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Considerations for Implementing and Researching a Strain Based Structural Health Monitoring System on an In-Service Bridge

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Considerations for Implementing and Researching a Strain Based Structural Health Monitoring System on an In-Service Bridge

BY

David Damien Gaylord
B.S., University of New Hampshire, 2010

THESIS

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in Partial Fulfillment of
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Abstract

CONSIDERATIONS FOR IMPLEMENTING AND RESEARCHING A STRAIN BASED STRUCTURAL HEALTH MONITORING SYSTEM ON AN IN-SERVICE BRIDGE

By

David Gaylord

University of New Hampshire, September, 2012

The neutral axis of a composite bridge girder provides information relating to the health of both the girder and the concrete deck. Using bonded foil strain gauges, this location may be a useful Structural Health Monitoring (SHM) metric. SHM is an emerging tool that will create safer and more reliable bridge systems. By leveraging technology to investigate the way a structure behaves and degrades over time, the engineering community will gain valuable insight for developing more resilient bridges and can be alerted to damage when it occurs. This research used bonded foil strain gauges to determine neutral axis locations at the Bagdad Road over US Route 4 Bridge in Durham New Hampshire. The locations were determined to be between 32.35 to 32.39 inches and 30.45 to 33.08 inches from the bottom of the composite section. The value was reasonably close to the position located using transformed section properties of an undamaged section, calculated to be at 31.73 inches from the bottom of the section.

This thesis was also used as a means to record the SHM system design process and to evaluate equipment for potential future SHM research projects that the University of New Hampshire (UNH) may be involved with. The methods of installation and data processing are included. Finally, future work is recommended that may further develop strain-based SHM monitoring supported by conclusions based on information and observations collected throughout the research.
Chapter 1: Introduction

Structural Health Monitoring (SHM) uses a blend of instrumentation and science that has the potential to save bridge owners and managers significant amounts of money and manpower through early damage detection. Information from these continuous monitoring systems can help remove uncertainties about the structural condition in bridges by detecting hidden damage or capacity. This research aims to facilitate and accelerate future SHM research projects in New Hampshire conducted by UNH by documenting the design and implementation of a strain-based structural health monitoring system. Protocols are developed and, instrumentation is deployed at the Bagdad Rd Bridge in Durham NH (NH Bridge Number 114/128) for evaluation of sensors and data acquisition hardware for potential use in future bridge SHM projects.

The process of SHM has seen great success in mechanical and aerospace engineering (Goranson, 1997). However, the practice of SHM in civil infrastructure, especially bridges, remains largely a research topic that needs to address several challenges before it becomes common practice outside of academia. Typically, mechanical systems are better understood by the fact that their geometry, material properties, and failure mechanisms are well known as a result of detailed analytical modeling and full-scale testing in controlled environments. Each civil structure, on the other hand, is unique. Even if two bridges or buildings are similar in design and tolerances regarding construction and materials, the fact that they bear on different soils and experience different environmental impacts will force them to behave and degrade differently. Still, considering the staggering size of our nation's bridge inventory, solutions to early damage detection and prevention have great potential to protect life and property.
To better understand structural behaviors and their relation to health metrics, varying types and conditions of structures will be recorded in huge databases that make health metrics possible from statistical correlations. This places proper data collection as the foundation of successful SHM implementation in bridges. The Federal Highway Administration’s (FHWA) Office of Infrastructure Research and Development launched the Long Term Bridge Performance (LTBP) Program in April of 2008 and notes the need for high quality data to support the initiative of providing more detailed and timely pictures of bridge health in its program overview (US DOT - FHWA, 2012). Accessibility, power, and communications are the obvious challenges specific to data collection. Reliable sensors, cabling, and data acquisition are perhaps less visible. Bridge monitoring often places electrical sensors in new environments. Previously, they have been used in laboratory settings or in situations where the conditions were either well controlled or the environmental impacts could be properly managed.

Numerous research efforts to use trusted technologies on bridges exist with a focus on collecting data that can be validated. The validation process usually involves correlating the measurements with hand calculations or other observations made from another type of instrument. Extracted structural behavior information from data can include neutral axis location, mode shape, or deflection. Several of these efforts currently exist at the University of New Hampshire and many other research institutions. At UNH, thorough evaluations of displacement and strain technologies are being carried out to determine strengths and limitations (Peddle & Lefebvre, Experimental Development of Bridge Girder Distribution Factors for Assessment and Load Rating, 2012).

This research focuses on the use of strain monitoring using bonded foil strain gages. The structure of this document will provide the reader with a best practices guide of not only
the design of the instrumentation plan, the hardware selection and installation procedures but
also the data acquisition, hardware and software programming. The state of structural health
monitoring and the methods of this SHM research are discussed in chapter 2. Chapter 3 reviews
the data acquisition selection process, and chapter 4 explains how the strain measurements are
made using bonded foil strain gauges. Chapter 5 documents the installation of sensors at the
Bagdad Rd Bridge. Chapter 6 explains the investigative goal of this research as it relates to the
installed sensors. The analyses of this work are included in chapters 7 and 8, and include
evaluation of the sensor behavior and neutral axis SHM research. Finally, chapter 9 presents
conclusions that resulted from this research and recommendations for future SHM research by
the structural health monitoring team at UNH.

1.1 Research Progression

This research began as part of an effort to instrument a bridge in Gilford, New
Hampshire to aid in accelerated construction processes. As part of research in the field of rapid
deck replacement, UNH has partnered with the New Hampshire Department of Transportation
(NHDOT) under the funding of the Federal Highway Administration’s Highway’s for Life program
to investigate the use of precast panels to replace the deck only in 60 hours or less. The goal of
this project is to save time. Reduced times will minimize disruptions to traffic flow, and
potentially reduce construction site accidents by shortening the number of hours crews will
work on projects. The instrumentation will be used to monitor the impact of the rapid re-
decking on the existing steel girders and, investigate potential roles for sensors placed on an
existing bridge during maintenance.

Due to a delay in the bidding process and the placement of netting underneath the
bridge that prevents deck debris from falling on cars in the underpass that also obstructs sensor
installation, the project was ultimately delayed. Through discussions with the NHDOT, permission was granted to use equipment purchased by this project on another bridge for SHM. The equipment is portable and modular and will be moved to the Gilford Bridge when appropriate. After a review of bridges in the area around Durham, the Bagdad Rd. Bridge was selected for several reasons that will be described in section 1.3. The goals of this research are to evaluate sensors that will be used in the Gilford Bridge Accelerated Bridge Construction (ABC) project, and accelerate future strain-based SHM project by documenting observations made during the development and implementation of a system using bonded foil gauges.

Documentation regarding the planned installation for the Gilford Bridge can be found in Appendix B.

1.2 Gilford Sensor Network

This section discusses plans for the future installation of a sensor network on an existing bridge for which rehabilitation is planned. The single span bridge shown in Figure 1-1, is located at the US Route 3 over State Route 11A bypass (NH bridge number 160/053) and is, as of the writing of this document, in need of a full depth deck replacement. The 8” concrete deck has a crown with a cross slope of ¼” per foot created by stepping the supporting stringers. The 7 stringers are W36x194 hot rolled shapes with 1”x10.5” welded cover plates and C15x33.9 channels for diaphragms. Additionally, the bridge has a 23° skew. To repair the bridge, and avoid further degradation and eventual load restrictions, a rapid deck replacement is being researched. The bridge has an average daily traffic volume of about 12,000 vehicles (NHDOT - Bureau of Traffic, 2012). The instrumentation of the Gilford Bridge was focused on two goals (1) to evaluate the structural steel both before and after the deck replacement and (2) to evaluate the use of instruments to aid ABC.
The full deck replacement is planned to involve nine precast and pre-stressed panels. The panels have longitudinal post-tensioning ducts to allow the panels to be post-tensioned together to act as a single slab. The construction process is planned to involve the placement of slabs one at a time; first by pre-leveling the slabs by use of leveling screws, lifting and placing on the steel, and then post-tensioning the slab to the next in the series of slabs. When all panels are in place, grout will be poured into slots left for the placement of shear studs and dams constructed for haunch formation. Figure 1-2 illustrates the placement and post tensioning process by showing how slabs will be tied together using the ducts as they make contact with the structural steel through the leveling screws.
The leveling of the slabs during construction is of particular interest due to the restricted amount of time that can be used for adjustments. This process will use the leveling screws to adjust the horizontal profile of the panels, creating a final deck of constant grade. Several methods have been proposed to predict the deflection of the steel and physically measure that deflection for comparisons and adjustments during construction. Methods of prediction involve structural models and curvature analysis; methods of measurement include the traditional method of survey equipment, the modern and impressive digital image correlation (Peddle, Goudrea, Carlson, & Santini-Bell, 2012) and the strain monitoring system that is also designed to compare pre and post rehabilitation bridge behavior.

Thus, the beginning of the research involved implementing a redundant strain-based monitoring system that can withstand impacts typical to a bridge deck demolition. In the event the construction process manages to damage a sensor, new sensors will not be able to be re-installed and calibrated during the small window of time available for rapid demolition and construction. Therefore, protection of sensor wires and redundancy was determined to be necessary. Additionally, conduit that carries wires from the sensors to the data acquisition
system would have to be rugged. For those reasons heavy Polyvinyl Chloride (PVC) pipe conduit was selected, and the sensors installed in the most important locations would also require some sort of redundancy.

The Gilford Bridge is ideal for evaluation of SHM protocols considering long term monitoring. Data sets for both the existing and the newly rehabilitated conditions from the same bridge will be available. If the ABC project at the Gilford Bridge moves forward, it will include instrumentation for long-term monitoring. Therefore the sensor network should be installed as early as possible to collect pre-rehabilitation data. If possible, the sensors should be in place and the system collecting data for at least a year before construction so that seasonal comparisons can be made.

The proposed sensor layout accounted for the long-term needs of an SHM system, as well as the short-term needs of monitoring and assisting the ABC, and is shown in Figure 1-3. The horizontal lines shown in the plan view represent beams. The numbered parallelograms represent the panel placements. The figure shows proposed gauge locations. Labels beginning with SG represent locations with strain gauges, and labels with TG represent locations with temperature gauges. The numbers give the gauges unique identifiers. The proposed system places strain and temperature gauges on the bottom of the top flange and the top of the bottom flange.
The sensor network was designed to ultimately have 56 strain gauges and 6 thermocouples. The strain gauges would measure neutral axis by being placed in pairs at the mid-span of the bridge as well as two other symmetrical interior points. The placement of sensors coincided with the center of panels as shown in Figure 1-3. By placing gauges at 3 longitudinal locations on each beam it was believed that higher order curvatures created by uneven load distribution could be detected during construction and other differences in panel-to-panel behavior during the lifetime of the structure could be detected. Two pairs of gauges were intended for the station at the mid span to provide redundancy as that location should see the maximum strains.

Netting, previously installed to prevent any deteriorating deck concrete from falling onto vehicles or pedestrians under the bridge, poses a challenge for the long-term instrumentation project. Concrete rubble is visible in the netting. As shown in Figure 1-4, the netting is stapled to timbers which are supported continuously along the bottom flanges of the stringers. The original instrumentation plan called for gauges to be placed on the top of the
bottom flange. This means modifications to the way the netting is supported will be required to carry out the original plan. Proposed solutions have involved supporting the netting on blocks or instrumenting the bottom of the flanges. The potential issues with these solutions are that modifications to the netting would be time consuming and could greatly increase the installation time. Furthermore, instrumenting the bottom of the bottom flanges will only support short-term research during construction because the locations are visible and would affect aesthetics. Also gauges placed at those locations are more exposed and vulnerable during regular bridge operation.

Figure 1-4: Netting Under Gilford Bridge

Figure 1-5 shows that the netting covers much of the underside of the bridge. The netting will need to be addressed before many of the sensors can be installed. Ultimately, this may affect the SHM system because of the inevitable increased time demands during installation may mean fewer gauges will be installed.
As solutions were being developed, delays in the bidding processes provided time to gain familiarity with the equipment purchased to build the SHM system. A bridge close to the UNH was sought that would have exposed steel girders, similar to Gilford, for this purpose. Strain gauges and thermocouples were installed at the Bagdad Road Bridge in Durham to evaluate the equipment and installation processes. The implications from this research that pertain to future SHM plans at Gilford are discussed in the conclusions Appendix B.

1.3 Bagdad Road Bridge

The bridge structure that is the main focus of this research is located on Bagdad Road in Durham NH (NH Bridge number 114/128). A locus map of the bridge location is shown in Figure 1-6. This four span bridge is State owned and only one span is over traffic, passing over US Route 4, as shown in Figure 1-7. This instrumentation plan is Phase One and will only focus on the spans not over traffic. Future work on this bridge may include additional instrumentation, as detailed in Appendix A.
The bridge is ideal for structural health monitoring research by UNH because instrumentation installation and maintenance involves no traffic management for 3 of the four spans. A photograph of the bridge is shown in Figure 1-8. Although access to the area for a vehicle such as a lift might not be possible currently, the earth underneath it has been compacted providing stable ground for scaffolding and ladders.
The two exterior spans are 45 feet long, and the two interior spans are 60 feet long. As shown in Figure 1-9, the width of the roadway is 32 feet. The bridge also carries two 5'-1" sidewalks. It was built in 1966 as part of a larger project that created the Durham Bypass, which re-routed US Route 4 around Durham. The consultant working on the bridge was Wright & Pierce of Portsmouth, New Hampshire and the contractor was R. G. Watkins and Son, Inc. of Amesbury, Massachusetts. The original bid for the project was approximately $110,200 (NHDOT - Bureau of Bridge Design).
There are several similarities between the superstructures of the Gilford and Bagdad Rd. Bridges. The Bagdad Rd. Bridge is supported by 6 lighter hot-rolled, W36x135 steel beams with thinner 0.5"x10.5" cover plates and uses the same steel channels, C15x33.9 for diaphragms. It also features a crown created in a deck of uniform transverse thickness by stepping the stringer bearing elevation. It differs from Gilford in that it has no skew and is expected to deflect in a different manner due to continuity over the interior support. The continuity presents a potential for collecting measurements during negative bending events where the simply supported condition of the bridge in Gilford should result in only positive bending.

The bridge is also scheduled for deck maintenance during the summer of 2012, which will provide another instance where data sets from before, after, and during rehabilitation are available. In the summer of 2012, the pavement and membrane will be replaced, possible deck repairs made, and an elastomeric plug joint installed at the western abutment, shown on the left hand side of Figure 1-10. Necessary deck repairs will be identified after the pavement and membrane have been removed. No structural repairs are anticipated (State Project 14461, page 18).
Features of the bridge that may be of particular interest to the SHM research community include the placement of shear connectors and the continuity of the beams. Shear connectors only exist in the positive bending regions of the two interior spans. This creates a difference in expected structural behavior between locations, as those with shear connectors should behave as fully composite sections and those without should behave as non-composite or partially composite sections. The continuity of the beams is created by welds that join adjacent beams together over the 3 bents. The four spans were joined together after the placement of dead loads, including the deck, creating a situation where the bridge beams support dead loads in a simply supported manner and live loads in a continuous manner.

1.4 Research at Bagdad Road

Instrumentation of the bridge was conducted during November 29th, and December 1st, 5th, and 9th, of 2011. The instrumentation involved installing fifteen strain gauges and two thermocouples on the two southernmost interior beams in the third span in from the western side, as detailed in Chapter 5. The strain gauges were positioned to investigate the placement and behavior of bonded foil strain gauges, gauges that could be used in future UNH SHM projects, including the Gilford Road Bridge, as well as to research a potential SHM metric by
measuring the structural response of the bridge. The thermocouples were only installed on one of the beams, for the purpose of monitoring temperature effects on the gauges and data acquisition system. More information regarding the sensors, and the currently instrumented locations, is included in chapter 4. More information regarding the installation is included in chapter 5.

A continuous, long-term SHM system has been envisioned for Bagdad Rd for the purpose of researching damage detection. Its implementation included assessing long-term power and communication utilities at the bridge, installing data acquisition equipment in an electrical enclosure, and processing some data at the bridge with an onsite computer. The full-scale system will depend on what installations actually occur in Gilford, as the equipment purchased for this research was originally intended for that bridge. Continuous monitoring was not performed at the bridge as cost of a constant power supply could not be justified for the limited initial number of sensors installed.

The first set of data was collected from the sensors on the afternoon April 30th, 2012. The data was primarily used to determine the neutral axis locations. The process and calculations are described in Chapter 8. The locations were close to predicted values derived from material and geometric properties that assumed an undamaged section. The experimentally determined value for one beam was only slightly higher than the predicted, which could easily be explained by the deck having a higher compressive strength than was specified in the original construction plans, or minor section loss from scaling in the steel. Minor section loss may be likely considering the approximately 2-inch long rust flakes found at the bridge site and shown in Figure 1-11.
Sensors at the Bagdad Road Bridge were also used to evaluate sensor placement and possible sensor malfunction. The sensors included full and quarter bridge strain gauges that are described in Chapter 4. The results indicated that a full bridge gauge placed on the top flange on one side of a beam as well as a quarter bridge gauge on the other side, are possibly malfunctioning. The results demonstrated the full bridge gauge configuration selected is inappropriate for placement on the beam webs. The results of both analyses highlight potential issues with sensor placement that are discussed in the conclusions of this thesis. The instrumentation also opens the door for other potential SHM related research pertaining to both the sensors and the metrics, also discussed in the last chapter.
Chapter 2: Background

Current structural health monitoring efforts were considered when designing the sensor networks for the bridges involved in this research. A review of surveyed literature is included in this chapter beginning with a discussion of current structural monitoring and the potential benefits introduced by continuous health monitoring. Design considerations related to SHM in general are included as well as a history of the design process and instrumentation goals for sensors at the Bagdad Rd Bridge.

2.1: Current Bridge Condition Monitoring and Maintenance Practices

The conditions of structural and mechanical systems periodically need to be evaluated to determine capacities and predict future maintenance as the states of systems degrade over time. Many systems are monitored in a discrete manner, meaning they are assessed on schedules at regular intervals. Other systems are monitored continuously with a meter that can raise notifications or alarms if a particular measurement threshold is exceeded. Most of those systems are also monitored with discrete inspections as well. An example is a vehicle that has an electrical monitoring system and also gets routine inspections.

Determining current capacity is important because managers and users must know whether or not a system can continue to function safely. Predicting maintenance is significant to managers who must continuously delegate limited resources on any number of concerns or needs. In the automobile example, it is important to know whether a vehicle has the capacity to continue to cool itself and prevent overheating, or whether a vehicle still has the capacity to break correctly and stop. Knowing when tires or brakes are approaching required replacement helps make owners aware they will need resources for maintenance soon. Electrical monitoring systems are well known for diagnosing the current condition of an automobile.
In a 2008 report titled “Bridging the Gap,” AASHTO listed 2 of the top 5 problems for bridges with age and deterioration as the number one problem and soaring construction costs as number three (AASHTO, 2008). They supported the claim by stating the average age of a bridge in the US was 43 years old and that the costs of steel, asphalt, concrete, and earthwork had risen by 50 percent in the 4 years before the report. Generally, more bridges are being built every year. As shown in Figure 2-1, between 1999 and 2009 over 15,000 bridges were added to the National Bridge Inventory (US DOT - RITA). It is clear that a huge amount of maintenance is, and will continue to be, needed to keep this massive inventory safe and operational.

![Total Number of Bridges in the United States](chart.png)

The current number of inventoried bridges in the United States, about 600,000, was tallied by The United States Department of Transportation’s (US DOT) Research and Innovative Technology Administration (RITA) using the National Bridge Inventory (NBI) (US DOT - RITA). This number represents bridges that are in the National Bridge Inventory (NBI). NBI bridges are subject to National Bridge Inspection Standards and use the definition of a bridge set forth in Code and Federal Regulations (23 CFR 650.3). The definition is:
“A structure including supports erected over a depression or an obstruction, such as water, highway, or railway, and having a track or passageway for carrying traffic or other moving loads, and having an opening measured along the center of the roadway of more than 20 feet between undercopings of abutments or spring lines of arches, or extreme ends of openings for multiple boxes; it may also include multiple pipes, where the clear distance between openings is less than half of the smaller contiguous opening." (US DOT - FHWA, 1995)

Some states have different definitions of what constitutes a bridge, in terms of length, width, carrying capacity etc. In New Hampshire, structures equal to or greater than 10 feet in length are considered bridges and are inspected according to NBIS standards. This creates the discrepancy between what RITA lists for bridges in NH; around 2,600 bridges, and what New Hampshire lists at about 3,800 bridges. In New Hampshire, inspections are performed on federally, state, and municipally owned bridges meeting the state definition. According to the NBIS, bridges must be evaluated every 24 month period with few exceptions (US DOT - FHWA, 1995).

Budget shortfalls make it difficult for state transportation agencies to keep up with maintenance demands. In the 2009 Report Card for America’s Infrastructure, the American Society of Civil Engineers (ASCE) pointed out that according to a report by The National Surface Transportation Policy and Revenue Study Commission published in 2007, $13 billion dollars is needed every year just to keep the number of deficient bridges from growing, while only $10.5 billion was being invested (ASCE, 2009). With approximately one in four bridges structurally deficient or functionally obsolete the goal should be to reduce the number of deficient or obsolete bridges, but that would require $17 billion per year. Not only do the large number of
bridges and budgetary shortfalls create challenges, coordination of bridge maintenance also needs to be considered. A common practice in the State of New Hampshire is to try to perform bridge maintenance while other construction is going on along the same route. The coordination reduces the impacts to drivers that frequent the route. This means when a resurfacing project or road realignment is being planned, managers need to predict if any bridges on the route may need maintenance. The current practice of predicting maintenance needs is typically based on the results of routine or special visual inspections.

Inspections can be subjective, and important information can be missed or neglected in the reporting and evaluation phases. A study evaluating the accuracies and reliability of inspection reports found experienced inspectors can have varying opinions when observing the same damage (Phares et al. 2004). Other important information noted during inspections may not ever be considered in analysis. One inspector that inspected the I-35 bridge in Minnesota that collapsed in 2007 had seen gusset plate deformation and figured it had happened during construction, and the gusset plates are believed to be a significant factor in the collapse as the design of some of the plates were a half inch too thin. (ENR: Engineering News-Record, 2009)

Non-destructive evaluations can provide more information about structural condition and are much less subjective but are often expensive and are less frequent than visual inspections. Although improvements can be made, the current system of inspections and repairs should not be discredited; it has created a dependable bridge network. Considering the staggering number of bridges in the United States, there are relatively few bridge failures. A survey of 503 bridge failures over 10 years showed that the vast majority of bridge collapses were contributed to man-made and natural external events, such as overloading or flooding. Deterioration accounted for only 8.6% of failures (Wardhana & Hadipriono, 2003). Bridges rarely
fail during regular operation. Therefore those that do, like the I-35 Bridge in Minnesota in 2007, appear as extreme and unfortunate occurrences.

As valuable as inspections and non-destructive evaluations are, they are discrete. What happens between inspections or evaluations will not be recorded or responded to until the next individual observation. This may not account for damage that occurs between inspections and these inspections are typically visual, and therefore, structural health related features not visible, like rebar condition can be overlooked. Although these out-of-sight deficiencies may not cause a bridge to fail, they could result in unintentional redistributions of stress that further accelerate bridge deterioration resulting in more frequent and costly maintenance needs. SHM offers a means to provide missing information to bridge engineers, potentially decreasing maintenance costs and further improving safety.

2.2 Structural Health Monitoring

Scrutinizing the way a structure responds to loading provides a way to investigate deficiencies that may not be externally visible. Furthermore, continuous monitoring offers a means to catch the deficiencies at first appearance, rather than at the next inspection cycle, allowing for repair before the damage has an opportunity to cause further deterioration to the system. Structural Health Monitoring (SHM) is the process of observing the way a structure behaves with an interest in damage sensitive parameters. By complimenting the current inspection process, it offers a means to provide bridge managers more information about current capacities and the rates at which structures degrade so they may make more accurate predictions of future maintenance needs.

Farrar, Doebling, and Nix described a process of vibration based SHM in a report printed in 2001. In the report, they describe a damage detection technique as a statistical pattern
The four part process is listed below. The process was later used to discuss SHM in general in a report by the Los Alamos National Laboratory. The report, titled “A Review of Structural Health Monitoring Literature: 1996-2001” covered hundreds of SHM articles out of numerous technical literature. In it, the authors chose to categorize SHM research based on the four steps. They broadened the fourth step described by considering damage techniques that did not necessarily rely on a structural model, thus re-labeling the step from Statistical Model Development to Feature Discrimination.

Four Part SHM Process
1. Evaluation
2. Data acquisition and cleansing
3. Feature extraction
4. Feature discrimination

Evaluation is the step that involves researching the structure. It identifies the environmental and operational constraints and establishes the customization of the particular SHM method. Data acquisition and cleansing is the physical data collection. It involves selecting sensors, determining measurement intervals, and normalizing and storing data. Feature extraction is the process of using measurements to determine characteristics of the structure. Feature extraction is used to condense data as significant numbers of measurements are reduced to manageable data sets, multiple accelerometer values may be converted to mode shapes for example. Lastly, feature discrimination is the process of analyzing statistical patterns to identify damage. This process typically requires a model in civil structures as data sets from a damaged structure typically aren’t available (Farrar, Doebling, & Nix., Vibration-Based Structural Damage Identification, 2001). This research includes work in all four of these areas: evaluating the Bagdad Road Bridge for SHM metrics that could be researched, acquiring and post-processing field data, extracting neutral axis location, and using the location to infer the health of a composite section.
A later report by Farrar and Worden, published in 2007, identified several challenges in structural health monitoring, as it moves from primarily research efforts to common practices. These challenges include but are not limited to (1) detecting local damage based on global behavior, (2) identification of damaged sensors, and (3) convincing owners that the cost of SHM systems has a benefit (Farrar & Worden, An Introduction to Structural Health Monitoring, 2007). These challenges are currently being addressed in several SHM projects, and as their findings are published, SHM is likely to become more broadly utilized. Several SHM research examples pertaining to civil infrastructure are summarized by Brownjohn (2006).

Multiple short-term studies in the State of Connecticut were summarized in a report and demonstrated significant near-term cost savings. The projects, conducted by the University of Connecticut, showed that short term SHM projects have saved the State over 2.5 million dollars in repair costs (Dewolf et al. 1998). Studies generally involved investigating potential crack propagation. One study, for example, noted that stresses in cracked diaphragms were only high enough at center span to cause the cracks to propagate. By demonstrating that cracks did not need to be repaired in the diaphragms at the quarter points, the State was able to save on the renovation costs. The University of Connecticut and the Connecticut Department of Transportation have worked together on several projects to accelerate the field of SHM research. An article by Cardini and DeWolf (2009) stated that in over 20 years of research, roughly 30 bridges have been monitored in Connecticut. Lui et al (2008) described the general process for SHM deployment used in several of the Connecticut monitoring studies.

Although the costs of SHM implementation were not included in the articles regarding the Connecticut projects, cost/benefit analyses in SHM projects are being evaluated throughout the industry. At the 5th International Conference on Structural Health Monitoring of Intelligent
Infrastructure, Dr. Daniele Inaudi reported on benefits of SHM implementation (2011). These benefits were divided into “hard” and “soft” benefits. Hard benefits are easily quantifiable and include extending the service life of bridges and finding hidden capacity. Soft benefits are less tangible and include reduction of risk and public image. The author used an anecdotal example to show how SHM-assisted extended lifetime could be used to save thirty percent on the repairs of a sample of bridges.

2.3 Future of SHM

As sensor networks become more reliable and SHM metrics develop, long-term continuous monitoring will be able to give engineers more information not only about the condition of bridges but how they behave, as well. Eventually, SHM systems may even help engineers build better structures. A future SHM system may sense a crack propagating at the same time it records a vibrations signature and measures the vehicle driving across and the distance between axles. Using that type of information, researchers will be able to definitively identify the source of damage and compare the structure to other structures that have experienced equal loading without an occurrence of damage. Those types of observations can result in more rugged structures that perform in a more favorable manner under that loading.

Sensor networks combined with advances in modeling and iterative techniques may even be able to locate and quantify damage providing the same sort of information that discrete non-destructive evaluations give bridge engineers on a continuous and automated fashion. Iterative procedures are being researched at UNH that could be used to create baseline models using measurements of the structures behavior (García-Palencia & Santini-Bell, 2012). By updating the baseline model over time so that they react to loading like the real structures,
virtual damage in the model may be indicative of real damage. Advanced systems may be able to run these updating routines so regularly that damage is detected immediately after it occurs.

Future sensor networks will be multipurpose and able to reliably provide other information in addition to structural behavior. The SHM network installed in the new Saint Anthony's Fall Bridge, which replaced the I-35 Bridge, contains temperature sensors that are used to trigger the anti-icing system (French, Shield, Stolarski, & Hedegaard, 2011). Bridge weigh-in-motion is being researched as a means to use strain sensors to weigh trucks, expanding the capacity of States to determine non-permitted overload vehicles (Cardini & DeWolf, Implementation of a Long-term Weigh-in-Motion System for a Steel Girder Bridge in the Interstate Highway System, 2009).

It becomes relatively easy to think about the potential benefits of continuous SHM when considering how an improved continuous health monitoring system would benefit a person. The nervous system in a body is much like current SHM systems, pain can often tell a person that something is wrong, but the person needs to see a doctor to examine why, similar to an early inspection that might be triggered by today's SHM networks. However, future networks may be able to report what's wrong. People would likely eat better, exercise more, and go to bed earlier if they continuously saw metrics about how the decisions they make affect their health. If large amounts of data were available from these systems for doctors, they would make better recommendations to their patients regarding lifestyle choices. And lastly, the monitoring could catch ailments so they may be treated earlier before they grow into larger more damaging afflictions. In a similar way, an SHM system could detect a fatigue crack or delamination in the early stages, when the repair costs are minor.
2.4 SHM Research as Part of This Thesis

The work conducted as part of this research could be categorized by steps in the SHM process described by Farrar et al (2001). The evaluation and data acquisition steps are described in this section, and the feature extraction and discrimination are described in chapter 6. The bridge was evaluated and the steel girders presented an opportunity to instrument with bonded foil strain gauges to detect neutral axis in a composite section. Data acquisition was conducted by installing strain sensors and reading them for roughly 40 minutes during heavy traffic flow. Neutral axis locations were extracted as features, and the discrimination involved comparing the experimentally determined locations to a location determined through structural mechanics.

The evaluations for this research were based on objectives for the long-term SHM system at the Gilford Bridge. At Gilford, the data from the sensor network was for both long-term monitoring and to investigate the use of strain sensors in the accelerated bridge construction process. Long term monitoring needs impacted the number of gauges required at each instrument location, and the accelerated construction process had a large impact on redundancies and the wiring required. At the Bagdad Road Bridge, the objective was to evaluate strain gauges and sensor placements that were chosen for the Gilford project and could potentially be used in future UNH SHM projects.

Neutral axis shifts during live load events were chosen for the long-term structural health monitoring metrics at Gilford and the Bagdad Road Bridge. The definition of the metric, in this case, is essentially a behavior that will be monitored over time for change that could indicate damage. Detection of neutral axis requires using at least two strain measurements at a
given cross section of a beam. Given that both bridges were scheduled for rehabilitation or replacement of the deck, this measurement should change over the course of both projects.

As for providing information that might support the accelerated building process, the sensor network was designed to detect load distribution and curvature. The load from the precast panels will be distributed to each beam through the use of leveling screws. The depth the screws protrude below the bottom of the panel can be adjusted before the panels are placed to account for tolerances in panel manufacturing and to adjust the horizontal profile of the finished deck. Incorrect load distribution could cause over stressing in stringers and accelerated degradation over the future life of the bridge. Additional details relating to the Gilford instrumentation plan and its development are included in Appendix B.

The sensor network at the Bagdad Road Bridge was implemented on a small scale for sensors and data acquisition equipment testing. A full-scale sensors network is detailed in Appendix A. The objectives at the Bagdad Road Bridge do not include measuring load distribution or other differences in beam to beam behavior so not every beam requires instrumentation. Also, although a basic partial deck replacement process is scheduled for Summer 2012, the existing deck will not be completely demolished and measurements during any demolition are not considered vital. To meet the needs of this research, only two beams were prioritized for installation. Interior beams were chosen because they were expected to have a higher response under live loads, given the sidewalks over the exterior beams, and to hide the installation and preserve the aesthetics of the bridge from travelers on US Route 4, below the bridge.
Beam D, shown in Figure 2-2, was chosen for evaluating optimal placement of strain gauges for neutral axis measurements. The impact of flawed measurements in strain, typically due to noise, when using two gauges was also evaluated. Three strain gauges were used to calculate neutral axis using linear regressions and compared to values produced by pairs of strain gauges within the set of the three gauges. The analysis will, therefore, also be able to show what the best locations are when neutral axis locations are made when using a pair of strain gauges. Both sides of the beam were instrumented with three gauges to increase confidence in the results and provide redundancy for the instrumentation system. Two thermocouples were also installed at this location to evaluate the behavior that temperature has on the strain measurements. Layouts of the instrumented cross sections are shown in Figure 2-3. The purpose of instrumenting Beam E was to evaluate the behavior of the sensors themselves by comparing measurements made from full and quarter bridge gauges.
The full bridge bonded foil strain gauges selected for this research function by combining strains measured in multiple directions. The process, which is further described in Chapter 3, may be sensitive to unintended local effects and, if great enough, the effects could render the gauges unusable for this type of monitoring. Comparisons were made by instrumenting both sides of the beam. The northern face of the beam was instrumented with the full bridge gauges, and the southern face was instrumented with quarter bridge gauges. An image of the full bridge gauges, Omega© model number SGT-4/1000-FB11, is shown in Figure 2-5. The quarter bridge gauges, Omega© model number KFG-3-350-C1-11L1M2R, shown in Figure 2-4. The thermocouple chosen to measure temperature, Omega© model number 5TC-GG-T-20-36, is shown in Figure 2-6. Much more information about comparisons using combinations of sensors is provided in Chapter 6.
The analysis of gauge behavior and data quality of field collected data is included in chapter 7. The post-processing of the collected data to determine neutral axis locations is included in chapter 8.
Chapter 3: Data Acquisition Selection

This chapter discusses the progression of data acquisition selection. As pointed out by DeWolf et al. in 1998, continuous monitoring systems have 4 main components. Those components are control units, sensors, software, and communications. This chapter describes the software and control units. Control units include data loggers and the computers that read and manage them. Sensors selection is described separately in the following chapter so that emphasis can be placed on how the sensors function. Communication options were not thoroughly evaluated as part of this project because the decision of whether to continuously monitor at the Bagdad Road Bridge is pending.

The equipment selected included thermocouples and bonded foil strain gauges from Omega Engineering®, CompactDAQ® data acquisition chassis, and several modules that could be exchanged to fit various measurement needs purchased from National Instruments® (NI). SHM needs at Gilford were still under investigation while the need to procure equipment and evaluate its behavior outside of the lab was growing. Modular data acquisition hardware was sought because it would allow for adjustments during the sensor network design that develop as needs were identified. This would also allow for easier expandability in future SHM research projects at the bridge. Modular systems can read different types and numbers of instruments by purchasing modules. Ultimately NI hardware was chosen because of its compatibility with the data collection and processing software LabVIEW®.
3.1 Software: LabVIEW

LabVIEW is also a product of NI. Short for Laboratory Virtual Instrumentation Engineering Workbench, it’s a developer’s platform that can be used to create programs and graphical user interfaces for those programs. The programs can read and post-process data and present live calculations allowing for features to be interpreted in real time. This reduces the amount of software that needs to run as part of the SHM and experimenting process. Rather than having proprietary software supplied by the data acquisition system manufacturer to record data, then excel or a similar program used to post-process data, and then a third software platform to present the graphical interface, LabVIEW includes these functions in a single program. At the time of this writing, a standard license of the software costs $2,699. However, UNH has an Academic Site License and, therefore, no software costs were involved in this project.

Each LabVIEW executable file, including programs and subroutines, has a user interface called the front panel and the controlling “code” in the attached block diagram. These programs are called virtual instruments (VIs) because their appearance and operation is meant to model a physical instrument, like an oscilloscope. The user interface is created on the front panel when the program is not running by placing graphs, numerical indicators, and controls. The block diagram then programs the user interface by the placement of VIs and structures. The VI’s and components that are placed on the front panel appear as blocks in the block diagram. The blocks can then be wired together in a way that controls the flow of data and how it’s processed.
Figure 3-1 shows an example VI front panel and Figure 3-2 shows the corresponding block diagrams. The rectangles in the block diagram labeled “Simulate Signal” and “Formula” are VIs and can be opened as programs to view or modify their own front panels and block diagrams. VIs that run on the block diagrams are often referred to as subVIs and, may or may not be opened during the operation of the front panel corresponding to the block diagram they are placed in. The squares labeled “Knob”, “Waveform Graph”, and “stop” are structures referred to as terminals that interact with subVIs in the block diagram when users interact with the front panel. Finally, the grey box around the block diagram is a “while loop,” a structure that causes the program to keep running, once it’s been started, until the user halts the program.
Although it was relatively easy to begin programming with LabVIEW to develop the programs used in this research, the software is complex. Because of the graphical nature of the interface, programming expertise from using other languages such as C, SQL, or MatLAB may not translate to familiarity with LabVIEW. This can lead to an underestimation of the complexity in writing sophisticated new programs. NI offers courses to develop proficiency that were not taken advantage of for this research due to budgetary and scheduling constraints. With further resource commitments, advanced programs with features such as password protection, client/server options, and web interfaces could be developed for further UNH-NHDOT SHM projects, using software that is on-hand that UNH already licenses.

3.2 Hardware

Rugged modular equipment was researched so the hardware would behave dependably in temperatures that exist at bridges in New England and could be easily expandable to meet developing research needs. Table 3-1 shows different types of data acquisition loggers that National Instruments offers. (National Instruments, 2010) These types of data loggers are common to the industry as other companies offer PCI, PXI, USB, Wi-Fi, and Ethernet devices.

Peripheral Component Interconnection (PCI) and PCI express equipment is connected to computers via slots in the motherboard, the same connections that would be used to connect video cards or modems. PXI stands for PCI eXTensions for Instrumentation and the equipment uses chassis to hold multiple modules. The PXI Systems Alliance (PXISA) is an industry consortium, founded in 1998, that promotes and maintains the industry standard (PXISA, 2012). The PXI standard has become a “major force” in the data acquisition field because it is an open platform and the equipment is cross compatible (Radio-Electronics.com). That means PXI cards made by one manufacturer would work in a chassis produced by another.
Data loggers or data acquisition systems are commonly referred to as DAQs. Portable DAQ and Desktop DAQ systems were out of consideration because they are fixed systems and not as easily adaptable as the modular systems. Of the modular systems, the CompactDAQ was chosen for many reasons. Although it will not be compatible with other manufacturer’s equipment, which was of no concern in this project, the equipment is less expensive and has built in signal conditioning out of the box (National Instruments, 2010). Better portability was an additional benefit that would result in smaller electrical enclosures because the portability comes in the form of smaller hardware.

The CompactDAQ equipment uses c-series modules. The carriers and chassis compatible with c-series modules are shown in Table 3-2. Carriers were eliminated from consideration because they can only read one module at a time. From the available chassis, the CompactDAQ chassis was chosen because of cost, and it did not require significant LabVIEW expertise. The CompactRIO® uses a separate controller and a field programmable gate array
(FPGA) system to manage timing and processing that requires additional programming experience to configure. In addition to expertise demands from FPGA programming, the R-series chassis were not in consideration because they are for expanding PXI systems (National Instruments).

Table 3-2: Carriers and Chassis Compatible with NI C-Series Modules

<table>
<thead>
<tr>
<th>Carrier/Chassis</th>
<th>Applications</th>
<th>Recommended Programming Experience</th>
</tr>
</thead>
<tbody>
<tr>
<td>USB Carrier</td>
<td>Portable, small channel count</td>
<td>None needed</td>
</tr>
<tr>
<td>Wi-Fi/Ethernet Carrier</td>
<td>Remote monitoring, structural monitoring, environmental monitoring, machine condition monitoring</td>
<td>None needed</td>
</tr>
<tr>
<td>NI CompactDAQ (USB and Ethernet Chassis)</td>
<td>General-purpose mixed-sensor DAQ, control, high-speed DAQ, portable system up to 256 channels</td>
<td>None needed</td>
</tr>
<tr>
<td>NI R Series Expansion Chassis</td>
<td>Large advanced test system, deterministic control and acquisition, manufacturing test</td>
<td>Comfortable with NI LabVIEW programming</td>
</tr>
<tr>
<td>NI CompactRIO</td>
<td>In-vehicle logging, rapid control prototyping, advanced control unit, custom design deployment</td>
<td>Comfortable with LabVIEW programming</td>
</tr>
</tbody>
</table>

Because the costs of the CompactDAQ chassis are a fraction of those for CompactRIO, about $1000 versus $9000 for 8-slot chassis, the CompactDAQ provides for an excellent way to introduce the technology to UNH and local SHM stakeholders. The majority of the cost in equipment comes from the modules, approximately $1000 for 4-channel strain cards, see
Appendix C, and the modules will be compatible with CompactRIO chassis should future researchers working with this equipment decide to upgrade. Table 3-3 shows a quick comparison of C-series reading equipment. The table highlights that CompactDAQ chassis have cost savings with only a slight loss in ruggedness and performance. Both Table 3-2 and Table 3-3 are available at the National Instruments website, ni.com, with additional information about the specific functions of each.

Table 3-3: Quick Comparison Table for C-series Module Reading Equipment

<table>
<thead>
<tr>
<th>Module</th>
<th>Ruggedness</th>
<th>FPGA</th>
<th>Ease of Use</th>
<th>Performance</th>
<th>Cost</th>
<th>Programming</th>
</tr>
</thead>
<tbody>
<tr>
<td>USB Carrier</td>
<td>***</td>
<td>No</td>
<td>*****</td>
<td>**</td>
<td>$</td>
<td>LabVIEW, ANSI C/C++, C#, Visual Basic .NET</td>
</tr>
<tr>
<td>Wi-Fi DAQ Devices</td>
<td>***</td>
<td>No</td>
<td>****</td>
<td>**</td>
<td>$</td>
<td>LabVIEW, ANSI C/C++, C#, Visual Basic .NET</td>
</tr>
<tr>
<td>NI CompactDAQ</td>
<td>****</td>
<td>No</td>
<td>*****</td>
<td>****</td>
<td>$$</td>
<td>LabVIEW, ANSI C/C++, C#, Visual Basic .NET</td>
</tr>
<tr>
<td>R Series Expansion</td>
<td>***</td>
<td>Yes</td>
<td>***</td>
<td>*****</td>
<td>$$$$</td>
<td>LabVIEW</td>
</tr>
<tr>
<td>CompactRIO</td>
<td>*****</td>
<td>Yes</td>
<td>***</td>
<td>****</td>
<td>$$</td>
<td>LabVIEW</td>
</tr>
</tbody>
</table>

The number of C-series modules and chassis were selected based on the initial needs for a long term monitoring project at the Gilford Bridge. This resulted in three data acquisition chassis. Each of which can manage up to eight modules that read the cards and send data to the controlling computer. It was assumed two chassis would be located at the monitoring site permanently while one chassis would be used to expand on the system while conducting experiments at the site during load tests, but generally would be kept at the laboratories at
UNH. Fourteen strain reading modules were purchased. Each reads up to four strain gauges meaning up to 56 gauges can be read when all 14 cards are utilized. These cards can be moved between bridge locations and UNH as research needs dictate. Two Thermocouple cards were purchased; the first card is capable of measuring 16 thermocouples and is intended for long-term deployment, the second has four channels and is intended for measurements at UNH. One accelerometer card was purchased for potential dynamic research at the bridge or UNH.

A water resistant, durable, secure NEMA-4 enclosure was purchased, which will house the equipment at the bridge site during the permanent installation. A fanless computer for controlling the data acquisition equipment was also purchased. A photograph of the open enclosure with the pc, 2 chassis, and several modules is shown in Figure 3-3. Lastly, enough wiring has been purchased for the currently installed equipment and much of what would be required for both a Gilford and Bagdad Road Bridge sensor installations. All of the equipment is detailed in Appendix C.

Figure 3-3: Photograph of Enclosure and DAQ Equipment
<table>
<thead>
<tr>
<th>3 Data acquisition chassis</th>
<th>Manufacturer: National Instruments</th>
<th>Model Number: NI-9178</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Each power up to 8 modules</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Used to read modules and send data to the computer.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• 2 chassis will be located at the monitoring site</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• 1 chassis will be used to conduct experiments at the University</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>14 Strain reading modules</th>
<th>Manufacturer: National Instruments</th>
<th>Model Number: NI-9219</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Each reads up to 4 strain gauges</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Can be moved between the bridge locations and the University as research needs dictate.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2 Thermocouple modules</th>
<th>Manufacturer: National Instruments</th>
<th>Model Number: NI-9211 (4-channel) &amp; NI-9213 (16-channel)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Up to 16 thermocouples can be read using the card for the bridge</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Up to 4 thermocouples can be read using the card for the University</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1 Accelerometer module</th>
<th>Manufacturer: National Instruments</th>
<th>Model Number: NI-9234</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Used for potential dynamic research at the Bridge or University</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1 NEMA-4 enclosure</th>
<th>Manufacturer: Omega Engineering, Inc.</th>
<th>Model Number: OM-AMU2060</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• water resistant, durable, and secure enclosure housing for the equipment at the bridge during permanent installation</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1 Fanless PC</th>
<th>Manufacturer: Habey</th>
<th>Model Number: MITX-6564</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• 1 Computer: used to control the data acquisition hardware and access recorded data</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wiring</th>
<th>Manufacturer: Omega Engineering, Inc.</th>
<th>Model Number: TX4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Enough wiring has been purchased for the currently installed equipment and much of what is required for a Gilford</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• 4-lead</td>
<td></td>
</tr>
</tbody>
</table>
Using data acquisition equipment that reads full bridge gauges comes at a small premium with respect to National Instruments products. Although a direct comparison can be difficult to make, because different cards have different features that researchers might feel adds or subtracts value, a general analysis can be performed. Considering only the chassis and modules, and neglecting the academic discount, the price of full bridge gauges was roughly $330 per channel compared to $210 per channel for quarter bridge gauges.

The costs per channel were taken from ni.com during the month of July 2012 and are presented in Table 3-5. At the time of this research, the 2 c-series modules capable of reading full bridge gauges are the NI-9219, which was used in this project and can read at speeds up to 100Hz, and the NI-9237, which can run at a much faster 50 kHz. The NI-9219 costs $1,029 and the NI-9237 costs about $1,180. The module that reads Quarter Bridge gauges, NI-9235, costs $1,544, can read at speeds up to 10 kHz, and has 8 channels. All modules mentioned here can read at 24 bits of resolution. high speeds are not necessary in long term SHM because of data storage demands. However, to produce more level comparison, the costs of the higher speed full bridge channels are compared to the cost of the quarter bridge channels, which is only offered at high speeds. A full 8-slot chassis was used to produce the channel counts.

<table>
<thead>
<tr>
<th>Channel Type</th>
<th>Channel Count per card</th>
<th>Total Channels</th>
<th>Cost of Chassis per Channel</th>
<th>Cost of Module per Channel</th>
<th>Cost per Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Bridge (NI-9237)</td>
<td>4</td>
<td>32</td>
<td>34.38</td>
<td>$ 295</td>
<td>$ 329.38</td>
</tr>
<tr>
<td>Quarter Bridge (NI-9235)</td>
<td>8</td>
<td>64</td>
<td>17.19</td>
<td>$ 193</td>
<td>$ 210.19</td>
</tr>
</tbody>
</table>

With respect to the sensors themselves, comparisons are even more difficult to make because a much broader selection of quarter bridge and full bridge gauges are available. The
sensors are inexpensive compared to the cost of the channels so the cost was not a significant factor in the gauge selection process. The sensors used in the research were about $21.00 per full bridge gauge and about $12.00 per quarter bridge gauge. It should also be noted that half as much wiring is needed for 2-lead quarter bridge gauges as a single line contains 4 leads and therefore 2 gauges can be connected to the DAQ with a single line. The full bridge gauges on the other hand require all four leads and, therefore, require a dedicated line. The cost of wire is roughly $0.20 per foot. Based on 90' lengths of wire, this results in a cost per sensor of $39.00 for full bridge gauges and $21.00 for quarter bridge. The costs for gauges and wires were taken from omega.com during July of 2012.

Considering that all other costs for the two systems are the same, including the computer, enclosures, software, personnel, installation, and overhead, the premium per channel for using full bridge over quarter bridge may be a small portion of the overall costs.

It should also be noted that the cards can read up to 100 samples per second per channel however they feature two modes, high speed and high resolution. The high resolution mode produces consistent values with a low noise to signal ratio but cannot be used above 2 Hz. The high speed mode on the other hand does not sacrifice any actual resolution but instead gives up a processing feature called delta-sigma ADC conversion that makes the high resolution collections so consistent. A correspondence regarding this is included in Appendix C. Another detail about the strain modules is that they cannot read three lead quarter bridge gauges, out of the box. Therefore, quarter bridge gauges used in this research are not the same as those used in another UNH SHM research project, the Powder Mill Bridge in Barre, MA. The monitoring system at the Powder Mill Bridge uses 3 lead quarter bridge gauges that feature an extra lead to compensate for temperature effects on the lead wires (Lefebvre, 2010). However a working
solution that would use resistors to modify the circuit was developed by engineers at NI and is also included in the Appendix C of this thesis.
Chapter 4: Measurements with Bonded Foil Strain Gauges

Bonded foil strain gauges were chosen as the strain sensors for this research project. Strain measurements allow for the calculation of neutral axis location, distribution factors, and curvature. Strain can be measured using a variety of sensor that all have limitations and challenges for use on civil structures, particularly the effects of varying temperature. Mainstream structural health monitoring systems will require sensors that can provide reliable measurements in the rugged environment that bridges exist in, and can be installed with a high success rate by contractors during construction. Research in the field of SHM can develop while sensor technology improves by using cost effective instruments and managing errors in post processing.

Bonded foil strain gauges were used in this research because they are cost effective, relatively easy to install, and there is an existing experience base with that type of sensor in the UNH SHM research group (Santini-Bell, Lefebvre, Sanayei, Brenner, Sipple, & Peddle, 2012). This chapter discusses how the gauges function, particularly the gauges chosen for this research.

4.1 Introduction to Strain Measurement

A fundamental of structural engineering is the method of arranging structural members such that applied forces result in elastic stresses in the material allowing the structure to deform rather than permanently displace. These stresses can be compressive or tensile and material can undergo a limited amount of stress before it fails. Stress cannot be measured directly. However a change in stress can generally be calculated from a known applied load as shown in equation 4-1. The equation shows the calculation of normal stress, meaning the load is applied axially to the cross section of interest. In equation 4-1, \( \sigma \) is the stress while \( P \) is the known load and \( A \) is the known cross sectional area the load is applied to.
When the load is unknown, or the distribution is more complicated, stress is typically measured using strain values. Strain ($\varepsilon$) is the measurement of the deformation that stress has caused. There are two types of strain generally referred to true strain and engineering strain. Engineering strain represents the change in length over the original length as shown in equation 4-2, where $\Delta L$ is the change in length and $L$ is the original length. The value is a ratio and is unitless; however, it is typically referred to in units of length over length. When stresses are relatively low, some materials, such as steel, behave in an elastic fashion and there is a direct correlation between stress and strain. The amount the material strains from elastic loading is given by Young's modulus, an experimentally determined value (Eq. 4-3). Values of the modulus for frequently used materials are widely published and, for steel, a value of 29,000 ksi is generally utilized.

$$\varepsilon = \frac{\Delta L}{L} \quad (Eq: \ 4-2)$$

$$\sigma = \varepsilon E \quad (Eq: \ 4-3)$$

By using the relationships between stress and strain, more information can be derived about how a structure behaves and handles load. By mounting vibrating wire strain gauges into concrete girders, Barr, Eberhard, and Stanton (2001) were able to calculate live load moments and distribution factors. Johnson and Robertson (2007) demonstrated a method of using strain values at several locations to determine deflected shapes and displacements for a variety of loading and support scenarios. They compared results from numerical models to those of calculations using curvature and displacement relationships. Although they demonstrated a
high correlation, they concluded that signal to noise ratios of sensors poses a major challenge in real world implementation.

Strain can be measured using several devices. Vibrating wire strain gauges use a tensioned wire mounted between two points. When the wire changes length the frequency at which it vibrates changes and an electromagnet reads the change (Geo Instruments, 2009). Various fiber optic strain gauges use light refraction in a mounted tube to measure strain. When the two mounts that holds the gauge separate, a fiber optic wire in the tube is pulled away from a reflective end (Sipple, 2007). Light that is reflected out of the fiber optics reflect off the reflective end and return back down the optic cable creating varying patterns in the light that are read by an instrumentation system. Digital Image Correlation (DIC) is a process of comparing multiple images of a specimen under strain. Software tracks groups of pixels through the sequence of images and determines strain by the changes between the groups (Peddle, Digital Image Correlation as a Tool for Bridge Load Rating and Long Term Evaluation, 2011). The bonded foil strain gauge is the instrument focused on in this research. The gauges utilize a filament that changes electrical resistance when elongated. The change is then read by electrical equipment to determine strain (Omega Engineering Inc.).
In order to understand and plan for the types of errors in strain-based monitoring systems utilizing bonded foil strain gauges, researchers need some basic understanding of how they function. This is a big challenge facing civil/structural engineers that serve the role of researchers in the field of SHM. This chapter describes the basics of how strain in the gauge is read as voltage change. It will begin with the basics of voltage measurements, then a description of how the Wheatstone bridge, the most common circuit in strain measurement, is utilized for different strain measuring needs. The chapter ends with a detailed description of the gauges used in this research and how they function.

4.2 Basic Voltage Measurements Using Variable Resistance

Electrical resistance gauges function by using the change in conductivity a material will undergo as it deforms. An understanding of how the measurement is made is needed to
identify and understand sources of error and make informed decisions during the gauge selection process.

Basic electrical measurements take advantage of Ohm's law. The law states that voltage (V) is the product of current (I) and resistance (R). The relationship is shown in equation 4-4.

\[ V = IR \]  
(Eq: 4-4)

Figure 4-5 illustrates a simple circuit featuring an excitation source and a single resistor. Current has been labeled with corresponding arrows to illustrate that it flows through the circuit.

![Figure 4-5: Illustration of a Basic Circuit with 1 resistor](image)

The hydraulic analogy is a widely used analogy for describing electrical circuits. The analogy describes energy as a type of fluid that flows through a circuit like pipes. In this analogy, the excitation is a source of pressure, or head as it's referred to in fluid mechanics. Current is the flow of this fluid. Similar to how flow in pipes and closed channels is constant, flow throughout the circuit is as well. If flow wasn't constant, fluid or electrons, would build up in the system which would require reservoirs or capacitors. Storing electrical fluid is not required for strain-based measurements so it won't be discussed further. Therefore, circuits mentioned here will feature a constant I.
When two resistors are connected in line with each other, what is known as “in series”, their resistance values are additive as shown in equation 4-5.

\[ V = I(R_1 + R_2) \]  
(Eq: 4-5)

Considering current is constant throughout a circuit, the equation highlights that voltage changes as it drops between resistors. Strictly speaking, voltage is the potential difference between two locations in an electrical circuit. That is what is also known as the electrical potential difference. Similar to how head pressure falls as fluid travels through clogged pipes or filters, voltage drops across each resistor. The drop between resistors is also highlighted in the diagram of a voltage divider shown in Figure 4-6.

![Figure 4-6: Basic Voltage Divider 1](image)

In Figure 4-6, \( V_s \) is a measure of voltage across the second resistor, or the voltage signal. The measure of voltage signal relates to the excitation and the values of the resistors by the following equation:

\[ V_s = \frac{R_2}{R_1 + R_2} \cdot V_e \]  
(Eq: 4-6)

A proof is included in Appendix E.
Looking at the equation for voltage signal, it can be seen how changes in resistance in either resistor can be determined if one resistance and the excitation is known or how both could be measured if they are related by some proportion. A bonded foil strain gauge essentially replaces one or more resistors in a circuit similar to this.

A bonded foil strain gauge functions when the filament within the gauge is subjected to the same elongation as the specimen that it is bonded to. Strain is transferred by shear forces in the rigid epoxy. The filament elongates, which changes the electrical conductivity of the filament for two reasons; both the physical elongation and the change in cross section of the filament due to Poisson’s effect. Considering the hydraulic analogy, this is similar to how water pressure drops flowing through a longer and thinner pipe compared to a wider and shorter geometry.

4.3 The Wheatstone Bridge

The problem with measuring the voltage through the voltage divider described in the previous section is the measured value is that of both the voltage across the resistor, and the change in voltage as shown in Figure 4-7:

Because bonded foil gauges produce small changes in resistance, the change in voltage \( \Delta V \) is relatively small. Thus the voltage across \( R_2 \), referred to as the steady state voltage \( (V_i) \), is
typically much larger and subsequently errors in its measurements that would seem relatively small have a large impact on observations of $\Delta V$. The influences of error in observing the steady state voltage make it desirable to isolate $\Delta V$ and measure that separately.

The Wheatstone bridge was not the first electronic circuit developed to isolate $\Delta V$. Other circuits were developed that used auxiliary source to add voltage to the system in ways that reduced the steady state voltage, eventually low enough that it could be considered insignificant (Murray & Miller, 1992). The Wheatstone bridge developed from those by using the same excitation voltage that powers the circuit to also supply the auxiliary voltage. The circuit is shown in Figure 4-8:

The Wheatstone bridge is essentially two voltage dividers connected in parallel. The voltage is measured between the two points that separately would be the initial point of voltage drop used in measuring voltage through a divider, points $A$ and $B$ (O'Haver, 2008). The circuit can be used to completely eliminate the steady state voltage as is the case when the bridge is said to be balanced. When the bridge is unbalanced the steady state voltage is on the scale of the change in voltage and, therefore, errors in its observation do not cause unacceptable error.

To prove how voltage across the two points is equal to zero when the bridge is balanced requires the use of Kirchhoff's first and second law; however, a satisfactory understanding can
be achieved by again utilizing the hydraulic analogy. In the hydraulic analogy, the Wheatstone bridge would be visually represented as a system of pipes as shown in Figure 4-9 and Figure 4-10.

![Figure 4-9: Wheatstone Bridge in the Hydraulic Analogy](image)

In this analogy the source of excitation, or pressure, is a pump. If the head loss in all four pipes is the same, the meter between junctions \( A \) and \( B \) will not observe any flow. A closer inspection of the flow at either point \( A \) or \( B \) explains this. The summation of flows at this location must always equal zero. This is essentially Kirchhoff's first law. That is; the summation of current into any node equals the sum of the current out. If it does not then current would be stored at that location. If the resistance in any pipe changes, a potential across \( AB \) will form. The potential measured between junction \( A \) and \( B \) is a function of the two voltage dividers that make up the Wheatstone bridge. Equation 4-7 shows the function for voltage across the meter.

\[
V_s = \left( \frac{R_1}{R_1 + R_2} - \frac{R_3}{R_3 + R_4} \right) V_e \quad \text{(Eq: 4-7)}
\]

A more detailed proof using Kirchhoff's first and second laws is follows and is based on Figure 4-11.
Kirchhoff's second law, otherwise known as Kirchhoff's loop law, states that the sum of potential around any closed network is zero. Because the current across \( AB \) is negligible due to the high resistance of the meter, Kirchhoff's first law can be used to prove that the current across resistor 1, \( R_1 \), the current across resistor 2, \( R_2 \), the current across resistor 3, \( R_3 \), and the current across resistor 4, \( R_4 \), will be equal in a balanced bridge. Two closed loops exist in the Wheatstone bridge as shown in Figure 4-11, the loop CAD and the loop CBD. The two loops provide the following equations:

\[
V_e - I_1 (R_1 + R_2) = 0 \quad (Eq: 4-8)
\]
\[
V_e - I_2 (R_3 + R_4) = 0 \quad (Eq: 4-9)
\]

Therefore:

\[
I_1 = \frac{V_e}{(R_1 + R_2)} \quad (Eq: 4-10)
\]
\[
I_2 = \frac{V_e}{(R_3 + R_4)} \quad (Eq: 4-11)
\]

The voltage \( V_j \) is a function of the difference in potentials in potential between \( AD \) and \( BD \). That is:
\[ V_s = V_{AD} - V_{BD} \]  
(Eq: 4-12)

By using Ohm’s law to convert voltages \( V_{AD} \) and \( V_{BD} \) yields:

\[ V_s = R_2 I_1 - R_4 I_2 \]  
(Eq: 4-13)

Substituting equations 4-10 and 4-11 into equation 4-13 yields:

\[ V_s = \frac{R_1}{R_1 + R_2} V_e - \frac{R_3}{R_3 + R_4} V_e \]  
(Eq: 4-14)

Further simplifying equation 4-14 by factoring out the excitation voltage \( V_e \) will yield equation 4-7.

Equation 4-7 shows how the steady state voltage can be eliminated with a balanced bridge. If each resistor in the bridge is equal, or if the proportion of \( R_2 \) to \( R_1 \) is equal to the proportion of \( R_3 \) to \( R_4 \), then the difference between statements is zero. The signal voltage would, therefore, be equal too:

\[ V_s = (0)V_e \]

The only voltage being measured when the initial state is a balanced bridge is from a change in resistance of one or a combination of any of the resistors that make up the circuit.

### 4.4 The Bonded Foil Strain Gauge

The bonded foil strain gauge is a device that’s been used to measure strains for various applications for many years. It functions by bonding to the surface of a material under strain with an application appropriate adhesive. The gauge has a thin filament inside of it that has a variable resistance. When the filament is stretched it both lengthens and becomes thinner due to Poisson’s effect. The variable resistance is typically measured with a Wheatstone bridge.
Changes in resistance are then converted into a strain value using a gauge factor. The general equation is shown below. $\Delta R$ is the change in resistance, $R_i$ is the initial resistance, $GF$ is the gauge factor and $\varepsilon$ is strain. The relationship is shown in equation 4-15

$$\frac{\Delta R}{R_i} = GF \cdot \varepsilon \quad \text{(Eq. 4-15)}$$

The filament inside of the gauge is made through a process known as etching. Typically etching involves covering a foil with an acid resistant chemical in a desired pattern. Then acid is poured over the foil until just the pattern remains. This creates a filament that is rectangular in cross section rather than cylindrical like in a wire (Murray & Miller, 1992). The rectangular section has a larger surface area than a circular section would, which increases the area in contact with the carrier. The patterns can vary depending on the size of gauge and the type of strain the gauge will measure. Shown in Figure 4-12, the pattern typically consists of several 180° turns that create several parallel filaments which further maximize contact area with the carrier matrix.

![Etched Filament, Carrier, Leads](image)

*Figure 4-12: Components of a Bonded Foil Strain Gauge*

Figure 4-13 illustrates an image of the Wheatstone bridge with a strain gauge used to replace the resistor between nodes C and B. Figure 4-14 shows the circuit depicted using the hydraulic analogy. In the hydraulic analogy the change in resistance could equate to a
depressed pipe that restricts flow. The restriction of flow causes an imbalance and more fluid, or electrons in the electric bridge, flow through the connection between C and A, which in turn causes fluid to travel across the meter.

There are many types of bonded foil strain gauges that have been developed for different needs. Gauges have been designed to measure different types of strain; shear strain, axial strain, strain due to torque, etc. The filament inside the gauge can be made of various alloys and the grids made up of the filament can replace one, two, or four of the resistors in the Wheatstone bridge. Gauges that are made of one variable resistance filament, as shown in Figure 4-13, are referred to as quarter bridge gauges, gauges that are made of two filaments are called half bridge gauges, and gauges that are made of four filaments are called full bridge gauges. Gauges can also be connected to a modified Wheatstone bridge (Murray & Miller, 1992) adding even more options to the number of gauges available.

The types of gauges used in this research, see Figure 2-4 and Figure 2-5, are two lead quarter bridge gauges and four lead full bridge gauges, both made with constantan alloy. Constantan is a copper-nickel alloy and is one of the most common alloys used in gauges. It has a significant fatigue life if strains are kept below $1500 \mu e$, which is much higher than strains
expected in SHM for an in-service bridge. Constantan also has a relatively low sensitivity to
temperature effects as compared to other alloys, if temperatures are in the range of -50° to
150°F. Other alloys are available for higher strain or higher temp measurements. (Murray &
Miller, 1992) Information on other types of gauges can be found in texts such as Murray and
Millers book or in technical literature.

Temperature affects all bonded foil gauges for several reasons including expansion and
contraction of the filament and carrier, and the effects of temperature on electrical
conductivity. Temperature effects on electrical conductivity cause an imbalance in the
Wheatstone bridge circuit when the gauge is located where temperature is different from the
rest of the Wheatstone bridge. This can be an issue for SHM applications where the
Wheatstone bridge is typically located inside the data acquisition hardware, which is typically
housed in a climate controlled enclosure, and the gauge is located on a structure that fluctuates
in temperature throughout daily and seasonal cycles. Effects of temperature on conductivity
can be reduced to a negligible amount by use of full bridge gauges; however temperature
effects on the gauge can only be mitigated.

Full bridge gauges compensate for temperature effects on conductivity by mounting all
four resistors of the Wheatstone bridge on the specimen. Two of the resistors of the
Wheatstone bridge have an additive effect on the output voltage of the gauge and two of the
resistors have a subtractive effect. Therefore, when a full bridge gauge is used, because all
resistors will be at the same temperature, effects of temperature will be added twice and
subtracted twice, thus maintaining a balanced condition. This, of course, would also imply that
any uniform strain on the resistors would be added twice and subtracted twice negating strain
measurements; however the grids that form the gauge are mounted in different directions. Full
bridge configurations can involve mounting resistors in different places to remove certain types of strain. The full bridge gauges used in this research were purchased from Omega and locate all resistors on the same carrier as shown in Figure 4-15.

The two resistors mounted in the principle stress direction replace resistors 2 and 3 that have the additive effect. The two other resistors replace resistors 1 and 4 which have a subtractive effect. However, since the two resistors are mounted in the perpendicular direction they experience a compressive strain due to Poisson’s effect as shown in Figure 4-17. Therefore, when the specimen experiences axial strain, their resistance change turns out to be additive as well. The combined effect in turn amplifies the signal. This amplification is illustrated in Figure 4-17 and further explained by the equations following Figure 4-18.
The total measured strain is due to the strain measured in each of the gauges:

\[ \varepsilon_t = +\varepsilon_2 + \varepsilon_3 - \varepsilon_4 - \varepsilon_1 \]  
(Eq. 4-16)

Resistors 2 and 3 are the resistors mounted in the principle stress direction:

\[ \varepsilon_2 = \varepsilon_3 = \varepsilon \]  
(Eq. 4-17)

Resistors 1 and 4 are the resistors mounted in the direction experiencing strain due to Poisson’s effect:

\[ \varepsilon_1 = \varepsilon_4 = (-\nu \varepsilon) \]  
(Eq. 4-18)

The total strain measured by the gage is:

\[ \varepsilon_t = +\varepsilon + \varepsilon - (-\nu \varepsilon) - (-\nu \varepsilon) \]  
(Eq. 4-19)

These gages will be monitoring steel, which has a Poisson’s ratio of 0.3, simplifying the equation to:

\[ \varepsilon_t = +\varepsilon + \varepsilon - (-0.3\varepsilon) - (-0.3\varepsilon) \]  
(Eq. 4-20)
The configuration has benefits of higher sensitivity and resistance to thermal and off-axis errors. A potential drawback of the full-bridge gauge is that while it cancels errors due to thermal effects on the conductivity of the gage, it also removes the ability to measure thermal effects of actual expansion and contraction of the material being gauged. The gauges might also be unsuitable for mounting on the web of the beams because of web compression, which would cause strain in the resistors mounted in the direction of Poisson's effect but not the other direction.

Although the full bridge configuration chosen for this research has been shown to compensate for effects due to differences between the temperature at the gauge and the temperature in the data acquisition equipment where the quarter bridge gauges cannot, the effects of temperature on the carrier and alloy cannot be negated and are more pronounced in the full bridge gauges. Those effects are shown in Figure 4-19 for the full bridge gauge and Figure 4-20 for the quarter bridge gauge. The effects cause two distinct variations. The first is the linear variation on the gauge factor, which can be read using the y-axis on the right side scale of each graph. The second is a non-linear error represented by the curved line and can be read using the y-axis on the left of the graph. At room temperature both effects are equal to zero, allowing for accurate measurements with little post-processing achievable in laboratories environments. However in outdoor conditions, sensors readings must be compensated for temperature fluctuations.
Figure 4-19: Thermal Effects on Full Bridge Axial Strain Gauge

The effects of temperature on the gauge factor can likely be neglected. The temperature expected in SHM projects in the New England area are expected to fluctuate between slightly below zero to slightly above 100 degrees Fahrenheit. Notice that the fluctuation between negative 4 degrees and positive 104 degrees results in a change of about
0.8% in the full bridge gauges. The second effect however cannot be neglected. It manifests as an apparent strain. In the same -4 to 104 degree F range the apparent microstrain can be seen to fluctuate from about -200 to 20 microstrains.

Figure 4-21 shows the two apparent microstrain curves of the two gauges used in this research on the same graph. The lines are plotted using equations that are given with the graph by the manufacturer, shown in Figure 4-19 and Figure 4-20. It can be seen in Figure 4-21, that temperature actually has a more pronounced effect on the full bridge gauges. This is likely because the resistance is higher at 1000 ohms over 350 ohms so temperature effects, as a multiplier, will create larger deviations when multiplied by the higher initial resistance of the full bridge gauges. In any event, manufactures provide these graphs as a tool to deal with these errors.

![Apparent Microstrain Curves of Full and Quarter Bridge Gauges](image)

Because live load effects are expected to cause only single to double digit microstrain, the temperature effect can overshadow measurements when the observations are not at room temperature. When observations are short term and at constant temperature, the apparent
micro-strain can be managed by zeroing the gauge, essentially subtracting the apparent strain at the start of the observation from each value recorded during the test. When observation periods occur over varying temperatures, such as throughout the course of a day, the apparent microstrain must be handled by measuring temperature at the gauge location and then subtracting the microstrain shown in the graph from each individual reading. This can also be handled using the formula at the bottom of the graph that represents a fourth order curve fit to the line.
Chapter 5: Installation

The installation of the first set of strain gauges and thermocouples at the Bagdad Road Bridge was conducted over four different days. Each installation day was dedicated to a single face of a single beam. A photograph of the location is between the two bridge bents shown in Figure 5-1. The instrumented locations and beam nomenclature are provided in Figure 5-2. The installation days were November 29\textsuperscript{th}, December 1\textsuperscript{st}, 5\textsuperscript{th}, and 9\textsuperscript{th} of 2011. The south face of Beam D was installed on the first day. The north face of Beam D was instrumented on the second day. The north face of Beam E was instrumented on the third day. The south face of Beam E was instrumented on the last day. The installation typically began at 10 am and was completed by approximately 3 pm daily due to available natural light and a sharp drop in temperature, which created undesirable conditions for strain gauge installation. Scaffolding was required to access the beams and was erected under the third span.

![Figure 5-1: Photo of the Underside of Span 3 Viewed from Under Span 4](image)

The available working surface on top of the scaffolding was limited, and therefore only one person could conduct the processes required for instrumentation. The scaffolding, which was 15-feet high and had a platform area of 5 feet by 7 feet, remained on site between the four
installation days. With a larger scaffolding platform, it is likely that both faces of the beam could be instrumented simultaneously. During seasons with longer days, installing sensors on multiple stringers in a single day could easily accelerate the installation process.

The installation of several more sensors was planned, for example, sensors that had purpose beyond the scope of this research but could meet other research needs. Because of time constraints, the decision was made to install the most important sensors first. Other sensors can be installed to create a more comprehensive damage sensing network or for better understanding of difference in behavior from member to member. See the Conclusions for a description of future work that could be conducted at the Bagdad Road Bridge.

5.1 Layout of Sensors

The girders that were ultimately instrumented were girders D and E, both at the center of span 3. The locations are labeled in the structural plan view of the bridge shown in Figure 5-2. Both faces of Beam D and the North face of Beam E were each instrumented with three full bridge strain gauges, one gage on the inside face of each flange and one gauge on the web. The South face of Beam E was instrumented with three pairs of quarter bridge gauges, corresponding to the same locations full bridge gauges were installed on other beam faces. Two thermocouples were also installed on the web of the North face of Beam D, as shown in Figure 5-2.
Pairs of quarter bridge gauges were oriented as described in Chapter 1 with one intended to measure longitudinal strain and one for transverse strain at approximately the same location. Sections of each beam are shown in Figure 2-3. Note that the quarter bridge gauges oriented in the transverse direction on the flanges are not shown in the section because they are mounted slightly ahead, longitudinally, of the gauges mounted in the longitudinal direction. Gauges on the flange are therefore not technically in the same cross section as the gauges on the web and longitudinal measuring gauges on the flange.

5.2 Installation Preparation

In preparing for the installation, a site evaluation was performed to assess how the beams could be accessed. The beams are approximately 17 feet off of the ground. The ground underneath the span was flat and stiff. A vehicle, such as a scissor or a boom lift, would have a good stable place to park under the span. However, a fairly long length of guardrail and the steep ditch between the road embankment of US Route 4 and the level surface under Span 3 prevents access from any vehicles that would arrive from the roadway under the bridge as
shown in Figure 5-3. Thick vegetation and a steep slope around the eastern abutment prevented vehicle access from the roadway above the bridge.

![Figure 5-3: Photo of Ditch Between Roadway and Underside of Span 3 at BRB](image1)

![Figure 5-4: Photo of Sloped Terrain and Vegetation Growing Around Eastern Abutment at BRB](image2)

Ultimately, scaffolding was rented from Seacoast Scaffolding of Concord, NH. The scaffolding included three five-foot bays, four leveling jacks, a ladder, guardrail, and several planks. The five-foot bays consisted of four columns and two cross braces. Leveling jacks served as the base of the system when the three bays were stacked, and were used to adjust the bearing elevation of the four columns creating a properly leveled structure. Three planks were placed on top of the scaffolding to create the platform, which provided access to the girders for sensor installation. The gated guardrail system was around the top bay and locked into the columns for structural integrity. The ladder was fixed to one of the sides of the scaffolding not containing braces.

A practice run of assembling the scaffolding was conducted in the structural high bay (S-106) of Kingsbury Hall at UNH. The practice run allowed for identifying challenges in the
assembly process without being distracted by environmental conditions or using valuable time out of the small window of daylight available at that time of year. A photo of the assembled scaffolding in the high bay is shown in Figure 5-5. One challenge identified was a lack of planks. Prior to the practice run only three planks were rented. Placing planks on top of the third bay to build the working surface proved challenging without planks located on the second bay for access. For that reason, two more planks were rented prior to the actual installation.

![Figure 5-5: Photo of Scaffolding Assembled during Practice Run](image)

Wires for the sensors were also prepared ahead of time. Preparation included cutting the wires and labeling them accordingly. The wires were cut to roughly 90-feet to account for the distance between the instrumented locations and the abutment, as well as enough slack to give flexibility to aspects of possible future configurations, such as locations for continuous data acquisition system housing. The labels were made from sticky file labels and were placed at roughly five-foot intervals down the entire length of each wire. They were placed with such frequency to allow for easy identification of the wire because ultimately the wires would be placed into a conduit of split wire loom and possible repairs may require extracting the wires.
out from a location not at the sensor or the abutment. The labels were numbered corresponding to a previous intended layout for the sensors and therefore are not necessarily in sequential order. Clear tape was placed over the labels to protect them from moisture. A photo of the installed labeled wires at the abutment is shown in Figure 5-6.

![Figure 5-6: Photograph of the Installed Labeled Wires](image)

Other preparation for the installation involved gathering everything needed to installed the sensors in an instrumentation toolbox. A portable gasoline generator was made available by Dr. Jean Benoit of UNH for tools that require power, such as an electric grinder. The details about the equipment are included in Appendix A.

5.3 Installation Process

As noted, scaffolding was used to reach the instrumentation locations. After a discussion with Steve Mandeville the safety coordinator for the Bureau of Materials and Research at NHDOT, it was concluded that considering the relatively short height of the scaffolding, the only safety requirements would be guardrail and a ladder so that access to the top of the scaffolding would not involve climbing on the scaffolding itself. Also, because the
location was significantly removed from the roadway by distance and a guardrail barrier, no traffic management was required. Hardhats and safety vests were worn during the entire installation process.

Scaffolding took roughly two hours to assemble on site. An image of the assembled scaffolding placed under girder D on the first day of installation is shown in Figure 5-7. A significant portion of the time was spent transporting the parts of the scaffolding to the site given the previously mentioned terrain challenges.

The general process for installing each strain gauge involved prepping the surface, bonding the gauge, soldering the gauge to the wire, covering the installation for environmental protection, and securing the wire. The installation procedure followed in this research is based on recommendation from Omega© with field modification provided by Geocomp, INC. Thermocouples did not require surface preparation because it was assumed the temperature at the surface of the paint is the same as at the surface of the steel and therefore the thermocouples were bonded to the paint. They also did not require soldering because they use
modular plug-style connections. An image from the manufacturer’s website is shown in Figure 5-8, model numbers OSTW-T-M and OSTW-T-F.

![Figure 5-8: Thermocouple Plug Connectors](image)

Prepping the surface requires grinding the paint off to expose the steel and removing debris. Grinding is performed with a disk grinder as shown in Figure 5-9, then coarser grit sand paper, and finally emery cloth to produce a smooth surface for the gauge to adhere to. The surface is then cleaned with acetone using individual rags until the rags do not show any debris from a single wipe.

![Figure 5-9: Photo of the Grinding Step of the Strain Gauge Installation Process at the BRB](image)
When grinding and prepping the surface, special care was used to impact the smallest area possible because the paint protects the steel from moisture and gives the bridge an aesthetic appeal. The larger of the two gauges, the full bridge gauges, are only 0.583" x 0.437". However a larger surface area must be prepped due to the nature of the disk grinder. Affected areas were typically no more than 2" x 2", as shown in Figure 5-10. Note that the location was marked with a permanent marker using a stencil to label the area the gauge would have to fit between. Figure 5-11 is the same prepped area after a gauge has been bonded to the steel.

The cold cure adhesive, Loctite 496, was used to bond the gauges to the beam. It is one of the most commonly used strain gauge adhesives according to Omega Engineering Inc. (omega.com), the strain gauge supplier. Bonding involves first placing the back of the gauge on the tacky side of a piece of translucent tape. Packing tape was used in these installations. Then a small amount of adhesive is dropped on the gauge. The gauge was then "taped" down and centered between the marks and uniform pressure was applied by hand for at least 1 minute as shown in Figure 5-12. Then the tape was removed as shown in Figure 5-13, which served as a quality assurance of the bond. While the tape was pulled back, the gauge was closely observed, if the gauge peeled back at all, it would indicate a delamination or air bubble in the adhesive, and the gauge would be removed and the application process restarted from the step of
cleaning the surface with acetone. After removing the packing tape, electrical tape was carefully placed behind the gauge to insulate the leads, preventing the steel surface from shorting the circuit to the data acquisition equipment.

The next step involved soldering the gauge leads to the lead wires. The wire contains four separate tinned copper leads that are all the same except for the color of their coating. Each full bridge gauge requires a single wire of each individual strain gauge in the configuration. Quarter bridge gauges however only use two leads as opposed to the full bridge gauges four leads; therefore a single four lead wire accommodates a pair of quarter bridge gauges. Because the four wire leads are compatible with all leads on the gauges, the color coding scheme of connections are up to the installer. It is important to keep track of which color was used to connect to which gauge lead so that when the leads are later connected to the data acquisition equipment it will be configured correctly. Diagrams were created for the full and quarter bridge gauges to standardize the configurations. The wire configuration for both gauges is shown in Figure 5-14.
Soldering involved taping the wire to the beam to reduce movement, heating the soldering iron, using it to place a small amount of solder on the leads from the gauge and the wire, and finally, heating the two soldered portions while they were in contact with the iron so that they would form together. Originally the intention was to use terminal strips that the gauges can be soldered to and the wire can be soldered to. The terminal strips provide a connection between the two leads without having to solder the flexible wires together, which can be a challenge. The strips, though, are bonded to the surface of the beam, similar to the strain gauge, and need to be heated to transfer the solder to the strips. The cold weather posed a challenge for the bonded strips because the thermal conductivity of the underlying beam and its cold temperature. Soldering to the strip when it was not bonded also proved to be a challenge as it severely warped the strip.

After the second gauge installation, the terminal strips were abandoned and then wires were directly soldered to each other. Although it was challenging and time consuming, the duration was reduced after the first day of installation by pre-soldering the wires prior to going to the site for further installations. Pre-soldering involved placing small amounts of solder on the wires and the gauge leads so that connections at the site could be formed by simply holding...
the two pre-soldered parts together and heating them. The images in Figure 5-15 and Figure 5-16 below show the comparison between an installation with terminal strip versus an installation where wires were soldered together.

![Figure 5-15: Photo of Gauge Installation – Soldered Using Terminal Strip](image1)

![Figure 5-16: Photo of Gauge Installation – Soldered Without Terminal Strip](image2)

When the soldering was complete, the entire affected area was covered with plumbers putty (Hercules® 25-101) to protect against moisture. The putty was first placed over the leads wires as shown in Figure 5-17. Effort was made to ensure putty was placed between the wires, preventing them from possibly touching and shorting the circuit to the data acquisition equipment. Then the gauge and entire area that was affected by the paint removal process, plus a half inch buffer, was covered with the putty as shown in Figure 5-18. Aluminum tape was used to further protect the installation from environmental effects as shown in Figure 5-19. Lastly the wires were then clamped to the beam flange as shown in Figure 5-20.
When all gauges were environmentally protected, the wires were secured to the beam flange with clamps. A voltmeter was used to evaluate the installation. The voltmeter measured the resistance of the circuit. The circuit in this case was the entire 90-feet of wire and gauge. If the resistance was infinite, it would indicate that something created a discontinuity, for example the solder or gauge was damaged. If the resistance was low it would imply that a short was created, for example if the leads had made contact with the steel beam or each other under the environmental protection. The resistances of the full bridge gauges are 1000 ohms and the resistances of the quarter bridge gauges are 350 ohms, both +/- 15%, according to the Omega manufacturer. The resistance of the 90-feet of wire lead, on the other hand, was 5 ohms when tested prior to installation, so the difference would be easy to discriminate.
This general process was repeated on three other installation days. Significant differences between the processes were that thermocouples were only installed on the south face of Beam D, and that quarter bridge gauges were installed on the south face of Beam E. As previously noted, the thermocouples did not require surface preparation or soldering. Plumbers putty was also not used for environmental protection, as it was assumed that the aluminum tape would be sufficient environmental protection.

Installing quarter bridge gauges involved bonding six gauges rather than three. An image of a pair of quarter bridge gauges is shown in Figure 5-22. However the installation took roughly the same amount of time because soldering was not required. The quarter bridge gauges were available “pre-wired” meaning that instead of having a two-inch lead as the full bridge gauges, they had a thirty-six inch wire attached to the gauges. The wire was taped together in a bunch under aluminum tape on the flange and gel splice connectors, type UY, shown in Figure 5-21, were used to connect to the lead wires from the gauge to the lead wires for the DAQ. The gel splices function by inserting the two wires into holes and then squeezing the splice with pliers. The two halves of the splice crush a piece of metal foil around the wires to create continuity and gel surrounds the wires and protects the connection from moisture.

Figure 5-21: Slice Type UY Connector (tekcomponenets.com)
Each installation was later covered with green duct tape to hide the instruments as shown in Figure 5-23. Considering the limited duration the scaffolding was rented and the weather conditions, the decision was made to secure the wires and return in the spring to run them to the eastern abutment for data acquisition. The wires were then secured with clamps for the duration of the winter. The wires from the north face of Beam D and the south face of Beam E were run under the flange and clamped to the opposite side so that later, when wires would be run to the abutment, they would all be entirely contained in the bay between the two beams.

Although the winter of 2011-2012 proved to be extremely mild and had little snowfall, there was no way of knowing that when the gauges were installed, and it was expected that at any time a significant snowfall could occur and impact accessibility at the site. Fellow UNH graduate students, Sam White and Adam Goudreau, returned in March of 2012 and used a ladder to route the wires to the abutment. Duct tape was used at roughly five-foot intervals to secure the split wire loom to the beam as it rests on the beam flange.
5.4 Significant Differences in Installation Conditions

Aside from the noted differences in sensor configuration, day to day conditions varied at the site. As shown in Table 5-1 of historical weather data retrieved from the nearest historic weather station in Portsmouth NH, (Weather Underground, 2012), the first and third days were the most humid, and the second and fourth were the coldest. Humidity only seemed to pose a challenge on the third day. Condensation formed on the beam at a rate fast enough to trickle down the beam face, and therefore, the area had to be wiped down several times throughout the instrumentation, as seen in Figure 5-24.

![Figure 5-24: Photo of Condensation on Beam Surface](image)

Cold temperatures seemed to have an effect on the adhesive, causing longer waits for the adhesive to cure. As a result, the type of pressure shown in Figure 5-12 was applied for longer durations on subsequent days. Soldering was also a challenge on the second day in the cold temperatures. Not only did the soldering iron take longer to heat but posed other challenges in terms of handling and solder placement. Soldering such small wires is difficult to do effectively with gloves on. Without gloves, the cold impacted dexterity rather quickly, often quicker than would take to solder all four leads of a single gauge. The cold caused minor
numbness and shivering which posed obvious challenges when attempting to solder the thin leads.

Table 5-1: Weather Conditions Mid-day during Installations

<table>
<thead>
<tr>
<th>Day</th>
<th>Temp at noon</th>
<th>Dew Point</th>
<th>Humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>11-29</td>
<td>55</td>
<td>51</td>
<td>91 %</td>
</tr>
<tr>
<td>12-1</td>
<td>46</td>
<td>25</td>
<td>58 %</td>
</tr>
<tr>
<td>12-5</td>
<td>50</td>
<td>43</td>
<td>92 %</td>
</tr>
<tr>
<td>12-9</td>
<td>45</td>
<td>28</td>
<td>67 %</td>
</tr>
</tbody>
</table>

Ideally, installations should occur during warmer time periods for both the comfort of the installers and the curing of the adhesives. The results of analysis conducted in Chapters 7 and 8 imply that the full bridge gauge used on the top flange of the north face of Beam E as well as one of the quarter bridge gauges on the south face of Beam D may be malfunctioning. Although no specific reasons for these malfunctions have been produced at the closing of this research, poor installation conditions may have been a factor.
Chapter 6: Experimental Design

The analytical portions of this research deal with evaluating the behavior of the sensors and demonstrating their use in gathering data for the development of an SHM metric. Through laboratory controlled and field experiments, a high level of confidence was produced in the readings from the bonded foil strain gauge. Post-processing of collected strain samples was performed to gain acceptance in the readings taken at the Bagdad Road Bridge. Then structural mechanics theory and predicted structural performance were used to investigate neutral axis position gauge readings during bending, a potential SHM metric. The results implied that potential issues that may have occurred when installing the gauges in the field do not significantly affect performance in the field.

6.1: Collecting a Meaningful Gage Reading

Before meaningful conclusions relating to structural health can be drawn regarding SHM measurements, there must be confidence in the measurements themselves. The instruments used in this field application are often either new technologies or technologies that have not been proven to have easily repeatable success in non-laboratory conditions. Confidence can also be weakened by sensors that often can malfunction in a way that doesn’t necessarily indicate damage to the sensor. These malfunctions produce values that are not accurate but may be believable to researchers not familiar with a structure or its predicted behavior. By building databases of accurate observations, the SHM community can build confidence in various technologies. The accuracy of those observations is evaluated by correlating multiple observations of the same phenomenon.

Peddle (2011) built confidence in digital image correlation (DIC) results by using linearly variable differential transducers (LVDT) to measure the deflection of a beam in bending in both
laboratory and field conditions. The first step of this analysis mimics that process. The gauge application procedure and the settings and programming used in the data acquisition (DAQ) equipment were evaluated by measuring weight hung from an instrumented specimen. The weights in this case are measured using a scale, similar to how LVDTs were used in the experiments Peddle carried out (2011). Strain gauge readings, material, and geometric properties of the specimen are then used to calculate the applied force, which is then compared to the weight determined by scales.

The second part of this analysis aims to address concerns related to the strain gauge performance in environmental conditions experienced in field applications, mainly temperature. Environmental conditions may impact strain gauge readings. Outdoor conditions also imply that sensors are likely to degrade faster than if they are used indoors. The need for redundancy in SHM sensor networks was highlighted in a journal entry by Farrar and Worden (2007). Difficulty in detecting damage also led the authors to describe needs for monitoring the sensors themselves for possible damage after they have been deployed in the field. By placing strain gages on both faces of the beam section, as shown in Figure 2-3, some level of correlation is available. Malfunction can be detected by differences in gage readings from opposite sides of the beam section. Although it's possible that both gauges could malfunction at the same time, it is unlikely, and it is even less likely that both malfunctions would cause the same type of behavior in the readings.

The final part of the analysis uses the gauge readings to calculate the position of neutral axis in the instrumented composite section of the beam. This position may be a valuable health metric, and calculating the position during each data collection conducted at the bridge may allow for feature tracking over time in an attempt to monitor aging. By using readings from
gauges that have been identified as malfunctioning, an investigation of the types of conclusions that might be drawn from erroneous values is also included.

6.2: Full Bridge Gauge Behavior on Beam Webs

The full bridge gauges evaluated in this research compensate for thermal expansion using four resistors. The two resistors that have a positive effect on the voltage readout from the gauge are oriented normal to the strain direction being measured, and the two resistors that have a negative effect on the voltage readout are oriented in the direction of strain caused by Poisson’s effect. More information on how these compensate for some thermal errors are in Chapter 4.

The orientation of the resistors increases the measure of strain read by the gauges by a factor of 2.6 times the true value. The process of magnification is expected to work well on the flanges where the largest longitudinal strains are expected to be from bending. As previously stated, each instrumented location will have three strain values to calculate neutral axis. There are concerns, however, for using the full-bridge gauges on the web of the beam as web compression could be a significant factor.

Each instrumented beam face is monitored using the same gauge type, meaning model and manufacturer. Using the same gauge type in each neutral axis calculation reduces complexity when dealing with multiple sources of error. All gauge types have similar behaviors that would be derived from the manufacturing process, and furthermore, the same environmental errors are being applied to all gauges at a location equally. For these reasons, it is desirable to use the same full bridge gauge on the web as on the flange rather than the quarter bridge gauges what would not be affected by web compression. However, first the effects of web compression needed to be evaluated before the readings from full bridge gauges placed on the web could be used in the neutral axis analysis with a high level of confidence.
To assess the impact of web compression on the strains reading on the web, quarter bridge strain gauges were installed in pairs opposite a full bridge strain gauge installation, as shown in Figure 6-1. One gage will measure strain in the horizontal direction and the other in the vertical. If strains in the vertical direction were close to Poisson's ratio multiplied by the horizontal strains, then the full bridge gages chosen for the flanges would have been usable on the web.

The quarter bridge gages measure differently than the full bridge gages by utilizing only one resistor, as discussed in Chapter 4. These gauges do not compensate for thermal expansion. Therefore, in this analysis, the thermal expansion or contraction in each of the two gauges was taken as the same. However, noise may pose a serious problem as it could cause a positive error in the reading of one gauge and a concurrent negative reading in the other. By mounting
two quarter bridge gauges in perpendicular directions as shown in Figure 6-1, the apparent
Poisson's effect can be determined.

The first interior girder on the south side of the bridge, Beam E, was selected for this
investigation. Three pairs of quarter bridge gauges were installed on the southern face of the
beam, and three full bridge gauges were installed on the northern. When the bridge is excited
and both gauges in a pair experience strain, the apparent Poisson's ratio will be calculated using
equation 6-1. The results of this analysis are shown in section 7.4.

\[ v_a = \frac{-\varepsilon_{\text{transverse}}}{\varepsilon_{\text{longitudinal}}} \]

(Eq. 6-1)

6.3 Neutral Axis Location

The theoretical neutral axis of a beam represents a horizontal plane above which
longitudinal stresses act tension or compression and below which stresses act in the opposite.
In a doubly symmetric rolled shape with a consistent modulus of elasticity that is in pure
bending, the plane is theoretically in the center of the section. Evenly dividing the geometry will
balance tension and compressive forces in the beam. In a composite section, the added
capacity of the deck moves the neutral axis upward, as shown in Figure 6-2. The neutral axis is
therefore of particular interest because it is a feature that can indicate changes in the capacity
of the deck or the steel as well as changes in the level of composite action. If shear studs
became corroded, for example, and the steel beams and concrete deck of a bridge were no
longer in full composite action, the calculated neutral axis from strain gauge readings should
shift indicating damage.
Figure 6-2: Illustration of Neutral Locations in Composite and Non-Composite Sections

Figure 6-2 shows a composite beam made of a concrete slab and steel rolled shape. When the beam is fully composite it is expected to have a neutral axis higher than half the depth of the beam and closer to the deck. When the beam is fully composite it has a single neutral axis, however, a non-composite beam will have two, a neutral axis for the deck and a neutral axis for the beam. The neutral axis of a rolled shape will be at half the depth of the beam, or lower in cases with an attached bottom cover plate like at the Bagdad Road Bridge. By instrumenting the steel, the location of the neutral axis can be watched over time to see if it moves suddenly from external events, such as impact, or slowly over time indicating degradation of the composite section or behavior.

Generally, the location of the neutral axis is assumed to be relatively static, meaning that it is in the same location regardless of load applied to the beam. The assumption holds true when the beam behaves linearly in the elastic range. However, mechanics show that materials do not behave entirely elastic. Concrete in particular has a non-linear and inelastic stress-strain relationship though it is usually assumed to be linear-elastic at smaller stresses. This indicates that as load increases, the neutral axis may move slightly. Other phenomena such as creep, or section loss, can also cause the location of the neutral axis to change over time. If this
movement is tracked with instrumentation, it could be used to access the hidden deck or shear connector health.

Neutral axis research using two strain gauges in a cross section has been conducted by UNH and other universities. Lefebvre designed a system using quarter bridge bonded foil strain gauges at the Powder Mill Bridge in Barre, MA (Lefebvre, 2010). Chakraborty and DeWolf used uniaxial strain gauges in pairs reading at high speeds to locate neutral axis during regular field monitoring. Their results showed the neutral axis moved suddenly for brief moments particularly when large trucks would pass over the bridge, sometimes as much as 12 inches, and suggested this could be the result of dynamic behaviors (2006).

This research expands on previous neutral axis based research by using multiple gauges in a cross section to investigate sensor behavior. A potential problem in measuring neutral axis locations is the presence of noise in the strain readings. Ideally only two strain values should be required because that is all that is needed to plot a straight line. Under elastic deformations, longitudinal strains will theoretically vary linearly throughout the depth of the section. Hence the assumptions that plane sections remain plane will hold true. However, using only two values carries the risk of noise or sensor malfunction causing erroneous neutral axis locations. This research uses an additional strain gauge, located at the center of the web, to produce more reliable results.

If noise causes significant difference between the calculated locations of neutral axis determined by different pairs of gauges, it could imply that more than just two gages in a cross section are required to determine a reliable neutral axis location. Requiring even just one more gauge at each location would result in 50% more strain gauges, data acquisition channels, storage demands, and installation times. This produces a potential cost to benefit ratio of two
versus three gauges and is therefore an interest to SHM system designers and was chosen as an analysis portion of this thesis.

6.3.1 Neutral Axis Location Methods

The process of measuring neutral axis can be thought of in two ways that both rely on the assumption of linear strain distribution. The first is using similar triangles, and the second is plotting stain versus depth within the section and solving for the y-intercept of the line it creates. Using similar triangles may seem more intuitive, while plotting strain versus depth within the section is shown to prove the interchangeable nature of the neutral axis location without the need to re-derive or prove the equation for each pair of sensors that can be used. Both methods provide the same mathematical expression. The illustration in Figure 6-3 shows the anatomy of the composite section that is used for this analysis.

![Illustration of Composite Section Instrumented For Neutral Axis Detection](image)

6.3.2 Method of Similar Triangles

If two strain values are available from any two locations in a composite section, the location of the neutral axis can be determined. To prove the method, consider an example with gauges installed on the top and bottom flanges as shown in Figure 6-3. Using strain values the strain diagram shown in Figure 6-4 can be generated. It can also be seen in Figure 6-4 that the location of the neutral axis is the position of the top gauge minus the length shown on the strain
diagram labeled c. If $NA$ is the vertical position of the neutral axis measured from the bottom of the composite section, the formula for its position is shown in equations 6-2.

$$NA = y_2 - c \quad \text{(Eq. 6-2)}$$

The linear strain distribution is the basis for the relationship shown in Equations 6-3 because of the properties of similar triangles.

$$\frac{-\varepsilon_2}{c} = \frac{\varepsilon_1}{d-c} \quad \text{(Eq. 6-3)}$$

The distance between the two gages is represented by $d$. Further simplifying for $c$ will result in equation 6-4.

$$c = \frac{d \varepsilon_2}{\varepsilon_2 - \varepsilon_1} \quad \text{(Eq. 6-4)}$$

Substituting $c$ into equation 6-2 yields the location of the neutral axis as measured from the bottom of the beam equation 6-5.

$$NA = y_2 - \frac{d \varepsilon_2}{\varepsilon_2 - \varepsilon_1} \quad \text{(Eq. 6-5)}$$
6.3.3 Y-Intercept Method

Another approach to determining neutral axis location also involves the strain diagram and the equation of a line. If strains versus depths are plotted, the neutral axis corresponds to the \( y \)-intercept of the linear equation as shown in the Figure 6-5.

![Figure 6-5: Illustrated Neutral Axis Located on Cartesian Coordinate System](image)

Equation 6-6 is the equation of a line:

\[
y = mx + b \quad \text{(Eq. 6-6)}
\]

The equation solved for the \( y \)-intercept with the term \( b \) replaced with the neutral axis location:

\[
NA = y - mx \quad \text{(Eq. 6-7)}
\]

The slope of the line, \( m \), is the difference in depth over the difference in strain values, as shown in Equation 6-8:

\[
m = \frac{\Delta y}{\Delta x} = \frac{y_2 - y_1}{\varepsilon_2 - \varepsilon_1} = \frac{d}{\varepsilon_2 - \varepsilon_1} \quad \text{(Eq. 6-8)}
\]

Substituting equation 6-8 into equation 6-7 the equation for the neutral axis is found:
Equation 6-9

\[ NA = y - \left( \frac{d}{\varepsilon_2 - \varepsilon_1} \right) x \]

The position of the neutral axis can, therefore, be solved by substituting any pair of values from the position of gauges and corresponding strain values into Equation 6-9. Either set of values, corresponding to the vertical height of the sensor and a strain reading from it, can be used for variables \( y \) and \( x \). Note that if \( y_2 \) and \( x_2 \) are used the resulting equation, it will be the same as the equation derived using the method of similar triangles in the previous section.

6.3.4 Linear Regression

The process of using 3 gauges to measure the neutral axis will require a linear regression. Because of noise in the strain readings, the three pairs of strain and vertical position data will rarely fall on the same line. The linear regression, otherwise known as the best fit line, is the line that best correlates with data that is assumed to behave linearly. Overall the line produces the least amount of discrepancy, of any possible straight line, when the square of the differences between all data points is summed and minimized. The process is also known as the method of least squares.

Figure 6-6 illustrates how noise in the measurements can cause a shift in the perceived neutral axis location. Besides the fact that the method of least squares introduces new equations, the method is the same in theory as the previously described y-intercept method. Strain values and vertical positions are plotted, and the intercept of the line with the y-axis is the location of the neutral axis, as shown in Figure 6-5.
The slope of a regression is given in Equation 6-10.

\[ m = \frac{n(\Sigma xy) - (\Sigma x)(\Sigma y)}{n(\Sigma x^2) - (\Sigma x)^2} \]  

(Eq. 6-10)

The y-intercept, neutral axis, can then be solved for using Equation 6-11.

\[ NA = \bar{y} - m\bar{x} \]  

(Eq. 6-11)

6.3.5 Limitations of Live Load Strains

The exact dead load strain cannot be known for several reasons. Furthermore, gauges are placed with an inherent error, or imbalance, that can only be managed by calibrating the gauge to read zero. The gauges will therefore only measure change in strain from the time they are calibrated. The full bridge gauges will primarily measure live load induced strains where the quarter bridge gauges will measure live load strains and strains that are caused by the coefficient of thermal expansion of steel, as described in Chapter 3. If, however, temperature effects cause curvature as a response to restraints at the bearings that restrain thermal expansion, the full bridge gauges would be expected to capture effects from those strains.
The inability of measuring dead load strains means that neutral axis calculations can only be made when a bending load is placed on the beam. At other times the gauges should return to values close to zero, where the only deviation from zero are extremely small and caused by electrical noise and other errors, such as thermal effects. If the gauges actually read zero, it can be seen that the calculated value of the neutral axis would be the value of \( y \) used in Equation 6-9. For example, if \( y_2 \) is used:

\[
NA = y_2 - \frac{d(0)}{(0 + 0)} = y_2
\]

Not knowing the dead load strains has no impact on the ability to measure neutral axis during live load events, assuming linearly elastic behavior. It can be seen in Figure 6-7 that imposing the live load strains on dead load strain diagram or simply using the live load strain distribution will located the same position of a neutral axis.

Because plane sections remain plane, strains will vary linearly throughout a section, and the ratio of dead load strains in two locations will be the same as the ratio of the live load strains in those same locations and therefore dead load strains are not required for measuring neutral axis locations.

Figure 6-7: Neutral Axis Locations from Dead Load, Live Load, and Combination of Dead and Live Loads
The neutral axis locations determined in this research are discussed and presented in chapter 8.

### 6.4 Error Management

Several sources of error exist when using bonded foil strain gauges. These sources include multiple temperature effects on the lead wires and gauges, as described in detail in chapter 4, as well as effects of unprofessional soldering and not cleaning the flux off the solder, residual strain from the pressure of holding the gauge during installation, and any sources that might exist in the data acquisition equipment. Furthermore, potential issues that were not expected in installations at the Bagdad Road Bridge could affect strain measurements such as issues with the glue and gauge off-axis issues. These sources of error may cause researchers to be skeptical of all results derived from systems using bonded foil strain gauges.

These sources of error can be categorized by additive and multiplicative errors. The temperature correction curves discussed in chapter 3 show examples of both effects. The apparent strain is a constant that is added to the measured strain value, whatever that might be. The effect on the gauge factor will change what is multiplied by the voltage signal from the gauge and is therefore a multiplicative effect. The additive error is believed to be eliminated during calibrations. The multiplicative error is believed to be negligible because it cancels out of equations for apparent Poisson's ratio and neutral axis calculation.

The concept can be demonstrated by analyzing equations used in this research and including the sources of errors. The total of all multiplicative errors in this case is labeled $E_{M_i}$ and $E_{A}$ is the total of all additive errors, the second subscript of each coefficient corresponds to the gauge the errors are affecting. Note that there is also a multiplicative effect on the additive error as well.
The equation for Poisson's Ratio Including Sources of Error:

\[ V_a = \frac{(-\varepsilon_{\text{transverse}})E_{M1} + E_{Al}E_{M1}}{(\varepsilon_{\text{longitudinal}})E_{M1} + E_{Al}E_{M1}} \]  
(Eq. 6-12)

The equation for Neutral Axis Location Including Sources of Error:

\[ NA = y_2 - \frac{d(\varepsilon_{A2}E_{A2} + E_{A2}E_{M2})}{[(\varepsilon_{A2}E_{A2} + E_{A2}E_{M2}) - (\varepsilon_{A1}E_{A1} + E_{A1}E_{M1})]} \]  
(Eq. 6-13)

Figure 6-8 shows the effect of the additive error on the strain measurements. Keeping in mind that the quarter bridge gauges cancel out strain due to thermal expansion and contraction, any deviation from zero in an unloaded member is expected to be the result of additive (or subtractive) errors.

\[ \varepsilon \]

\[ \Delta \]

**Figure 6-8: Illustration of Typical Strain Reading over Time at the Bridge**

Because all points on the line, such as point A, should be zero before the event occurs, values of strain at every point must be equal to \( E_AE_M \). Then, during the event, the strain is equal to \( E_AE_M + \varepsilon E_m \). In the analyses, a calibration value was subtracted from every event that was determined by averaging values over a period of time in every minute. Of course, there is a small difference between the value from calibration of and the value that occurs right at the...
If delta is small, close to zero, it can be negated from the equations. This produces equations 6-14 and 6-15:

\[
V_a = \frac{(-\varepsilon_{\text{transverse}})E_{Mt} + \varepsilon_{\text{MT}}E_{Mt}}{\varepsilon_{\text{longitudinal}}E_{Ml} + \varepsilon_{\text{MT}}E_{Mt}}
\]

\[
NA = y_2 - \frac{d(\varepsilon_2E_{M2} + \varepsilon_{\text{AZ}}E_{M2})}{[(\varepsilon_2E_{M2} + \varepsilon_{\text{AZ}}E_{M2}) - (\varepsilon_1E_{M1} + \varepsilon_{\text{AT}}E_{Mt})]}
\]

\[
V_a = \frac{(-\varepsilon_{\text{transverse}})E_{Ml}}{\varepsilon_{\text{longitudinal}}E_{Ml}} \quad \text{(Eq. 6-14)}
\]

\[
NA = y_2 - \frac{d\varepsilon_2E_{A2}}{(\varepsilon_2E_{M2} - \varepsilon_1E_{M1})} \quad \text{(Eq. 6-15)}
\]

If the multiplicative error can be assumed the same in both gauges, it can further be eliminated from the equations, first by factoring in the equation for neutral axis.

\[
V_a = \frac{(-\varepsilon_{\text{transverse}})E_M}{\varepsilon_{\text{longitudinal}}E_M}
\]

\[
NA = y_2 - \frac{d\varepsilon_2E_M}{(\varepsilon_2 - \varepsilon_1)E_M}
\]

And the original equations without errors are produced:

\[
V_a = \frac{-\varepsilon_{\text{transverse}}}{\varepsilon_{\text{longitudinal}}} \quad \text{(Eq. 6-1)}
\]

\[
NA = y_2 - \frac{d\varepsilon_2}{\varepsilon_2 - \varepsilon_1} \quad \text{(Eq. 6-5)}
\]

The likelihood that multiplicative errors are close in both gauges is assumed to be high.

The temperature correction curves showed that although minor changes in temperature had a
large impact on the apparent microstrain, the effect on gauge factor was extremely small, less
than 1% over the whole range of temperatures over the bridge. The small differences between
temperatures at the gauges, with regards to multiplicative error, are negligible. The gauges on
each face of each beam were installed on the same days so any multiplicative errors caused by
installation might be similar, and furthermore, the wire leads are close in length and exposed to
the same temperature, and they are all read by the same data acquisition equipment.

The same method of removing drift in the full bridge gauges also removes strain due to
thermal expansion between the point of calibration and the event in quarter bridge gauge use.
This may or may not be an issue for structural health monitoring. Thermal expansion may be
able to tell certain things about the way a structure is behaving. However, eliminating thermal
induced strain may help to focus on the way the structure is reacting to excitation. This may be
all that is needed to produce values important to structural capacity such distribution factors
and neutral axis locations.
Chapter 7: Analysis – Sensor Measurement Quality

Several analyses were conducted as part of this research that was discussed in Chapter 6. The first phase of analysis involves a small scale experiment conducted to evaluate the gauges. The second phase of analysis assesses the differences between the indoor behavior of the gauges on the small scale experiment and the outdoor behavior of the gages on the Bagdad Road Bridge. The third phase of analysis evaluates the use of the full bridge strain gauges on the web of the beam for neutral axis location. The fourth and final phase of analysis of this research focused on calculation of the neutral axis location from gauge readings during bridge excitation compared to the predicted and expected neutral axis location.

Data collection for the first part of the analysis was conducted on April 9th, 2012 in the UNH structural high bay (S106). Data for the remaining parts was largely collected on April 30th, 2012 at the Bagdad Road Bridge, with some preliminary data collections on April 15th and April 21st. The data was post-processed and normalized using procedures detailed in the following sections. Only strain values were collected for this research, leaving temperature effects as a priority for future researchers, Adam Goudreau and Samuel White, funded by this project at UNH. The strain values collected on April 15th and April 21st at the bridge were to diagnose any issues with the gauges and make sure they were functioning correctly. These collections were short in duration, lasting no more than two to three minutes. The strain values collected on April 30th were tallied over 37 minutes and were used to create a pool of live load events that could be used to extract out values necessary for the second and third phases of the analysis portion of this research.
7.1 The Flat-Bar Tests

The first small scale experiment was conducted solely to gain familiarity with the DAQ equipment, programming, and the gauge mechanics and application procedure. The gauge was placed on a specimen and strained uniaxially to simplify the mathematically evaluation. This step was important because there are several settings that can affect the way the equipment turns the electrical signal into a strain value, and simply observing a response does not mean that the settings or application is correct. On an in-service bridge, observations may be difficult to verify due to the complexity of the structure and sensor performance in environmental conditions. To make observations easy to verify, gauges were mounted on a small flat bar, as shown in Figure 7-1 and Figure 7-2. Placing the bar in tension and using the strain value, geometric, and material properties of the bar, the weight supported in tension by the bar was mathematically derived using easily determined parameters.

Figure 7-1: Photo of Flat Bar Specimen
The steel flat bar shown in Figure 7-1 and Figure 7-2 measures 0.25 inches in thickness by 1.01 inch width, and is about 10 inches long. Two 3/8-inch holes were drilled into each end of the bar. The holes allow hooks to hold the bar and to suspend weights. It is instrumented with two of the full bridge gages described in Chapter 4, at mid-length. Using Equation 7-1, which can be derived by substituting Equation 4-1 into 4-3, allows for the back calculation of the known weight for comparison.

\[ P = \varepsilon EA \]  
\text{(Eq. 7-1)}

Originally it was expected that a single gauge would be required to calculate the applied force. However, tests using a similar set up conducted by another graduate student at UNH, Jim Browne, showed that two gauges were required to capture the total strain due to tension in a flat bar. A program written in LabVIEW collected strain values using the NI 9219 C-series module and a NI 9162 USB chassis at 2 Hz. The DAQ stored the raw measurements and also multiplied them by user entered width, thickness, and modulus values, based on the test set-up.
shown in Figure 7-3. A screen shot of the front panel of the program and a thorough description of its block diagram is in Appendix D.

Figure 7-3: Illustration of Flat Bar Pull Experiment

The weight calculated from each strain gauge was displayed on the screen as well as the average of the two values. Three roughly 36 pound weights were hung from the bar one at a time adding up to 108 pounds. The weights were loaded and unloaded roughly 10-15 seconds apart to gather a reasonable sample size of collected data at each total applied weight. The results are shown in Figure 7-4 and Table 7-1. Looking at the calculated weight from each gage separately, it would appear the gauge is reporting a fluctuating incorrect value. However the average of the two values is a flat line that is close to the actual applied weight.
Table 7-1: Calculated Weight during the Flat Bar Tests

<table>
<thead>
<tr>
<th>Step</th>
<th>Actual Weight (lb.)</th>
<th>Weight from Side 1 (lb.)</th>
<th>Weight from Side 2 (lb.)</th>
<th>Avg. Weight Applied (lb.)</th>
<th>Difference %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 weight (+35.9 lb)</td>
<td>35.9</td>
<td>65.7</td>
<td>8.1</td>
<td>36.9</td>
<td>2.79%</td>
</tr>
<tr>
<td>2 weights (+35.8 lb.)</td>
<td>71.7</td>
<td>96.2</td>
<td>48.4</td>
<td>72.3</td>
<td>0.84%</td>
</tr>
<tr>
<td>3 weights (+35.5 lb.)</td>
<td>107.2</td>
<td>81.8</td>
<td>133.9</td>
<td>107.5</td>
<td>0.28%</td>
</tr>
</tbody>
</table>

Some interesting things can be observed in this test. It can plainly be seen that what is going on at the surface of the material is not representative of the global behavior. It was assumed that hanging the bar from a hook, and then hanging the weights of the bar with a hook had created a pinned-pinned connection and therefore the bar would be in pure tension. The most likely explanation for differences between the two faces is that there is a presence of bending. The bending is super-imposed on the bar, adding or subtracting from the tension effect. The gauge, however, is only capable of measuring the combination of effects.

Bending could occur for two reasons. The first is that the bar could initially be slightly bent, and that applying weight to the bar, straightens it out. Figure 7-5 shows this phenomenon with an exaggerated deflected shape. Notice how bending, or unbending in this circumstance, places difference actions on the two gauges. The other explanation is that the holes drilled into
the bar to create the pinned-pinned condition are not actually straight, or not perpendicular to
the length of the bar. Hanging weight from the plane of the hole actually causes bending in this
case. The bending causes similar phenomenon to the unbending in the previous example, this is
shown in Figure 7-6.

![Figure 7-5: Illustration of Flat Bar Straightening](image1)

![Figure 7-6: Illustration of Flat Bar Bending](image2)

Hanging the third weight had an interesting implication to the bending and unbending
scenarios. When hanging the first and second weight, the calculated force on side one
consistently overestimated the known applied weight, and the side two consistently
underestimated the known applied weight. However, when the third weight was hung, it
produced the opposite result. The gauge on side one overestimated the applied weight while
the second gauge on the other side underestimated the applied weight. This may mean that
the bar is not just bent in single curvature as shown in Figure 7-5, and that varying weights, and
the straightening of different curves causes multiple unbending scenarios. This switch could
also indicate there are multiple non-perpendicular planes in the hole that the hook is suspended
from, and that hanging the third weight caused the hook to dislodge and fall into a location that
engaged a different uneven plane.
Another interesting observation from the pair of gauges is the suggestion that noise may actually be a much smaller portion of the signal than originally suspected. Noise is the fluctuation from one signal to the next that theoretically should be at the same value. The differences are caused by electronic and magnetic phenomenon in the equipment, lead wires, and the gauge itself. Examining the blue and red lines separately in Figure 7-4, there appears to be a significant amount of noise indicated by variation in sensor reading. However, examining the green line on Figure 7-4 that represents the average of the two strain gauge readings, there appears to be little fluctuation at all. The chances of noise in two gauges being consistently equal and opposite in magnitude from each other are likely small. The best explanations for the fluctuation from signal to signal in both gauges are that they are likely due to some sort of dynamic effect related to vibration in the bar and not measurement error.

The most significant observations from the small scale experiment is that what happens on the surface of a member may not be representative of the global behavior of the member as whole, and higher excitation in the mode of observation produces increasingly accurate results. The superposition of bending and the presence of dynamic effects during loading imply that effects out on the instrumented bridge, such as torsion or out of plane deflection, could also cause unexpected results. The manner that observations became closer to true values as more weight was hung implies that these unexpected results diminish as the phenomenon of interest increases. Therefore as one effect starts to greatly overshadow other effects, measuring the effect becomes easier. This supports engineering judgment that suggest the most accurate observations at the bridge will occur at the highest loads.
7.2 Gauge Behavior at the Bagdad Road Bridge

A preliminary evaluation of the strain gauges at the Bagdad Road Bridge was conducted to compare the differences in gauge readings at the bridge versus at the UNH high bay. Differences between the sensor installations included significantly longer lead wires, varying temperatures, and covering in the form of environmental protection, as well as any differences that might have occurred during the outdoor installation, such as those derived from the glue curing in a cold and humid environment. Initial gauge readings showed that gauges at the bridge had no detectable difference in signal to noise ratio, however the sensor experiences significantly more drift. The drift is likely the result of apparent strain due to temperature effects.

7.2.1 Full-Bridge versus Quarter Bridge Sensors

Figure 7-7 through Figure 7-9 show readings from the full bridge strain gauges at the Bagdad Road Bridge versus the gauges installed on the flat bar specimen discussed in section 7.1. Figure 7-10 shows readings from the quarter bridge strain gauges located on the south face of Beam E compared to an ambient quarter bridge strain gauge readings. Note that the scale on Figure 7-10 is approximately six times the scales on Figure 7-7 through Figure 7-9. The ambient gauge was used because mounting a quarter bridge strain gauge to a flat bar specimen, similar to the one mentioned in section 7.1, was not conducted as part of this research. Instead, a small amount of confining pressure was applied to the ambient gauge to simulate an installation using a clip and a pad so that the gauge would not move from small air flows and strain. All figures show eight seconds of data collected at 2 Hz from unloaded conditions. Note the consistent small deviation from zero is to be expected and is likely due to temperature drift, and can be compensated for by calibration.
Figure 7-7 through Figure 7-10 show that gauge locations, indoors or outdoors, do not have a significant impact on noise. Variations in sequential readings were relatively the same in both installations. Table 7-2 shows the standard deviations of the strain readings from all gauges. If the presence of noise had a larger influence on the gauge values it would be expected that the standard deviations would increase as variation from reading to reading. The standard deviations of the bar samples were 0.0150 and 0.0335 με, respectively, and the standard deviations of the gauges at the Bagdad Road Bridge were between 0.0146 and 0.0317 με. The ambient quarter bridge gauge had a standard deviation of 1.023 με and the quarter bridge strain gauges at the Bagdad Road Bridge were between 0.905 and 1.091 με.
<table>
<thead>
<tr>
<th>Standard Deviations (µε)</th>
<th>Bars (Full &amp; Ambient)</th>
<th>Beam D: North Face (Full)</th>
<th>Beam D: South Face (Full)</th>
<th>Beam E: North Face (Full)</th>
<th>Beam E: South Face (Quarter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar Side 1</td>
<td>0.0150 Top</td>
<td>0.0209 Top</td>
<td>0.0246 Top</td>
<td>0.0146 Top</td>
<td>1.0905 Top</td>
</tr>
<tr>
<td>Bar Side 2</td>
<td>0.0335 Middle</td>
<td>0.0220 Middle</td>
<td>0.0234 Middle</td>
<td>0.0267 Middle</td>
<td>0.9235 Middle</td>
</tr>
<tr>
<td>Ambient</td>
<td>1.0234 Bottom</td>
<td>0.0189 Bottom</td>
<td>0.0317 Bottom</td>
<td>0.0230 Bottom</td>
<td>0.9054 Bottom</td>
</tr>
</tbody>
</table>

These observations also highlight the differences in noise that can be expected between the applications of full versus quarter bridge strain gauges. The standard deviations from these samples are roughly 42 times higher for quarter bridge strain gauges than for full bridge strain gauges. Howell and Shenton wrote about similar differences when discussing a strain monitoring system in 2006, pointing out that full bridge gauges in their system experience standard deviations of 0.5 µε for full bridge gauges versus 9.4 µε for quarter bridge (Howell & Shenton, 2006). Although they experienced higher standard deviations, likely due to differences in hardware and collections speeds, the same pattern of significantly more noise in quarter bridge strain sensors is apparent.

### 7.2.2 Sensor Drift

During the initial diagnostic of the gauges, there was a slight drift that was not observed in the flat bar test and was observed in the sensors at the Bagdad Road Bridge, shown in Figure 7-12. The drift manifests itself as a changing trend in gauge readings that can not immediately be seen from one value to the next because it is small in comparison to noise at that scale. However, the trend is seen when looking at strain values over collection durations as small as a minute. Localized thermal expansion of the steel is not expected to be the cause of the trend as the gauges are designed to cancel out that effect and rather is expected to be caused by the apparent strain output of the gauge as temperature changes. Both phenomena are discussed in detail in Chapter 4. Curvature induced in the beam as a result of restraints confining thermal...
expansion could also cause gauges to experience strain, and is a possibility considering the expansion joint, shown in Figure 7-11, is being replaced in an upcoming maintenance project (NH DOT Bureau of Bridge Design, 2010). However, the possible effect was not considered in this research.

![Figure 7-11: Photo of Expansion Joint at the BRB](image)

Figure 7-12 shows the drift as it occurred over a 2 minute collection on the south face of Beam D. The gauges can be calibrated before a collection so that they initially all read zero, however, by the end of just 2 minutes of collection, the readings have trended away to a maximum deviation of -0.5 microstrain. The deviation is fairly small compared to the load induced strains, observed by the three large spikes in strain readings at 32, 84, and 108 seconds, but could grow to be much larger than strains resulting from typical traffic loads in collections lasting more than a few minutes. Deviations in large collections can be accounted for by calibrating frequently through the data collection periods or through post-processing.
The method of post-processing used in this research when collections lasted longer than a couple of minutes was to find a duration within a minute of data that appeared to experience no live load and take the average of it, then subtract that average from all samples within the minute. This resulted in a line that centered at zero and still captured the behavior of the instrumented member. In addition to removing the apparent microstrain error, this method also removes any other potential additive errors, as was described in section 6.4.

Figure 7-13 shows a comparison of gauge readings from Beam D on the bottom flange before and after the post-processing. The figure shows a minute worth of data taken from the fourth of five collections recorded on April 30th, 2012. The calibration had occurred roughly 30 minutes prior, before the start of the first collection. During the time between 380 and 390 seconds into the collection, no observable live load events had occurred, so the average of strain values for those 10 seconds were subtracted from all values within that minute of the record.
Note that the drift in Figure 7-12 is much more pronounced than in Figure 7-13. That is because the drift in Figure 7-12 occurs just 2 minutes after calibration where the drift shown in Figure 7-13 occurred roughly 30 minutes after calibration. The x-axis depicts the time, in seconds, into the recording the figure corresponds with; several records were made after that initial calibration and will be described in detail in section 7.3. The values subtracted from each value as part of this calibration were 3.7 and $\mu e$.

Removing drift helps to isolate actual strain due to loading. Each time the bridge is loaded it is considered to be excited. Analyzing the bridge responses during excitations allowed for the full bridge behavior on the web to be analyzed and for neutral axis position to be researched without the need to focus on multiple sources and magnitudes of error. Eventually, detecting actual strain due to temperature may be helpful to SHM research at UNH. In fact, it may be necessary to collect temperature strain for determining such things as deflected shape using curvature. However, until temperature induced error can be successfully removed, it will be impossible to know what strain in an unloaded bridge is due to thermal expansion and contraction versus due to the several ways temperature produces error in the measurements using bonded foil gauges, which include effects on the sensors themselves, the lead wires, the DAQ hardware, and potentially the adhesive and environmental protection.
7.3 Generating the Live Load Event Database

To obtain a sample of strain values that were significantly more than those caused by noise in the sensors, a data collection was conducted that aimed to capture loads induced by school buses entering or leaving Oyster River High School. The proximity to the high school is shown in Figure 7-14.

Data was collected for over 37 minutes in 5 separate files called records. Each record was divided up into one minute segments, except for the last segment which was made of the remaining seconds in the record that did not sum to a minute. The minutes were then calibrated separately using the process described in the previous section. Using the full bridge gauges on bottom of Beam D, 156 live load events were identified. Histograms of peak strain from each beam face are shown in Figure 7-15 through Figure 7-18.

Figure 7-14: Aerial Photo of Bridge Proximity to Oyster River High School (googlemaps.com)
Some things are immediately apparent from the histograms. Only six events caused readings higher than 12 microstrains in the beams. Because that amount of strain, as compared to the typical values measured during the collection, was high they may have been caused by school buses. However, because nothing was used to record vehicle information as motorists crossed and researchers were positioned beneath the bridge, there are no observations to confirm this.
The events were then labeled by the record number and the seconds into the record; 4:175 for example, and recorded into a separate data base. The entire database can be found in Appendix F.

Analysis on all 156 events produced widely varying results in terms of comparisons and feature extractions. One example is shown in Figure 7-19. The scatterplot shows the difference between values from bottom gauge readings on Beams D and E. Although Beam D generally experienced higher strain than Beam E, the amount varies much more widely at lower peak strains. The largest amount of scatter occurs during events when small strains occur in the bottom flange, particularly those less than 3 με.

When considering all events extracted from the sample, the bottom flange of Beam D was between -12% and 429%, excluding extraneous strain reading that were categorized as outliers. However, considering just live load events that produced measurements of at least 3 με in both sides of the bottom flange of Beam D, resulted in a significantly smaller range of 14-41%, a fraction of the range that occurred over all events.

Figure 7-19: Scatter Plot of Percent Difference between Peak Strains Beam to Beam
The same type of scatter appeared in feature extractions as well. The scatter existed in the pool of neutral axis locations determined from all events. An example is shown in Figure 7-20 that plots peak strains in Beam D versus neutral axis location. The largest amount of scatter exists, again, below 3 με. Reducing the database by eliminating events that caused less than 3 microstrains in both sides of the bottom flange of Beam D produced a pool of samples with less scattered characteristics. The standard deviation for neutral axis locations on the north face of Beam D reduces from 1.16” to 0.55”, and 0.62” to 0.42” on the south face when going from all events to events causing over 3 με.

For further analysis, only significant events are used. The pool of data was reduced from the original 156 events to 101 events using the criteria that the event had to cause strain of at least 3 με in both sides of the bottom flange of Beam D. The database of 101 events is hereby referred to as the Live Load Event Database. Small values excluded from the database may have been caused by traffic in the westbound lane, which is not above the instrumented girders. During the collections used for this research, there were no observations made regarding the vehicle crossing information including size and direction of travel. This
information would have been extremely valuable in this post-processing and therefore, methods of recording vehicle size and position should be investigated.

Vehicles in the westbound lane will likely still induce a response in the gauges on Beams D and E, especially large vehicles, from a global deflection and twist of the superstructure. However, the significance of other types of responses, such as warping, torsion, or dynamic effects, likely contribute to a larger portion of the strains in the beams under the eastbound lane. One of the basic assumptions in developing the Live Load Event Database is that the largest possible strains from traffic loads will correspond to events where bending is predominant. Using larger strain values for analysis has the benefit of reduced effect from noise, because of a higher signal to noise ratio. Assuming the level of noise, in the form of variation in measurement to measurement, is expected to be constant regardless of the force applied to the girder.

7.3.1 Beam to Beam Comparison

As noted for the larger pool of all recorded events, the strain measurements collected on Beam D are generally higher than those collected on Beam E. In the Live Load Event Database, the average the ratio of Beam D strain measurements to Beam E strain measurements was 1.41 with a standard deviation of 0.18. The higher responses measured from Beam D may be due to the position of the vehicle as it drives across the bridge or additional stiffness from the curb and pedestrian sidewalk. Figure 7-21 shows a cross section of the superstructure of the Bagdad Road Bridge. The center of the painted white line that indicates the breakdown lane or non-traffic lane is approximately 57 inches from the granite curb. Using the measurements of the deck section on the original plans, a distance of 3” to the inside of edge of Beam E was determined. Travelers are likely to follow typical traffic laws and
stay evenly within the painted lines, indicated by the path shown with arrows in Figure 7-21. This path places the vehicles closer to Beam D than Beam E.

Figure 7-21: Deck Cross Section with Highlighted Lane Lines and Likely Vehicle Path on the Bagdad Road Bridge

7.4 Full Bridge Strain Gauge Use on the Web

As mentioned in Chapter 3, the full bridge strain gauges used for this research function by mounting all strain sensing resistors of the Wheatstone bridge circuit on the specimen by placing two resistors in the direction of principle stress and two in the direction of Poisson's effect. This creates an additive effect as the two resistors in Poisson's direction have a negative effect on the Wheatstone bridge and are compressed; therefore, their resistance increases the voltage in to voltage out ratio and amplifies the signal. Chapter 6 further discussed how this could be a concern when placing the gauge on the web of beams because the presence of web compression could also add to the signal thus artificially amplifying it.

7.4.1 Apparent Poisson's Ratio

As one means to investigate the possible interference from web compression, quarter bridge strain gauges were mounted on the south face of Beam E, as detailed in Chapter 6. In addition to placing a pair on the web, pairs were placed on both flanges to expand on the investigation of possible superimposed strains on measurements with the full bridge strain gauges. After noting how web compression could also affect strain measurement collected from
the web, it is not difficult to see how torsion or warping could affect strain measurements collected from the flange.

An example of an Apparent Poisson's Ratio is shown below using event 5:110, and measurements were taken from the pair of quarter bridge strain gauges on the web. The calculation uses equation 6-1, explained in chapter 6. During the event, a strain of 8.38 με was measured by the gauge facing the longitudinal direction and a value of -2.47 με was measured in the transverse direction.

\[ \nu_a = \frac{-\varepsilon_{\text{transverse}}}{\varepsilon_{\text{longitudinal}}} = \frac{-(2.47)}{8.38} = 0.295 \]

![Apparent Poisson's Ratio at Middle Gauge Pair](image)

Figure 7-22: Histogram of Apparent Poisson's Ratio Results Calculated from Gauges on the Web

Results derived from the values that were obtained on April 21\textsuperscript{st} were inconclusive. The event 5:110 that calculated values close to the expected ratio were uncommon. Figure 7-22 shows a bar graph of apparent Poisson's ratios for the pair of gauges on the web. The average is 0.04, with a maximum of 7.10 and a minimum of -5.38, and a standard deviation of 1.15. The results do not make sense. Expectations are that a higher level of compression in the web, than
would be caused by Poisson's effect during the longitudinal strains due to bending, will result from web compression as vehicles pass. That web compression would therefore result in a higher value than the well-known Poisson's ratio of 0.3 for steel material. In this case the majority of events caused an apparent Poisson's effect lower than 0.3.

Averaging close to zero initially implies that either the gauge measuring vertical effects on the web is reading close to zero or the gauge measuring horizontal effects is reading values that are too high. However, inspections of the measurements made by the middle gauge mounted in the horizontal direction were consistently reasonable as they fell between the values reported by the top and bottom sensors. Furthermore, the middle gauge mounted in the vertical direction measured a wide range of values significantly away from zero, with a range of -2.55 to 2.65 and a standard deviation of 1.091. More research should be conducted that investigates the calculated ratios compared to the position of traffic, as well as further inspection of possible malfunctions in the gauge mounted in the vertical direction.

The apparent Poisson's ratio method does appear to function as expected on the bottom flange. Figure 7-23 shows a histogram of apparent Poisson's ratios derived from the pair of quarter bridge strain gauges on the bottom beam flange, using the Live Load Event Database. The average apparent Poisson's Ratio for the bottom flange is 0.31, which is much closer to the expected value of 0.30 than with the middle gauge pair. This concludes that the full bridge gauges are appropriate for use on the bottom flange. However, as shown in the histogram, the values did trend to slightly lower than 0.30, so more samples should be analyzed to confirm the conclusion.
The top flange value results were largely meaningless. The noise to signal ratio of the strain gauges, coupled with values that are close to zero, created significantly varying results. The limited results that were close to expected values may have been just as likely due to coincidence as from meaningful gauge results. The range was -133.13 με to 13.41 με with an average of -1.18 με and a standard deviation of 14.74 με.

Figure 7-24 shows calculated Poisson's ratios versus measured longitudinal strain value. It highlights that although lower strain values are part of the reason for the high amount of scatter in the sample of middle strain gauge pair values, low values are likely not the only cause. The bottom strain gauge values also are much more scattered at lower loads than at higher loads. However, the middle gauge values are generally more scattered, regardless of the loading. It can be seen in Figure 7-24 that of the four live load events causing a greater than 8 με reading in the middle longitudinal gauge, only a single value was close to the true Poisson's ratio.
7.4.2 Middle Strain Reading versus Linear Interpolation

Considering the possible malfunctioning of the quarter bridge gauge on the web, another method was used on the samples to evaluate sensors on the web. A linear interpolation assumes that the strain gauges on the top and bottom flange are functioning correctly. Then, because the gauge on the web is located at half the height between the other sensors, each strain reading is expected to be halfway between the two measurements. The equation used to determine the expected value was then compared to the value is shown in Equation 7-2.

\[
\varepsilon_{expected} = \frac{\varepsilon_{bottom} - \varepsilon_{top}}{2} + \varepsilon_{bottom} \quad \text{(Eq. 7-2)}
\]

The measured values were anticipated to be artificially higher due to the effects of web compression; therefore, the percentage that measured over expected was calculated using Equation 7-3, where the measured strain is recorded by the middle gauge, located on the web.
\[
\% \text{ over } = 100 \times \frac{\varepsilon_{\text{measured}} - \varepsilon_{\text{expected}}}{\varepsilon_{\text{expected}}} \quad (\text{Eq. 7-3})
\]

A sample calculation using the values from the northern face of Beam D during event 4:218.5, is provided, below. During this live load event, strain values of \(-0.65\), \(2.39\), and \(4.43\ \mu\varepsilon\) were measured from the full-bridge strain gauges on the top flange, web, and bottom flange respectively.

\[
\varepsilon_{\text{expected}} = \frac{4.43\mu\varepsilon - (-0.65\mu\varepsilon)}{2} + (-0.65\mu\varepsilon) = 1.89\mu\varepsilon
\]

\[
\% \text{ over } = 100 \times \frac{2.39\mu\varepsilon - 1.89\mu\varepsilon}{1.89\mu\varepsilon} = 26.5\%
\]

Table 7-3 summarizes the results for the entire sample of 101 events in the Live Load Event Database. Note that 12 outliers were dismissed when considering measurements made with the quarter bridge gauges on the southern face of Beam E. Outliers were taken as values outside of a \(-200\%\) to \(+200\%\) range. The range for percentages over expected for all other beam faces was \(-16\%\) to \(42\%\) which means that no events came close to the bounds used for dismissing outliers derived from quarter bridge readings on Beam E. The fact that outliers only needed to be excluded from measurements made with quarter bridge gauges, even in a range of values still an order of magnitude greater than those resulting from full bridge gauge measurements, highlights how scattered the features extracted from the quarter bridge gauges tended to be.

<table>
<thead>
<tr>
<th>Beam / Face</th>
<th>Average</th>
<th>Standard Deviation</th>
<th>Outliers</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam D / North Face</td>
<td>22.7 %</td>
<td>7.33 %</td>
<td>0</td>
<td>1.59 – 41.7 %</td>
</tr>
<tr>
<td>Beam D / South Face</td>
<td>4.91 %</td>
<td>7.11 %</td>
<td>0</td>
<td>-13.3 – 20.7 %</td>
</tr>
<tr>
<td>Beam E / North Face</td>
<td>-0.38 %</td>
<td>5.77 %</td>
<td>0</td>
<td>-16.3 – 18.7 %</td>
</tr>
<tr>
<td>Beam E / South Face</td>
<td>13.87 %</td>
<td>61.8 %</td>
<td>12</td>
<td>-169.1 – 126.6 %</td>
</tr>
</tbody>
</table>
Table 7-3 shows that middle strain gauge values, made with full bridge gauges, on the northern face of Beam E are consistently over expectations. In fact, the range was 1.59% to 41.7%. Therefore no values were equal to below zero in the entire sample. However, results were closer to expectations in other sets of strain gauges. Measurements on the web taken on the southern face of Beam D averaged around 5% over expectations, which could be expected in a small sample size. Measurements from the north face of Beam E are even closer to expected values, theoretically zero percent, averaging at less than a half percent.

The fact that measured strain values collected from the gauge on the web on the north face of Beam D are consistently higher than expected could be that the beam is deflecting in an unexpected manner or it could be that the strain gauge on the bottom flange is malfunctioning. This could be supported by the fact that, as shown in section 7.3, values from the bottom flange of the north face of Beam D were consistently lower than those measured on the opposite side of the flange. A possible beam distortion scenario is illustrated in Figure 7-25. In this scenario, the web is placed into a small amount of curvature from the effect of web compression. The strain gauge would then measure artificially higher because the bending strain is superimposed on the strain due to Poisson’s ratio, as both would be acting in the same direction. The scenario is similar to what caused exaggerated values on one side of the flat bar in the analysis described in section 7.1.
Figure 7-26 illustrates how a strain gauge malfunction in the bottom flange could affect the expected value of strain experienced by the web. The scenario could occur when an error causes the bottom strain gauge to read too low, which could easily happen if it was not bonded properly, for example if an air bubble existed in the adhesive. This would lower the expected values of strain between the bottom value and the top value, which in turn would make an accurate measurement in the middle appear to be exaggerated. An analysis of the differences for the sample used to evaluate apparent Poisson's ratio is shown in Table 7-4. It excludes the 12 outliers previously mentioned that caused results from measurements made with quarter bridge gauges to be outside of a -200% to 200% range.

<table>
<thead>
<tr>
<th>Beam</th>
<th>Average</th>
<th>Standard Deviation</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam D</td>
<td>15.7 %</td>
<td>1.78 %</td>
<td>9.51 - 19.4 %</td>
</tr>
<tr>
<td>Beam E</td>
<td>11.6 %</td>
<td>31.1 %</td>
<td>-60.8 - 84.3 %</td>
</tr>
</tbody>
</table>

Table 7-4 shows the bottom strain gauge readings on the southern face of Beam D were on average 15.7% higher than the strain gauge readings on the northern face of Beam D. The behavior was also fairly consistent, indicated by the relatively low standard deviation. This
indicates the possibility of the gauge on bottom flange of Beam D is reading values too low. The possibility would explain why the expected values for the middle gauge are highest on that beam face.

Similar behavior also existed on Beam E, which could indicate that some global behavior, such as dishing, is causing the southern faces of the beams on the instrumented side of the bridge to strain more than the northern faces. However, the conclusion is difficult to draw because the results are much more scattered, indicated by the high standard deviation. The scatter is likely caused by a larger presence of noise in the quarter bridge strain gauges, described in section 7.2. Additional data sets are required to draw this conclusion with a reasonable level of confidence. Recommendations include taking more samples with concurrent truck position data and to specifically investigate the behavior of the full bridge gauge on the bottom flange of the north face of beam D.

### 7.4.3 Interpolation during Negative Bending

Calculating expected strain values during negative bending is a potential opportunity to evaluate the behavior of the full bridge gauges on the web. Because negative bending will occur when the vehicle is in the span 2 or span 4 as shown in Figure 7-27, the vehicle will not be in the instrumented span 3 to cause the web compression.

Figure 7-27: Illustration of Vehicle Placements that Cause Negative Bending in Span 3

Figure 7-28 shows two live load events captured on April 15th, 2012 during the initial evaluation of the sensors at the bridge. Negative bending is apparent in the figure, particularly
in the top in middle gauges, as they can be seen going into compression just a moment before and after the peak tension values of the live load event. The top gauge appears to be going into the slightest amount of tension during these time as well, which is opposite of its typical behavior during the positive bending events.

It can also be seen in Figure 7-28 that the excitation in the strain gauges during negative bending is small, compared to the magnitudes experienced during positive bending. For this reason, only the six events that caused readings over 12 με were analyzed. Because the vehicles have to travel through span 2 and span 4 to pass over span 3, two values from negative bending could be captured from each of these events. This created a database of 12 negative bending occurrences for the following analysis.

The same analysis that was conducted in section 7.4.2 on the positive bending events was conducted on the negative bending sample. The results are shown in Table 7-5. The same range of ±200% was used to exclude two outliers in the quarter bridge strain gauge readings on the south face of Beam E. Higher standard deviations in all comparisons were likely the result of higher noise signal ratios. Although the sample size is too small to draw any significant
conclusions, there is an indication that the measurements collected via the strain gauges are higher than expected on Beam D and lower on Beam E.

Table 7-5: % Measured Value Greater than Expected Value (12 samples)

<table>
<thead>
<tr>
<th>Beam / Face</th>
<th>Average</th>
<th>Standard Deviation</th>
<th>Outliers</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam D / North Face</td>
<td>28.29 %</td>
<td>14.22 %</td>
<td>0</td>
<td>6.03 – 51.6 %</td>
</tr>
<tr>
<td>Beam D / South Face</td>
<td>10.49 %</td>
<td>9.84 %</td>
<td>0</td>
<td>-7.08 – 24.9 %</td>
</tr>
<tr>
<td>Beam E / North Face</td>
<td>-17.3 %</td>
<td>6.57 %</td>
<td>0</td>
<td>-4.37 – 27.1 %</td>
</tr>
<tr>
<td>Beam E / South Face</td>
<td>-9.50 %</td>
<td>69.6 %</td>
<td>2</td>
<td>-107.0 – 108.2 %</td>
</tr>
</tbody>
</table>

Further analysis could have implications similar to those described in 7.4.2. The first is that full bridge strain gauges on the web may be artificially raised due to both web compression and some other sort of out-of-plane movement from the global response of the bridge that causes local bending in the beam, similar to the shape shown in Figure 7-25. Out of negative and positive live load induced bending, the average amount readings were in excess of expected values were actually higher during the negative events. This is counterintuitive as web compression is expected to increase when vehicles are closer to the instrumented location. However this could be due to the effect of higher noise to signal ratios. The second implication again points to the strain gauge on the bottom flange of the north face of Beam D as not functioning properly because it again collected values that resulted in the middle gauge readings to exceed expectations, more so than on the south face. If the readings in the web are consistently above expected values in both positive and negative bending, and sensor malfunction is not detected, than the web may go into compression from bending, regardless if a vehicle is above the instrumented location.
As discussed in section 6.3, the neutral axis location may be used to track the level of composite action and can indicate if capacity in the deck or steel has been lost. Determining the neutral axis frequently over time may be a means to detect sudden damage or track slow degradation of the steel or deck. Neutral axis location, therefore, is a metric that is being researched by the SHM community (Liu, Olund, Cardini, D’Attilio, Feldblum, & DeWolf, 2008), (Olund & DeWolf, 2007), and (Lefebvre, 2009). In those studies, 2 strain gauges were used to determine the location. This research expands on those investigations by using multiple gauges on each beam face to determine the locations. Each group of gauges belonging to a beam face was divided into 3 sets of 2 gauges and 1 set containing all gauges. The measurements from each set of gauges were used to calculate the neutral axis location and are presented in section 8.2.1 through 8.2.5 and further discussed in section 8.3. Results were compared to expected values to infer the health of the composite section and compared among multiple sets to make observations about gauge placement.

Using a structural mechanics approach, the location of the neutral axis was calculated using transformed section properties and was 31.7” from the bottom of the steel, as shown in Figure 8-1. The bottom of the steel in this case is the bottom of the cover plate. By hand calculation (see appendix E) both Beams D and E are assumed to have the same neutral axis location because the curb is taken as outside of the effective width of Beam E and, therefore, does not contribute to the cross sectional properties.
Neutral axis locations were calculated using data from the Live Load Event Database that was described in section 7.3. The four sets of data used to calculate the position are from the top and bottom flange strain gauge readings, top flange and middle of web strain gauge readings, middle of web and bottom flange strain gauge readings, and a linear interpolation of all three values. Although results from the analysis of the full bridge strain gauges on the web indicated that there was likely some local effect on the strain gauge that caused error in the readings, neutral axis calculations depending on the middle gauge were conducted anyway to evaluate the range of locations that could be deduced from erroneous readings.

8.1 Sample Calculation

Sample calculations for all four sets are shown below. The readings are taken from event 2:115, on the south face of Beam D. Results from the event are shown on Figure 8-2. The calculations use equations 6-5 and 6-11. Recall that when using a pair of strain gauges equation 6-5 is utilized, and when calculating using three or more values equation 6-11 is utilized.

For a pair of gauges:
When considering all 3 gauges:

\[ m = \frac{n(\Sigma xy) - (\Sigma x)(\Sigma y)}{n(\Sigma x^2) - (\Sigma x)^2} \]

\[ NA = \bar{y} - m\bar{x} \]

**Beam D**

Figure 8.2: Data Points for Event 2:115 Illustrated on South Face of Beam D

**Top & Bottom Pair (d = 34.02)**

\[ NA_{top \& bottom} = 35.31in - \frac{34.02in(-0.4805\mu e)}{(-0.4805\mu e - 6.216\mu e)} = 32.87in \]

**Top & Middle Pair (d = 17.01)**

\[ NA_{top \& middle} = 35.31in - \frac{17.01in(-0.4805\mu e)}{(-0.4805\mu e - 3.019\mu e)} = 32.97in \]

**Middle & Bottom Pair (d = 17.01)**

\[ NA_{middle \& bottom} = 18.30in - \frac{17.01in(3.019\mu e)}{(3.019\mu e - 6.216\mu e)} = 34.36in \]

Linear regression of all 3

\[ \Sigma xy = (-0.4805 \times 35.31) + (3.019 \times 18.30) + (6.216 \times 1.290) = 46.30 \]

\[ (\Sigma x)(\Sigma y) = (-0.4805 + 3.019 + 6.216)(35.31 + 18.30 + 1.290) = 480.6 \]

\[ \Sigma x^2 = -0.4805^2 + 3.019^2 + 6.216^2 = 47.98 \]
\[(\Sigma x)^2 = (-0.4805 + 3.019 + 6.216)^2 = 76.64\]

\[m = \frac{3(46.29) - 480.6}{3(47.52) - 76.62} = -5.077\]

\[\bar{y} = \frac{1}{3} (35.31 + 18.30 + 1.290) = 18.30\]

\[\bar{x} = \frac{1}{3} (-0.4805 + 3.019 + 6.216) = 2.918\]

\[NA = 18.30 - (-5.18)(2.918) = 33.12\text{in}\]

The strain values plotted versus depth are shown in Figure 8-3. Note that in this instance the reading from the middle gauge value was only 6.20% over expected. If the middle gauge is considered an erroneous value, it can be seen that including it in calculation had a larger impact when combined with the bottom gauge than with the top gauge. This is likely the result of the low readings from the top gauge. Because the reading plotted on the x-axis of the strain diagram is close to zero, the y-intercept of a line plotted using the data point will be close to the y value regardless of the other value or values in the set.

Figure 8-3: Strain Diagram Corresponding to Event 2:115 on South Face of Beam D
8.2 Results from the Live Load Event Database

This section shows the resulting neutral axis locations calculated using the four previously describe pairings. In the analysis of full bridge strain gauges, installed on the north and south faces of Beam D and the north face of Beam E, practically all samples were included. In the analysis of the quarter bridge strain gauge values some results were excluded as outliers. Outliers, in this case, were results that calculated a neutral axis value outside the bounds of the beam: \( y < 0 \) or \( y > 43.73 \). The bins of the histograms divide each range of results into 12 equal sized ranges.

8.2.1 Results from the Top and Bottom Pairs

Figure 8-4 through Figure 8-7 are histograms of the neutral axis locations calculated from the collected strain readings for top and bottom flange gauges with events divided into twelve equal sized bins. Table 8-1 shows the data ranges and standard deviations for each set. 30 outliers were excluded from the sample when calculating the values using reading from the quarter bridge gauges on the south face of Beam E that resulted in locations outside bounds of the composite section and, therefore, not practically applicable.
The results shown on the histograms indicate normal distributions with the exception of the north face of Beam E and possibly the north face of Beam D. Bimodal distributions could be the result of varying vehicle position having an effect on the beam. Also, although the south face of Beam E appears to be skewed to the right, this is likely a result of removing outliers. The predicted neutral axis location of 31.7” from transformed section calculations is closer to the upper bound in the range of acceptability. Referring to Figure 8-1, the upper bound, corresponding to the top of the concrete deck, is 12” away from the predicted value at 43.7”, and the lower bound, corresponding to the bottom of the steel cover plate, is 31.7” away from
the predicted values at 0". It is plausible that if values over 12 inches above the predicted value were also plotted, the histogram would appear more normally distributed.

<table>
<thead>
<tr>
<th>Beam / Face</th>
<th>Average (in.)</th>
<th>Standard Deviation</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam D / North Face</td>
<td>31.77</td>
<td>0.5530</td>
<td>30.53 – 33.07</td>
</tr>
<tr>
<td>Beam D / South Face</td>
<td>33.17</td>
<td>0.4077</td>
<td>32.04 – 34.25</td>
</tr>
<tr>
<td>Beam E / North Face</td>
<td>35.94</td>
<td>1.079</td>
<td>33.86 – 38.83</td>
</tr>
<tr>
<td>Beam E / South Face</td>
<td>31.81</td>
<td>6.918</td>
<td>11.91 – 43.64</td>
</tr>
</tbody>
</table>

The analysis using values from top and bottom pairings of gauges show relatively consistent behavior on 3 of the 4 beam faces. The locations derived for both faces of Beam D and the south face of Beam E are all within 1.5". Although the values from the south face of Beam E are more scattered than for other faces, this is to be expected as the values come from quarter bridge gauges. The major difference among beam faces occurs in the north face of Beam E which, on average, results in locations that are over 2.5" higher than in other beam faces. This could be interpreted as damage, for example section loss in the steel that results in movement upwards, however, the values from the south face agree with the transformed section properties of an undamaged section.

8.2.2 Results from the Top and Middle Pairs

Figure 8-8 through Figure 8-11 are histograms of the neutral axis locations calculated from the collected strain readings taken on the top flange and on the web of the two beams with events divided into twelve equal sized bins. Table 8-2 shows the data ranges and standard deviations for each set. 29 outliers were excluded from the sample when calculating the values using reading from the quarter bridge gauges on the south face of Beam E that resulted in locations outside bounds of the composite section and, therefore, not practically applicable.
The histograms show similar results as the ones deduced using top and bottom pairings. Both faces of Beam D appear to have results that are normally distributed, although results from the north face may be trending slightly towards bimodal behavior. The north face of Beam E is more distinctly bimodal and the south face appears to be skewed to the right, again likely the result of including a larger range of samples below the expected value than above.
Table 8-2: NA Positions From Top and Middle Gauge Readings

<table>
<thead>
<tr>
<th>Beam / Face</th>
<th>Average (in.)</th>
<th>Standard Deviation</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam D / North Face</td>
<td>32.30</td>
<td>0.4868</td>
<td>31.22 – 33.38</td>
</tr>
<tr>
<td>Beam D / South Face</td>
<td>33.25</td>
<td>0.3841</td>
<td>32.20 – 34.28</td>
</tr>
<tr>
<td>Beam E / North Face</td>
<td>35.99</td>
<td>1.156</td>
<td>34.01 – 39.41</td>
</tr>
<tr>
<td>Beam E / South Face</td>
<td>32.54</td>
<td>5.913</td>
<td>10.30 – 43.68</td>
</tr>
</tbody>
</table>

The analysis using values from top and middle pairings were similar to the pairings for top and bottom gauges. The results show consistent behavior again in all beam faces except the north face of Beam E. The locations derived for both faces of Beam D and the south face of Beam E are all within 1.0”, an even smaller range than occurred when using top and bottom pairings. Once again, the values from the south face of Beam E are more scattered than on other faces, likely a result of using quarter bridge gauges. Also repeated are unexpected values occurring in the north face of Beam E, which again on average are 2.5” over values from other beam faces.

8.2.3 Results from the Middle and Bottom Pairs

Figure 8-12 through Figure 8-15 are histograms of the neutral axis locations calculated from the collected strain readings taken on the bottom flange and on the web of the two beams with events divided into twelve equal sized bins. Table 8-3 shows the data ranges and standard deviations for each set. An astounding 48 outliers were excluded from the sample when calculating the values using readings from the quarter bridge gauges on the south face of Beam E, and 5 outliers on the north face of Beam D that resulted in locations outside bounds of the composite section and, therefore, not practically applicable.
When using the middle and bottom gauges, the histograms for the north faces of each beam no longer appear bimodal. An explanation for the north face of Beam E is that including the five outliers that resulted in neutral axis locations above the deck would have changed the bin widths and added more sample to the right hand side of the chart making it appear more bimodal. The distribution on the south face of Beam E is difficult to draw conclusions from, likely a result of reducing the sample size so significantly. Note that the apparent peaks in
Figure 8-15 are between 6 and 8 occurrences where peaks in the other 3 histograms are 20 and over.

Table 8-3: NA Positions From Middle and Bottom Gauge Readings

<table>
<thead>
<tr>
<th>Beam / Face</th>
<th>Average (in.)</th>
<th>Standard Deviation</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam D / North Face</td>
<td>38.29</td>
<td>2.303</td>
<td>31.86 – 42.30</td>
</tr>
<tr>
<td>Beam D / South Face</td>
<td>34.71</td>
<td>2.080</td>
<td>29.51 – 40.55</td>
</tr>
<tr>
<td>Beam E / North Face</td>
<td>35.82</td>
<td>1.687</td>
<td>31.12 – 42.06</td>
</tr>
<tr>
<td>Beam E / South Face</td>
<td>30.38</td>
<td>7.631</td>
<td>14.64 – 43.44</td>
</tr>
</tbody>
</table>

The results from using middle and bottom gauges were much more varied than when using pairs that include the top gauge, indicated by much higher standard deviations, and in general, the calculated locations were significantly higher, with the exception of the south face of Beam E. Higher neutral axis locations in Beam D may be the result of web compression causing artificially high readings in the gauge on the web. These high readings would create diagrams with steep slopes and high y-intercept, as illustrated in Figure 6-6. More results from the south face of Beam E could be used to further investigate this concept, as the quarter bridge gauges installed on that face will not be affected by web compression. This initial small batch of 53 samples has an average that is significantly lower than those derived from beam faces instrumented with full bridge gauges.

The highest average, at 38.6” taken on the north face of Beam D, may be a result of erroneously low values in the bottom gauge readings or erroneously high values in the middle gauge readings. Both notions are supported in chapter 7 where the ratio of readings on the bottom flange showed the north side had consistently lower values than on the south side, and the values at the middle gauge were consistently over expectations. The ratio of values from the southern side to the northern side was 1.41 (section 7.3.1). The middle gauge reading on
the north face of Beam D were, on average, 22.7% over expectations during positive bending events and 28.3% over expectations during negative bending events (7.4.2 & 7.4.3).

8.2.4 Results from the Linear Regression

Figure 8-16 through Figure 8-19 are histograms of the neutral axis locations calculated from the set of all strain readings on a beam face during events using linear regressions, again with results divided into twelve equal sized bins. Table 8-4 shows the data ranges and standard deviations for each set. In this case, only 18 outliers were excluded from the sample when calculating the values using readings from the quarter bridge gauges on the south face of Beam E that resulted in locations outside bounds of the composite section and, therefore, not practically applicable.
The histograms show results that are much more similar to the results derived from using the pairs of top and bottom, and top and middle gauges, than the results from the previous section that used middle and bottom gauges. Possible bimodal distributions are again apparent in the north face of Beam E and less in the north face of Beam D.

Table 8-4: NA Positions From Linear Regressions

<table>
<thead>
<tr>
<th>Beam / Face</th>
<th>Average (in.)</th>
<th>Standard Deviation</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam D / North Face</td>
<td>32.62</td>
<td>0.5877</td>
<td>31.36 – 33.93</td>
</tr>
<tr>
<td>Beam D / South Face</td>
<td>33.38</td>
<td>0.4516</td>
<td>32.00 – 34.40</td>
</tr>
<tr>
<td>Beam E / North Face</td>
<td>35.88</td>
<td>0.9093</td>
<td>33.77 – 37.89</td>
</tr>
<tr>
<td>Beam E / South Face</td>
<td>31.78</td>
<td>5.954</td>
<td>17.66 – 43.33</td>
</tr>
</tbody>
</table>
Table 8-4 reinforces the similarities between the linear regression and the pairs that contained the top gauge readings. The results again have the lowest standard deviations occurring from measurements taken on Beam D, and the north face of Beam E once again is more than 2.5" above other values. This implies that measurements from the top gauge have a large influence on the derived neutral axis location, as any set that utilizes the gauge shows consistent behavior.

8.2.5 Comparison of Sets Common to Each Beam Face

This section uses the data from sections 8.2.1 through 8.2.4 to discuss implications from the findings specific to the individual beam faces. Sections 8.2.1 through 8.2.4 presented neutral axis calculations by comparing a given set of gauges, for example top and bottom on the north face of Beam D, to other sets of gauges that used the same gauged locations on other beam faces. By categorizing sets of gauges by location on the beam it was found that the top gauge has a large influence on the resulting neutral axis location. This section categorizes neutral axis locations specifically by the beam face they are calculated for, by placing results from all sets that belong to each face on the same box plot. The box plots are show in Figure 8-20 through Figure 8-23. The center of each box represents the media value. The upper bound of the box plot is equal to the third quartile and the bottom bound is equal to the first quartile. The error bars extend to the maximum and minimum values for the set. The red line on each plot represents the value calculated for the healthy transformed section property, 31.7". Healthy means in this case that there is no section loss in the steel or the cover plate and no cracking in the deck, which has a compressive strength of 3.5 ksi.
The box plots show that, in general, the calculated neutral axis locations are above the value determined by transformed section properties. The sets from the north face of Beam E seem to agree with each other the most, which is to be expected given the results of section 7.4.2 showed that on average the readings from the middle of the web strain gauge, resulted in less than a 1% deviation from the expected value found through linear interpolation between the two gauges. Lastly, the neutral axis location calculated from the quarter bridge strain gauge
readings produce the widest range of values, highlighting that results from those gauges can be scattered.

These results have interesting implications for the SHM system at the Bagdad Road Bridge and structural health monitoring systems in general that rely on neutral axis positioning. The positions that were derived using the gauges on the web of Beam D highlight a weakness in SHM systems that use only two gauges per cross section because the readings were shown to be artificially increased through web compression in chapter 7, and yet the resulting feature extractions produced believable values. Beam E is of interest for the system at the Bagdad Road Bridge because the results from the north face indicate the neutral axis is high enough that damage may have occurred, however the south face of the beam indicates a healthy section. This raises questions about the differences that could be occurring on the two faces of Beam E. Two distinct possibilities exist that could be causing the difference; either the top gauge on the north face of Beam E is malfunctioning, or the process of excluding outliers from results using the quarter bridge gauges created samples that on average have erroneously low neutral axis locations.

The first possibility is supported by the results of section 7.4.2, where the full bridge gauge on the web of Beam E produced values close to expectations, as opposed to Beam D where both gauges produced readings that exceeded expectations. If the gauge is malfunctioning and constantly reading zero, the expected strain value on the web would be higher than if the gauge produced negative values during bending, and strains that are artificially magnified by web compression could agree with those expectations. Negative values were common during events at Beam D (an example is shown in Figure 7-28). Unfortunately,
the readings on the top flange are generally too small to be reasonably evaluated for consistent behavior considering the high noise to signal ratio in the quarter bridge gauges at low values.

The second possibility is supported by the fact that the majority of outliers excluded from the samples of quarter bridge gauge readings on Beam E were excluded for being above the composite section and not below it. Recall that the upper bound is 12” away from the position in a healthy section and the lower bound is 31.7” away. By including locations between 12” above and 31.7” below the transformed section position, and not in the same range above the position, may have resulted in a lower average that actually hides possible damage. This suggests that improved means of excluding outliers should be developed, which are more sophisticated than simply excluding values that fall outside of the section.

8.3 Neutral Axis during Negative Bending Events

The sample of negative bending events that was described in section 7.4.3 was also used to determine neutral axis locations. Calculating neutral axis locations during negative bending may produce opportunities to investigate structural health parameters that positive bending situations do not. An example would be situations where cracks in the deck do not affect the compressive capacity of deck but reduce the tensile capacity. Conclusions from the sample are difficult to make because it is so small, only 12 occurrences, and the readings during negative bending were significantly smaller and thus had a higher noise to signal ratio.

An example strain diagram is shown in Figure 8-24 using the negative bending event that caused the largest peak strain in either beam of any negative bending event. As opposed to the positive bending example strain diagram shown in Figure 8-3, the strain diagram is drawn on the compressive side during negative bending events, indicated by the negative strain values. Also note that although this was the largest negative bending event of the twelve, it caused less
than a three microstrain reading in the bottom flange, which was actually the limit used to remove small, and considered more noise influenced, samples from the Live Load Event Database.

![Strain v Depth (Event 5:236 Beam D)](image)

Figure 8-24: Example Strain Diagram Derived from a Negative Bending Event

Table 8-5 shows the averages, standard deviations, and ranges of the calculated neutral axis locations. Although more negative bending events should be collected, initial results are similar to those for positive bending events; the neutral axis location is slightly higher than the position calculated using transformed section properties when using all sets of gauges on Beam D except the pair of middle and bottom gauges, which were significantly higher. The results from the north face of Beam E indicate possible damage or sensor malfunction, and the results from the quarter bridge gauges are again more varied, which is demonstrated by the large amount of outliers that needed to be excluded from the sample.
Table 8-5: Neutral Axis Location Results From Negative Bending

<table>
<thead>
<tr>
<th>Set</th>
<th>Average</th>
<th>Standard Deviation</th>
<th>Outliers</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam D: North Face</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top &amp; Bottom</td>
<td>32.20</td>
<td>0.5644</td>
<td>0</td>
<td>31.20 – 33.29</td>
</tr>
<tr>
<td>Top &amp; Middle</td>
<td>32.77</td>
<td>0.5028</td>
<td>0</td>
<td>31.60 – 33.62</td>
</tr>
<tr>
<td>Bottom &amp; Middle</td>
<td>42.25</td>
<td>3.658</td>
<td>4</td>
<td>33.77 – 43.37</td>
</tr>
<tr>
<td>Linear Regression</td>
<td>33.17</td>
<td>0.6175</td>
<td>0</td>
<td>31.76 – 34.19</td>
</tr>
<tr>
<td><strong>Beam D: South Face</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top &amp; Bottom</td>
<td>33.43</td>
<td>0.6112</td>
<td>0</td>
<td>32.31 – 34.53</td>
</tr>
<tr>
<td>Top &amp; Middle</td>
<td>33.56</td>
<td>0.6488</td>
<td>0</td>
<td>32.30 – 34.68</td>
</tr>
<tr>
<td>Bottom &amp; Middle</td>
<td>37.16</td>
<td>3.611</td>
<td>1</td>
<td>31.63 – 42.57</td>
</tr>
<tr>
<td>Linear Regression</td>
<td>33.73</td>
<td>0.9029</td>
<td>0</td>
<td>32.29 – 35.51</td>
</tr>
<tr>
<td><strong>Beam E: North Face</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top &amp; Bottom</td>
<td>36.24</td>
<td>0.6391</td>
<td>0</td>
<td>35.43 – 37.32</td>
</tr>
<tr>
<td>Top &amp; Middle</td>
<td>36.47</td>
<td>0.8341</td>
<td>0</td>
<td>35.45 – 37.84</td>
</tr>
<tr>
<td>Bottom &amp; Middle</td>
<td>30.93</td>
<td>1.709</td>
<td>0</td>
<td>28.19 – 34.29</td>
</tr>
<tr>
<td>Linear Regression</td>
<td>35.00</td>
<td>0.6899</td>
<td>0</td>
<td>33.65 – 36.02</td>
</tr>
<tr>
<td><strong>Beam E: South Face</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top &amp; Bottom</td>
<td>40.70</td>
<td>3.583</td>
<td>8</td>
<td>35.75 – 43.41</td>
</tr>
<tr>
<td>Top &amp; Middle</td>
<td>25.66</td>
<td>7.871</td>
<td>6</td>
<td>7.871 – 39.52</td>
</tr>
<tr>
<td>Bottom &amp; Middle</td>
<td>27.14</td>
<td>7.23</td>
<td>6</td>
<td>17.53 – 37.32</td>
</tr>
<tr>
<td>Linear Regression</td>
<td>29.56</td>
<td>12.41</td>
<td>2</td>
<td>2.816 – 42.74</td>
</tr>
</tbody>
</table>

As stated, the pool of samples is too small to draw conclusions from but the process shows that positions can be derived from negative bending events. This could have implications for future research at the bridge. Although it will take much longer to produce a sample of reasonable size, as only large trucks and school buses may produce satisfactory readings, the results may produce more information from the SHM system using already in place sensors.

8.4 Evaluation of Neutral Axis Results

In general, it can be seen that the readings from the top flange and middle of the web strain gauge pairs, or the top and bottom flange pairs, produced much more consistent results than that of the middle and bottom. The results may be particularly unexpected in Beam D because, as shown in chapter 8, the middle gauges are likely not functioning as intended. Recall that the collected data from the middle of the web strain gauge were consistently over expected...
values in Beam D. These erroneous values reduce the confidence in the neutral axis location calculated using any pair of strain gauges that include a full bridge strain gauge on the web.

The results from Beam E highlight an interesting concept. If a gauge is placed close to the neutral axis, then the small readings will cause the strain diagram to always pass close to the neutral axis, as shown in Figure 8-25. The dashed lines in the figure represent strain diagrams produced by erroneous values in a strain gauge located at $y_i$. The wide range of erroneous values produces a small shift in neutral axis locations. This could pose a problem for SHM systems with strain gauges installed on or near the neutral axis. In this case, if the strain gauge were to malfunction and no longer collect meaningful values, the calibration routine would zero the strain gauge. This would produce an expected zero value and if movement of the neutral axis actually had occurred for any reason, for example damage, it would go undetected.

![Figure 8-25: Illustration of Gauge Error on Neutral Axis Location When Strain Gauge is Located Near NA](image)

At this time, this issue is not believed to be occurring in the installation of Beam D, however, it could be occurring in the installation of Beam E. Table 8-6 shows results from an analysis of the ratios from top to bottom strain gauge readings in a pair. Because plane sections are assumed to remain plane, the ratio of top to bottom strain gauge readings should be
consistent. These ratios are from the samples used to derive neutral axis locations using the top
and bottom strain gauge readings on each face, therefore, in case of the south face of Beam E,
30 outliers have been excluded from the 101 event sample.

Table 8-6 shows that the north face of Beam E has a ratio of top to bottom strains that is
closest to zero of any beam face because the strain gauge on the top flange produces readings
typically were close to zero. The ratio also has a higher standard deviation than both of the full
bridge strain gauge pairs on Beam D, which could indicate that behavior of the strain gauge on
the top flange of Beam E, event to event, is not consistent. The standard deviation from values
on the north face of Beam E is also higher than the two other beam faces instrumented with full
bridge gauges, which could support that the top gauge is behaving less consistently than other
full bridge gauges. The south face of Beam E contains the largest standard deviation which is
likely caused by the quarter bridge gauges, however, it could be an indicator that the behavior
of the top flange on Beam E is simply more varied than in Beam D.

<table>
<thead>
<tr>
<th>Beam / Face</th>
<th>Average</th>
<th>Standard Deviation</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>D / North</td>
<td>-0.1164</td>
<td>0.0202</td>
<td>-0.1636 to -0.0704</td>
</tr>
<tr>
<td>D / South</td>
<td>-0.0674</td>
<td>0.0137</td>
<td>-0.1064 to -0.0321</td>
</tr>
<tr>
<td>E / North</td>
<td>0.0173</td>
<td>0.0302</td>
<td>-0.0445 to 0.0937</td>
</tr>
<tr>
<td>E / South</td>
<td>-0.192</td>
<td>0.3802</td>
<td>-2.203 to 0.1967</td>
</tr>
</tbody>
</table>

Another result that highlights the top strain gauge on the north face of Beam E may not
be functioning correctly is the calculated neutral axis location. Table 8-7 shows that the average
calculated neutral axis location was higher on that beam face than any other beam face in all
instances where a top strain gauge was utilized. The position, on average, is too close to the
location of the top gauge, which is at 35.3”, to be ignored and should be further investigated.
Table 8-7: Average Neutral Axis Locations from Pairs Utilizing Gauge on the Top Flange

<table>
<thead>
<tr>
<th>Gauge Pairs</th>
<th>Beam D: North Face</th>
<th>Beam D: South Face</th>
<th>Beam E: North Face</th>
<th>Beam E: South Face</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top &amp; Middle</td>
<td>32.30&quot;</td>
<td>33.25&quot;</td>
<td>35.99&quot;</td>
<td>32.54&quot;</td>
</tr>
<tr>
<td>Top &amp; Bottom</td>
<td>31.77&quot;</td>
<td>33.17&quot;</td>
<td>35.94&quot;</td>
<td>31.81&quot;</td>
</tr>
</tbody>
</table>

Examining the neutral axis locations derived from only full bridge strain gauges shows a higher location in Beam E as opposed to Beam D. This is either caused by the two sections truly having different neutral axis that differ by that large of an amount, or the top strain gauge of the set on the north face of Beam E is malfunctioning. Different neutral axis locations from beam to beam are not expected as hand calculations showed they both had the same location. Therefore, the difference could be the result of damage. Ongoing research at the bridge may locate damage, and a maintenance project involving partial and full depth replacements at the bridge may also confirm damage to the composite section, but the sensor should still be investigated for malfunction so that it may be replaced in a timely manner so that deriving neutral axis locations using full bridge gauges on Beam E can resume. In the event that damage has moved the neutral axis location to the position of the gauge, and the gauge is still functioning during the repairs, it should be able to detect the movement back to a normal position. No movement would certainly support the idea that the gauge needs immediate replacement.

8.5 Baseline Neutral Axis

It is important to produce a neutral axis location for each beam so the results of this research can serve as a data point in any pool of samples used to track neutral axis position over time. These locations will serve as a baseline neutral axis. The values are expected to change as a result of maintenance and aging. Because the results of sections 7.4 and 8.4 indicated the full bridge gauges on the web of each beam and the full bridge gauge on the top flange of Beam E
may not be producing reliable readings, results from sets using those gauges have been omitted from consideration.

Figure 8-26 labels the gauges used for determining baselines. The omitted gauges leave the only sets of the top and bottom gauges on both faces of Beam D and all sets on the south face of Beam E. The baseline neutral axis location for Beam D is therefore derived from a sample size of 202 events measured by the pair of top and bottom gauges on each side. The baseline neutral axis for Beam E is determined by using the results from the linear regression of all three readings because combining results from the individual pairs would involve counting some individual readings multiple times, and the set of three readings contains the most amount of data of any option. Furthermore, a single outlier that fell below 12” from the location of the neutral axis determined by structural mechanics, 31.7”, was omitted to balance the effect of omitting outliers that were over 12” above the location, a concept that was discussed in detail in section 8.2.5. This resulted in a sample size of 81.

The baselines consist of 95% confidence intervals. Table 8-8 shows the intervals for both beams.
Table 8-8: Baseline Neutral Axis Locations (95% CI)

<table>
<thead>
<tr>
<th>Beam</th>
<th>Number or Samples</th>
<th>Neutral Axis Location (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>101</td>
<td>32.35 – 32.59</td>
</tr>
<tr>
<td>E</td>
<td>83</td>
<td>30.49 – 33.08</td>
</tr>
</tbody>
</table>

The locations are shown graphically in Figure 8-27 and Figure 8-28. In Beam D, the results are slightly higher than the location calculated using structural mechanics. The higher location could be caused by a deck that has a higher compressive strength than the assumed 3500 psi or could be the result of section loss in the steel over time resulting in a lower area of steel than was used in the hand calculations as no section loss was assumed. In Beam E the range of values is centered on the hand calculated value. This could be the result of uniform capacity loss in the section over time or a section that is not damaged at all.

Beam D

![Figure 8-27: Baseline Neutral Axis Location in Beam D versus Transformed Section](image)
The baseline results do not imply significant damage in either section. Although the quarter bridge gauges produced more varied results, as indicated by higher standard deviations and greater amount of outliers over the full bridge gauges throughout the analysis, the results are still satisfactory enough to draw conclusions from. Neutral axis heights determined at other locations in the bridge where no shear stud exist to connect the deck and the steel beams, such as in negative bending regions or the two outside spans, should contain lower results that can be used to verify this methodology. Comparisons should be made with neutral axis heights at those positions to verify that this method is capable of detecting non-composite or partially composite action. Those comparisons would support the notion that this method can detect damage to the shear studs, which is typically hidden from bridge inspectors.
Chapter 9: Conclusions and Future Work

The primary focus of this research was to describe instrumentation planning, including sensor selection, location and data acquisition system design, and development and demonstration of metrics for long term structural health monitoring based on the readings from the instrumentation system. Demonstrating successful data collection and using the collected data to produce a meaningful health parameter is significantly valuable in an emerging industry that seeks to use sensors in all new environmental conditions and on structures with unique construction and unknown behavior. Through placing bonded foil strain gauges on the Bagdad Road Bridge and calculating neutral axis locations, a sensor system that can be used in future SHM research conducted by the University of New Hampshire was evaluated for both strengths and weaknesses. The method of locating neutral axis locations demonstrates the SHM process and proves it is capable of delivering a metric that could be valuable to bridge engineers as a way to quantitatively evaluate a bridge.

Bonded foil strain gauges have been widely used by mechanical engineers for decades to produce reliable results in laboratory conditions. These sensors are also known to have a high sensitivity to temperature fluctuations that are unavoidable in civil infrastructure, especially bridges. Other strain monitoring technologies are available and may be technically better suited to capture dependable strain readings in field conditions. However, the availability and low cost of bonded foil strain gauges cannot be ignored when considering sensor selection and SHM metrics using strain values. Managing the use of these sensors offers a means to supply an abundance of data to advance the development of SHM metrics at a low cost and relatively easy implementation so that research can move forward with hopes of saving valuable tax dollars and creating a safer infrastructure inventory.
A significant portion of this research was used to evaluate one particular bonded foil strain gauge configuration. The strain gauge, a full bridge strain gauge that utilizes two resistors mounted in the direction to measure strain from principle stress and two resistors mounted in the direction to measure strain from Poisson's effect, was manufactured by Omega. However, the configuration is common and other gauges that function by combining strain values in the same directions, or other directions, are typical in the industry. The strain gauge selected for this research has the benefit of reduced noise and compensation for thermal expansion and contraction of the steel they are bonded to. Paired with these benefits however is a more constrained sensor placement as this research suggests they should not be used on the web of the beams. Additional laboratory and field testing using the quarter bridge strain gauges installed on Beam E is warranted.

Neutral axis locations are one of many parameters that can be read by sensors and used by engineers to potentially evaluate bridge health. Assuming the location is correct, values derived from short-term monitoring are immediately useful as they can identify levels of composite action or could be considered in determining if a section is compact, because the depth of web in compression can be readily derived. Values tracked during long term monitoring can be used to identify sudden changes indicating abrupt damage or behavior changes over time indicating degradation. Using bonded foil strain gauges, the locations of the neutral axis in two composite sections were found with a relatively high level of confidence in a short period of time.

Specific conclusions regarding the equipment used in this research are presented in section 9.1. Conclusions regarding SHM metric designs are given in 9.2.1. Potential future research that further expands on the use of the Bagdad Road Bridge using new and existing
sensors is presented in terms of method and process in section 9.3. Implications for Gilford are discussed in section 9.4, and lastly, this research thesis ends with closing remarks provided in section 9.5.

9.1 SHM Equipment Selection

The equipment and sensor selection was based on the needs for the Gilford SHM system and influenced by the lessons the UNH SHM research team had learned and was continuing to learn from the Powder Mill Bridge in Barre, MA SHM network. State of the art SHM sensor networks can be made up of a wide array of devices for monitoring structural phenomenon. In many cases, the goal of the monitoring system is to provide data that can verify a structural finite element model or access structural behavior, to evaluate the condition of the system. In the case of Gilford, sensors might be used to provide real-time information relating to the ABC procedures on the deck panel placement and the impact on the existing steel beams.

The design of the Gilford SHM system was inspired by the system at the Vernon Ave Bridge. The sensor network on the bridge contains quarter bridge strain gauges, thermistors, tilt-meters, and accelerometers (Lefebvre, 2010). The most important type of measurement to capture at Gilford was strains, as those observations could potentially be used to calculate curvature and extract displacement. Because construction created the potential for damaging any number of sensors and the placement of slabs could potentially create some complicated curves, the network was designed to be both broadly implemented, by installing gauge pairs at multiple locations on each beam, and redundant, by placing extra pairs at mid-span. These objectives placed a high emphasis on strain monitoring. Therefore, accelerometers and tilt-meters were removed from considerations to focus resources, both time and money, on developing a strain-based SHM system that used bonded foil strain gauges.
9.1.1 Bonded Foil Strain Gauge Selection

Bonded foil strain gauges were used for two primary reasons. Experiences from the Vernon Ave Bridge were available to guide the development of the new strain-based system, and, second since the system at Gilford needed strain monitoring at so many locations, inexpensive sensors would be required. The new system, however, would try to improve on strain monitoring with bonded foil strain gauges by scrutinizing the strain gauge selection process specifically relating to environmental impacts on the sensor’s behavior. Ultimately, full bridge strain gauges were selected for Gilford and the Bagdad Road Bridge instead of the quarter bridge strain gauges used at Vernon Ave. The intentions were to use gauges that had a smaller noise to signal ratio and would be less affected by temperature effects.

The full bridge strain gauges turned out to be more sensitive to temperature than the quarter bridge strain gauges used in this research. One cause for higher thermal sensitivity may be that the full bridge gauges have 1000 ohms of initial resistance, and the quarter bridge gauges have 350 ohms of initial resistance, and when temperature affects the resistance as a multiplier, the larger initial resistance may produce greater variations. Regardless, this type of error may be easily manageable using manufacturer provided apparent microstrain equations coupled with temperature data from the gauge’s location, and the gauge might, in fact, be more immune to difficult to manage thermal effect.

On the other hand, full bridge gauges demonstrate the significant benefit of a more reliable measurement. The reduction of noise to signal ratio was observed in the standard deviation of instrumented specimens at rest. The standard deviation average values from quarter bridge strain gauges were 42 times higher than those for the full bridge strain gauges. This scatter was further evident by the significant amount of outliers that required exclusions.
from data sets in addition to the higher standard deviations. Although the use of quarter bridge gauges did not significantly impact the ability to detect a neutral axis location in Beam E, the sensors posed serious limitations when trying to use the lower measurements, such as in the analysis that involved negative bending occurrences. Even in the normal range of measurements from positive bending events, the higher noise to signal ratio results in a significant amount of features derived from quarter bridge gauge readings that are simply unusable. Using full bridge strain gauges, comes at a premium, about $370 per channel and gauge compared to $231 per channel and gauge. A more specific cost benefit analysis is difficult to produce because the value of more reliable measurements is largely intangible at this time.

Because the full bridge gauges produce more reliable measurements and remove uncertainty in the form of eliminating actual thermal expansion and electrical imbalances between the sensor and the DAQ, they are recommended for other UNH SHM research. This behavior will help focus on other causes of error. For example, in the collection performed at Bagdad Road Bridge, it could be said with relative certainty that steadily changing strain over the duration of the collection was due to temperature errors and not thermal expansion or contraction, or temperature imbalances in the Wheatstone bridge.

9.1.2 Data Acquisition Equipment Selection

The process of selecting data acquisition equipment was fairly straightforward because of the experience working with DAQ equipment at UNH, however, more time testing and researching the nuances of the hardware may have produced valuable considerations that could have affected decisions. Parameters like the high resolution data collection speed limits and the inability to read 3-lead quarter bridge gauges by the unmodified cards were not realized until after the equipment was already purchased. By purchasing fewer low-speed NI-9219 modules
and a few high-speed NI-9237, the system would have been more flexible in terms of the types of data it could collect, including, for example, strains due to dynamic effects. However, incentives for purchasing equipment in bulk, where a 25% discount was offered for purchasing more than 10 NI-9219 modules, would have likely resulted in a similar selection. Given the perceived time constraints, satisfactory equipment that is appropriate for its intended use was purchased, with no hardware limitations impacting the objectives of this investigation or the objectives at Gilford. The equipment should be useful for SHM projects by UNH for years to come.

Data acquisition equipment chosen for the research was selected because the system would be easily expandable and adaptable, the manufacturer, National Instruments® has a good reputation with researchers at UNH and in the industry of SHM and instrumentation, and the controlling software is well developed and fully licensed for educational use by UNH. NI® representatives from the company were helpful with technical support. Hardware made by NI® is used in many of the labs at UNH, including c-series modules that are compatible with the chassis purchased for this research. The controlling software, also made by NI®, has enormous capabilities and the few programs written as part of this research barely scratched the surface of what it can do. There is significant potential for how robust future SHM projects can be when utilizing this equipment.

As of the conclusions for this research, nothing specific would suggest that the data acquisition cards or chassis are inappropriate for the strain monitoring goals at Bagdad Road or in Gilford. Because those hardware components would be the same at both locations, if the Gilford ABC project does proceed, no modifications to the data acquisition system are recommended.
9.2 SHM Metric Design

Metrics that relate to structural design codes are essential to promoting structural health monitoring in areas where it has struggled to gain wide-spread acceptance in the field of bridge design and construction. Design codes provide universal language to bridge engineers and managers that structural modeling may not. Design codes have well developed and known histories. Although many aspects of modeling are universal and consistent, such as element types and boundary conditions, many other aspects are not, such as meshing or best software package. Furthermore many workforces simply may not use structural modeling in design evaluation. By using metrics that relate to structural codes, researchers developing SHM can communicate with any engineer that uses the design codes.

Neutral axis locations were chosen for the SHM metric in this research. By using similar technologies and considerations, like gauge placement, other metrics could be developed that relate to structural codes, such as distribution factors. These measurements communicate instantly and without the need of a model, information about the behavior of a bridge to most engineers familiar with bridges. Additionally these measurements can be used directly in the rating of bridges using the standard Manual for Bridge Evaluation (AASHTO, 2011) considering the parameter for the depth of web in compression when determining section compactness, for example.

9.2.1 Neutral Axis Calculations

Neutral axis locations and movements may be a direct indicator of structural health. Theoretically, the position should be able to indicate determine levels of composite action, strength of the concrete, section loss in the steel, even poor connectivity to the cover plate. Sudden movement can be an instant indicator of damage to any of those components. The
location was detected in this research with a high level of confidence. The locations of between 32.35" and 32.59" from the bottom of the steel in Beam D and 30.49" to 33.08" in Beam E indicated little damage, if any. The expected value if shear studs were completely damaged, for example, is calculated to be at 16.2" as opposed to an undamaged section of 31.7". More research regarding this metric should be conducted following the recommendations in the future work section of this conclusion.

9.2.2 Gauge Placement

Placing a strain gauge on the top flange, which is close to the neutral axis in many bridges, has both risks and benefits. Neglecting the fact that the location is required for correct use of the full bridge strain gauge analyzed as part of this research, the location alone poses unique geometry properties that could both enhance damage detection or render it inoperable when used as a pair of strain gauges for the measurement.

The benefit of having a strain gauge close to the neutral axis is that if the deck were suffer a severe reduction in capacity or the shear connecters became compromised, the strain gauge would be placed in an opportune location to detect the downward shift expected by that type of damage. The risk, on the other hand, with having a strain gauge close to the neutral axis is that it if used in pairs, it can mask malfunction of either strain gauge, even completely hide neutral axis detection, and render the damage detection system useless.

These issues may be of concern in any case instance only pairs of gauges are used because a gauge malfunctioning and reading close to any single value could be inadvertently calibrated to read zero thus masking true the location of the neutral axis and moving it to an apparent location, at the malfunctioning gauge. However, in continuous monitoring systems
this sudden malfunction should be detected as a sudden movement and likely investigated soon after.

As for gauge placement on the web of beams, it may provide more range for locations away from the neutral axis, but as shown in this research, sometimes the neutral axis is located within the web. In an attempt to put more distance between the gauges, researchers may be likely to instrument the top of the web and therefore gauge a location just as likely to contain the neutral axis as the flange. In any case, if the web is to be instrumented in future projects, different gauges should be evaluated prior to installation, as implications of this research show that strain effects local to the web are likely interfering with the combination of strain effects in the full bridge strain gauges.

9.3 Future work

The work that was performed as part of this research lays the foundation for several potential future investigations. Only a fraction of the purchased equipment has been deployed, and even with the significant amount reserved for the Gilford ABC project, several modules that can collect temperature and strain were designed to be used for initiatives in the structural laboratory at UNH or, in this case, at the Bagdad Road Bridge.

9.3.1 Gauge Behavior Analysis

Laboratory and field experiments to further evaluate the behavior of the strain gauges are recommended. The research described in this work involving quarter bridge strain gauges should be conducted on other beams, particularly on the web. While initial results of analysis with the quarter bridge gauges indicated that the full bridge strain gauges will work correctly on the beam flanges, only one beam flange was tested with quarter bridge gauges. There is still a chance that this may not be true on other beam flanges. By instrumenting other beam flanges
with quarter bridge gauges, more confidence can be gained with the use of the full bridge gauges.

As for the instrumentation of the web, apparent Poisson's ratio results were inconclusive when analyzing readings from the pair of quarter bridge gauges on the web of Beam E. Although the gauge measuring strains in the longitudinal direction is expected to be functioning correctly, the results of this research imply the gauge measuring strain in the transverse direction may not be. Data from the load test, and more field data if needed, should be used to conclude if the sensor is, in fact, malfunctioning. If so, it should be replaced. Instrumenting other beam webs can help provide more understanding of how beam webs function during bridge loading, perhaps showing the hypothesis that beam webs bend in various deflected shapes depending on the position of the vehicle. Any gauges that are believed to be malfunctioning, such as the gauge on the top flange of the north face of Beam E, should also be identified and evaluated for replacement during this time.

The analysis of gauge behavior conducted in this research was carried out with two-lead quarter bridge gauges. However, using the work-around produced by NI® engineers, three lead gauges could be used to draw comparisons with the existing two lead gauges. Furthermore full bridge gauges that do not function by combining strains from multiple directions may be used to measure strains in a single direction and to carry out this analysis. This would allow research to take advantage of the lower noise to signal ratios produced by full bridge gauges. Other types of strain gauges compatible with the data acquisition equipment, such as weldable gauges, could also be evaluated. Although measuring strains using uniaxial gauges should be the priority of future work in this area, the work involved with installing additional sensors should not be overlooked as a chance to investigate other technologies. Hopefully, this type of valuable
research that contributes greatly to the SHM community by identifying reliable devices can continue at the bridge for many years.

9.3.2 Neutral Axis Calculations

Current research supports that the deck and shear connectors are intact and acting as expected. Other locations on the Bagdad Road Bridge offer means to test whether the sensors and neutral axis calculations can truly detect situations where the deck does not contribute to the bending stiffness of the section. The negative bending regions of spans 2 and 3 as well as the entirety of spans 1 and 4 contain no shear connectors. Although friction may prevent some slippage, the absence of shear connectors is expected to produce behavior that is dominated by non-composite behavior. The heights between neutral axis locations found in this research compared to values expected from non-composite behavior are over a foot and a half apart, providing a wide range that should be easy to detect regardless if friction causes some minor non-composite action. If the deck can slide in relation to the beam, the neutral axis calculations in these locations are expected to be at 16.2 inches from the bottom of the steel.

Neutral axis locations should be found in the center of span 4. The wiring for currently installed sensors are accessible at the eastern abutment of span 4 making it possible to read instruments from both span at that location without the need to run wiring over traffic. Calculated neutral axis locations from a suitable sample size of large load traffic events should be used to develop a comparison that supports using this technology to access the level of composite action. Lastly, more advanced methods of programming should be investigated to automate the neutral axis location calculations. Graduate student Sam White intends to carry out these initiatives by prioritizing further instrumentation in span 4 and collecting a reasonable database and then analyzing the data was programs he is currently writing.
9.3.3 Temperature Effects

Temperature compensation in the bonded foil strain gauge should be evaluated for the possibility of completely removing temperature induced errors, which would remove the manual compensation process. Temperature affects the gauge factor, produces an erroneous apparent strain, imbalances the Wheatstone bridge for quarter bridge gauges, and induces error by affecting electrical resistances in wiring and data acquisition equipment. The apparent microstrain is expected to be the most significant error.

Temperature effects in this research were compensated for by removing the average unloaded condition strain values from each measurement made over each minute. This was a time consuming process that was described in detail in chapter 7 and would not be practical for long-term continuous monitoring. However, formulas, pointed out in chapter 4 that exist for both the full and quarter bridge gauges, supposedly can determine the apparent strain measured by gauges that have undergone a temperature change during a collection.

Thermocouples were installed as part of this research and were confirmed to be working, however, data has yet to be collected and analyzed from them. By pairing temperature values with strain values and the equations of chapter 3, apparent strain may be eliminated. If apparent strain is significant enough, this would properly bring strain values to zero when the bridge is unloaded. If the formulas and apparent microstrain management does not reduce the signals to zero, then programming may offer a solution to mainstream the post-processing approach used in this research.

It is recommended that this research begin with using a flat bar similar to the one described in section 7.1 because the flat bars have easy to determine properties. Long leads and temperature effects on equipment and the environmental protection that cover the gauges
could complicate the analysis out at the Bagdad Road Bridge. This means removing the apparent strain at the bridge may not bring values to zero. This could mask results that imply apparent microstrain has not been properly removed using the formulas. By proving the method works on the flat bar first, non-zero values at the bridge collected while implementing the formula will suggest other effects are significant.

9.3.4 Strain-based Deflection Calculations

If temperature effects can be correctly addressed, methods of correlating strain to deflection should be evaluated. Deflections at the Bagdad Road Bridge are being measured using Digital Image Correlation (DIC) by Adam Goudreau. Other full bridge gauges than those used in this research that are not meant to remove thermal expansion and contraction should be researched so that temperature induced curvature can also be taken into effect. The gauge research and selection may be conducted by Sam White because of the experience working with strain data and sensors developed from the load test.

For a strain-based system to be useful in construction processes, one of the goals for the system in Gilford, real time measurements will be required with little, if any, post processing. Using LabVIEW, a program that outputs curvatures and deflections from corrected strain values and displays them in real time may be written by Sam White. The program should then be verified at the Bagdad Road Bridge, where sensor installation and load tests will not impact traffic under the bridge and only minimally above the bridge. The verification process should be carried out using Adam Goudreau’s DIC results because it has been shown to reliably measure deflections without the need for additional instrumentation such as LVDTs.
9.4 Implications for Gilford

This research has implications for Gilford. Although the data acquisition equipment is appropriate, the gauges may not be. The strains due to the placement of the slabs could be detected, but with these gauges the curvature from temperature would have to be measured using other means such as DIC or survey. Since the temperature effects have been shown to cause significant variation in less than an hour, frequent measurements would have to be made of the temperature induced curvature, and by that frequency, DIC or survey should just be used exclusively. With any gauges, additive errors may cause the measurements to be too inaccurate to calculate the deflections with the precision needed to set leveling screws. A sensor network could still be beneficial in both construction and research goals during the project. The specific considerations are included in appendix B.

9.5 Final Remarks on Long Term Structural Health Monitoring

Widely implemented structural health monitoring seems somewhat inevitable considering the safety and cost saving potentials. Increasing demands on the nation’s infrastructure coupled with aging bridge populations will necessitate an evolution of structural assessment. Repairs will need to be made in a timely manner so that damage does not propagate, and structures will have to be built smarter so that they require less repair. Therefore, structural health monitoring systems that can detect when and how damage has occurred will be increasingly valuable. Considering the staggering amount of money and manpower required to maintain the infrastructure, even minor improvements to maintenance methodology could have significant financial benefits.

To develop the technologies faster, research should aim to communicate more of the physical instrumentation process and include more information about what happened when
things went wrong. To promote further implementation, more data, about where cost savings have benefited from instrumentation should be published. Journal and research databases are saturated with articles that simply correlate limited sensor readings with structural models. Although this type of research is important to the long term development in SHM, it does little to prove a real short-term cost benefit to installing SHM equipment. That is why this research aimed to demonstrate the use of technologies that can lead to realized cost savings in the current budgetary cycle. Should more neutral axis location research show that locations can determine hidden damage or capacity, and movement can detect sudden damage, then the value of using this equipment over costly and intermediate non-destructive evaluations may be realized.

This research was conducted to accelerate future UNH structural health monitoring projects and has demonstrated that, with the capabilities of technologies available today, information relevant to structural health can be deduced in a relatively simple manner. Descriptions of currently available hardware and how it functioned after outdoor installation were included. More investigation on the capabilities and limitations of the equipment and other SHM metrics is encouraged. By documenting the procedure and exploring sources of sensor error, as was documented here, future sensor and metric evaluations will develop faster. There is a solid chance that all bridges designed today will have electronic equipment feeding bridge managers continuous information regarding the condition of the structure. This research and further investigations using strain monitoring may lead to a safer and more cost-effective future.
References


http://www.fhwa.dot.gov/research/tfhrc/programs/infrastructure/structures/ltbp/about.cfm#overview


Appendix

A: Installation Details

This section includes details related to the installation at the Bagdad Rd Bridge. The Initial Instrumentation Plan is included in section A.1. The document described the layout of sensors that were considered a first phase of instrumentation. As was discussed in chapter 5, the installation of gauges was prioritized and many of the sensors dictated in the document were not installed. The actual instrumentation that occurred is now considered the first phase, and when a second phase is planned, these proposed installation location should be evaluated for inclusion, if they still support research goals.

The application procedure document made for the initial installation is included in section A.2. Note that the strain relieving terminal strips were not used after the second gauge was installed. More details are discussed in section 5.3. Drawings that represent the actual instrumentation, or the instrumentation conducted as phase 1, are included in section A.3. A list of equipment used during gauge application and lead wire installation is included in section A.4.

Section A.4 includes documents related to the strain gauges. This includes the sheets that were filled out after the installation which may include notes for some sensors, as well photographs of each strain gauge. Note that because the thermocouples do not include any adhesion and are held to the face of the beam using tape, checklists were not used and photos of the uncovered gauges were not taken.
A.1 Initial Installation Plan

David Gaylord
11/25/2011
Erin Bell
UNH Department of Civil Engineering

Initial Instrumentation of the Bagdad Road over US Route 4 Introduction

On Monday Nov 28th we will be installing an initial batch of strain gauges. The station will require six strain gauges and two thermocouples. Observations from the initial installation will be used to plan installation of the remaining gages, which will be performed tentatively during the following weekend.

Schedule:

<table>
<thead>
<tr>
<th>Task</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport and Set-up Scaffolding</td>
<td>8:30-10:00 am</td>
</tr>
<tr>
<td>Grinding and Prepping Surfaces</td>
<td>10:00-11:30 am</td>
</tr>
<tr>
<td>Glue Gauges in Place</td>
<td>11:30 am - 12:30 pm</td>
</tr>
<tr>
<td>Break for Lunch and Allow Time for 1-hour cure</td>
<td>12:30-1:30 pm</td>
</tr>
<tr>
<td>Solder Gauges and Apply environmental protection</td>
<td>1:30-3:00 pm</td>
</tr>
<tr>
<td>Secure Wires:</td>
<td>3:00-4:00 pm</td>
</tr>
<tr>
<td>Disassemble Scaffolding and transport back to UNH</td>
<td>4:00-5:00 pm</td>
</tr>
</tbody>
</table>

The schedule provides significant time to complete all tasks patiently and safely. If the times are far underestimated, and additional time is available to install at other stations, another station may be instrumented.

Instrumentation Layout:

The beam selected for the initial installation is the third interior beam from the southeast side of the bridge, labeled station D in the following figure. The particular location requires the most gauges out of all stations. It was chosen for the initial installation for two reasons. If significant weather conditions...
prevent additional installation for an extended period of time, this location will provide the maximum amount of data of any station. Secondly, the station provides the most amounts of observations that can be made about the procedure without having to worry about reconfiguring the scaffolding.

A single strain gauge will be installed each side of each flange 3" from the edge of the flange. Single strain gauges will be installed on each face of the web in the same section as the gauges on the flange at half the depth of the beam, 1' 5" from either flange.
Gauging Procedure

Installing strain gauges will involve grinding a minimal amount of pain from the surface of the beam. The gauges measure 0.583" x 0.437". Care will be taken to remove the smallest amount of paint as possible, by limiting excess scrapes caused by the equipment outside the footprint of the gauge. The area will be given smooth surface with fine-grit sandpaper. The gauges will be glued with a cold curing adhesive, with tape applying pressure to the surface of the gauge for 1-hr.

An intermediate strain relieving strip will be glued to the surface of the beam 1" inch away from the bottom of the gauge. The wire that will run to the data acquisition system will be soldered to the strip and the leads from the gauges will then be soldered to the strip providing connectivity. The roll of wire for each gauge will then be sealed in plastic and taped to the flange till a time has been arranged to run the wires through split wire loom back to the data acquisition system.

The gauge and strain relieving strip will be covered in paste to protect it from the environment. Then the area will be covered with aluminum tape. Later the tape will be painted to hide the entire installation. More details are available in the instructions included as an appendix to this document.
The thermocouples involve a much simpler installation and no removal of paint. They will simply be taped with the aluminum tape on the web of the north face of the beam at 4" from each flange. The wire will be secured to the flange in the same manner as the wire connected to the strain gauges.

Scaffolding

OSHA compliant scaffolding has been rented from Seacoast Scaffolding in Concord NH. Scaffolding will be erected and used in accordance with DOT safety requirements. A meeting with Steve Mandeville, Safety and Environmental Coordinator for NHDOT Materials and Research was conducted to review the safety procedures and investigate any additional procedures that may be required caused by the close proximity to the road. All scaffolding will be level and platforms will be used to keep it from settling. All workers and non-workers at the site will wear hardhats and safety vests.

Debriefing

Following the installation a debriefing meeting will be held to discuss the installation and plan the remainder of gauge installation. Using the times for each step of gauge installation as well as scaffolding assemble and disassemble a schedule will be created to install the remaining 17 strain gauges and 4 thermocouples. Although the previous observed times will be used, methods of improving the installation procedure, for both accuracy and reduced duration, will be discussed.

Evaluations

By installing gauges on this member and other members, the methods to monitor strain values at locations on a steel beam for a period of time will be evaluated. This will include gauge selection, proper placement, installation procedures, programing, environmental protection, and duration of installation.

The installation of the 6 strain gauges described in this document will be used to analyze differences between using a linear interpolation between 2 strain values to calculate a neutral axis versus using a
linear regression from 3 gauge values. This important evaluation has a severe impact on the number of
gauges and data acquisition channels that would be required for other structural health monitoring
systems. Differences in strain values from gauges at the same height (in section) on the beam will be
used to observe any potential strain value range in future installations. If this range grows over time it
could indicate failure of the gauge, adhesive, or environmental protection.

Pre-cured sealed Gauges

Adhesives used to glue the gauges to the beams should be investigated, both in regards to the effect on
measurement accuracy and lifespan of the installation. Recommended curing for typical strain gauge
adhesives involves heating a specimen to a very specific temperature with a specific applied pressure
that are not practical for instrumentation on civil structures. Pre-cured sealed gauges are manufactured
by Vishay measurements with a bonded foil gauge similar to those that are to be used at both the
Bagdad Rd and Gilford Bridge projects. Comparing values from gauges cured at the bridge to these
gauges will be used to evaluate the chosen adhesives for the SHM systems.

The gauges are pre-adhered to a 0.005" thick shim in laboratory settings. The shim is then soldered to
the surface of the beam at the location of interest. The heat given off by tools used for this type of
measurement will not cause a measurable stress concentration and no heat distortion of the metal
surface. The heat energy is measured in milli-joules is negligible compared to typical submerged arc
welding which is typically measured in kilojoules.
A.2 Strain Gauge Application Procedure

Strain Gauge Application Procedure (11/25/2012)

1. Grind and prep a surface approximately 1"x1" centered at the designated location. Stencil the mark with a permanent marker with the center of the stencil located at the designated location. Do not fill in the center of the stencil.

2. Glue the gauge at the center of the mark following the procedure for gluing strain gauges.

3. Apply a piece of electrical tape at the bottom of the gauge to shield the leads from the steel surface of the beam.

4. Glue the strain relieving strip at the opposite end of the tape. Be careful to glue the strip to the beam and not to the electrical tape.
5. Use duct tape to secure the correctly labeled wire close to the gauge. The end of the shielded portion of the wire should be about \( \frac{1}{2} \)" away from the strain relieving strip. Secure the rest of the wire.

6. After the glue has cured solder the wires and leads to the strip at the correct locations. Then apply the environmental protection to the entire surface of the installation, including the full area of the ground surface, the soldered wires, strain relieving strip, and any portions of the wire extending past the duct tape.

7. Use aluminum tape to cover the entire area.
Station  | Face  | Instruments                      
----------|-------|-----------------------------------
D         | North | 3 Full Bridge Strain Gauges & 2 Thermocouples 
D         | South | 3 Full Bridge Strain Gauges       
E         | North | 3 Full Bridge Strain Gauges       
E         | South | 6 Quarter Bridge Strain Gauges    

Bagdad Road Over US Route 4
Instrumentation Plan
A.3 Equipment Used during Gauge Instrumentation

The following tables include the items that were used during each installation. The items have been broken up into categories of surface preparation equipment, gauge adhesive and environmental protection, soldering equipment, and miscellaneous. It should be noted that an image of the stencil is not included because it was lost shortly after the installations.

Surface preparation included a Ryobi AG402 grinder for removing paint, 80 grit sand paper and emery cloth to smooth the surface, acetone and tissues to clean residuals off the surface, and latex gloves that were worn when handling the acetone and would remain on through the application and bonding of the gauge.

Table A-1: Surface Preparation Equipment Used during Installation

<table>
<thead>
<tr>
<th>4-in Angle Grinder</th>
<th>80-Grit Coarse Sandpaper</th>
<th>Emery Cloth Sandpaper</th>
<th>Container of Acetone</th>
</tr>
</thead>
<tbody>
<tr>
<td>(homedepot.com)</td>
<td>(homedepot.com)</td>
<td>(homedepot.com)</td>
<td>(homedepot.com)</td>
</tr>
</tbody>
</table>

Latex Gloves
(homedepot.com)

Box of Plain Tissues
(homedepot.com)

Sensor adhesion and weather protection items included the Loctite 496 adhesive and packing tape used to bond the gauges to the exposed steel, the Hercules “Sta Put” plumbers putty (stock number 25-101) to cover the sensor and the area affected by the removal of the
paint, electrical tape to isolate the lead wires from the conductive steel, foil tape (Nashua Tape Product 324A Cold Weather) to protect the installation from weather, and green tape to hide the installation and wires on the face of the beam.

Table A-2: Sensor Adhesion and Weather Protection Items Used during Installation

<table>
<thead>
<tr>
<th>Item</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loctite-496 Adhesive</td>
<td>grainger.com</td>
</tr>
<tr>
<td>Vinyl Electrical Tape</td>
<td>homedepot.com</td>
</tr>
<tr>
<td>Foil Tape 324A Cold Weather</td>
<td>homedepot.com</td>
</tr>
<tr>
<td>Scotch Masking Tape</td>
<td>homedepot.com</td>
</tr>
<tr>
<td>Plumbers Putty</td>
<td>homedepot.com</td>
</tr>
<tr>
<td>Green Duct Tape</td>
<td>staples.com</td>
</tr>
</tbody>
</table>

Soldering equipment and related items included a soldering iron (Radio Shack Cat No: 64-2055A), lead-free solder (Radio Shack Cat No: 64-089), and water and rags to clean the soldering iron.

Table A-3: Soldering Equipment and Related Items Used during Installation

<table>
<thead>
<tr>
<th>Item</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soldering Iron</td>
<td>radioshack.com</td>
</tr>
<tr>
<td>Led-free solder</td>
<td>radioshack.com</td>
</tr>
<tr>
<td>Bottle Water</td>
<td>staples.com</td>
</tr>
<tr>
<td>Rags</td>
<td>homedepot.com</td>
</tr>
</tbody>
</table>

Miscellaneous equipment included the digital voltmeter used to ensure the installed gauge and lead wires were connected properly, the chalk used to mark the installation location,
and the wire strippers that were used if repair needed to be made to the connection that would include cutting of the soldered portions of the lead wires and making another attempt. Lastly, the gel splice connectors were used to connect the quarter bridge gauges as described in chapter 5.

Table A-4: Miscellaneous Items Used during Installation

<table>
<thead>
<tr>
<th>Digital Voltmeter</th>
<th>Chalk</th>
<th>Wire stripper</th>
<th>Gel Splice Connector</th>
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</thead>
<tbody>
<tr>
<td>(sperryinstruments.com)</td>
<td>(staples.com)</td>
<td>(homedepot.com)</td>
<td>(tekcomponents.com)</td>
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</tbody>
</table>

A.4 Installed Gauge Records

Details about each sensor are shown in Table A-5 including information about which number lead wire the gauge is connected to as well as information included in the calibration sheets, such as gauge factor and other information used to identify the specific sensor by the manufacturer. Photographs of each strain gauge and detail sheets are also included. Note that the bottom portion of the detail sheet is not filled out because it pertains to DAQ connectivity details that may vary each time the gauges are connected or may become established if long-term or continuous monitoring is established at the bridge.
### Table A-5: Installed Strain Gauge Details

<table>
<thead>
<tr>
<th>Gauge</th>
<th>Beam</th>
<th>Face</th>
<th>Location</th>
<th>Wire#</th>
<th>GF</th>
<th>Batch</th>
<th>CHT\lot No</th>
<th>Model No.</th>
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<tr>
<td>15</td>
<td>E</td>
<td>N</td>
<td>Bottom</td>
<td>15</td>
<td>2.12</td>
<td>5206</td>
<td>147</td>
<td>SGT-4/1000-FB11</td>
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<td>16</td>
<td>E</td>
<td>N</td>
<td>Web</td>
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<td>2.12</td>
<td>5206</td>
<td>147</td>
<td>SGT-4/1000-FB11</td>
</tr>
<tr>
<td>17</td>
<td>E</td>
<td>N</td>
<td>Top</td>
<td>17</td>
<td>2.12</td>
<td>5206</td>
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<td>S</td>
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<td>161A</td>
<td>Y2501</td>
<td>KFG-3-350-C1-11L1M2R</td>
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<td>S</td>
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<td>1/2c</td>
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<td>5</td>
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### Table A-6: Installed Thermocouple Details

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<th>Face</th>
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<td>22302</td>
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<td>S</td>
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<td>PL2010/10</td>
<td>22302</td>
<td>5TC-GG-T-20-36</td>
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Figure A-1: Photograph of Full Bridge Strain Gauge Installed on the Bottom Flange of Beam D, South Face

Figure A-2: Photograph of Full Bridge Strain Gauge Installed on the Web of Beam D, South Face
Figure A-3: Photograph of Full Bridge Strain Gauge Installed on the Top Flange of Beam D, South Face

Figure A-4: Photograph of Full Bridge Strain Gauge Installed on the Bottom Flange of Beam D, North Face
Figure A-5: Photograph of Full Bridge Strain Gauge Installed on the Web of Beam D, North Face

Figure A-6: Photograph of Full Bridge Strain Gauge Installed on the Top Flange of Beam D, North Face
Figure A-7: Photograph of Full Bridge Strain Gauge Installed on the Bottom Flange of Beam E, North Face

Figure A-8: Photograph of Full Bridge Strain Gauge Installed on the Web of Beam E, North Face
Figure A-9: Photograph of Full Bridge Strain Gauge Installed on the Top Flange of Beam E, North Face

Figure A-10: Photograph of the Pair of Quarter Bridge Strain Gauges Installed on the Bottom Flange of Beam E, South Face
Figure A-11: Photograph of the Pair of Quarter Bridge Strain Gauges Installed on the Web of Beam E, South Face

Figure A-12: Photograph of the Pair of Quarter Bridge Strain Gauges Installed on the Top Flange of Beam E, South Face
Figure A-13: Photo of Taped Sensor on South Face of Beam D, Showing Thermocouples
Figure A-14: Strain Gauge Sheet for Full Bridge Strain Gauge on Bottom Flange of Beam D, South Face
Figure A-15: Strain Gauge Sheet for Full Bridge Strain Gauge on Web of Beam D, South Face
Figure A-16: Strain Gauge Sheet for Full Bridge Strain Gauge on Top Flange of Beam D, South Face
Figure A-17: Strain Gauge Sheet for Full Bridge Strain Gauge on Bottom Flange of Beam D, North Face
### Bagdad Road over US Route 4 — Strain Gauge Sheet

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**Location (to center of gauge)**

- **Face Location**: Top / Bottom (Web)
- **Distance To Edge**: 0
- **Distance To Chan.**: 10
- **Photo #**: 10
- **Photo Time**: 2:47

**Process**

1. Grind Surface
2. Smooth / Clean
3. Mark Location
4. Apply Gauge
5. Apply Terminal Pad
6. Tape Surface
7. Tape Wire
8. Solder Connections
9. Apply putty
10. Tape / Label Gauge
11. Photograph Installation
12. Document Installation

**Notes**

*No terminal pad was used*

---

**Figure A-18:** Strain Gauge Sheet for Full Bridge Strain Gauge on Web of Beam D, North Face
Bagdad Road over US Route 4 – Strain Gauge Sheet

| Gauge ID # | 11 |
| Station Letter | D |

**Location** (to center of gauge)

- Face Location: South / North
- Distance To Edge: 3" / Top / Bottom / Web
- Distance To Chan.: 10' / Black Signal
- Photo #: II / White Excitation
- Photo Time: 1:47

**Process**

1. Grind Surface
2. Smooth / Clean
3. Mark Location
4. Apply Gauge
5. Apply Terminal Pad
6. Tape Surface
7. Tape Wire
8. Solder Connections
9. Apply putty
10. Tape / Label Gauge
11. Photograph Installation
12. Document Installation

**Notes**

No terminal pad was used

**Gauge ID #**

**Location**

- Chassis #
- Mod #
- Channel #

**Notes**

Testers Initials: __________

Figure A-19: Strain Gauge Sheet for Full Bridge Strain Gauge on Top Flange of Beam D, North Face
Figure A-20: Strain Gauge Sheet for Full Bridge Strain Gauge on Bottom Flange of Beam E, North Face
Figure A-21: Strain Gauge Sheet for Full Bridge Strain Gauge on Web of Beam E, North Face
Figure A-22: Strain Gauge Sheet for Full Bridge Strain Gauge on Top Flange of Beam E, North Face
Figure A-23: Strain Gauge Sheet for the Pair of Quarter Bridge Strain Gauges Installed on the Bottom Flange of Beam E, South Face
Bagdad Road over US Route 4 - Strain Gauge Sheet

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**Location**

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<td>Top / Bottom / Web</td>
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<table>
<thead>
<tr>
<th>Distance To Edge</th>
<th>Top / Bottom / Web</th>
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**Process**

1. Grind Surface
2. Smooth / Clean
3. Mark Location
4. Apply Gauge
5. Apply Terminal Pad
6. Tape Surface
7. Tape Wire
8. Solder Connections
9. Apply putty
10. Tape / Label Gauge
11. Photograph Installation
12. Document Installation

**Notes**

- No terminal pad was used.
- Note: drawing does not match layout. Red + Black wires connected to transverse mounted gauge. Wire-Green connected to longitudinal.
- No soldering, silver type JV was used.

**Gauge ID #**

<table>
<thead>
<tr>
<th>Location</th>
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</thead>
<tbody>
<tr>
<td>Chassis #</td>
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<tr>
<td>Mod #</td>
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<td>Channel #</td>
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**Notes**

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<th>Testers Initials:</th>
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Figure A-24: Strain Gauge Sheet for the Pair of Quarter Bridge Strain Gauges Installed on the Web of Beam E, South Face

202
Figure A-25: Strain Gauge Sheet for the Pair of Quarter Bridge Strain Gauges Installed on the Top Flange of Beam E, South Face
B: Gilford SHM Design

This section includes the considerations and design for the Gilford Bridge SHM system. Strain monitoring was chosen to support long-term monitoring by locating neutral axis and for research related to sensor supported construction by providing data to calculate curvature.

B.1 General Considerations

A set of instruments under each panel was initially considered. With more gauges, better information about load distribution and curvature could be detected; however, the costs of equipment and times required for installation can quickly become unreasonable. Ultimately, locations under 3 of the 9 panels were selected. The most valuable location was at the center span of each beam. Because damage to the system was possible during the demolition of the old deck and no repairs could be made between that time and the time panels were placed, redundancy for the most valuable location was needed. By incorporating extra pairs of gauges at the center span of each beam, the total pairs of strain gauges on each beam rose to 4.

Temperature measurements would also be required for calibration of the strain measurements. By measuring temperature at the two exterior beams of the bridge and at the center beam, temperature variations across the width of the deck could be detected. Temperature gauges would also be placed in pairs at location to detect a linear variation throughout the depth of the superstructure. This evaluation led to a total of 56 strain gauges and 6 temperature gauges.

In addition to creating a need for redundancy in the sensor network, the demolition of the existing deck also placed a unique demand on connectivity. Typically, conduit used to carry wires for SHM systems are designed to hide wires and provide some basic environmental protection. At the Gilford Bridge the network would also have to provide protection from falling
debris. Schedule 40 PVC pipe was chosen as a relatively inexpensive conduit system to carry wires. Each piece of the PVC system would include a quarter inch slit for placing wires after the conduit was installed, and to provide access needed for any repairs that may be required during the lifetime of the SHM system. When the pipe was installed the slit would be angled slightly downward to prevent debris or water from falling and accumulating in the pipe as shown in Figure B-1.

![Illustrated Proposed Hard Conduit Cross Section](image)

**Figure B-1: Illustrated Proposed Hard Conduit Cross Section**

### B.2 Proposed Long-term Monitoring Network Design

This section refers to drawings that are both included at the end of this section and on the data CD. The drawings are included on the CD so that, if needed, they can be printed to their originally intended size of 11”x17”. Appendix F has more information about data and files that are on the CD.

Figure B-5 shows the plan view of the proposed sensor network with labeled sensors. The labels are formatted so that each gauge has a unique ID that captures the beam and station the gauge is on. The first number represents the station, and the letter represents the beam. The second number represents the number of the sensors that would then be locatable in a reference document. Figure B-6 and Figure B-7 are beam elevations for locating the stations when facing west or east from the center of the bridge.
Figure B-8 shows cross sections of all proposed gauge locations on interior and exterior beams. Note that the maximum number of gauges is shown only for dimensioning and that, as shown in Figure B-5, most stations have fewer gauges. In the case of exterior beams where stations 1 and 3 have fewer gauges, the proposed strain gauge locations closest to the beam web are recommended for instrumentation so that out-of-plane bending has a lower effect. In the cases of interior beams, the face of the beam being instrumented may be affected by confinement issues, which are detailed below.

The distance between the top of the bottom stringer flanges and the bottom of the connections to the diaphragms is not specified on the original plans. Therefore, several diameters of conduit are under consideration for Gilford. Smaller diameters will have a better chance of fitting under the connectors but will leave less room inside of the pipe for wires, which could make repairs to the system more difficult. Figure B-9 shows the varying proposed diameters with the number of THX-400 wires. The wires are illustrated as both distributed throughout the section of pipe and as they would rest on the bottom. The distributed graphic aims to display how much room might be available between wires, which might be of concern when trying to remove wires during maintenance.

Figure B-10 shows the conduit as it would fit under the most confined conditions that could be extrapolated from the original plans. The most confined conditions are defined by the 3” minimum between the bottom of the bottom flange and the bottom of the channel that is the diaphragm, which means the diaphragm could be close to the bottom flange. Furthermore, since the connection isn’t detailed, the rectangular plate could be as close to the bottom as the top of the fillet, which is roughly an inch for W36x194 beams. Given tolerances in
manufacturing, this could create a space confined to just 1”, which would not allow for even ¾” diameter PVC, which has an outside diameter of 1.050”.

It can be seen in Figure B-10 that the stepped elevations of beams to create the crown in the deck means that the confinement only affects one side of the beam and that any proposed size pipe could comfortably fit on the opposite beam face, with the exception of the center girder. This means that for stations 1 and 3, the side of the beam facing the inside of the bridge can be instrumented on 6 of the girders to avoid confinement. As for station 2, where redundant gauges are recommended, both beam faces should be instrumented to capture possible out of plane bending, with the exception of the exterior girder, where all gauges will be installed on the inside face to preserve aesthetics. This means that clearance issues may arise in 7 locations; at 1 diaphragm connector on the exterior faces of beams B, C, E, and F, as well as 3 diaphragm connectors on beam D.

Figure B-2 through Figure B-4 show potential solutions where confinement issues may be inevitable. They include using flexible conduit or leaving the wire bare at the location of the diaphragm connectors.

Figure B-2: Gilford Bridge – Illustration of Exposed Wired Option for Dealing with Hard Conduit Clearance Issues
Figure B-11 shows a proposed method of protecting strain gauge locations. The method would use a piece of cold formed steel bent in a Z shape to cover the location where the conduit is discontinuous and the gauge is bonded to the steel. Figure B-12 shows a version of the same method where the netting obstacle has resulted in the conduit being raised and attached to a location higher on the beam web. As shown in the figure, a hole would be required in the plate for the lead wire. Furthermore, the discontinuity in the pipe would no longer be covered, however, at a high enough location the top flange may be able to provide enough protection from construction debris.

Table B-1 and Table B-2 show the proposed designations for DAQ equipment purchased for this project. Two 8 card chassis are recommended for permanent installation at Gilford. The tables show the proposed connectivity of each channel, in each card, of each chassis in 2
scenarios. The first is prior to construction where 4 strain reading cards would be used at UNH to experiment with the equipment and prepare for construction. In this scenario, 4 of the card slots are used for varying purposes including testing the redundant gauges by switching them out with primary gauges, evaluating quarter bridge gauges and gauge effects on the web, and potential dynamic research with accelerometers. The second scenario occurs during construction where all redundant gauges must be read, which will require all 14 strain cards.

The following labels are used in the table:

- QTR: reserved for investigating quarter bridge gauges
- Web: reserved for investigating strain gauges on web
- Switch: used to test redundant gauges
- Accelerometer: used for dynamic research
- Gauge ID: previously described gauge ID (see Figure B-5), for example 1D1
- Dummy1 & Dummy2: thermocouple channels for use to be decided

B.3 Considerations for proposed Gilford SHM systems based on this research

A reduced sensor network has been proposed for Gilford. Although the system would be installed in a significantly shorter period, there would be several sacrifices. The reduction would place gauges only on the bottom of the bottom flange of the stringers, avoiding the netting obstacle and providing enough cover to negate the need for a complicated hard conduit system. Figure B-13 illustrates the gauge as installed on the bottom of the bottom flange. The system would only be capable of short term monitoring as the instrumented locations could be struck by vehicles in the future, and the location of the wires and gauges would be visible, affecting the aesthetics of the bridge. The system would not be capable of determining neutral axis location so it could not verify things like composite action.
Installing the system solely to predict curvature has not been proven and, therefore, the risk of installing it for no benefit reduces the worth of the system compared to the more complicated installation of the larger system. However, if the system is still reduced to just the bottom flange, this research suggests that either 2 gauges should be installed or the gauges should be installed at the neutral axis of weak bending because both beams D and E showed differences in measurements on the bottom flange. 2 gauges might be able to pick up an off-center placement of a leveling screw because of warping due to eccentric loading but will require the placement of 42 gauges if all the original intended locations are to be instrumented.

The long term monitoring system has several potential benefits that should be considered when deciding the fate of the sensor network that will ultimately be installed in Gilford. The system would certainly be useful after construction as it could be used to prove that the new deck installation procedure improved the overall condition of the bridge. The continuous monitoring system could be used in the following decade to show that the risk of using new construction processes did not come at the price of a structure that degrades at an accelerated rate. Lastly, the sensor network would provide valuable data about steel behavior before, during, and after maintenance. That data could be used to evaluate the location of the neutral axis in a severely deteriorated structure versus a rehabilitated structure using the same equipment in a short period of time and the stress on the steel from the placement of slabs on the old steel.
Table B-1: Proposed Equipment Configurations Prior to Gilford Construction Project

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Table B-2: Proposed Equipment Configurations during Gilford Construction Project

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</table>
Note: Exact distance to diaphragm not available in design drawings. Based on center of bearing.

Note: Cannot be determined if distances in plans to diaphragm are to center of plate, center of channel, or other significant location.

Gilford Bridge (US 3 Over NH 11-A)
Instrumentation Plan
Exterior Sections (All)

Interior Sections (All)

Temperature Gauge

Strain Gauge
1.5" Diameter
(OD = 1.9"
(ID = 1.61"
20 Wires

1.0" Diameter
(OD = 1.315"
(ID = 1.049"
12 Wires

1.0" Diameter
(OD = 1.315"
(ID = 1.049"
10 Wires (OD = 0.19"

0.75" Diameter
(OD = 1.050"
(ID = 0.824"
6 Wires (OD = 0.19"

Wiring: 4 lead, shielded (OD = 0.19"
Conduit: Electrical PVC, Schedule 40
w/ 1/4" slit cut longitudinal angled slightly downward.
Figure B-11: Gilford Bridge – Drawing of Original Proposed method of Protecting Strain Gauged Location
Figure B-13: Gilford Bridge – Drawing of Proposed Conduit Location for Short Term Monitoring at Gilford
C: Equipment Information

This appendix includes information related to the data acquisition hardware. Section C.1 includes information about the data acquisition hardware and photographs of the equipment from the manufacturer's website. Section C.2 includes the quote for the equipment. Section C.3 includes correspondence with technical support at National Instruments.

C1. Data Acquisition Hardware Information

As discussed in Chapter 3, modular equipment was purchased from National Instruments. Photos of the equipment from the manufactures (ni.com) website are presented below in Figure C-1 through Figure C-5.

NI-9178: CompactDAQ 8-Slot USB Chassis

NI-9219: 24-bit Universal Analog Input C-Series Module

NI-9111: 4-Channel, 14 S/s, 24-Bit, ±80 mV Thermocouple Input Module

NI-9213: 16-Channel, 75 S/s, 24-Bit Thermocouple Input Module

Figure C-1: Image of Modular DAQ Chassis

Figure C-2: Image of Module Used for Reading Strain Gauges

Figure C-3: Image of 4-Channel Thermocouple Module

Figure C-4: Image of 16-Channel Thermocouple Module
NI-9234: 4-Channel, ±5 V, 51.2 kS/s per Channel, 24-Bit IEPE

Figure C-5: Image of Module Used for Reading Accelerometers
C.2 Quote for Data Acquisition Equipment from National Instruments

<table>
<thead>
<tr>
<th>Quotation No. 1540543</th>
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<td>Please indicate the above quote number when ordering for faster processing.</td>
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<th>Item</th>
<th>Description</th>
<th>Quantity</th>
<th>Unit Price</th>
<th>Discount</th>
<th>Extended Price</th>
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<tr>
<td>1</td>
<td>cDAQ-9178, CompactDAQ chassis (6 slot USB)</td>
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<td>$1,099.00</td>
<td>10.00%</td>
<td>$989.10</td>
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<td></td>
<td>Standard Delivery time: 1 - 3 business days ARO.</td>
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<td>2</td>
<td>NI 9219 4-Chs-Ch Isolated, 24-bit, ±50V, 100ks/s Universal AI Module</td>
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<td>25.00%</td>
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<td>3</td>
<td>NI 9214 16-Ch Isothermal TC, 24-bit C Series Module</td>
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<td>$1,299.00</td>
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<td></td>
<td>for high accuracy thermocouple measurements (includes terminal block)</td>
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<td>NI 9211 4-Ch s8 mV, 14 S/s, 24-Bit Thermocouple Differential Analog Input Module</td>
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<td>5</td>
<td>NI 9234, 24-Bit Sigma-Delta ADCs, 51.2 kS/s Max</td>
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<td>Sample Rate, 4 Input Simultaneous, Software Selectable IEPE and ADCC Coupling, Anti-Aliasing Filters, 102 dB Dynamic Range</td>
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<td>Power Cord, AC, U.S., 120 VAC, 2.3 meters</td>
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Sub-Total: $26,137.90 20.22% $16,385.40
Shipping and Handling: $60.79
Total: $16,446.19

Currency quoted in: U.S. Dollars

To ensure the highest quality service in order processing and support after delivery, please provide end-user information with your purchase order.

Additional Information:
- Payment Terms: Net 30
- Freight Terms: NI Weight Based Shipping

Unless expressly indicated by NI herein, all sales are subject to the enclosed National Instruments terms and conditions of quotation and sale. National Instruments shall not be bound by any conflicting or additional Terms and Conditions. Standard shipping dates are based on product availability at time of quotation and are subject to change without notice. Not all products produced by National Instruments are made in the U.S.

Yours sincerely,
National Instruments
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Customer and National Instruments ("NI") agree that the purchase and sales of NI hardware and software products ("the Products") and NI hardware and software services and support (the "Services") are made under these terms and conditions, and that NI SHALL NOT BE BOUND BY CUSTOMER'S ADDITIONAL OR DIFFERENT TERMS. Customer's order and purchase of the Products and Services shall constitute acceptance of these terms and conditions.

1. TITLE. Title to the Products shall pass at NI's plant. NI retains a security interest and right of possession in the Products until Customer makes full payment.

2. TAXES. Product prices are exclusive of, and Customer shall pay, applicable sales, use, service, value added or like taxes, unless Customer has provided NI with an appropriate exemption certificate for the delivery destination acceptable to the applicable taxing authorities.

3. PRICES AND PAYMENT. All quotations shall expire thirty (30) days from date of issuance, unless otherwise set forth on the quotation or agreed in writing. Customer shall make payment in full prior to or upon delivery by cash, check, bank draft, or money order, unless NI approves Customer for credit terms. If NI approves Customer's credit application, payment shall be due no later than thirty (30) days from the date of NI's invoice. All sums not paid when due shall accrue interest daily at the lesser of a monthly rate of 1.5% or the highest rate permissible by law on the unpaid balance until paid in full. Except for Canada where payment shall be in Canadian Dollars, payments for orders accepted in the United States shall be made in U.S. Dollars. In the event of any order for several units, each unit(s) will be invoiced when shipped. Exceptions will be made for government purchase orders.

4. CANCELLATION. All orders are subject to acceptance by NI. NI's booking of an order shall constitute its acceptance of an order.

5. DELIVERY. NI shall deliver the Products to a carrier at NI's plant. Customer shall pay all applicable freight charges. On Products sold to Customers in the United States, Canada, and Mexico, NI shall prepay all freight charges and other necessary fees and shall bear the risks of carrying out custom formalities and clearances. NI will invoice the customer for applicable charges as shipping and handling fees. Orders are entered as close as possible to the date requested, but NI shall not be liable for failure to deliver Products if such Products are not available at NI's plant.

6. LIMITED WARRANTY. NI hardware Products are warranted against defects in materials and workmanship for one (1) year from the date NI ships the Products to Customer ("Delivery Date"). All software Products are licensed to Customer under the terms of the applicable National Instruments license. For a period of ninety (90) days from the Delivery Date, NI software Products (when properly installed on NI hardware Products) (a) will perform substantially in accordance with the accompanying written materials, and (b) the medium on which the software product is recorded will be free from defects in materials and workmanship under normal use and service. Any replacement of a licensed software product will be warranted for the remainder of the original warranty period or thirty (30) days, whichever is longer. Customer must obtain a Return Material Authorization number from NI before returning any Products under warranty to NI. Customer shall pay expenses for shipment of repaired or replacement Products to and from NI. After examining and testing a returned product, NI will notify the customer the product is defective. Customer shall return the product at Customer's expense, and a charge made for examination and testing.

7. CUSTOMER REMEDIES. NI's sole obligation (and Customer's sole remedy) with respect to the foregoing Limited Warranty shall be to, at its option, return the fee paid or repair/replace any defective Products, provided that NI receives written notice of such defects during the applicable warranty period. Customer may not bring an action to enforce its remedies under the foregoing Limited Warranty more than one (1) year after the accrual of such cause of action.

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11. WARNING: (1) NI PRODUCTS ARE NOT DESIGNED WITH COMPONENTS AND TESTING FOR A LEVEL OF RELIABILITY SUITABLE FOR USE IN OR IN CONNECTION WITH SURGICAL IMPLANTS OR AS CRITICAL COMPONENTS IN ANY LIFE SUPPORT SYSTEMS WHOSE FAILURE TO PERFORM CAN REASONABLY BE EXPECTED TO CAUSE SIGNIFICANT INJURY TO A HUMAN. (2) IN ANY APPLICATION, INCLUDING THE ABOVE, RELIABILITY OF THE SOFTWARE PRODUCTS CAN BE IMPAIRED BY ADVERSE FACTORS, INCLUDING BUT NOT LIMITED TO FLUCTUATIONS IN ELECTRICAL POWER SUPPLY, COMPUTER HARDWARE MALFUNCTIONS, COMPUTER OPERATING SYSTEM SOFTWARE FITNESS, FITNESS OF COMPILERS AND DEVELOPMENT SOFTWARE USED TO DEVELOP AN APPLICATION, INSTALLATION ERRORS, SOFTWARE AND HARDWARE COMPATIBILITY PROBLEMS, MALFUNCTIONS
12. **FORCE MAJEURE.** Ni shall be excused for any delay or failure to perform due to any cause beyond its reasonable control, including but not limited to acts of government, natural catastrophes, acts of Customer, interruptions of transportation or inability to obtain necessary labor or materials. Ni's estimated shipping schedule shall be extended by a period of time equal to the time lost because of any excusable delay. In the event Ni is unable to perform in whole or in part because of any excusable failure to perform, Ni may cancel orders without liability to Customer.

13. **LIMITED INDEMNITY AGAINST INFRINGEMENT.** Ni shall, at its own expense, defend any litigation resulting from sales of the Products to the extent that such litigation alleges that the Products or any part thereof infringe any United States patent, copyright, or trademark. Provided that such claim does not arise from the use of the Products in combination with equipment or devices not made by Ni or from modification of the Products, and further provided that Customer notifies Ni immediately upon its obtaining notice of such impending claim and cooperates fully with Ni in preparing a defense. If Customer provides to Ni the authority, assistance, and information Ni needs to defend or settle such claim, Ni shall pay any final award of damages in such suit and any expense Customer incurs at Ni's written request, but Ni shall not be liable for a settlement made without its prior written consent. If the Products are held to be infringing and the use thereof is enjoined, Ni shall, at its option, either (i) procure for the Customer the right to use the Products, (ii) replace the Products with others which do not constitute infringement, or (iii) remove the infringing Products and refund the payment(s) made therefor by Customer. The foregoing states the Customer's sole remedy for, and Ni's entire liability and responsibility for, infringement of any patent, trademark, or copyright relating to the Products provided hereunder.

14. **ACkNOWLEDGMENT/GOVERNING LAW.** Customer acknowledges reading these Terms and Conditions, understands them and agrees to be bound by them. A waiver of any provision of this agreement shall not be construed as a waiver or modification of any other term hereof. With respect to all orders accepted by Ni outside the United States, disputes arising in connection with these Terms and Conditions of Sale shall be governed by the laws of the State of Texas without regard to principles of conflicts of laws. With respect to all orders accepted by Ni outside the United States, disputes arising in connection with these Terms and Conditions of Sale shall be governed by the laws of the country and locality in which Ni accepts the order without regard to principles of conflicts of laws.

15. **EEO COMPLIANCE.** As applicable, Customer shall comply with the following Equal Employment Opportunity requirements: 41 CFR sec 60-1.4(a), Equal Opportunity; 41 CFR sec 60-250.5, Equal Opportunity for Special Disabled Veterans and Veterans of the Vietnam Era; and 41 CFR sec. 60-741.5, Equal Opportunity for Workers with Disabilities.

16. **SERVICES.** Limited Warranty. Ni warrants that Services will be performed in a good and workmanlike manner. Except as expressly stated in the preceding sentence, Ni makes no express or implied warranties with respect to the Services, including but not limited to (a) any warranty relating to third party products or (b) any warranty concerning the results obtained from the Services or the results of recommendation. Ni may make, including without limitation any implied warranties concerning the performance, merchantability, suitability, non-infringement or fitness for a particular purpose of any of the deliverables or of any system that may result from the implementation of any recommendation Ni may provide. In order to utilize Services, differences in the Services must be reported to Ni in writing within 90 days of completion of the Services. Limitation of Liability. Ni is not liable for any incidental, indirect, special, or consequential damages arising out of or in connection with the Services provided by Ni, including without limitation loss of use of the Products or any other software or data, including inability to utilize to perform results or any other consequence of such damages. Ni is not liable for any damages resulting from the possibility of such damages. Ni has been advised of the possibility of such damages, and Ni has accepted the risk of such damages. Ni's entire liability and responsibility for, infringement of any patent, trademark, or copyright relating to the Services provided by Ni, including without limitation loss of use of the Products or any other software or data, including inability to utilize to perform results or any other consequence of such damages. Ni is not liable for any damages resulting from the possibility of such damages. Ni has been advised of the possibility of such damages, and Ni has accepted the risk of such damages.
C.3 Correspondence with National Instruments Technical Support

David Gaylord <daviddgaylord@gmail.com> Mon, Apr 30, 2012 at 4:48 PM
To: support@ni.com

On Mon, Apr 30, 2012 at 4:46 PM, <support@ni.com> wrote:

Hi David,

This is Daniel with National Instruments. Please reply to this email with
the screenshot that you took so that we can proceed with the
troubleshooting.

Regards,
Daniel

attachment processed.xlsx
761K

support@ni.com <support@ni.com> Mon, Apr 30, 2012 at 5:37 PM
Reply-To: support@ni.com
To: David Gaylord <daviddgaylord@gmail.com>

Note: Your reference number is included in the subject field of this
message. It is important not to remove or modify this reference
number, or your message may be returned to you.

Hi David,

I am sorry but I need to leave for the day. I will get back to you tomorrow
with some more information. The good thing is that I was able to reproduce
the issue from my end so we don't need you to be in the lab (that you only
can go to on Mondays). If you call back with the service request number
1839345 I left some notes and the next engineer would be able to pick up
where we left off until I can get back to you tomorrow.

Regards,

Daniel Rojas
Applications Engineer
National Instruments
http://www.ni.com/support

support@ni.com <support@ni.com> Tue, May 1, 2012 at 2:00 PM
Reply-To: support@ni.com
To: David Gaylord <daviddgaylord@gmail.com>

Note: Your reference number is included in the subject field of this
message. It is important not to remove or modify this reference number, or your message may be returned to you.

Hi David,

I could find out the issue. The reason we are seeing those plateaus is that due to the Delta Sigma ADC type the 9219 has, it samples at a High Resolution, and therefore, low speed. If you would like to increase the sampling rate, we would need to change the ADC Timing Mode to "High Speed". Here is a KB that shows how to do that in MAX as well as in LabVIEW. I tried it on my end with the 9219 I have and it works just fine.


Regards,

Daniel Rojas
Applications Engineer
National Instruments
http://www.ni.com/support

---

David Gaylord <daviddgaylord@gmail.com> Tue, May 1, 2012 at 7:07 PM
To: support@ni.com

Thank you much Daniel. Can I ask you, what is resolution and how much of it am I giving up by using the high speed mode?

Dave

---

support@ni.com <support@ni.com> Wed, May 2, 2012 at 10:21 AM
Reply-To: support@ni.com
To: David Gaylord <daviddgaylord@gmail.com>

Note: Your reference number is included in the subject field of this message. It is important not to remove or modify this reference number, or your message may be returned to you.

Hi David,

Upon using the AI.Resolution DAQmx channel property node, I get confirmation that we have 24 resolution bits regardless of the ADC Timing Mode. The only thing that happens is that the conversion time decreases from 500 ms to 10 ms. Delta Sigma ADCs, as opposed to other ADC types, use negative feedback in order to provide better noise immunity to the signal. This is why you can play with the conversion time with these types of ADC. So you will still get the same resolution.

Regards,
Hi Daniel,

Are you saying that I will get the same quality of data regardless of mode or that I'll have the same resolution but more noise if I switch to high speed mode?

Thank you much,
Dave

Hi David,

I am saying that you will have the same resolution but with more noise if you switch to high speed mode. This is because the Delta Sigma ADC has less time to do the math before it presents to you a signal that will have more noise immunity.

Regards,

Daniel Rojas
Applications Engineer
National Instruments
http://www.ni.com/support

Hi David,

Here are the two configuration types. Let me know if this is what you need!
Hey David,

So I looked up the product specs for your Vishay LEA-06-W125E-350/3R strain gauge (the gauge is made by their Micro-Measurements division). I've posted a link to the sheet that I consulted below. Anyhow, I gave them a call to get a bit more clarification as to how this particular gauge actually functions. Their office was closed for the day but I will try again tomorrow (I have phone shift here until 1 pm but will try to get in touch with them as soon as I'm off).

From what I can tell, it looks like this set-up is a Quarter Bridge Type 1. This means that technically a 9219 will not work with this 3-wire strain gauge. However, I talked to some other engineers here and we came up with a work-around that lets you essentially complete the Quarter Bridge 3-wire using the 9219 yourself. The advantage of the 9237 (that does support 3-wire for Type 1) is that it comes with a signal accessory that you plug in, basically containing a resistor to complete this bridge. You can do
this with the 9219 if you connect a 350 ohm resistor to the white wire on your strain gauge and then connect this to the EX- terminal on the 9219 (see the configuration diagram I sent in my last e-mail). The black wire goes to EX+ and the red wire is your CH+.

So -- it may be possible to use this workaround with the 9219, or you could get the 9237 which is what this type of measurement is better suited to. I'll still give Micro-Measurements a call tomorrow and see what they think.

I'll give you a call tomorrow afternoon after I talk to Micro-Measurements, and feel free to get in touch in the mean time if you have any other questions or thoughts.


Regards,

Courtney Lessard
Applications Engineer
National Instruments
C.4 Temperature Correction Curves for Strain Gauges

These correction curves are supplied by the manufacturer. The curves come with the packaging for quarter bridge gauges and must be requested using the CHT number for the full bridge gauges.

![Figure C-6: Temperature Correction Curve for Full Bridge Gauges](image_url)

![Figure C-7: Temperature Correction Curve for Quarter Bridge Gauges](image_url)

**ENGINEERING DATA SHEET**

Gage type: KG-S-350-C1-11LM2R  
Lot No.: Y2651  
Batch: 151A  
Exp. Temp. Coef.: 1.7 x 10^-5/°C

\[ \varepsilon_{app} = -0.22 \times 10^2 + 0.21 \times 10^1 \times T^1 - 0.47 \times 10^-1 \times T^2 
+ 0.83 \times 10^-3 \times T^3 + 0.82 \times 10^-6 \times T^4 \]  

(Temperature changes by stages.)

For 2 wire gauges the zero drift due to lead wire is added to above equation.

Tolerance: ±0.85 [μm/°C]
D: Information about LabVIEW Programs

This Appendix details the LabVIEW programs that were created and used as part of this research. Figures of each programs front panel and block diagrams are included as well as an outline that describes the inputs, outputs, and flow of data through the program. The section begins with a description of aspects common to all of the programs.

D.1 LabVIEW Tools Common to All Programs in this Research

LabVIEW has a wide variety of function and only a few were utilized in this research. The following pages show each program used, both the “front panel,” which the user of the program interacts with, and the “block diagram,” which resides in the background and is where the general flow of the data and calculations are configured. An outline of each program is also included. Certain features are common to all programs and are described below:

- Items in the block diagram are called “VIs” short for virtual instruments.
- The grey box around the VIs in the block diagram shows that the program is contained in a while loop. The while loop causes the program to iterate continuously. Without the while loop, the program would collect 1 strain sample when the user clicked “run” and would halt.
- The grey hatched box around the “write to measurement” VI, labeled “write” in each block diagram, is a case structure. The case structure is attached to a Boolean switch that can be operated from the front panel when the program is running. When the case structure is on, the program runs the VIs in the structure, and will halt those operations when the case structure is turned off.
- The case structure receives a value of true from the switch when it is pressed, or latched, and turns on the VI that writes the measurement file stored on the controlling computer. When the button is unlatched, clicked on again, it stops the action of the write to measurement file.
- The “write to measurement file” VI is set to include only 1 header for each iteration. Otherwise, every sample would receive a new heading. Only 1 time column is configured because all gauges are configured to read at the same times. It is also configured to store the collected data in a tabular delimited file with a .lmv extension, and to rename an existing file if the intended file storage location already has a file in it with the same name.
- The “DAQ Assistant” is the VI that collects data from the equipment and moves it to the rest of the program. Its properties are adjusted by double clicking on it. Those properties include sampling rates, sensor configurations, and calibration information.
Waveform charts are used instead of waveform graphs because the DAQ Assistant is set up to collect continuously and refresh the program after every sample. Not shown in the screen captures because they were captured when the programs were off, waveform charts display samples over a specified amount of time and therefore can display several of the samples at a time with lines between the data points. Waveform graphs, on the other hand, only display the last iteration and since the iteration is only 1 sample, no line would be drawn.

Blue wires represent data that will change after each iteration as the DAQ assistant collects and feed new data to the program. Orange wires show the flow of constants, which do not have to be updated during iterations.

Splitters divide or combine signals. Splitters can be used to show multiple strain signals collected by the 1 DAQ assistant on multiple charts or to combine signals that have been split so they appear on the same chart.

**D.2 Flat Bar Test Program**

This program collects strain data and, using inputted flat bar parameters, calculate the force of tension or compression applied to the bar. A screen capture of the front panel is located in Figure D-1 and a screen capture of the block diagram is location in Figure D-2. An outline of the program is as follows:

- The user enters information about the flat bar in the numerical entry boxes on the left hand side of the front panel. These parameters are thickness, width, and the modulus of elasticity.
- The DAQ Assistant is shown on the block diagram. It is configured to collect 2 strain signals and then a splitter is used to display the strains on two different waveform charts on the front panel.
- As shown on the block diagram, the thickness and width are multiplied to produce a cross sectional area, which is then displayed under the left corner of the left chart on the front panel.
- The modulus, area, and strain data are then multiplied together to obtain a force value, and the values are displayed in two numerical display boxes on the front panel labeled force 1 and force 2. These represent the calculated tension or compression derived from each gauge on the specimen.
- The two force values are then added together and divided by two to generate an average value that is also displayed on the front panel in a numerical display box.
- At any point, the user can click on a "collect data" button that latches the Boolean switch, and the "write to measurement file" VI stores raw strain. Note that the wire to the DAQ assistant is connected before the splitter so that it receives both strain signals.
Figure D-1: Front Panel for the Flat Bar Test Program

Figure D-2: Block Diagram for the Flat Bar Test Program
D.3 In-Field Gauge Diagnostic Program

This program was used to initially test each set of gauges on April 21st 2012. The front panel can be used to evaluate gauge behaviors and is shown in Figure D-3, and the corresponding block diagram is shown in Figure D-4. An outline of the program is as follows:

- Data is collected by the DAQ Assistant and sent to the large waveform chart, the splitter, and the write to measurement file vi enclosed in a case structure.
- A single waveform chart, which appears as the larger chart on the front panel, and the wire to the “write to measurement file” VIs are connected before the splitter and, therefore, receive data from all three gauges.
- By showing all signals on a single graph, gauge to gauge behavior could be evaluated. Significant deviations from zero when the bridge is unloaded or larger amounts of noise for example, could immediately be identified.
- The splitter receives data at the same time as the large waveform chart and divides the 3 signals and sends them to 3 waveform charts that appear smaller on the front panel. If the gauges began to significantly drift in different directions during an evaluation, the 3 charts would serve as a means to zoom in on each different signal.
- At any point, the user can click on a “collect data” button that latches the Boolean switch, and the “write to measurement file” VI stores raw strain. Note that the wire to the DAQ assistant is connected before the splitter so that it receives both strain signals.

Figure D-3: Front Panel for the In-Field Gauge Diagnostic Program
D.4 Program to Read All Gauges Currently Installed Simultaneously

This program was written to read all gauges installed as part of this research simultaneously. The front panel is shown in Figure D-5 and corresponding block diagram is shown in Figure D-6. An outline of the program is as follows:

- Data is collected by the DAQ Assistant and sent to a large splitter that divides the single stream of data that includes all sensors into multiple data streams, one for each sensor.
- Smaller splitters then combine the sensors into categories of longitudinal strains for each beam face, in section strains for the south face of Beam E, and temperature readings for the south face of Beam D.
- The data is displayed versus time, by category, in the waveform charts on the front panel. Each large waveform displays longitudinal strain values. The smaller chart on the bottom displays the in-section strains and the smaller chart on the top displays temperature values.
- At any point, the user can click on a “collect data” button that latches the Boolean switch and the “write to measurement file” VI stores raw strain. Note that the wire to the DAQ assistant is connected before the splitter so that it receives both strain signals.
Figure D-5: Front Panel for the Current Bridge Monitoring Program

Figure D-6: Block Diagram for the Current Bridge Monitoring Program
E: Miscellaneous

![Diagram of a voltage divider circuit]

E.1 Voltage Divider Proof

\[ V_s = \frac{R_2}{R_1 + R_2} \cdot V_e \]

Proof:

Voltage excitation to the circuit:

\[ V_e = I \cdot (R_1 + R_2) \]

Voltage read across resistor 2:

\[ V_s = I \cdot R_2 \]

Solving this equation for I and substituting it into equation yields:

\[ V_e = \frac{V_s \cdot (R_1 + R_2)}{R_2} \]
## E.2 Neutral Axis Hand Calculations

<table>
<thead>
<tr>
<th>Bridge Characteristics</th>
<th>Bridge Span:</th>
<th>$\text{Span} = 60\text{ft}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Beam Spacing:</td>
<td>$S_{\text{beams}} = 8\text{ft}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Girder Characteristics:</th>
<th>Thickness of the flange:</th>
<th>$t_f = 0.79\text{in}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Width of the flange</td>
<td>$b_f = 12\text{in}$</td>
</tr>
<tr>
<td></td>
<td>Depth of the beam:</td>
<td>$d = 35.6\text{in}$</td>
</tr>
<tr>
<td></td>
<td>Gross area of the beam:</td>
<td>$A_g = 39.7\text{in}^2$</td>
</tr>
<tr>
<td></td>
<td>Width of coverplate:</td>
<td>$b_{cp} = 10.5\text{in}$</td>
</tr>
<tr>
<td></td>
<td>Thickness of coverplate:</td>
<td>$t_{cp} = 0.5\text{in}$</td>
</tr>
<tr>
<td></td>
<td>Area of coverplate:</td>
<td>$A_{cp} = t_{cp} \cdot b_{cp} = 5.25\text{in}^2$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Deck Characteristics:</th>
<th>Thickness of haunch portion on sides of beams</th>
<th>$t_{\text{haunch1}} = 0.915\text{in}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Width of haunch (3&quot; on each side of flange)</td>
<td>$b_{\text{haunch1}} = 6\text{in}$</td>
</tr>
<tr>
<td></td>
<td>Thickness of haunch portion above beam</td>
<td>$t_{\text{haunch2}} = 0.125\text{in}$</td>
</tr>
<tr>
<td></td>
<td>Width of haunch portion above beam</td>
<td>$b_{\text{haunch2}} = b_f$</td>
</tr>
<tr>
<td></td>
<td>28 Day Compressive Strength of Concrete</td>
<td>$f_c = 3.5\text{ksi}$</td>
</tr>
<tr>
<td></td>
<td>Thickness of the concrete surface</td>
<td>$t_{\text{slab}} = \left( \frac{7 + \frac{5}{8}}{8} \right)\text{in}$</td>
</tr>
<tr>
<td></td>
<td>Thickness of the bituminous wearing surface</td>
<td>$t_{\text{bws}} = \left( \frac{2 + \frac{5}{8}}{8} \right)\text{in}$</td>
</tr>
</tbody>
</table>

**Effective deck width**  

$$b = \min(0.25\text{Span}, S_{\text{beams}}, 12 \cdot t_{\text{slab}}) = 91.5\text{in} \quad \text{(AASHTO LFD 17th Sec.10.38.3.1)}$$
Deck Reinforcing Layouts (project plans, bridge sheet 5 of 6)

**Top layer (number 4s, 12" on center)**

- **Cover:** cover\_top := 1.5in
- **Spacing:** \( s_{\text{top}} := 12\text{in} \)
- **Diameter (Num. 4):** \( d_4 := 0.5\text{in} \)
- **Area (Num. 4):** \( A_4 := 0.2\text{in}^2 \)

Number of bars in top layer:
\[
\text{bars}_{\text{top}} = \frac{b}{s_{\text{top}}} = 7.625
\]

Area of steel in top layer:
\[
A_{ts} := A_4 \cdot \text{bars}_{\text{top}} = 1.525\text{-in}^2
\]

**Bottom layer (number 5s, 8" on center, with 16 gap above beam)**

- **Cover:** cover\_bot := 1in
- **Spacing:** \( s_{\text{bot}} := 8\text{in} \)
- **Diameter (Num. 5):** \( d_5 := 0.625\text{in} \)
- **Area (Num. 5):** \( A_5 := 0.31\text{in}^2 \)

Number of bars in top layer:
\[
\text{bars}_{\text{bottom}} = \frac{(b - 16\text{in})}{s_{\text{top}}} = 6.292
\]

Area of steel in bottom layer:
\[
A_{bs} := A_5 \cdot \text{bars}_{\text{bottom}} = 1.95\text{-in}^2
\]
Transform section properties:

Units: $\text{ksi} = \frac{1000 \text{ lb}}{\text{in}^2}$, $\text{kfc} = \frac{1000 \text{ lb}}{\text{ft}^3}$

Modulus of steel beam: $E_B = 29000 \text{ksi}$

Correction factor for source of aggregate
Taken as 1 unless more info is provided: $K_1 = 1$

Weight of concrete:

$$\omega_{\text{concrete}} = \begin{cases} 0.15 \text{kfc} & \text{if } f_c \leq 5.0 \text{ksi} \\ \left[\left(1.145 + \frac{f_c}{\text{ksi}}\right) \text{kfc}\right] & \text{if } 5.0 \text{ksi} < f_c \leq 15 \text{ksi} \\ \text{"error" otherwise} \end{cases}$$

(AASHTO table 3.5.1-1
Note: includes 0.005 kcf load for reinforcing described in C3.5.1)

Modulus of deck

$$E_D = 33000 \text{ksi} \cdot K_1 \cdot \left(\frac{\omega_{\text{concrete}} - 0.005 \text{kfc}}{\text{kfc}}\right)^{1.5} \cdot \sqrt{\frac{f_c}{\text{ksi}}} = 3.409 \times 10^3 \cdot \text{ksi}$$

(AASHTO LRFD 5th Eq. 5.4.2.4-1. Note: weight of concrete does not include reinforcing)

Modular ratio

$$n = \frac{E_B}{E_D} = 8.507$$

(AASHTO LRFD 5th Eq. 4.6.2.2.1-2)

Area of transformed deck:
(Short term)

$$A_{dt} = \frac{b \cdot t_{\text{slab}} - A_{ts} - A_{bs}}{n} = 81.601 \cdot \text{in}^2$$

Area of transformed haunch:
On sides of beams
(Short term)

$$A_{ht1} = \frac{b_{\text{haunch1}} \cdot t_{\text{haunch1}}}{n} = 0.645 \cdot \text{in}^2$$

Area of transformed haunch:
Above beams
(Short term)

$$A_{ht2} = \frac{b_{\text{haunch2}} \cdot t_{\text{haunch2}}}{n} = 0.176 \cdot \text{in}^2$$

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Centroid of geometric components:

Datum to center of beam: \( y_b = 0.5 \cdot d + t_{cp} = 18.3\text{-in} \)

Datum to center of deck: \( y_d = t_{cp} + d + 0.5t_{slab} = 39.913\text{-in} \)

Datum to center of haunch on sides of beams: \( y_{h1} = t_{cp} + d - t_s + 0.5t_{haunch1} = 35.768\text{-in} \)

Datum to center of haunch above beams: \( y_{h2} = t_{cp} + d + 0.5t_{haunch2} = 36.163\text{-in} \)

Datum to center of coverplate: \( y_c = 0.5 \cdot t_{cp} = 0.25\text{-in} \)

Datum to top steel layer: \( y_{ts} = t_{cp} + d + t_{haunch2} + t_{slab} - \text{cover_top} - 1.5 \cdot d_s = 41.413\text{-in} \)

Datum to bottom steel layer: \( y_{bs} = t_{cp} + d + t_{haunch2} + \text{cover_bot} + d_s + 0.5 \cdot d_s = 38.1\text{-in} \)

Neutral Axis of Fully Composite Section:

\[
y_{\text{bar}} = \frac{y_{b} \cdot A_g + y_{d} \cdot A_{dt} + y_{c} \cdot A_{cp} + y_{h1} \cdot A_{ht1} + y_{h2} \cdot A_{ht2} + A_{bs} \cdot y_{bs} + A_{ts} \cdot y_{ts}}{A_{g} + A_{cp} + A_{dt} + A_{ht1} + A_{ht2} + A_{ts} + A_{bs}} = 31.729\text{-in}
\]

Neutral Axis of Steel in Non-Composite Section:

\[
y_{\text{bar2}} = \frac{y_{b} \cdot A_g + y_{c} \cdot A_{cp}}{A_{g} + A_{cp}} = 16.192\text{-in}
\]
F: Data CD Inventory

This section lists the information that will be on the data CD that is attached with this thesis. The files include data, which would be inappropriate and largely unusable in printed form. The files also include drawings, both PDFs as well as the original AutoCAD documents, so that adjustments and larger prints can be easily made. The root of the CD contains folders and each folder contains the information in the following outline:

- **Data**
  - **Raw Data:**
    - Flat Bar Test Data
    - Diagnostic Collection Data
    - Peak Traffic Data
  - **Processed Data**
    - Flat Bar Test Results
    - Processed Diagnostic Data
    - Processed Peak Traffic Data
    - Live Load Event Database
    - Negative Bending Event Database
    - Comparison Database Beam D
    - Comparison Database Beam E
    - Neutral Axis Database Beam D
    - Neutral Axis Database Beam E
- **Drawings**
  - **Bagdad Rd Bridge**
    - Intended Installation Plan
    - As-Instrumented Plan View
    - As-Instrumented Elevations of Beam
  - **Gilford Bridge**
    - Proposed Sensor Network Plan View
    - Proposed Sensor Network Elevations
    - Proposed Sensor Network Girder Cross Sections
    - Hard Conduit Diameter Options
    - Hard Conduit Options Shown on Bridge Cross Section
    - Z-cover Illustration
    - Raised Conduit Illustration
    - Proposed Conduit Location for Short Term Monitoring