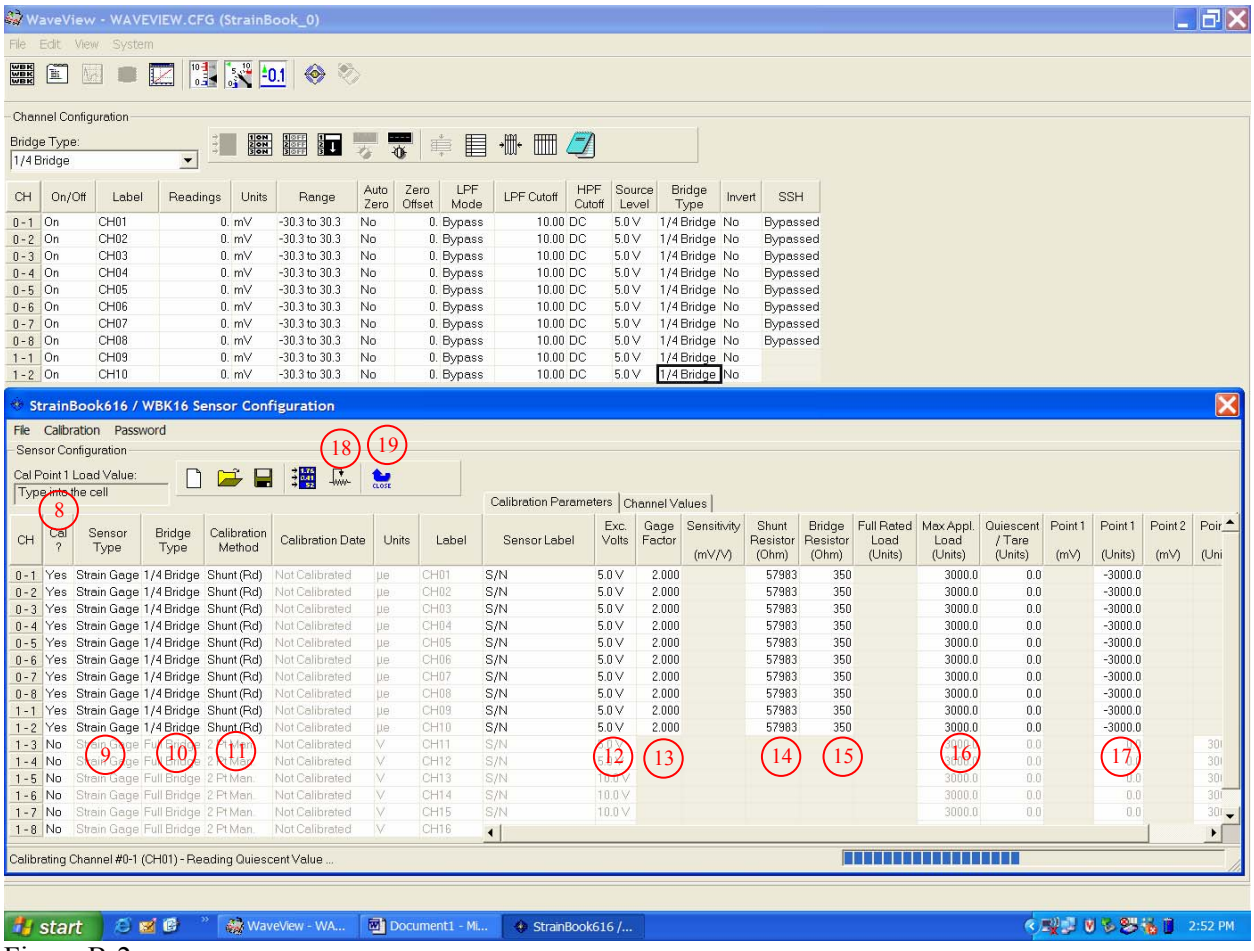

Figure B-2.

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APPENDIX C: PRINCIPLE PROCEDURES AND DESCRIPTION ON CONTROLS AND INDICATORS IN THE FIELD MONITORING SOFTWARE

Principle Procedures in Running the Field Monitoring Software

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C1. *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:

- 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.
- 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.

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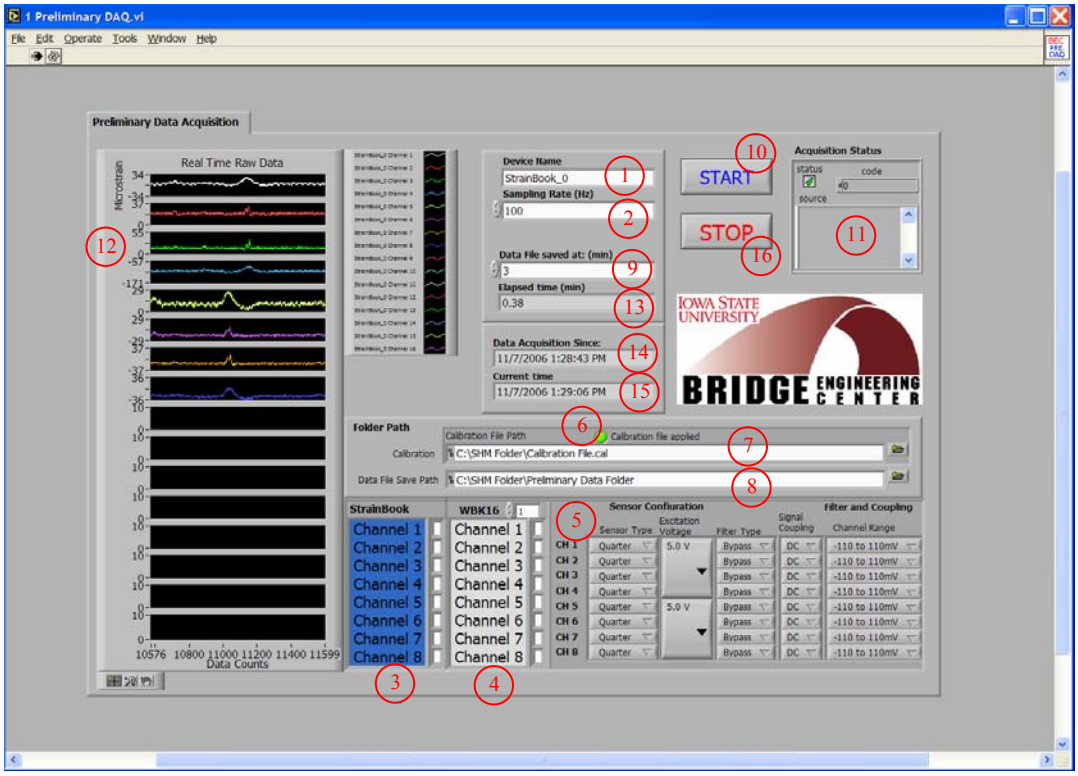

Figure C-1. Screen shot of *1 Preliminary DAQ.VI* front panel.

C2. *2 FFT-PSD Analysis.VI* (shown in Fig. C-2)

i. Select a data file from those that were saved in the 'Preliminary Data Folder' by using the browsing tool in control #1.

ii. 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.

iii. 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.

iv. 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.

v. 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.

vi. 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.

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vii. 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).

viii. Move to the Strain History' tab control (#11) and enter the cutoff frequency determined in step *vii*.

ix. Click the "Plot Strain History" control (#14) to see the effect of filtering for the selected sensor. Indicator #17 will display the strain history.

x. 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.

xi. 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:

xii. Perform the "step *i*" through "step *v*", but this time, select a data file that contains traffic plus noise induced strain.

xiii. Select a sensor with a mouse click within control #8 and move to the 'Strain History' tab (#11).

xiv. Enter three filter parameters (#12) that will be applied to the selected strain data: cutoff frequency (Hz), ripple (dB), and filter order.

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)

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may be necessary to determine the appropriate filter order. The default is set as 2nd order and the order must be an even number.

xv. 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.

xvi. 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.

xvii. 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.

xviii. 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:

xix. 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'.

xx. Repeat "steps *xiii*" through "step *xix*" until the filter parameters and the event detection thresholds have been established for all sensors.

xxi. 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 Paremeters.txt'.

xxii. 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.

xxiii. Click the 'STOP' control (#23) to stop the program.

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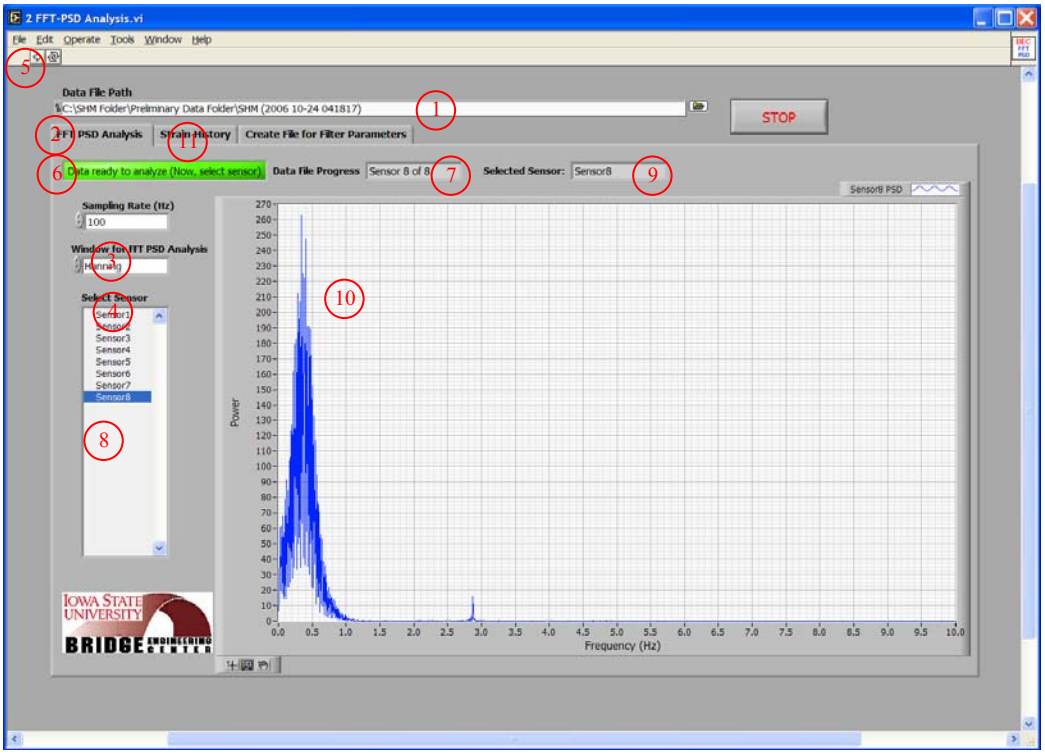
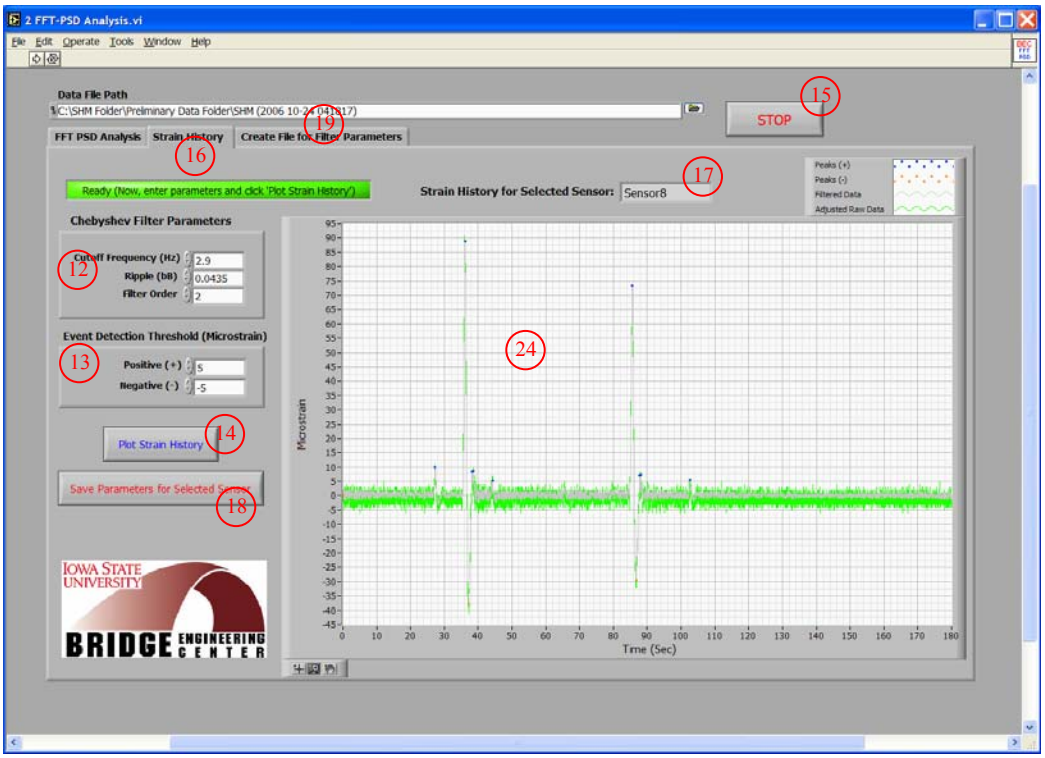


(a) FFT-PSD plot display for the selected sensor



(b) Strain record display for the selected sensor

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

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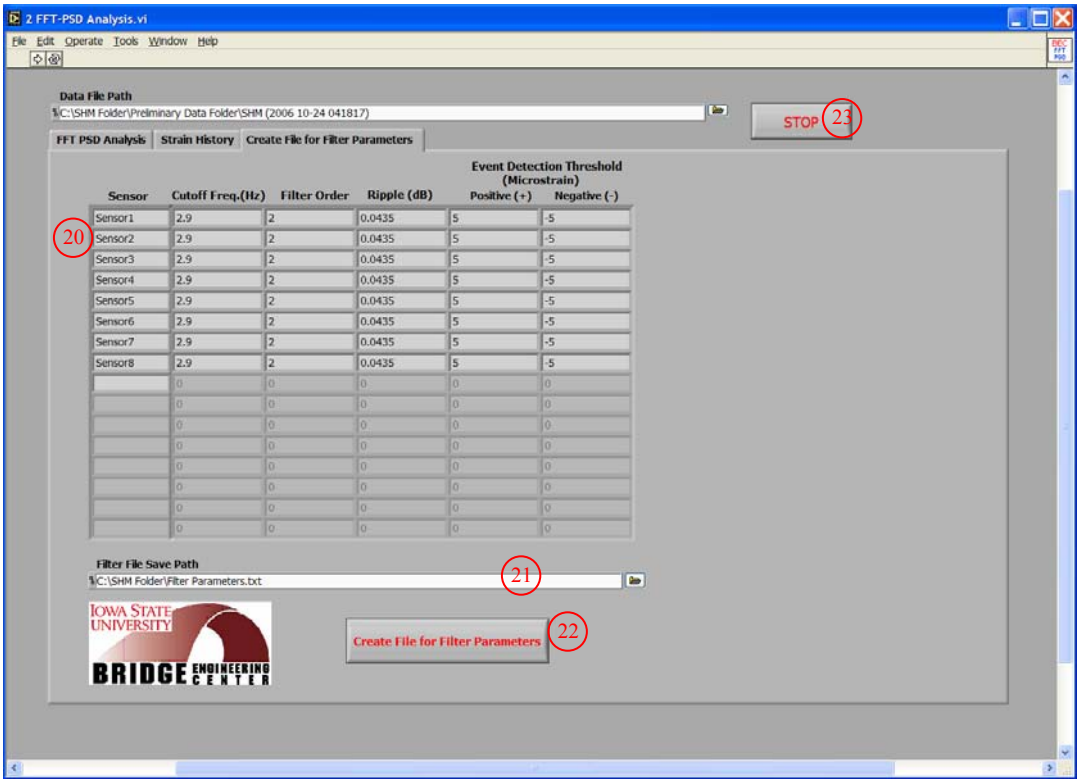

(c) Filter parameters display

Figure C-2. (continued).

C3. *3 Input.VI* (shown in Fig. C-3)

i. 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'.

ii. Configure each channel (#3) based on the type of strain sensor and its setting used.

iii. Enter the device name in control #4. The device name used here must match what was used during the hardware system setup.

iv. Enter the sample rate (#5) at which the data acquisition is to be performed (number of samples per second).

v. 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

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the alarm event (overload or impact, both of which exceed the overload event threshold specified in control #8).

vi. Enter the plus and minus event detection thresholds (#7) that will be applied to the collected strain data.

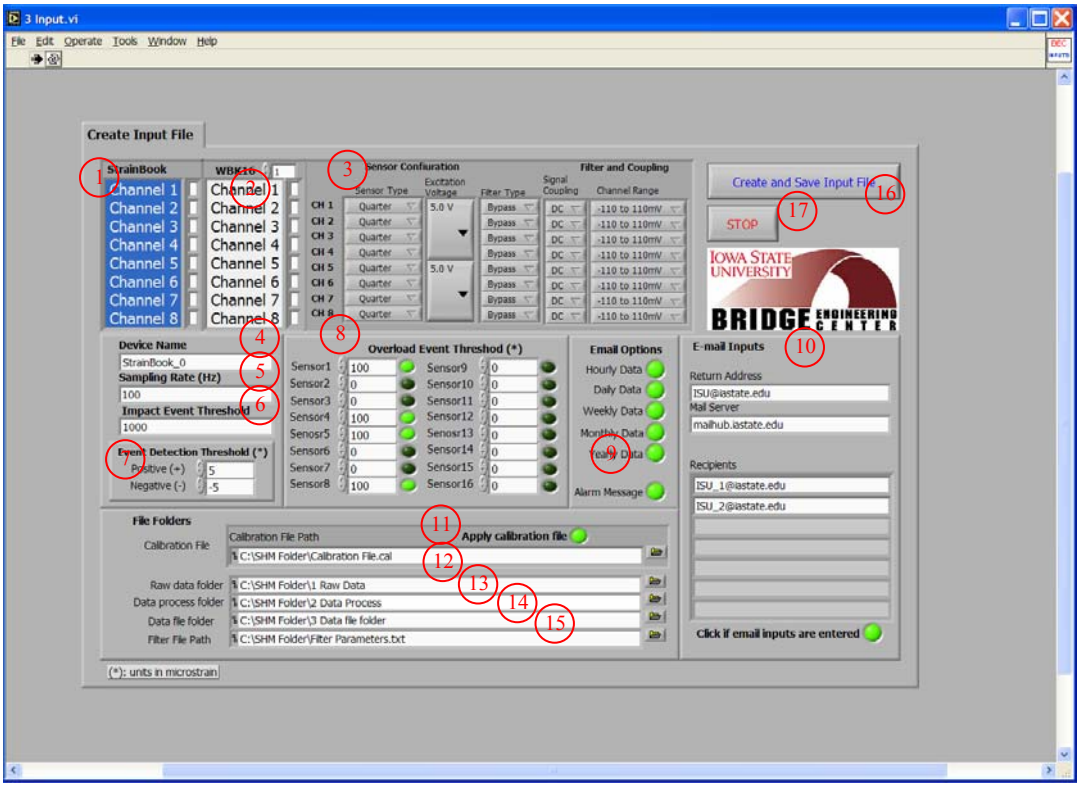

Figure C-3. Screen shot of *3 Input.VI* front panel.

vii. 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 any 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*.

viii. 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:

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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

ix. 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:

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

x. 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.

xi. 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.

xii. 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.

xiii. 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.

xiv. Set the path (#15) for the filter parameters file that contains the peak detection thresholds and filter parameters.

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xv. 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.

Once the input file is created, stop the program by pressing the STOP control (#17).

C4. ***4 MainDAQ815.VI (shown in Fig. C-4)***

i. As soon as 4 MainDAQ815.EXE is installed as a service program, it will be automatically initialized.

ii. 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.

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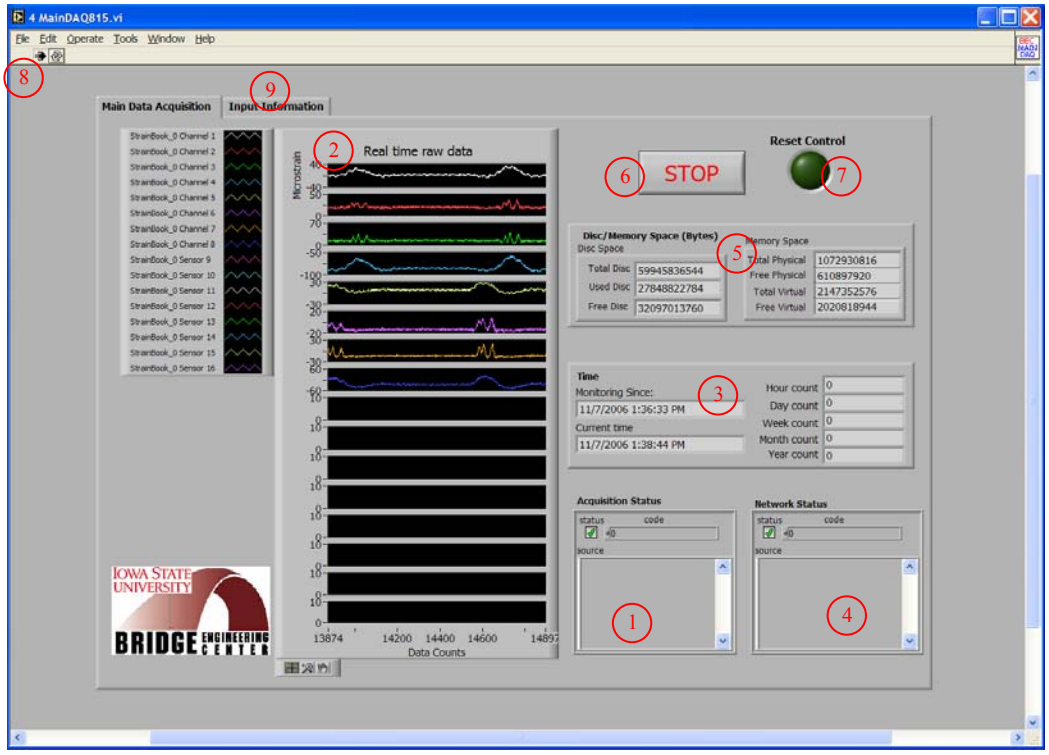
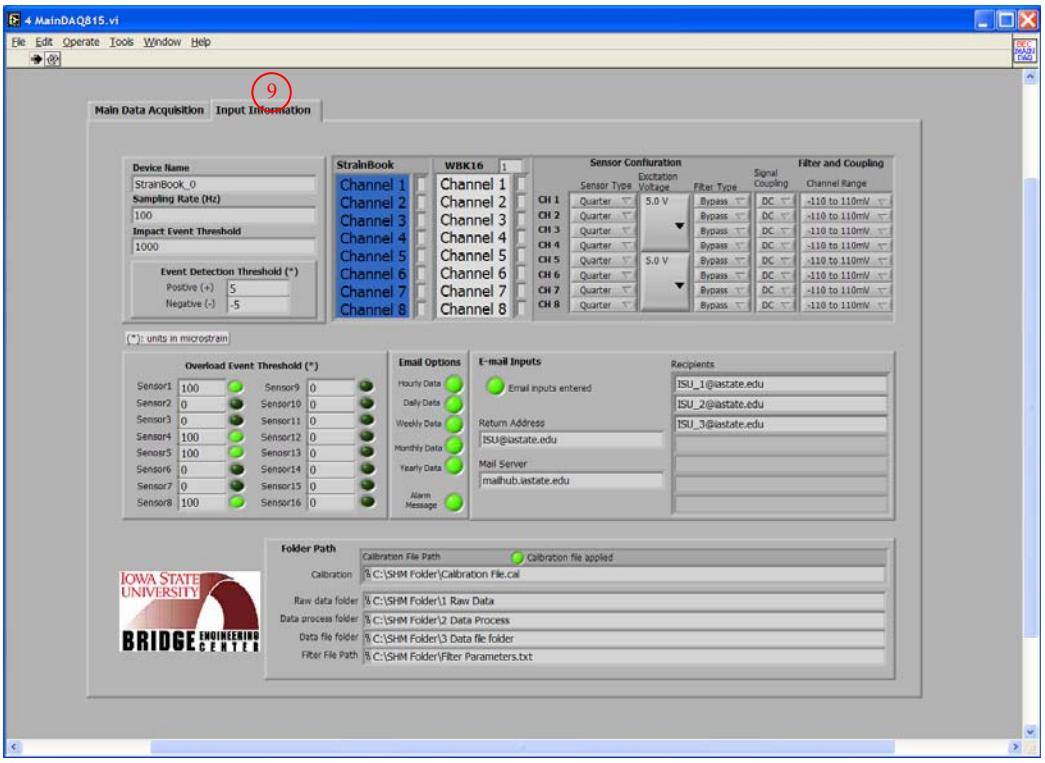


(a) Illustration of Main Data Acquisition tab



(b) Illustration of Input Information tab

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

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- 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).

iii. 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'.

C5. *5 View Strain History.VI* (shown in Fig. C5)

i. Select the data file (#1) that contains collected strain records.

ii. Set the path (#2) to the filter parameters file that contains the event detection thresholds and filter parameters that were previously established.

iii. Enter the sample rate (#3) that was used during data acquisition.

iv. 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.

v. Stop the program by pressing STOP button control (#7).

C6. *6 View Hourly File.VI* (shown in Fig. C-6)

i. 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.

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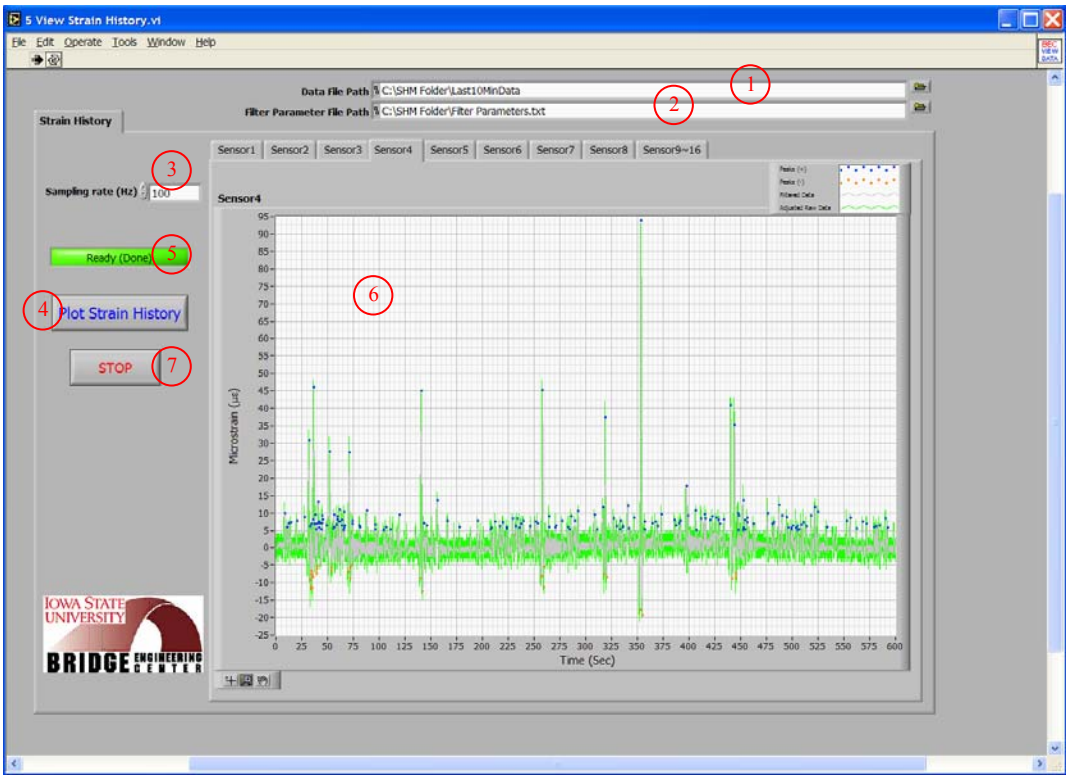

Figure C-5. Screen shot of *5 View Strain History.VI* front panel.

ii. 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'.

iii. To view the data file in an Excel Worksheet, set the LED option (#3) to true (bright green).

iv. 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.

v. 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.

vi. Stop the program by pressing STOP control (#9).

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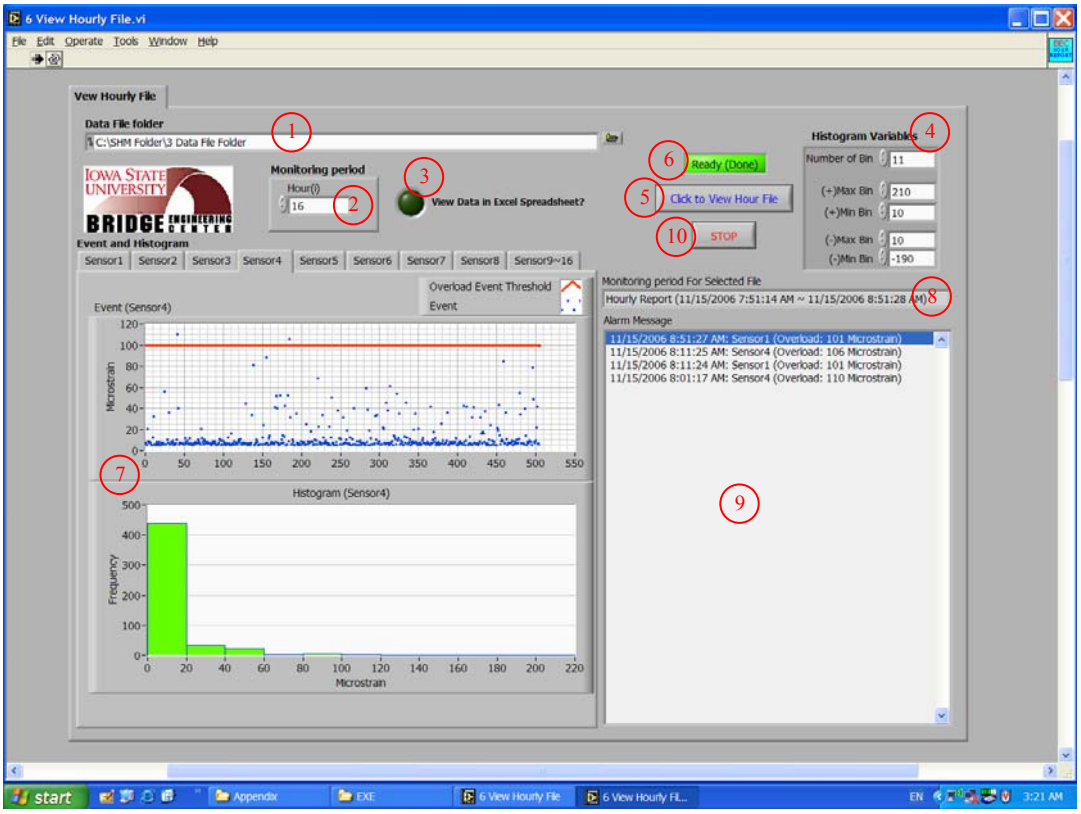

Figure C-6. Screen shot of *6 View Hourly File.VI* front panel.

C7. *7 Create Report (From Single File).VI* (shown in Fig. C-7) and *8 Create Report (From Multiple Files).VI* (shown in Fig. C-8)

i. Select the directory (#1) in which the data files are archived. The default is set to 'C:\SHM Folder\3 Data File Folder.'

ii. 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.

iii. To view the data file in an Excel Worksheet, set the LED option (#3) to true (bright green).

iv. 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

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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.

v. 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.

vi. 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).

vii. 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' 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:

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

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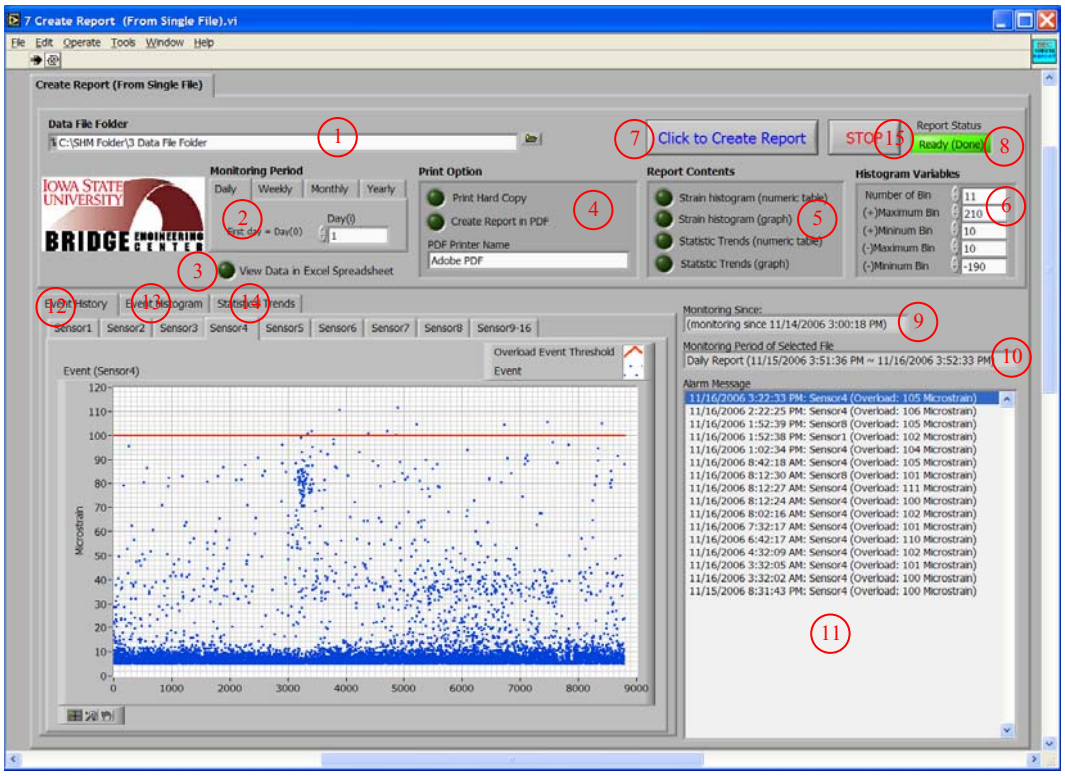

Figure C-7. Screen shot of *7 Create Report (From Single File).VI* front panel.

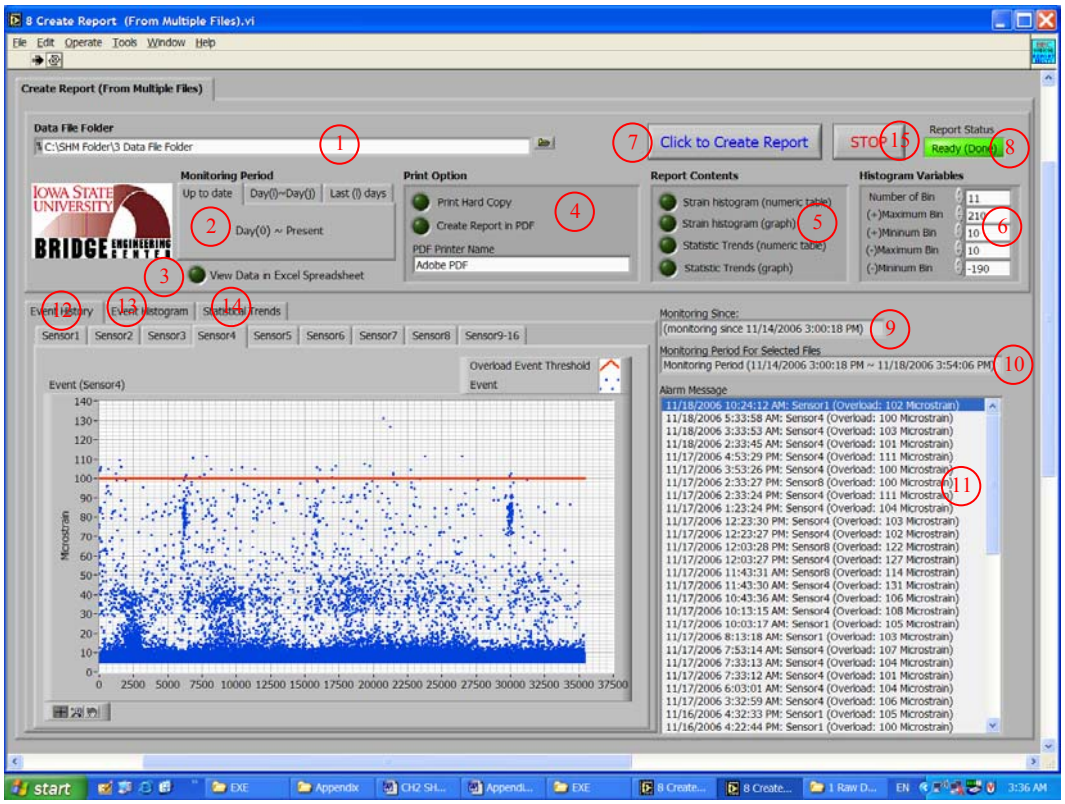

Figure C-8. Screen shot of *8 Create Report (From Multiple Files).VI* front panel.

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Description on controls and indicators

Table C-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 C-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 sample 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.

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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 Threshold Control (Microstrain)**	Plus and minus event detection thresholds within which no peak (or event) will be detected.
14	**Plot Strain History Control**	When pressed, strain history will be displayed in graph indicator #17 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.

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Table C-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.

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Table C-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 C-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).

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Table C-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 C-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 Controls**	Allows users to change the format of histogram plot.
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

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		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).

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APPENDIX D: INSTALLATION OF *4 MainDAQ815.EXE* AS A SERVICE PROGRAM

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i. Install FireDaemon software.

i. Double click on the FireDaemon Service Manager icon (shown in Fig. D-1).

ii. In the FireDaemon Pro Service Manager window, go to 'Select' in the menu bar and select 'New' option as shown in Fig. D-2.

iii. 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).

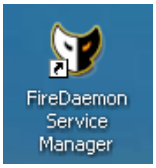

Figure D-1. FireDaemon Service Manager icon.

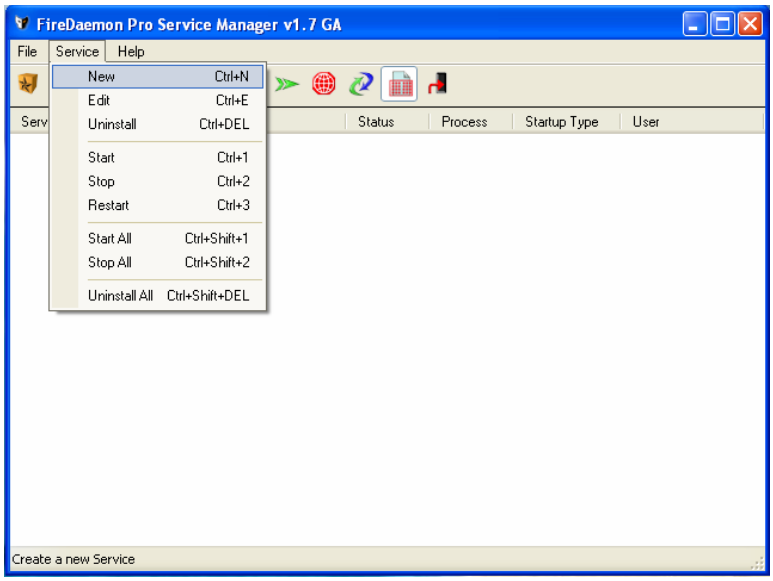

Figure D-2. Creating a new service program in the FireDaemon Pro Service Manager window.

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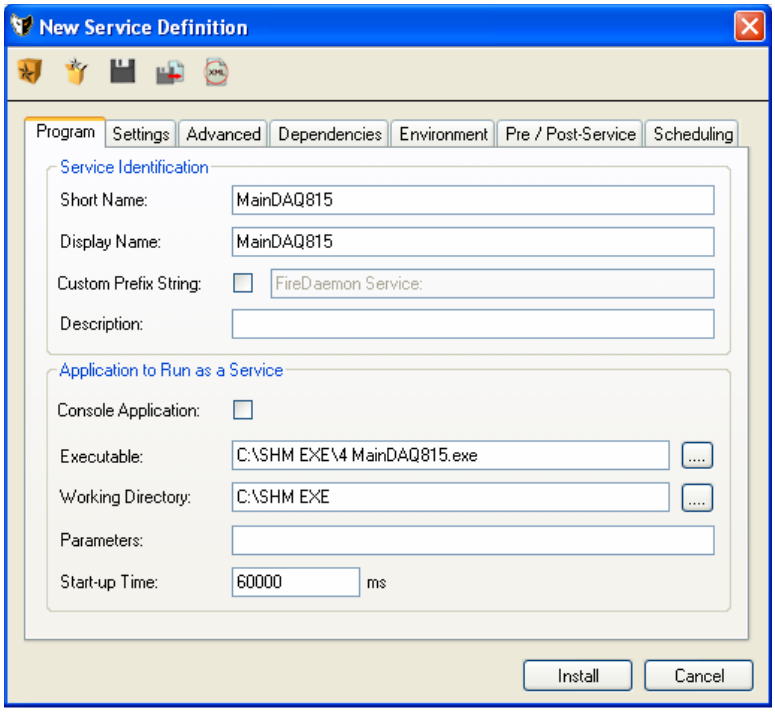
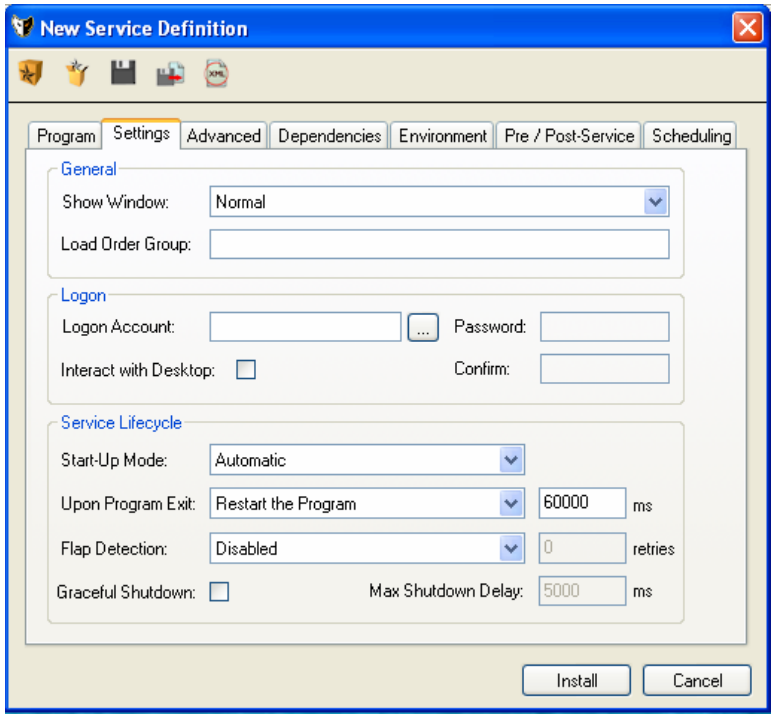


(a) Program tab



(b) Settings tab

Figure D-3. New Service Definition window.

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iv. Under the 'Settings' tab in the 'New Service Definition' window (shown in Fig. D-3b)

a. Enable the 'Interact with Desktop' option by clicking the check box (if selected, a green check mark will appear in the check box).

b. Set the 'Start-Up Mode' to 'Automatic'

c. 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).

d. Click 'Install' to install *4 MainDAQ815.EXE* as a service program.

v. If successfully installed, a prompt dialog box will appear indicating that the installation process is complelted (Fig. D-4) and the service program created will be listed in the FireDaemon Pro Service Manager window as shown in Fig. D-5.

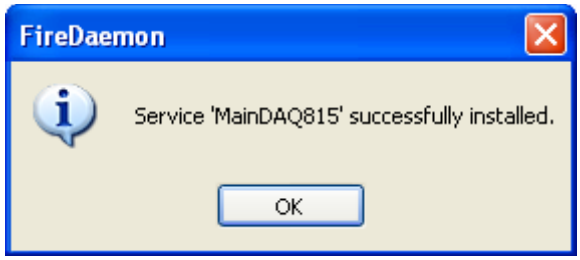

Figure D-4. Prompt dialog box.

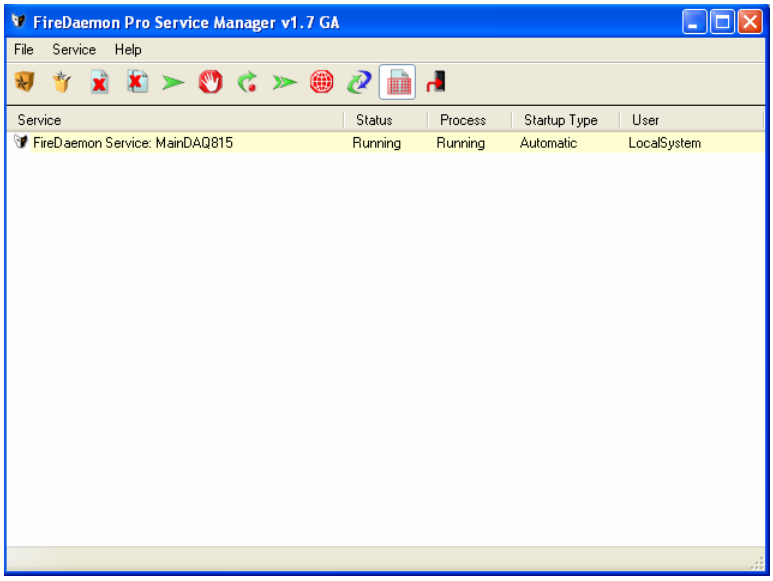

Figure D-5. FireDaemon Pro Service Manager window (service MainDAQ815 installed).

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APPENDIX E: CHANGING SECURITY SETTING ON *McAfee VirusScan* SOFTWARE

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Right click on the McAfee VirusScan software icon that can be found on the right bottom corner of the taskbar and select 'VirusScan Console' as shown in Fig. E-1.

1. Double click on 'Access Protection' in the VirusScan Console window (Fig. E-2).

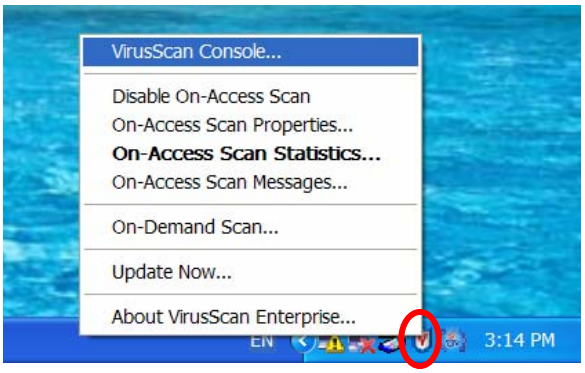

Figure E-1. Desktop screen showing VirusScan software icon.

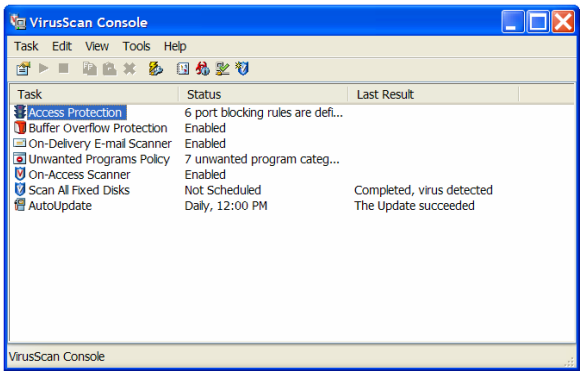

Figure E-2. 'VirusScan Console' window.

2. As shown in Fig. E-3, select 'Prevent mass mailing worms from sending…' (highlighted in blue if selected) and click 'Edit' button in the 'Access Protection Properties' window.
3. Type in the name of the EXE file (to be excluded from blocking) as shown in Fig. E-4 and click 'OK' which will close the current window and move back to the 'Access Protection Properties' window. Note that each EXE file is separated with a comma.
4. In the Access Protection Properties window, click 'Apply' and then 'OK'.

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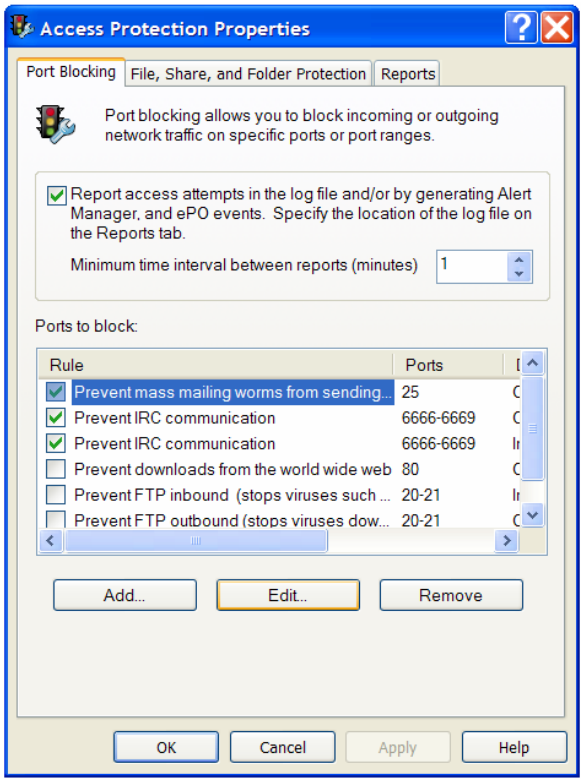

Figure E-3. 'Access Protection Properties' window

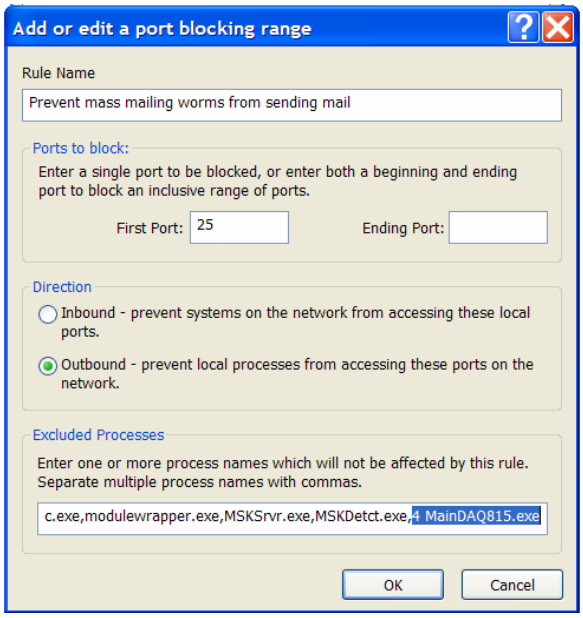

Figure E-4. 'Add or edit a port blocking range' window.

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APPENDIX F: WELDABLE STRAIN GAGE AND GENERAL APPLICATION INSTRUCTIONS

F1. Weldable Strain Gage 279
F2. General Application Instructions 280

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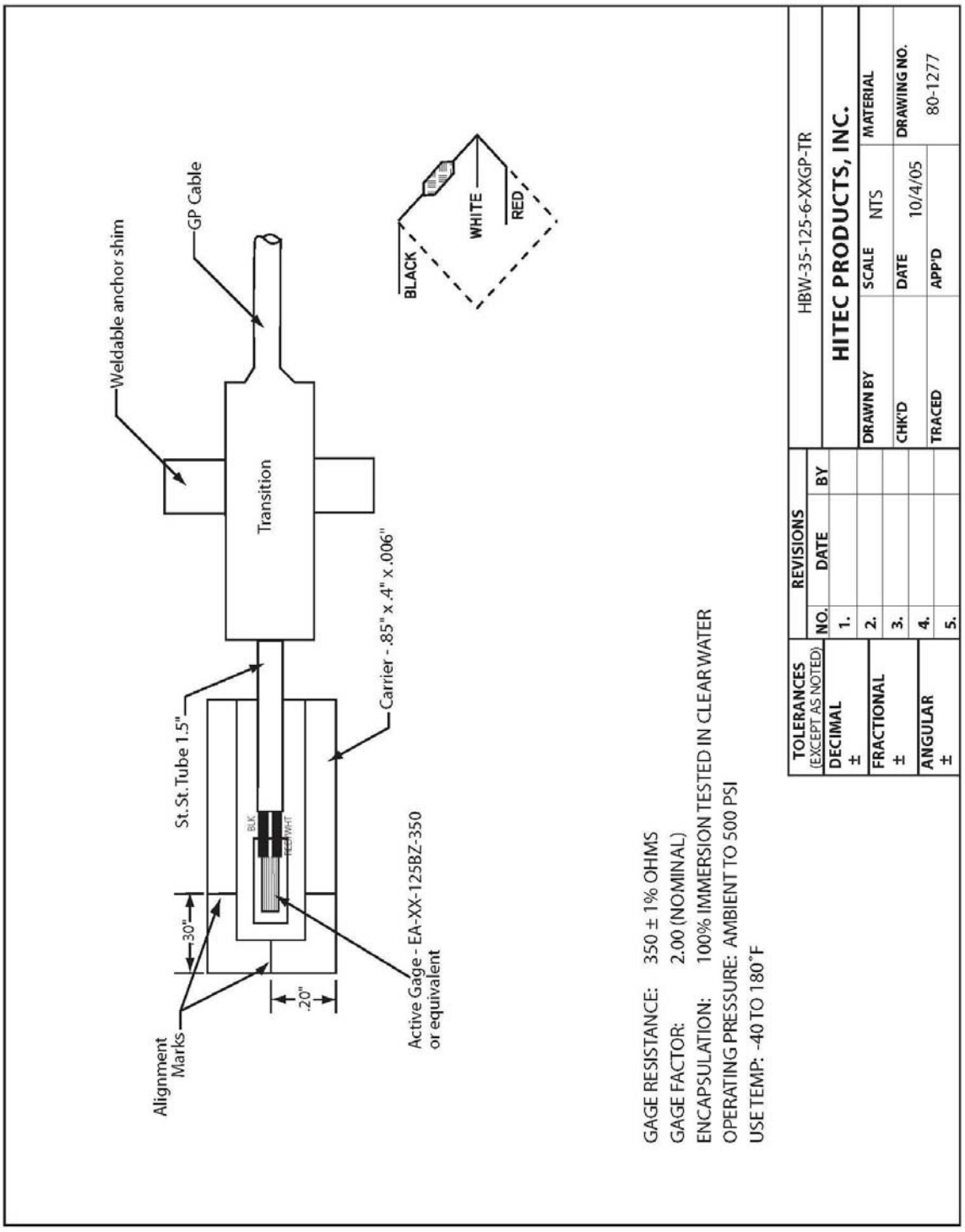
F1. Weldable Strain Gage



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F2. General Application Instructions

HPI HITEC PRODUCTS, INC.
P.O. Box 790 • Ayer, MA 01432 USA
Tel: 978-772-6963 • Fax: 978-772-6966
www.hitecprod.com

GENERAL APPLICATION INSTRUCTIONS

HBW SERIES WELDABLE STRAIN GAGE

A. SURFACE PREPARATION

1. Inspect sensor location on specimen for deep pitting and correct gage location. (Figure 1)
2. Clean entire area with power grinder or coarse sander. Metal should be free of all rust and pitting. (Figure 2)
3. Locally clean the gage sensor area with fine sandpaper. Metal should have almost a "polished" look to it. (Figure 3)

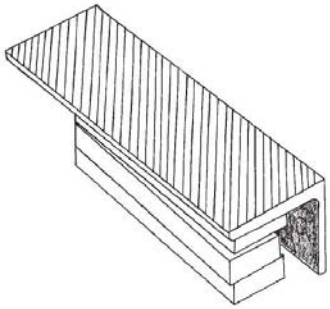

Figure 1: SPECIMEN

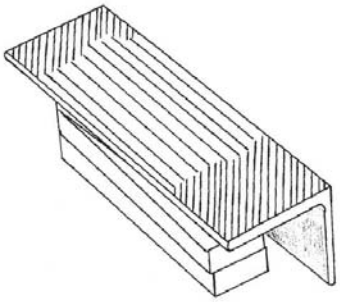

Figure 2: ROUGH CLEAN

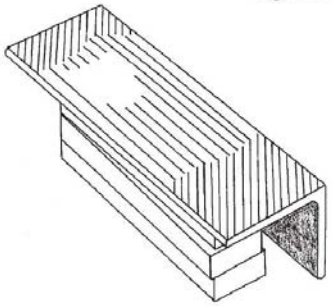

Figure 3: FINAL CLEAN

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B. GAGE INSTALLATION

1. Using a capacitive discharge spot welder, establish proper weld schedule with sample carriers supplied with gage. A power setting of 12 - 18 watt seconds with a probe force of 3 - 6 pounds is a good starting point. Start low and gradually increase power until a good weld is achieved. Grasp the practice shim with a pair of pliers and peel from specimen. After proper welding the removal of the carrier will be difficult and will leave small weld nuggets on the specimen. The nuggets should be 40 to 60 mils in diameter. (Figure 4) (See Installation Tips C-1)

2. Remove strain gage from packaging and inspect for dust and particles that may be on the gages from shipping. Wipe welding area with gauze pad or clean cloth. Bend transition section tabs down to the sides of the water proofing compound. Bend the transition sections tabs flush with the bottom of the waterproofing compound. (Figure 5)

3. Wash installation area with conditioner A and rise with Neutralizer 5 or equivalent cleaning system to remove any remaining oxides or dirt.

4. Tape (or hold) transition section to specimen in a suitable location so that the sensor may be placed in the proper location with a stress relief in the ribbon wire (or stainless steel tubing). Do not let cable hang from the transition section. Cable should be taped or wires to the specimen.

5. Tack weld transition section tabs with 3 to 5 spot welds on each side. This will hold the strain gage in position while the remaining welds are made.

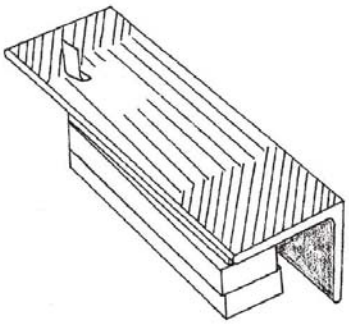

Figure 4: WELD TEST SCHEDULE

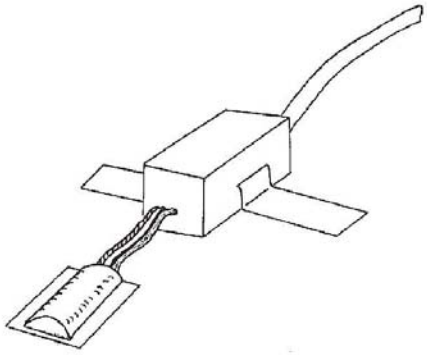

Figure 5: SENSOR READY FOR PROPER INSTALLATION

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6. Finish welding the transition section tabs to specimen. (Figure 6)

7. Place a piece of tape across the gage just below the horizontal alignment marks on the side of the carrier and place on the specimen.

8. Tack the gage in place with one (1) weld at each of the side alignment marks. Carefully remove the tape.

9. Continue welding the gage in place. The first line of welds should be adjacent to the hermetic sealand 1/16" on center. Sequence on welds should be:

    a) Vertically down from right side alignment mark, looking at gage from transition end.
    b) Vertically up from right side alignment mark.
    c) Vertically down from left side alignment mark.
    d) Vertically up from left side alignment mark.
    e) Horizontally across gage top.

10. Complete the installation by adding a second row of tack welds between and 1/32" outboard of the first row.

11. The installation is now complete. No additional environmental protection is required

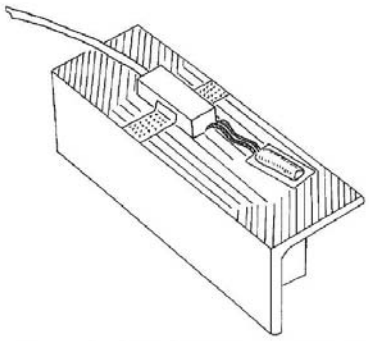

Figure 6: TRANSITION INSTALLATION

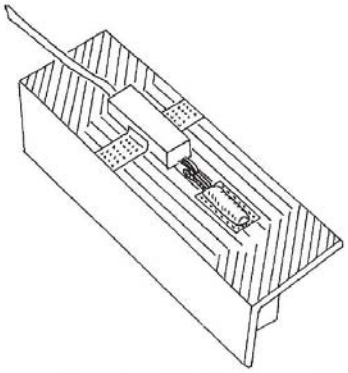

Figure 7: FINAL INSTALLATION

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C. INSTALLATION TIPS

1. The hermetic sealing provides excellent protection against gage damage caused by possible weld sparking.If sparking does occur check for proper surface preparation, proper probe force, and probe dressing.

2. Probe should be dressed with fine sandpaper to provide a 1/32" tip radius. Dress probe frequently (after every gage installation) or whenever severe sparking has occurred. (Figure 8)

3. Transition tubing is bendable allowing adjustment of the gage/transition alignment. Excessive bending of the transition tubing should be avoided.

4. Transition tabs can be trimmed if necessary.

5. When installing onto a curved surface, care must be taken to insure intimate contact between the sensor and the curved surface.

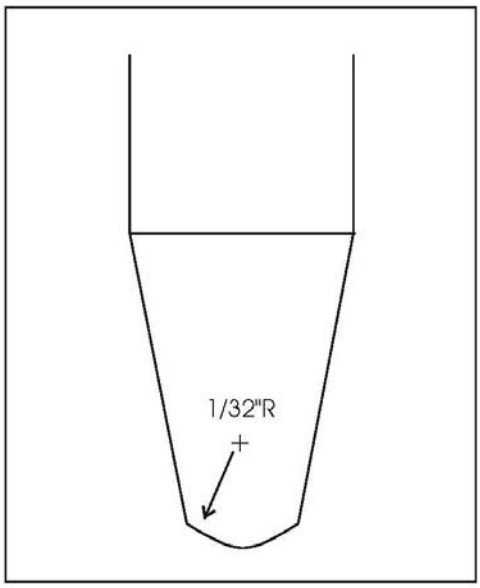

Figure 8: PROBE TIP GEOMETRY

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APPENDIX G: STRAINBOOK/616 AND WBK16 SPECIFICATIONS

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StrainBook/616™

Specifications

Specifications

Channels: 8 built-in, expandable to 64
Input Connector: Standard female DB9 per channel
Input Type: Differential
Input Impedance: 100M Ohms
Coupling: AC and DC, software selectable
Accuracy:
  Offset Drift: 1µV RTI/°C
  CMRR @ DC to 60 Hz: 100 dB at gains > 100
Cross-Talk Rejection: > 90 dB @ less than 1 kHz
Bandwidth:
  50 kHz @ gains < 1 to 100
  10 kHz @ gains > 100 to 2000
  1 kHz @ gains > 2000
Bridge Configuration:
  Full-bridge (4 and 6 wire)
  Half-bridge
  Quarter-bridge (2 and 3 wire)
Bridge Completion: User supplied resistors on removable headers (headers included)
Bridge Resistance: 60 to 1000 Ohms
Overall Gain: 1 to 20,000, software selectable in 86 steps
Shunt Calibration: software selection of 3 user-supplied resistors
Auto-Balance: Selected per channel
Auto-Calibration: Either by actual measurement or by calculated load
Offset Adjustment:
  ±3 V RTI @ gains 1 to 10
  ±300 mV RTI @ gains 10 to 100
  ±30 mV RTI @ gains 100 to 2000
  ±3 mV RTI @ gains 2000 to 20000
Excitation Source: Two banks can be independently set to 0.5, 1.0, 2.0, 5.0, 10.0 VDC or "off" Bank 1 is for Channels 1 through 4; Bank 2 is for Channels 5 through 8.
Excitation Accuracy: ±5 mV
Excitation Capacity: 85 mA per channel with fold-back current limiting
Filtering: 4-pole Butterworth, software-selectable and factory-set to 10 Hz, 1 kHz, or bypass; field-changeable
Warm-up: 30 minutes to rated specifications
Environment: Operating: 0° to 50°C, 0 to 95% RH, non-condensing
Storage Temperature: -20° to 70°C
Power Consumption: 1.22A @ 15V (min); 1.84A @ 15V (max)
Input Power Voltage Range: 10 to 30 VDC
Vibration: MIL STD 810, Category 1 and 10
PC Communication: 10/100BaseT Ethernet
Dimensions: 285 mm W x 220 mm D x 70 mm H (11" x 8.5" x 2.70")
Weight: 1.32 kg (2.9 lb)

Triggering

Multi-Channel Analog Trigger (up to 64 channels)
  Range: Selectable per channel to input range
  Latency: 2 µs/channel, plus 4 µs maximum
TTL Trigger
  Input Signal Range: 0 to 5V
  Input Characteristics: TTL-compatible with 10K Ohm pull-up resistor
  Latency: 300 ns
Software Trigger
  Latency: 100 µs typical

External Clock

Connector: Available on DB25 digital input
Input Signal Range: 5V TTL compatible
Input Characteristics: 50K Ohms pull up (to +5V) in parallel with 50 pF
Input Protection: Zener clamped -0.7 to +5V
Delay: 200 ns
Signal Slew Rate Requirement: 20V/µs minimum
Rate: Up to 1 MHz
Divisor Ratio: Divide by 1 through 255, selectable
Clock Counter Accuracy: <0.02%
Clock Counter Range: 0.01 Hz to 100 kHz

External Sync Ports

Number of External Sync Ports: 2, on rear panel
  Maximum Number of Units to be Synchronized: 4 units, scan synchronous (post trigger)
Maximum Length of Sync Cables: 15 feet (4.57 m), total for all cables

Sequencer

Operation: Programmable for channel, gain, and for unipolar/bipolar range in random order
Depth: 128 location
Channel-to-Channel Rate: 1 µs to 1.1 µs/channel, all channels equal
Maximum Repeat Rate: 1 MHz
Minimum Repeat Rate: 100 seconds per scan
Expansion Channel Sample Rate: Same as on-board channels, 1 to 1.1 µs, fixed

High-Speed Digital Inputs/General-Purpose Outputs

Connector: DB25 Female
Configuration: 16 TTL-compatible pins, selectable for input or output
Input Characteristics: TTL-compatible
Output Characteristics: ALS TTL output in series with 33 Ohms
Output Updates: Outputs may be changed via program control
Input/Output Protection: Diode clamped to ground and +5V

Period Counter

Operation: Internal counter calculates and reports the external clock's period; counter can be read with each scan
Clock Counter Accuracy: <0.02% error
Clock Counter Range: 0.01 Hz to 100 kHz

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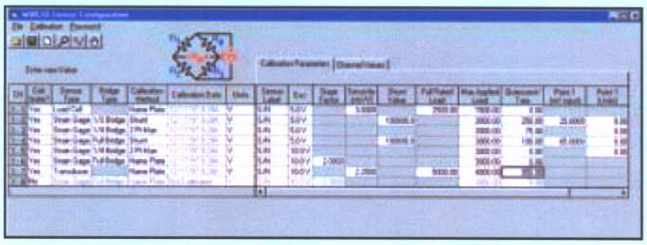
WBK16™

Specifications & Ordering Information

Software

Gain adjustments, bridge balancing and other sensor calibration with the WBK16™ is effortlessly handled with WaveView™, IOtech's *Out-of-the-Box*™ software for WaveBook systems. The sensor calibration portion shown below enables a strain gage or transducer application to be easily configured, calibrated, and set up using an intuitive graphical user interface with guidance through the configuration and calibration.



Auto Balance with Auto-zero. Balancing the bridge is quick and convenient. No pots to adjust, LEDs to monitor, or dials to twist. Simply select the channels to auto balance and the WBK16 does the rest. Auto balance removes the static portion of the strain load and auto zeros the input to compensate for any input drift.

Simultaneous Sampling. The WBK16/SSH adds simultaneous sample and hold capability to all eight input channels. When multiple WBK16/SSH modules are installed, all channels on all modules sample within 100 ns of one another.

Specifications

Input Connector: Standard female DB9 per channel.
Channels: 8
Input: Differential
Input Impedance: 100M Ohms
Coupling: AC and DC software selectable
Accuracy:
Offset Drift: 1∝V RTI/°C
CMRR @ DC to 60 Hz: 100 dB at gains > 100
Cross Talk Rejection: > 90 dB @ less than 1 kHz
Bandwidth:
50 kHz @ gains <1 to 100
10 kHz @ gains >100 to 2000
1 kHz @ gains > 2000
Bridge Configuration:
Full Bridge (4 and 6 wire)
Half bridge
Quarter bridge (2 and 3 wire)
Bridge Completion: User supplied resistors on removable headers (included)
Bridge Resistance: 60 to 1000 Ohms
Overall Gain: 1 to 20,000, software selectable in 86 steps
Shunt Calibration: Software selection of 3 user supplied resistors
Auto-Balance: Selected per channel
Auto-Calibration: Either by actual measurement or calculated load
Offset Adjustment:
±3V RTI @ gains 1 to 10
±300 mV RTI @ gains 10 to 100
±30 mV RTI @ gains 100 to 2000
±3 mV @ 2000 to 20,000
Excitation Source: Two independent banks setable to 0.5V, 1V, 2V, 5V, 10V and off
Excitation Accuracy: ±5 mV
Excitation Capacity: 85 mA per channel with foldback current limiting

CN-189 and CN-115 header connectors provide bridge completion

Filtering: 4-pole Butterworth software selectable and factory set to 10 Hz, 1 kHz, or bypass; field changeable
Power Consumption: 1.0A @ 15V (min)
1.7A @ 15V (max)
Operating Temperature: 0° to 50°C
Storage Temperature: 0° to 70°C
Humidity: 0 to 95% RH, non-condensing
Dimensions: 285 mm W x 221 mm D x 35 mm H (11" x 8.5" x 1.375")
Weight: 1.32 kg (2.9 lbs)
Vibration: MIL STD 810, category 1

Ordering Information

Description	Part No.
8-channel strain gage module, including AC adapter	WBK16
8-channel strain gage module with simultaneous sample and hold, including AC adapter	WBK16/SSH
Load cell shunt cal option for WBK16	WBK16/LC

Accessories & Cables

Rack mount kit	RackDBK2
120 Ohm bridge resistor	BCR/120/1
350 Ohm bridge resistor	BCR/350/1
1000 Ohm bridge resistor	BCR/1000/1
Header connector	CN-115
Connector/adapter DB9 to screw terminal	CN-189
5-pin male DIN to 5-pin male DIN provides convenient connection between WaveBook power input connectors and DBK30A (also used to daisy-chain input power to WBK expansion modules)	CA-115
5-pin DIN to automobile cigarette lighter power cable	CA-116

For complete information on accessories and cables, visit **www.iotech.com/acc**

Related Products

WaveBook Series	p. 17
WBK Options	p. 34

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APPENDIX H: *STAAD.Pro* INPUT FILES USED IN *BEC ANALYSIS* VALIDATION

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H.1.2. Type 4 290
H.1.3. Type 3S2 A 290
H.1.4. Type 3S2 B 290
H.1.5. Type 3-3 290
H.1.6. Type 3S3 291
H.2. Iowa Legal Trucks (DF = 2.769 and IM = 20%)..... 291
H.2.1. Type 3 291
H.2.2. Type 4 291
H.2.3. Type 3S2 A 291
H.2.4. Type 3S2 B 291
H.2.5. Type 3-3 292
H.2.6. Type 3S3 292

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**Note: the codes for all cases are the same except those in the red and blue boxes. The red box shows the type of Iowa legal truck and the blue box contains information on the axle weights and their configurations and the number of load cases created to simulate a moving load. Each axle weight was determined by simply multiplying the axle weight by the "DF" and "1+IM*100."*

H.1. Iowa Legal Trucks (DF = 2.769 and IM = 22%)

H.1.1. Type 3

STAAD PLANE
START JOB INFORMATION

JOB NAME IOWA LEGAL TRUCK TYPE3

ENGINEER DATE 12-Dec-06
END JOB INFORMATION
INPUT WIDTH 79
UNIT FEET KIP
JOINT COORDINATES
1 0 0 0; 2 1 0 0; 3 2 0 0; 4 3 0 0; 5 4 0 0; 6 5 0 0; 7 6 0 0; 8 7 0 0;
9 8 0 0; 10 9 0 0; 11 10 0 0; 12 11 0 0; 13 12 0 0; 14 13 0 0; 15 14 0 0;
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309 309 310; 310 310 311; 311 311 312; 312 312 313; 313 313 314; 314 314 315;
315 315 316; 316 316 317; 317 317 318; 318 318 319; 319 319 320; 320 320 321;
UNIT INCHES KIP
DEFINE MATERIAL START
ISOTROPIC STEEL
E 29000
POISSON 0.3
DENSITY 0.000283
ALPHA 6.5e-006
DAMP 0.03
END DEFINE MATERIAL
UNIT FEET KIP
MEMBER PROPERTY AMERICAN
1 TO 68 PRIS YD 1.588 ZD 1.588
69 TO 94 PRIS YD 1.713 ZD 1.713
95 TO 102 PRIS YD 1.81 ZD 1.81

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```
103 TO 128 PRIS YD 1.713 ZD 1.713
129 TO 192 PRIS YD 1.588 ZD 1.588
193 TO 218 PRIS YD 1.713 ZD 1.713
219 TO 226 PRIS YD 1.81 ZD 1.81
227 TO 252 PRIS YD 1.713 ZD 1.713
253 TO 320 PRIS YD 1.588 ZD 1.588
CONSTANTS
MATERIAL STEEL MEMB 1 TO 320
SUPPORTS
99 PINNED
1 223 321 FIXED BUT FX FZ MX MY MZ

DEFINE MOVING LOAD
TYPE 1 LOAD 28.71453 28.71453 27.02544
DIST 4 15
LOAD GENERATION 341
TYPE 1 -19 0 0 XINC 1

PERFORM ANALYSIS PRINT ALL
FINISH
```

H.1.2. Type 4

```
JOB NAME IOWA LEGAL TRUCK TYPE4

DEFINE MOVING LOAD
TYPE 1 LOAD 23.64726 23.64726 23.64726 21.113625
DIST 4 4 11
LOAD GENERATION 341
TYPE 1 -19 0 0 XINC 1
```

H.1.3. Type 3S2 A

```
JOB NAME IOWA LEGAL TRUCK TYPE3S2 A

DEFINE MOVING LOAD
TYPE 1 LOAD 26.180895 26.180895 26.180895 26.180895 18.57999
DIST 4 22 4 10
LOAD GENERATION 362
TYPE 1 -40 0 0 XINC 1
```

H.1.4. Type 3S2 B

```
JOB NAME IOWA LEGAL TRUCK TYPE3S2 B

DEFINE MOVING LOAD
TYPE 1 LOAD 28.71453 28.71453 28.71453 28.71453 20.26908
DIST 4 33 4 10
LOAD GENERATION 373
TYPE 1 -51 0 0 XINC 1
```

H.1.5. Type 3-3

```
JOB NAME IOWA LEGAL TRUCK TYPE3-3

DEFINE MOVING LOAD
TYPE 1 LOAD 23.64726 23.64726 22.802725 20.26908 20.26908 24.491805
DIST 4 10 10 4 15
LOAD GENERATION 365
TYPE 1 -43 0 0 XINC 1
```

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H.1.6. Type 3S3

```
JOB NAME IOWA LEGAL TRUCK TYPE3S3
```

```
DEFINE MOVING LOAD
TYPE 1 LOAD 23.64726 23.64726 23.64726 21.95817 21.95817 20.26908
DIST 4 4 20 4 11
LOAD GENERATION 365
TYPE 1 -43 0 0 XINC 1
```

H.2. Iowa Legal Trucks (DF = 2.769 and IM = 20%)

H.2.1. Type 3

```
JOB NAME IOWA LEGAL TRUCK TYPE3
```

```
DEFINE MOVING LOAD
TYPE 1 LOAD 28.2438 28.2438 26.5824
DIST 4 15
LOAD GENERATION 341
TYPE 1 -19 0 0 XINC 1
```

H.2.2. Type 4

```
JOB NAME IOWA LEGAL TRUCK TYPE4
```

```
DEFINE MOVING LOAD
TYPE 1 LOAD 23.2596 23.2596 23.2596 20.7675
DIST 4 4 11
LOAD GENERATION 341
TYPE 1 -19 0 0 XINC 1
```

H.2.3. Type 3S2 A

```
JOB NAME IOWA LEGAL TRUCK TYPE 3S2 A
```

```
DEFINE MOVING LOAD
TYPE 1 LOAD 25.7517 25.7517 25.7517 25.7517 18.2754
DIST 4 22 4 10
LOAD GENERATION 362
TYPE 1 -40 0 0 XINC 1
```

H.2.4. Type 3S2 B

```
JOB NAME IOWA LEGAL TRUCK TYPE3S2 B
```

```
DEFINE MOVING LOAD
TYPE 1 LOAD 28.2438 28.2438 28.2438 28.2438 19.9368
DIST 4 33 4 10
LOAD GENERATION 373
TYPE 1 -51 0 0 XINC 1
```

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H.2.5. Type 3-3

```
JOB NAME IOWA LEGAL TRUCK TYPE 3-3
```

```
DEFINE MOVING LOAD
TYPE 1 LOAD 23.2596 23.2596 22.4289 19.9368 19.9368 24.0903
DIST 4 10 10 4 15
LOAD GENERATION 365
TYPE 1 -43 0 0 XINC 1
```

H.2.6. Type 3S3

```
JOB NAME IOWA LEGAL TRUCK TYPE 3S3
```

```
DEFINE MOVING LOAD
TYPE 1 LOAD 23.2596 23.2596 23.2596 21.5982 21.5982 19.9368
DIST 4 4 20 4 11
LOAD GENERATION 365
TYPE 1 -43 0 0 XINC 1
```

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APPENDIX I: EVALUATION REPORT

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

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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	78	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	137849	8093	2456	271	452	56	5	1	1	0	0

Bin Minimum	0	20	40	60	80	100	120	140	160	180	200
Sensor2	32836	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	95521	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	3603	2600	919	22	9	2	1	0	0

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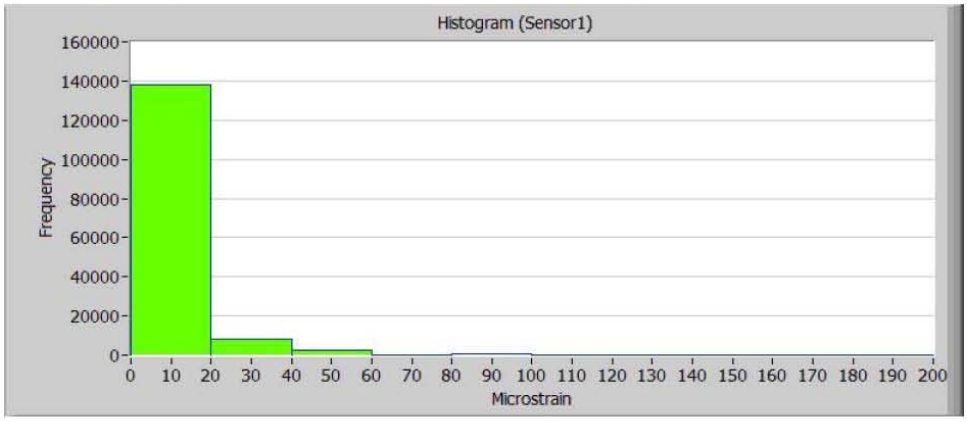
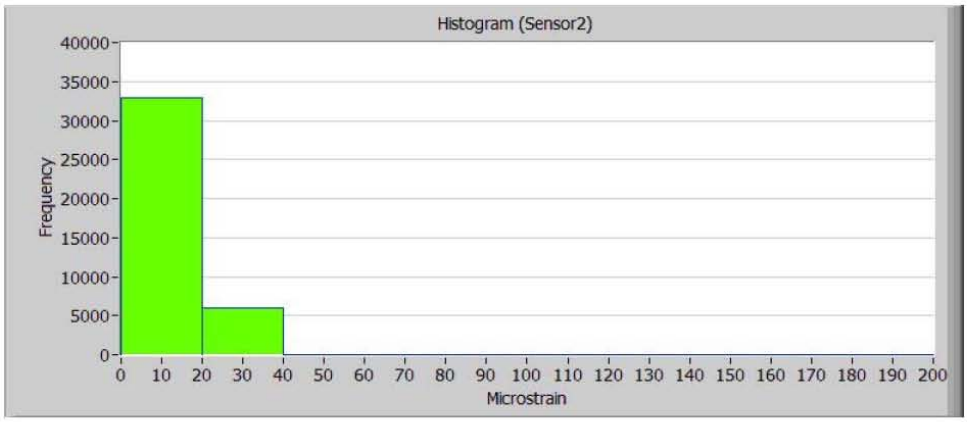
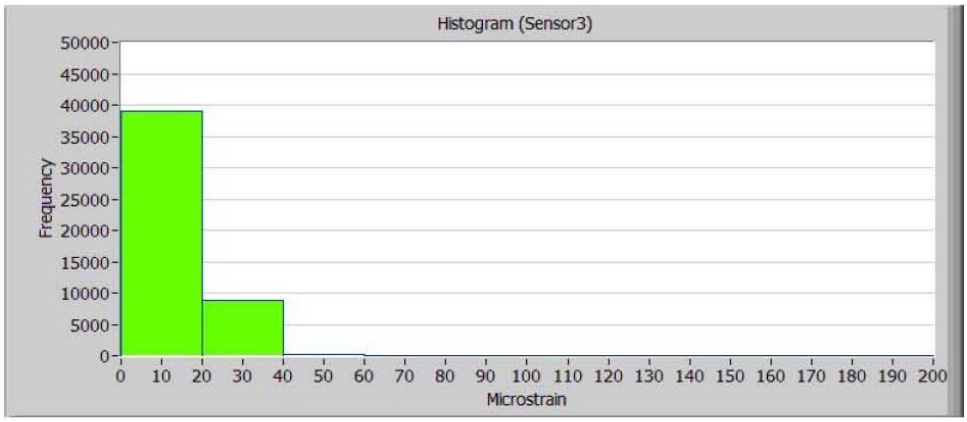
Monitoring Period (11/14/2006 3:00:18 PM ~ 12/14/2006 4:37:46 PM)







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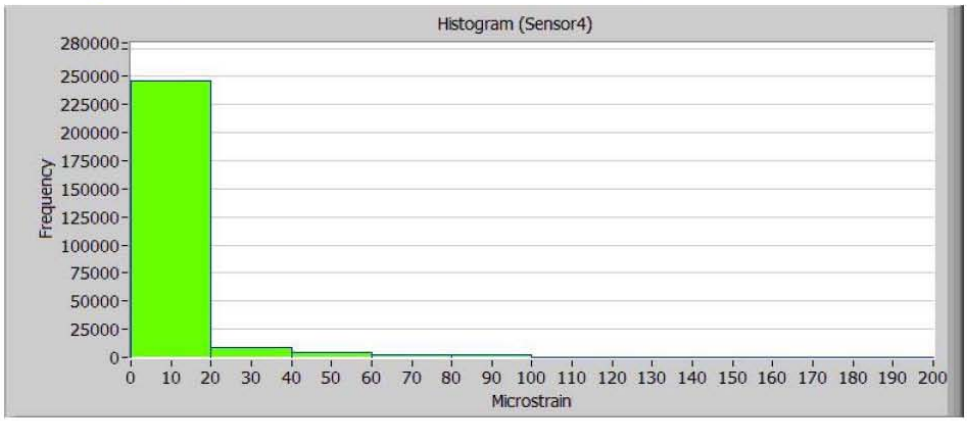
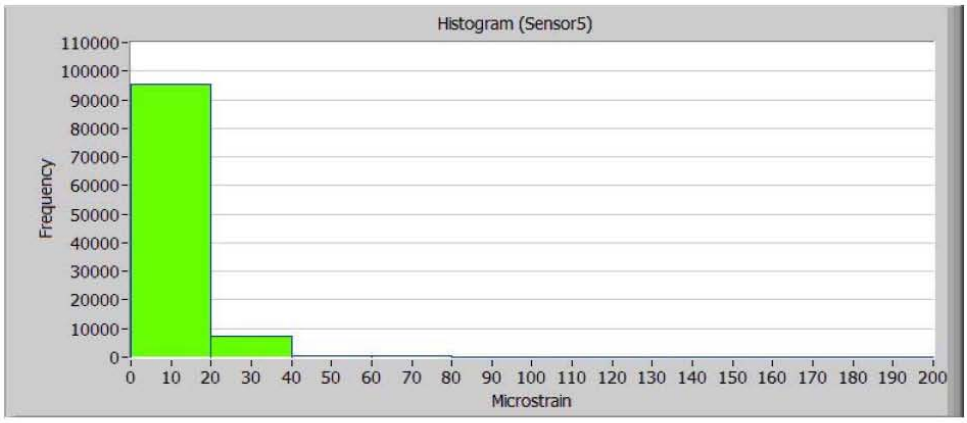
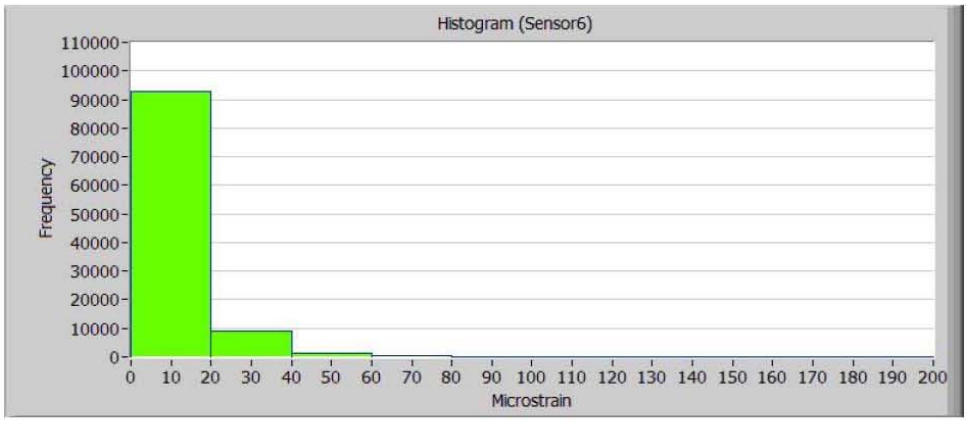
Monitoring Period (11/14/2006 3:00:18 PM ~ 12/14/2006 4:37:46 PM)







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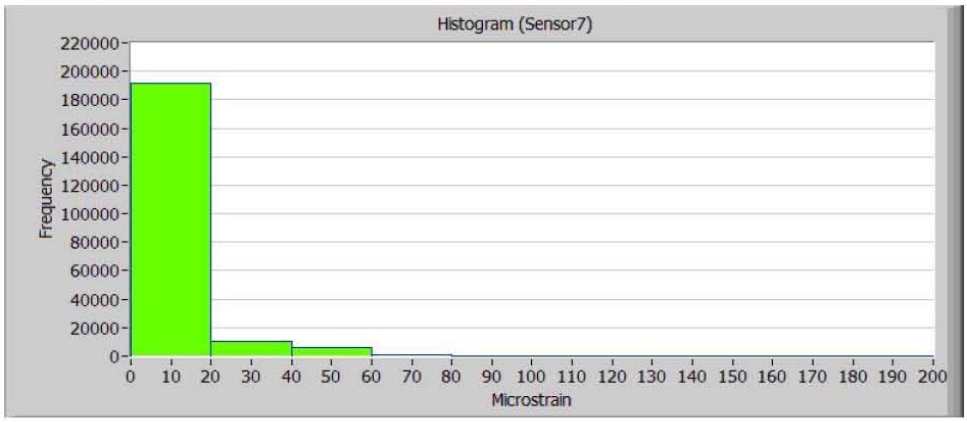
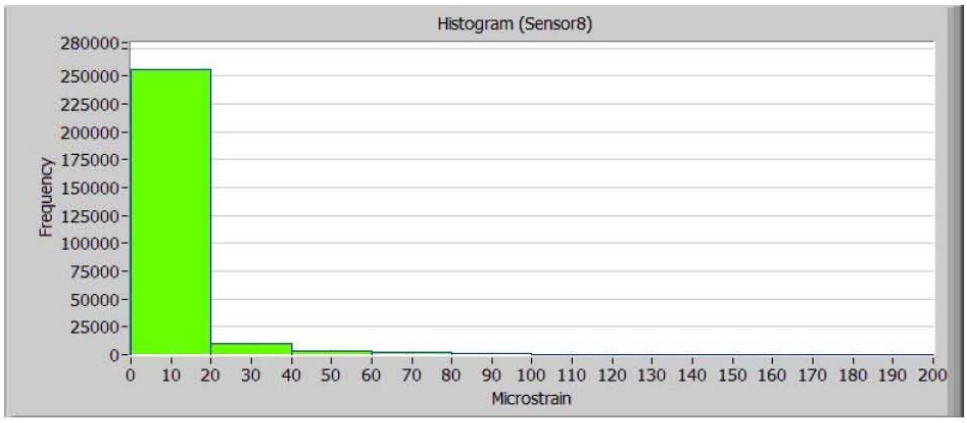
Monitoring Period (11/14/2006 3:00:18 PM ~ 12/14/2006 4:37:46 PM)





Daily Trends (Maximum & Average)

Maximum (microstrain)

	Sensor1	Sensor2	Sensor3	Sensor4	Sensor5	Sensor6	Sensor7	Sensor8
Day0	105	51	47	110	93	80	68	106
Day1	102	41	46	111	99	76	71	105
Day2	105	47	64	131	95	77	104	122
Day3	102	41	47	111	91	74	68	93
Day4	97	42	43	99	89	65	67	93
Day5	105	37	47	109	88	68	73	106
Day6	110	37	48	113	94	67	75	100
Day7	137	51	53	134	112	80	101	110
Day8	98	37	46	104	85	67	72	96
Day9	165	41	45	109	156	84	74	103
Day10	94	35	45	108	79	67	69	102
Day11	82	34	39	103	75	54	62	91
Day12	110	39	48	145	96	69	86	122
Day13	119	38	52	115	124	71	86	103
Day14	109	39	53	103	91	70	81	111
Day15	130	78	91	129	114	69	82	100
Day16	109	37	43	108	108	69	67	94
Day17	101	38	46	106	87	66	69	99

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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	106	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	86	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	98
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	9	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

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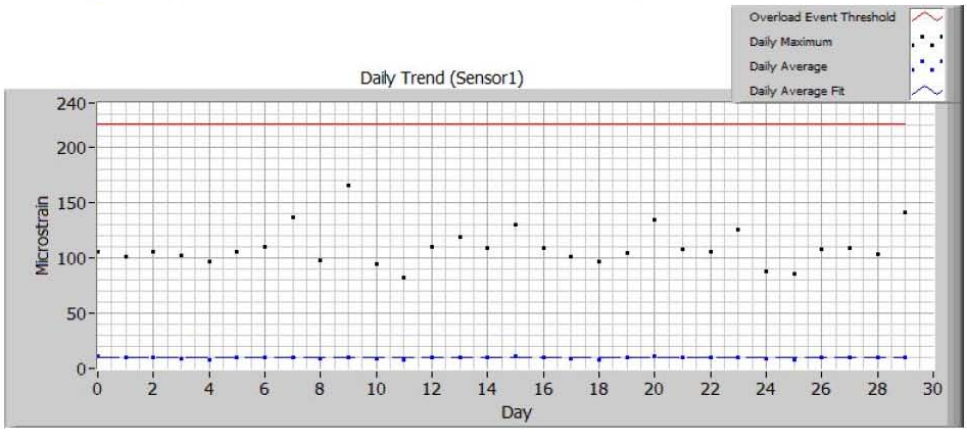
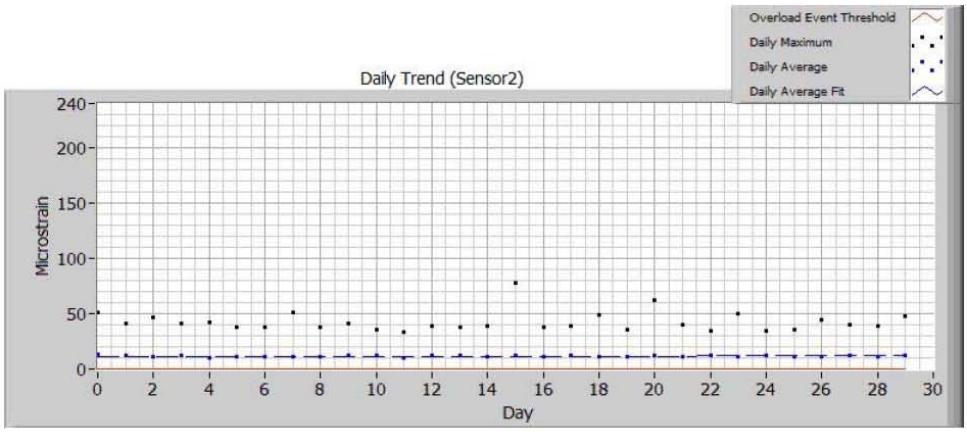
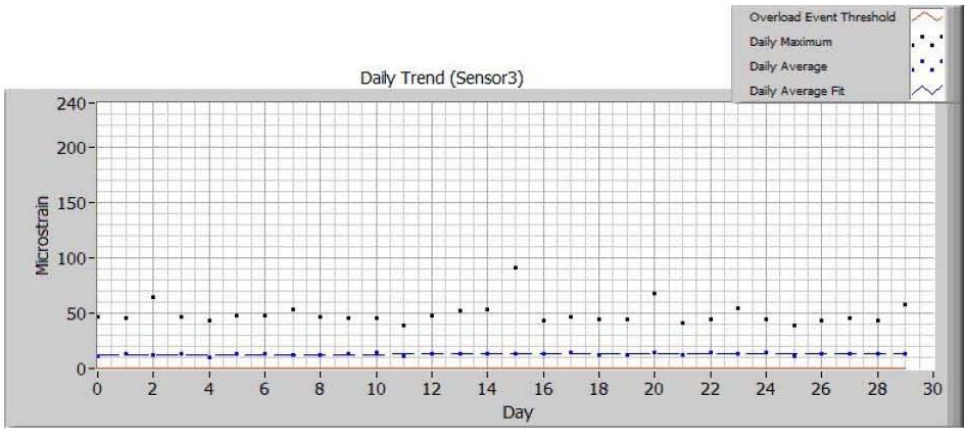
Monitoring Period (11/14/2006 3:00:18 PM ~ 12/14/2006 4:37:46 PM)







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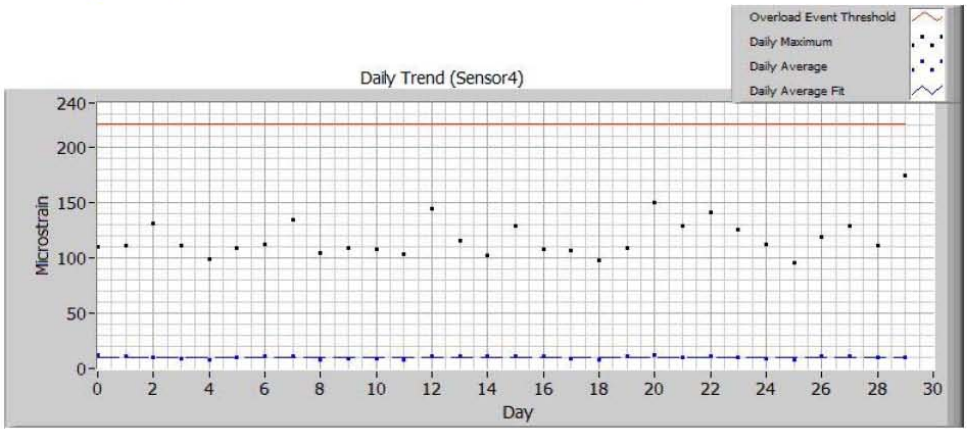

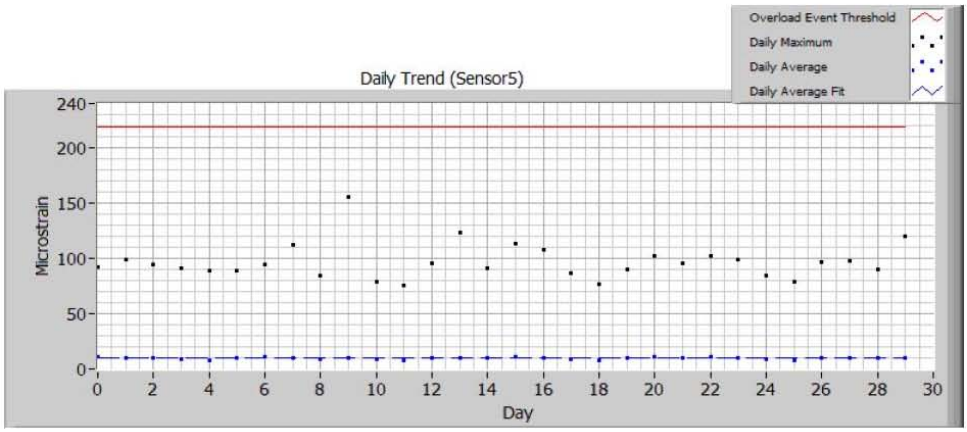

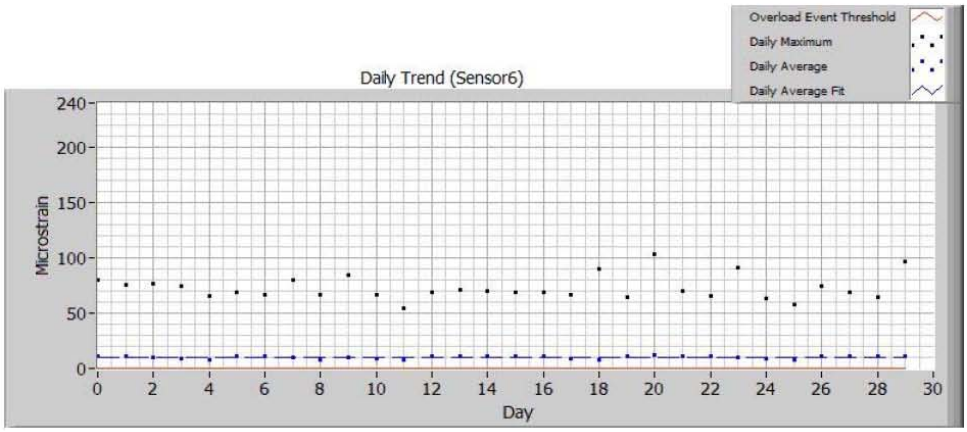

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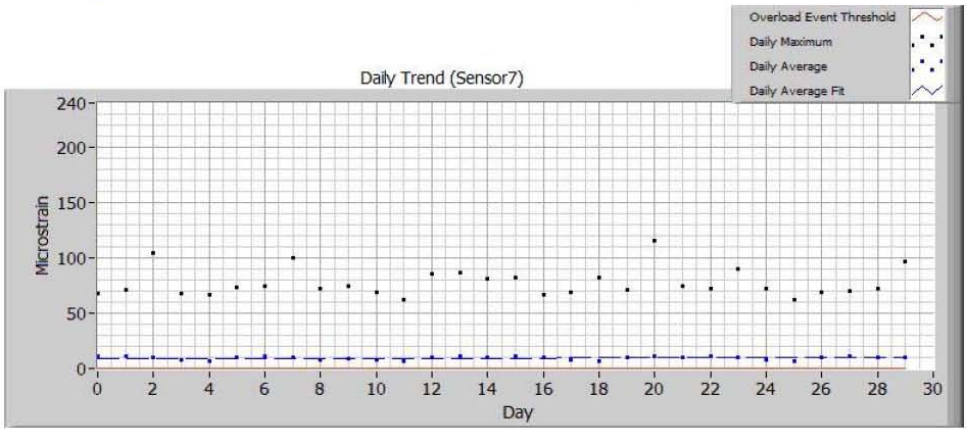

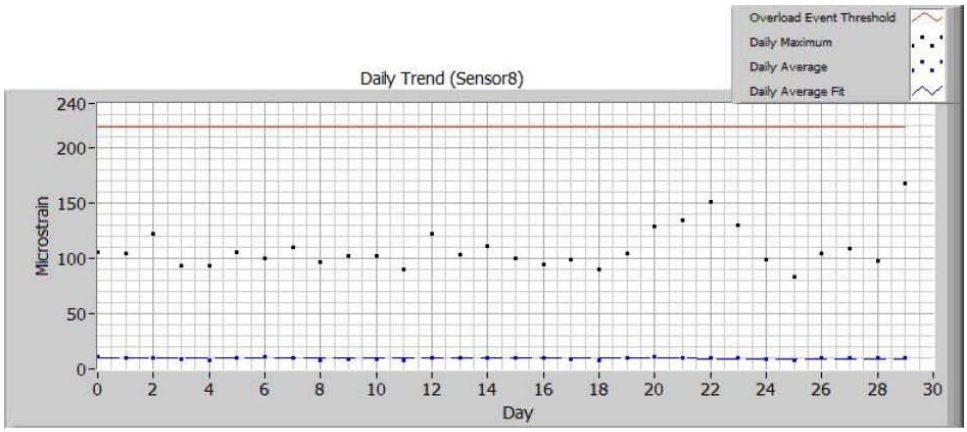

End of Report
(monitoring since 11/14/2006 3:00:18 PM)

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