Photocopy and Use Authorization

In presenting this thesis in partial fulfillment of the requirements for an advanced degree at Idaho State University, I agree that the Library shall make it freely available for inspection. I further state that permission for extensive copying of my thesis for scholarly purposes may be granted by the Dean of the Graduate School, Dean of my academic division, or by the University Librarian. It is understood that any copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Signature ___________________________________

Date _______________________________________

Field Performance of HES Class 50AF Concrete with Fibers as Field-Cast Connection between Deck Bulb-T Girders in Accelerated Bridge Construction Applications

by

Chris Clauson

A thesis

submitted in partial fulfillment

of the requirements for the degree of

Master of Science in the Department of Civil and Environmental Engineering

Idaho State University

Summer 2019

To the Graduate Faculty:

The members of the committee appointed to examine the thesis of Chris Clauson find it satisfactory and recommend that it be accepted.

____

Dr. Arya Ebrahimpour,

Major Advisor

____

Dr. Mustafa Mashal,

Committee Member

____

Dr. Marco Schoen,

Graduate Faculty Representative

Acknowledgments

I would like to thank all those who helped me throughout this project. I could not have done it without the support of my family, colleagues, and professors.

Specifically, I would like to thank my advisor, Dr. Ebrahimpour, for his guidance and help in the field. I would also like to thank Ali Shokgrozar for his help with the finite element modeling and instrumentation portion of this project. Special thanks to the many students who helped in the field during the instrumentation and load testing of the bridge. Without all of your help this project would have not been possible. I would also like to thank Michael Adams from Campbell Scientific for his help in diagnosing issues with the data collection system and Dr. Baldwin for helping diagnose electrical grounding issues at the bridge site. Finally, I would like to thank my wife, Ilse Clauson, and the rest of my family for their love, support, and patience during this project.

This project would not have been possible without the financial support of Idaho Transportation Department and Federal Highway Administration.

Table of Contents

List of Figures

List of Tables

Field Performance of HES Class 50AF Concrete with Fibers as Field-Cast Connection between Deck Bulb-T Girders in Accelerated Bridge Construction Applications

Thesis Abstract – Idaho State University (2019)

The Idaho Transportation Department (ITD) is proposing to place high-early strength (HES) concrete with polypropylene fibers in 25-cm (10-in.) closure pours between girders. A previous research project was carried out to determine the effectiveness of the HES material and the connection detail by testing small and larger specimens with headed bars. Among the six closure pour concrete mixes considered, one was selected that had the largest compressive and tensile strength values and the lowest shrinkage value. An ITD-specified mix has been implemented in construction of a new bridge near Preston, Idaho. In this project, the bridge was instrumented with 94 sensors to monitor the performance of the HES concrete under known truck loading and commercial trucks. A finite element model was also refined to replicate strain data observed during load testing.

Key Words: Bridge, Closure Pour, High-Early Strength, Concrete, Strain, Instrumentation, Finite Element, Bridge Loading

Chapter 1 Introduction

1.1 Background and Motivation

According to the Federal Highway Administration, approximately 47,000 of the 616,000 (7.6 percent) bridges in the United States are in poor condition and only 28% of bridges in Idaho are in good condition ("U.S. Department of Transportation: Federal Highway Administration" 2019). The need for reconstruction of old bridges and construction of new bridges comes at a large cost. For this reason, it is important to research alternatives to cut costs without reducing the performance or lifetime of these bridges.

Accelerated Bridge Construction (ABC) is one method being used to improve costly and time-consuming bridge construction and improve safety for the traveling public. Using precast bridge components is one technique used to reduce construction time. This reduces the amount of concrete that needs to be transported, placed, and cured at the bridge site. ABC can also reduce the amount of time a bridge needs to be closed or have limited traffic over it for construction so the impact on traffic is minimized.

When using the ABC method of constructing a bridge it is important to provide adequate connections between the precast or prefabricated components. Doing so will allow for proper load distribution and better long-term performance of the bridge. For concrete girder bridges this can be done by using a closure pour connection where rebar extrudes from each girder and overlap each other in a concrete connection. Figure 1.1 shows an example of a closure pour connection.

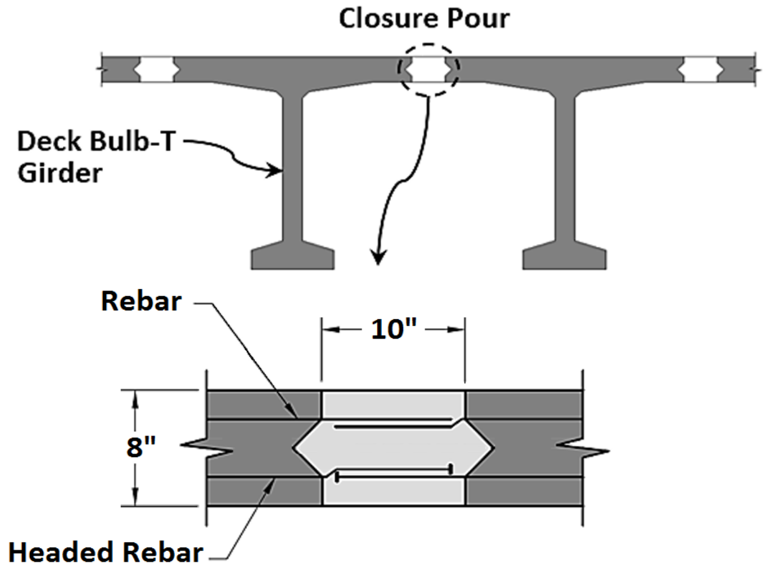


Figure 1.1 Closure Pour Connection

Prior research has been completed by Casanova, et al. (2018) on creating a new conventional concrete mix for these closure pour connections. Traditionally, Ultra High Performance Concrete (UHPC) has been used in these connections. The only downside to using this material is the installed cost is significantly greater than that of conventional concrete.

1.2 Problem Statement and Scope

UHPC has been used in closure pour connections for its material properties. The compression strength for UHPC can be more than double that of high strength conventional concrete (Casanova 2018). As previously stated, UHPC is an expensive material to use on these bridge connections due to the amount of time and labor needed for installation and quality control. UHPC usually needs to be mixed on site in smaller batches and placing the material usually consists of using wheelbarrows to transport the material to the location on the bridge where it is needed. With conventional concrete, the material can be batched at any concrete batch plant and transported to the bridge site in a mixing truck. The material can then be pumped to the desired location on the bridge. Idaho Transportation Department (ITD) bridge engineers have estimated that the cost savings of using conventional concrete rather than UHPC can be over $100,000 per bridge based on the actual bid prices from the ITD's contractors.

Casanova, et al. (2018) has done research on creating a high early strength (HES) concrete for use in these connections and had good results. Consequently, ITD has chosen to incorporate a similar mix into the closure pour connection details for a replacement bridge on State Highway 36 (SH-36) over Bear River near Preston, Idaho.

1.3 Objectives

This research focuses on the instrumentation, data collection, and finite element modeling of the SH-36 Bridge over Bear River. Specifically, the objectives of this project are to assess the performance of the HES concrete used in this connection detail and create a finite element model of the bridge to use for confirmation of experimentally obtained data from the bridge site. Another tool which was used to assess the feasibility of HES concrete in these connections was field observation. Field observation provides valuable information on what differences there are between the constructed bridge and the design plans. To complete all the objectives of the project, rebars inside the closure pour connection have been instrumented with strain gages and once the closure pour connection was finished, the concrete surface underneath the closure pour was instrumented with strain gages. The bridge was then loaded under known loads both statically and dynamically. Commercial traffic was also recorded to observe the behavior of the connection under normal daily traffic. Once the loading phase was completed, the data was summarized and a computer model was created to replicate the bridge structure. The computer model was then loaded with the same load pattern as the known static load to compare the strain observed in the instrumented closure pour areas. After the collected data is processed and analyzed, recommendations can be made on the feasibility of HES conventional concrete used in closure pour connections.

1.4 Thesis Overview

This research has been completed with collaboration from the Idaho Department of Transportation (ITD) and is an extension of the previous research done by Casanova et al (2018). This research investigates the feasibility of HES concrete used in closure pour connections between bridge girders by means of instrumentation of the bridge. The research has been summarized and described in the following chapters.

1. Introduction: In this chapter a brief overview is presented on the background, scope, and objectives of this project.
2. Literature Review: This chapter discusses prior research on instrumentation, loading, data collection, and finite element modeling of bridges.
3. Instrumentation: Instrumentation of the materials in the closure pour connection and proper installation and protection of the instruments is presented in Chapter 3.
4. Bridge Loading: This chapter describes the loading of the bridge and the different arrangements of the known loads.
5. Data Collection: The data collection system used for this project is discussed in this chapter along with the protection of the instrumentation and wiring.

6. Finite Element Modeling: This chapter discusses the finite element model created to replicate the SH-36 Bridge.
7. Results: Chapter 7 summarizes the data collected during this project and describes the process used to analyze and compare the data. Data obtained both experimentally and numerically are discussed in this chapter.
8. Summary, Conclusions, and Future Work: This chapter summarizes the results and discusses the conclusions made from this research. Potential for future work is also discussed.

Also included are table of contents, figures, tables, and appendices. The appendices include material data sheets, instrumentation installation instructions, program in Campbell Scientific Loggernet, and complete strain data.

Chapter 2 Literature Review

The first step in any research project is to review previous literature to determine what the best approach is and review any issues encountered during similar projects. The literature review for this thesis will consist of four main components which relate to the research within this project. The first section deals with instrumentation of bridges and is focused on literature involving the instrumentation of typical bridges under various loading conditions. Secondly, prior research on static and dynamic loading of bridges is reviewed. This includes using large trucks of known weight to obtain experimental data for use in the process of refining a Finite Element Model (FEM). The third section reviews and explains both manual and electronic data collection and analysis on earlier research. The data collection mainly focuses on strain and temperature in and around the bridge. Section four summarizes literature on the creation of a FEM including modeling bridge elements and determining boundary or support conditions. The fourth section also reviews prior research on the refining of finite element models using updated material properties and the inclusion of non-structural components. This chapter ends with a summary of the research reviewed within this chapter.

2.1 Instrumentation

The practice of instrumenting bridges has been an effective way to determine how bridges perform under static and dynamic loading. It is the most effective way to get real time data on how a bridge is functioning. Instrumentation can include the use of strain gages, potentiometers, Linear Variable Differential Transformers (LVDTs), accelerometers, anemometers, thermometers and much more. Strain gages are used in many bridge monitoring projects for their accuracy and small size. There are three main types of strain gages: vibrating wire, resistive, and fiber-optic. Hedegaard, et al. used all three types of strain gages in the instrumentation of the new I-35W St. Anthony Falls Bridge in Minneapolis, Minnesota after the collapse in 2007 and explained what each is used for. For the I-35 project, vibrating wire gages were used primarily for static measurements, resistive gages were used for dynamic measurements, and fiber-optic gages were utilized to determine the longitudinal curvature of a specific span of the bridge due to their long gage length (13 ft) (Hedegaard et al. 2013). For this project only resistive gages were used since they were long enough to capture true strain values and collect static and dynamic strain data. There are many important contributing factors when selecting and installing strain gages on steel and concrete surfaces. According to Micro-Measurements (2019), strain gages which are to be installed on concrete should be long enough to cover multiple lengths of the largest aggregate to get an average strain and not the local variations in strain due to cement and aggregate contact ("Strain Gage Selection: Criteria, Procedures, Recommendations" 2018). For strain gage installation on reinforcing bar Micro-Measurements recommends using CEA-Series strain gages ("Strain Gage Installations for Concrete Structures" 2015). Both recommendations were followed during the selection of strain gages for this research project.

Strain gage installation is a delicate and time-consuming procedure to ensure the gages are installed properly. The Micro-Measurements Tech Tip publication on Strain Gage Installation for Concrete Structures provides instructions on how to properly prepare the surfaces of rebar and concrete for gage installation. This involves grinding down the ribs on the rebar and pre-filling the pores in the concrete with the proper adhesive ("Strain Gage

Installations for Concrete Structures” 2015). These steps were followed as instructed in the Tech Tip and all recommendations on adhesive and gage selection were followed. Furthermore, proper surface cleaning procedures and placement of gage layout lines were done in accordance of the Micro-Measurement suggestions in the Tech Tip previously mentioned. One of the more challenging aspects of gage installation underneath the bridge on a flat surface is clamping the gage while the adhesive cures. For this project, most of the strain gages had to be installed upside down. Micro-Measurement Tech Tip 610 talks about strain gage clamping techniques and a version of one of the figures in the document was used to clamp the gages underneath the bridge. Figure 2.1 shows the clamping technique suggested by Micro-Measurements (“Strain Gage Clamping Techniques” 2015). The actual clamping procedure used in this project will be discussed in Chapter 3.

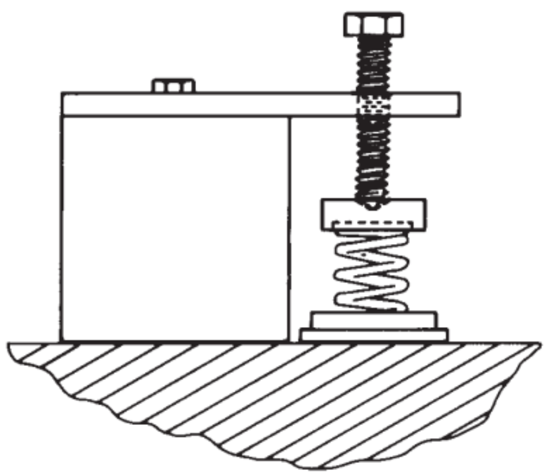


Figure 2.1 Clamping Technique for Flat Surfaces

For clamping on rebar Micro-Measurements suggests to use a clamping plate which matches the contour of the piece to be instrumented (“Strain Gage Clamping Techniques” 2015). For this project polyvinyl chloride (PVC) pipe halves were used to obtain the curved contour shape of the rebar. More information on the clamping procedure used in this project is provided in Chapter 3.

Protection of strain gages is important to ensure proper measurements and the longevity of the gages. Micro-Measurements suggests using M-Coat JA to protect the strain gages as stated in Tech Tip 611 (“Strain Gage Installations for Concrete Structures” 2015). For this project a different gage protectant was used called M-Coat F. This decision was made since M-Coat F was used in a prior research project on the same topic outlined in Casanovas’ thesis (Casanova 2018) and Micro-Measurements M-Coat F application instructions states M-Coat F is typically used in Bridge and rebar applications and on vertical or inverted surfaces (“M-Coat F Application Instructions” 2014). The final step in protecting the instrumentation is to protect the lead wires attached to the gages. For the gages embedded in the concrete Micro-Measurements recommends placing the lead wires in a conduit to protect them from damage during placement and curing of the concrete (“Strain Gage Installations for Concrete Structures” 2015). For this project the lead wires for the rebar gages were protected using clear plastic tubing through the bottom of the bridge. Further protection of lead wires will be discussed later in this thesis.

Lead wires also need protection from electric and/or magnetic fields which can cause changes in low frequency analog signals (“Preventing and Attacking Measurement Noise Problems” 2001). According to Micro-Measurements, in an ideal instrumentation lead wires do not add or subtract anything from the measurement signal (“Leadwire Selection” 2010). It is also indicated there are many ways to protect cables from electric and magnetic fields but the most popular are twisted and shielded wires. The length of the wires greatly contributes to the amount of noise seen in the system. Micro-Measurements states wires fifty feet or more can have significant levels of noise introduced into the system ("Noise Control in Strain Gage Measurements" 2013). For this project the maximum analog cable length is estimated to be forty-two feet, so there should not be a need for noise protection in the system. More discussion on noise protection and cable will be discussed in Chapter 5.

2.2 Bridge Loading

Bridges see many types of loads but the most common is the vehicles which travel across them. Bridge engineering researchers have examined how the load is distributed between members in the bridge or how individual elements of the bridge behave under certain loads. Load testing of a bridge can be done both statically and dynamically to mimic the types of loading a bridge will see during its life cycle. The load can be placed on the bridge in such a way to induce maximum stresses at the instrumented locations or maximum stresses on the overall structure. Bridges are usually sectioned off by lanes and longitudinally by a predetermined length in order to obtain different arrangements of load. Provines, et al. sectioned their bridges into three lanes: centerline, upstream, and downstream (Provines et al. 2014). Sanayei, et al. also divided their bridge up transversely the same way for two lanes of traffic (Sanayei et al. 2012). Many studies performed both static and dynamic tests with trucks of known load. Further, Chajes and Shenton explain each test should be repeated to make sure the data collected is reliable and repeatable (Chajes and Shenton 2006). The same practices will be used in this project and will be discussed in further detail in future chapters.

The objective of the static load test is to obtain strain data from the bridge in order to calibrate the finite element model (FEM) by replicating the stresses observed in the bridge (Sanayei et al. 2012). Static load tests are generally done with a truck of known axle weights parked in different arrangements. Hedegaard, et al. used eight sand trucks of known weight in five different static loading scenarios to examine longitudinal bending, load distribution, transverse bending, and load distribution due to torsional bending (Hedegaard et al. 2013). Provines, et al. parked unloaded trucks at mid-span and collected static strain data to determine if the loaded truck can be placed on the bridge. If they determined the bridge could handle a fully loaded truck they performed the same tests with the truck at mid-span to determine a load rating procedure for railroad flatcar bridges (Provines et al. 2014). In another study Sanayei, et al. performed static tests on three different travel lanes with a tri-axle dump truck of known axle weights traveling along the bridge and stopping at designated locations for ten seconds each to let the dynamic effect of the truck settle out of the bridge. Each of the tests were repeated three times for reliability (Sanayei et al. 2012).

Dynamic loading is done by having a load travel across the bridge at a predetermined speed. The dynamic test data includes vibration seen in normal travel across the bridge. From this research of existing literature one of the most widely used dynamic tests performed on bridges is the crawl test where a truck travels across the bridge at a low speed. The purpose of traveling across the bridge at such low speeds is to reduce the dynamic effect of the load (Barr et al. 2006). Most crawl tests performed in this literature search were performed at speeds around 5 miles per hour (mph). Some projects involved faster dynamic loading tests in increments until the bridge speed limit was reached to determine the strain seen by the bridge under normal operating conditions.

2.3 Data Collection

Data collection is the process of reading and recording the data from an experiment for it to be analyzed and processed. The most important components of data collection are the sampling rate, data integrity, and type of data collected. In a dynamic load test, it is important to have a fast sampling rate in order to not miss any peaks in the data. It is also ideal not to have too much data so the right sampling rate can make data collection and processing much easier and more effective. The sampling rate for previous studies has ranged from 10-200 hertz (Hz) but only Sanayei, et al. used a sample rate larger than 50 Hz (Sanayei et al. 2012). Due to the range in sampling rate it was determined the optimum sampling rate for this project based on a trial and error method. For the number of sensors being used in this project (94 sensors) the maximum sampling rate the DAQ can record is 50 Hz (50 samples per second). A decision was made to sample at 30 Hz and analyze the data to determine if the data was complete.

Data integrity is a large concern in the use of data acquisition systems. If not addressed, data can become skewed and provide results not representative of the actual conditions occurring at the gage locations. Sources of error can come from magnetic/electrical fields, temperature fluctuations, and long lead wires. Sources of magnetic/electrical fields at a bridge site would include utilities, generators, and vehicles. If these sources affect the data, the strain data will appear as if it is oscillating like in **Error! Reference source not found.**. This oscillating e ffect is usually called electrical “noise”. This noisy data came from a project where strain on steel truss bridges was measured under wind loading (Rutz et al. 2008).

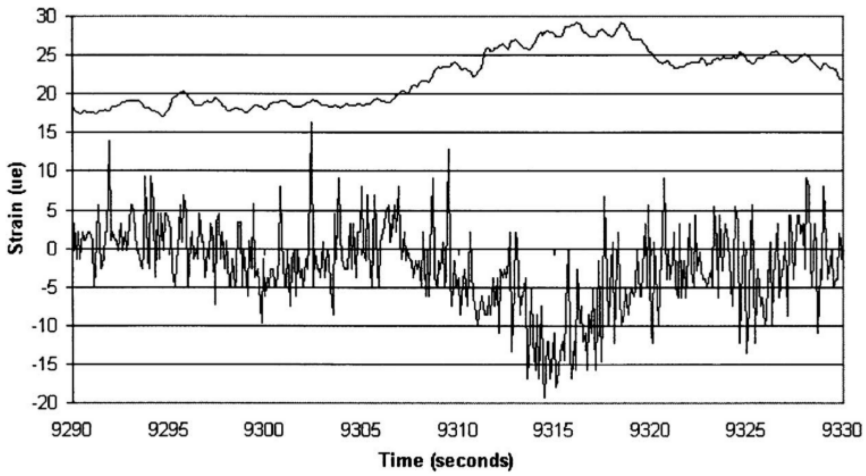


Figure 2.2 Noisy Strain Data

There are a few methods to reduce the amount of electrical noise seen in data. One method is to use shielded cable. The shielding protects the cable inside from most of the outside sources of noise and the shield is connected to a ground to eliminate sources of noise. The next method is to use twisted pair of wires. The twisted pairs of wires offer protection from both electrical and magnetic fields. Since the measurement is a differential measurement, the change in the wire due to electrical and magnetic fields are the same to both wires since they are tightly connected in a twisted pattern and therefore impact the data less ("Preventing and Attacking Measurement Noise Problems" 2001). Another method the Campbell Scientific data acquisition system uses to reduce electrical noise is integrating and averaging the signal to the measurement device. By doing this certain frequencies can be targeted and eliminated from affecting the data ("Preventing and Attacking Measurement Noise Problems" 2001). The data acquisition system used in this project is a Campbell Scientific system so this method has been used to help reduce noise in the data.

The next section of data integrity is temperature fluctuations. Temperature fluctuations can affect the resistance of the wires which can in turn affect the strain data. The best way to cancel out the effects of temperature fluctuations is to try and make sure all wires experience the same temperature fluctuations. For three wire strain gages, it is best to make sure lead wires are all of the same length and placed together ("4WFBS120, 4WFBS350, 4WFBS1K 4-Wire Full-Bridge Terminal Input Modules (TIMs)" 2017). This will ensure the wires have the same resistance and experience the same fluctuations in temperature.

Long lead wires are the third potential source of error in data acquisition. When lead wires become longer the wires resistance become more of a factor in the data. Campbell Scientific provides mathematical and shunt calibration methods to account for longer lead wires. Another error which can be encountered when long lead wires are present is a sensitivity reduction in the system. The methods used to correct this error are the same as previously mentioned with the increased resistance due to longer lead wires. These methods are outlined in the manual for Campbell Scientific's Terminal Input Modules (TIMs) ("4WFBS120, 4WFBS350, 4WFBS1K 4-Wire Full-Bridge Terminal Input Modules (TIMs)" 2017). For this project, experiments were conducted in the laboratory to determine the effects of the longer lead wires and it was determined with a maximum lead wire length of 42 feet, the strain data is unchanged so the methods outlined above will not need to be used to correct for longer lead wire. Micro-Measurements also mentions problems due to lead wire length start to occur when lead wires are 50 feet or more ("Noise Control in Strain Gage Measurements" 2013).

The third part of data collection is the type of data being collected. Through research of previous literature there are many different types of data collected from bridges such as strain, deflection, temperature, corrosion of reinforcing bars, acceleration, and tilt angles. For this project, strain data was collected to determine the behavior of the closure pour connections between bridge girders under different loading conditions. In previous research, Rutz, et al. collected strain, wind speed, wind direction, and temperature data to analyze the stresses on historic truss bridges in the state of Colorado (Rutz et al. 2008). Jáuregui, et al. used strain data from the I-40 Bridge over the Rio Grande River to evaluate the bridge and compared the data to the finite element model of the bridge in order to refine the model (Jáuregui and Barr 2004). In another project Cardini and DeWolf used strain data to determine the live load distribution, peak strains, live load stresses, and neutral axis location of the bridge and its elements. A finite element model was then created to verify the results of the acquired data (Cardini and DeWolf 2009). Hedegaard, et al. collected strain, temperature, acceleration, and displacement data to determine the behavior of the bridge and refine their finite element model (Hedegaard et al. 2013).

2.4 Finite Element Modeling

Finite element modeling (FEM) is an important tool used to estimate the behavior of bridges before they are built. Most research dealing with bridges involves both physical measurements and computer modeling. There are three main steps in FEM which contribute to the accuracy of a model. The first step is modeling the bridge structure. Different elements are used to represent the girders, deck, columns, and reinforcing throughout the bridge. Secondly the supports need to be modeled to correctly replicate the actual support conditions occurring at the bridge. The final step is to refine the computer model to account for differences between the actual bridge and the bridge plans.

Modeling the bridge structure itself involves knowing all dimensions and properties of the materials used in the construction of the bridge. Different elements can be used to model the various structural components of the bridge. The most widely used type of element in bridge modeling is the shell element. Hedegaard, et al. used shell elements to model the pre-stressed strands inside the box girder flanges. The shell elements were given no bending stiffness and the appropriate axial stiffness to properly represent the stiffness of the strands (Hedegaard et al. 2013). Bell, et al. modeled a bridge with a concrete deck placed on steel stringers and used shell elements to model the deck and the steel reinforcing in the deck (Bell et al. 2013). Jauregui and Barr also used shell elements to model the concrete deck of the I-40 Bridge over the Rio Grande River (Jáuregui and Barr 2004). Frame elements have been used to model steel girders in composite bridges. Also, solid elements are sometimes used to model bridge decks. Each element type has different properties allowing it to better represent the bridge being modeled. Choosing the element type to use in a model is determined on a case by case basis as it depends on how detailed the model needs to be and what properties are most important to represent accurately in the model.

Another important aspect of modeling the bridge is using an element which is sized properly. The size of the element determines how detailed the results will be. One should balance the element size to avoid long computational times but also still get reliable results. Hedegaard, et al. used an element size of 24 in. by 24 in. This resulted in roughly 500 elements along the length of the bridge and anywhere from 8 to 15 elements throughout the depth of the girders (Hedegaard et al. 2013). Jauregui and Barr used elements sizes of 14.5 in. by 12 in. transversely and longitudinally respectively. This was done to match the girder spacing. The girders were also modeled with 12 in. longitudinal elements to match the deck model for ease of modeling (Jáuregui and Barr 2004). For this project an element size of 4 in. by 6 in. will be used as it will provide reliable results and save on time during the modeling process.

Correctly modeling the boundary conditions has a large influence on the overall model behavior. When modeling the overall bridge, boundary conditions are considered the bridge supports. The fixity of the supports is what is to be determined. This is usually altered to better match experimental results as there is no good way to determine how rigid the supports are at the bridge site. Bell, et al. modeled the bridge deck and steel girders supporting the deck. Elastomeric bearing pads were used in between the steel girders and cap beams to support the bridge. The elastomeric pads were modeled using linear rotational springs with the proper stiffness values to represent the steel reinforced bearing pads used on the bridge (Bell et al. 2013). Jauregui and Barr considered three different support conditions in their finite element model. The first condition used pin supports at the fixed bearing locations and roller supports at the expansion bearing locations. The first model did not consider the pier stiffness. The second model used frame elements to model the pier. The base of the pier was fixed and the connection between the columns and the girder was rigidly constrained. For the third model, the intermediate connections were completely fixed so as not to allow translation or rotation This was done to represent the extreme upper limit of pier stiffness (Jáuregui and Barr 2004). Hedegaard, et al. modeled three out of the four spans of the I-35W St. Anthony Falls Bridge because there is an expansion joint between span four and five separating the forces acting on either side of the joint and keeps them from distributing across the joint. The profile view of the bridge is shown in Figure 2.3. For their model, Piers 2 and 3 were assumed to be fixed at the base. Vertical constraints were used to model the bearing pads at Abutment 1 and Pier 4. Pin supports were used to model the connections at Piers 2 and 3 (Hedegaard et al. 2013).

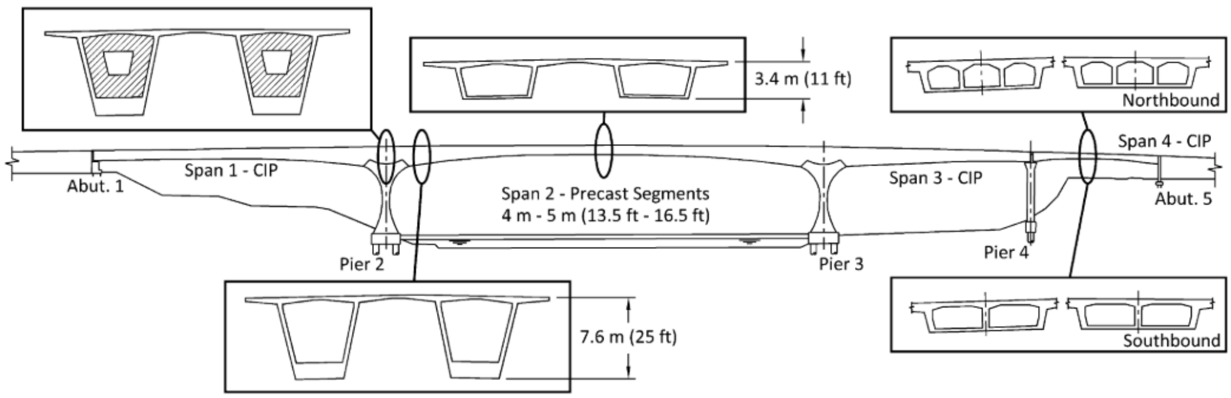


Figure 2.3 Profile View of I-35W St. Anthony Falls Bridge

The final step taken after a finite element model is produced and analyzed is to refine the model to better represent the actual conditions at the bridge site. The usual method for determining if the steps taken to refine the model are working is to compare the results of the model to experimentally obtained data using field instrumentation. There are multiple refinements which can be done to update a finite element model. The first and most common step is to update the concrete compression strength when the concrete from the project is tested in a laboratory. When concrete is produced at the plant it is made to be stronger than what the specifications ask for. This is to reduce any possibility of a batch of concrete not achieving the required strength. This step was taken by all researchers included in this literature review. It is important to include all elements of the bridge into the model as they will almost certainly affect the stiffness and weight of the overall bridge. Bell, et al. modeled the safety curbs on the bridge since they observed the safety curb reinforcement was placed before the pour of the deck and would contribute to the overall stiffness of the bridge (Bell et al. 2013).

Through research of existing literature dealing with the instrumentation and testing of bridges, many ideas were confirmed or realized which needed to be considered in this project. Properly attaching and protecting the instrumentation is important to ensure the longevity of the devices. Recording data needs to be done with care as the sampling rate and noise associated with data collection is crucial to collecting quality data. Creating a FEM of bridge is another large part of this project and extensive research was done on existing literature to make sure all components were covered. Correctly modeling bridge elements and the boundary conditions were covered in the literature review. Refining a FEM was also reviewed to determine what steps could be taken initially to create an accurate model which closely estimates the behavior of the bridge being studied in this project.

Chapter 3 Instrumentation

3.1 Introduction

The SH-36 bridge over Bear River was instrumented with 94 strain gages. All instrumentation is located along a cross section approximately twenty feet from the west end of the bridge. Lines representing the instrumented cross section and each of the four closure pour connections are shown in Figure 3.1. All strain gages, except for the six bulb strain gages are located at the four intersections of the red lines.

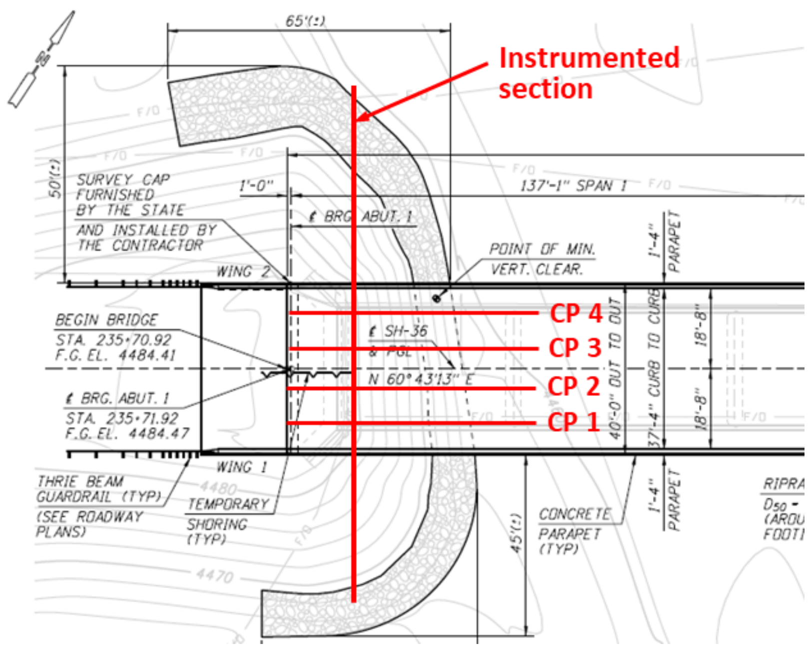


Figure 3.1 Line of Instrumented Cross Section

3.2 Rebar Gages

On May 7-8, 2018, 64 strain gages were installed at the Forterra Structural Precast plant in Caldwell, ID. All the girders along the instrumented section on the southwestern span were instrumented with strain gages on the reinforcing steel protruding from the girders which became part of the closure pour connection. The strain gages used for instrumenting the rebar in this project were 0.25 in. long and have a resistance of 350 ohms. They were purchased from Micro-Measurements and came with 10 feet of pre-attached lead wire. Further information on the strain gages used in this project can be found in Appendix A. There were 16 strain gages installed in each connection. Four headed rebars, two from each girder being connected, were instrumented with the rebar strain gages. Each of the four rebars were instrumented with four strain gages at two locations along the length of the rebar.

Figure 3.2 shows a diagram of one headed rebar with strain gage locations. Two strain gages were placed on opposite sides of the rebar close to the interface between the girder and the closure pour concrete. Two more gages were installed on opposite sides of the rebar at a location close to the headed bars. Figure 3.3 shows one of the girders after all eight strain gages were installed on the reinforcing bars.

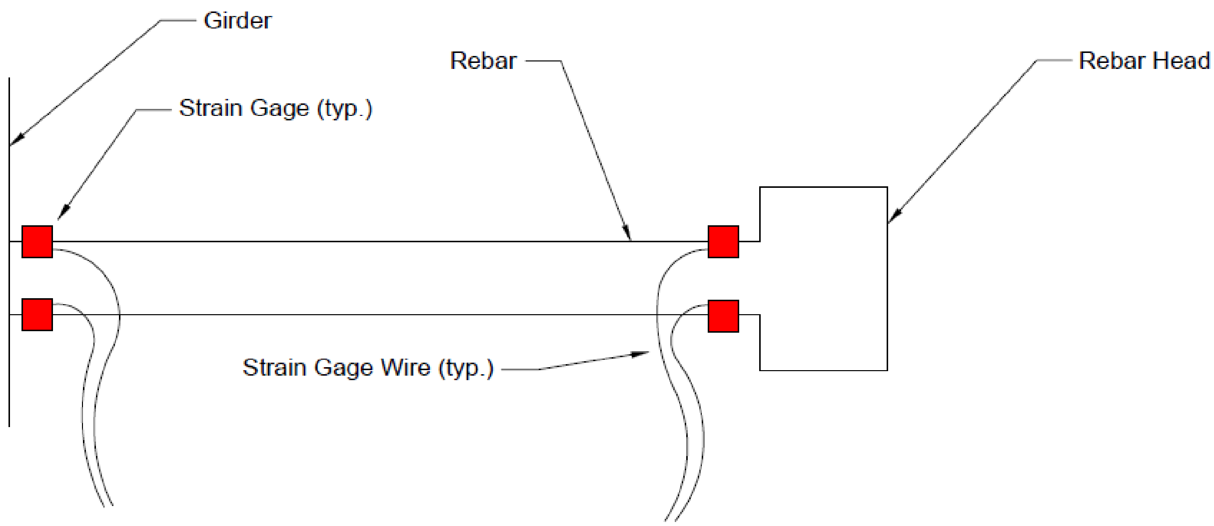


Figure 3.2 Rebar Strain Gage Diagram

Figure 3.3 Instrumented Rebars

The first step in the instrumentation process was to determine which headed rebars would be instrumented. It was decided the rebars to be instrumented would be located approximately twenty feet from the end of the top flange of the prefabricated girders at the southwest abutment. A line showing the section of the bridge which was instrumented can be seen in Figure 3.1. The decision on the location of the strain gages (i.e., 20 ft from the end of the top flange) was made in order to safely install the concrete gages at the bridge site and still obtain transverse bending without any effects from the abutment to girder connection. Girders were measured and rebars which were selected to be instrumented were marked with yellow tape. The installation process followed the same procedure as was previously followed for phase one of the ITD research project. The ribs on the rebar were ground off with an electric grinder in order to prepare a smooth surface for gage installation and remove any imperfections on the steel surface. Figure 3.4 shows the rebar after the grinding process was complete.

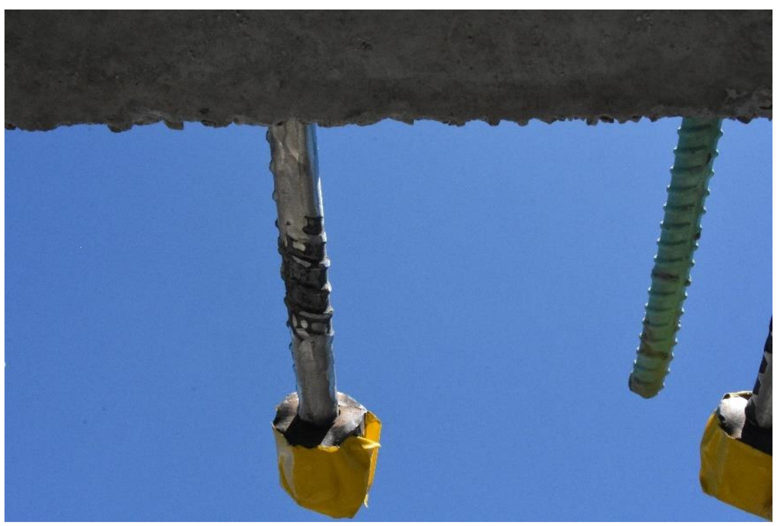


Figure 3.4 Rebar with Ribs Removed

After the grinding process was complete, the surface was cleaned using the conditioner and neutralizer purchased from Micro-Measurements. Once the surface was clean of debris, a digital caliper was used to measure four diameters of the rebar at all locations where strain gages were to be installed. The diameters of the rebars were measured to obtain more accurate data when converting strain to stress observed in the rebar. The next step involved using a special gage installation tape from Micro-Measurements to tape the strain gages down to a clean piece of glass. This is done in order to place the strain gage on the rebar without touching the strain gage. Then the taped gages were transferred to the rebar. Once all gages were placed and ready for installation, a two-part epoxy (Micro-Measurements M-Bond AE-10) was prepared and placed underneath the gages and tape and were clamped for at least eight hours to ensure proper bonding. The data sheet for the epoxy used in this project can be found in Appendix A. The clamping procedure used is demonstrated in Figure 3.5. The clamping mechanism consisted of rubber pads to distribute the clamping pressure uniformly over the strain gages. In addition, 1.5 in. PVC pipes were cut in half longitudinally to create two PVC pipe halves. The PVC pipe pieces were glued to a small piece of wood for the spring clamps to apply pressure without slipping off the pipe. This clamping technique was tested in the lab and the strain gages adhered to the rebar without any problems.

Figure 3.5 Rebar Clamping Technique

Once the clamps were removed, the tape covering the gage was also removed and two coats of polyurethane were applied over the gages to protect them from any dust or moisture. After the polyurethane dried, a protection called M-Coat F was applied over the gage areas to protect from damage caused by placement and curing of concrete. This protection was recommended by and purchased from Micro-Measurements. The M-Coat F protection consisted of a layer of butyl rubber placed completely around the rebar at strain gage locations followed by a layer of aluminum tape. The lead-wires were run through a small plastic tube which protected the wires which were encased in the closure pour concrete. The completed instrumentation and protection can be seen in Figure 3.6. Large PVC pipe halves were then taped over the instrumented rebar to protect the gages during transportation and placement of the girders. Once the girders and formwork were in place the PVC halves were removed and the wires which were protected by means of small plastic tubing which was run down through the formwork. Figure 3.6 shows a closure pour fully prepared for placement of concrete. The process of placing the concrete is shown in Figure 3.7. The placement of concrete consisted of concrete trucks delivering the closure pour concrete to the bridge site where it was then loaded into a pump truck at the end of the bridge and pumped through a large hose along the length of the closure pour for placement.

Figure 3.6 Closure Pour Prepared for Concrete

Figure 3.7 Placement of Concrete in Closure Pour

After the concrete cured, the forms underneath the bridge were removed and the gages were tested to make sure all gages measured 350 ohms of resistance. A picture from below the bridge after the forms were removed is shown in Figure 3.8. Complete surface preparation, gage installation, and protection instructions are provided in Appendix B.

Figure 3.8 Closure Pour with Rebar Gages Installed

3.3 Concrete Gages

Installation of concrete gages took place after the closure pour connections were poured, cured, and formwork was removed. The numbering system used in this project to identify closure pours is shown in Figure 3.9. The closure pour connection furthest downstream is labeled CP 1 and the remaining three were numbered in order. Closure Pour 1 was poured in August and the other three were poured the first week of November.

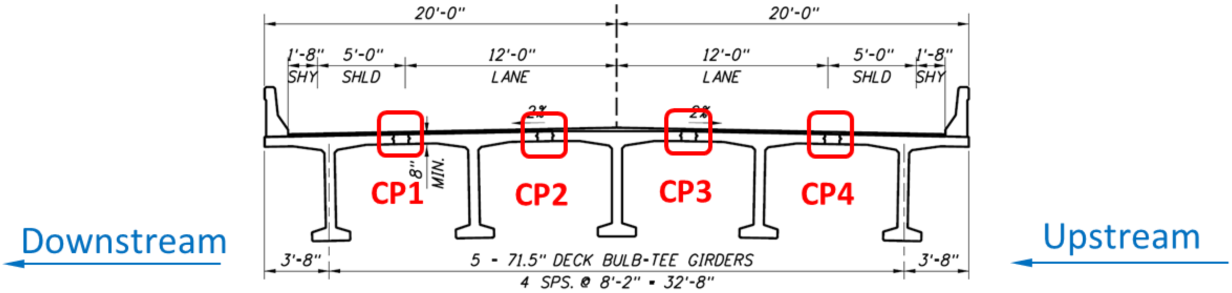


Figure 3.9 Closure Pour Numbering System

Each closure pour was instrumented with 6 concrete strain gages in the orientation shown in Figure 3.10. One strain gage was placed over each interface between the girders and the closure pour concrete. Two more gages were placed on each side of one of the interfaces to observe if similar strains are occurring through the location of the interface. Two more gages were also placed at the center of the closure pour to observe the transverse and longitudinal strains occurring in the closure pour material.

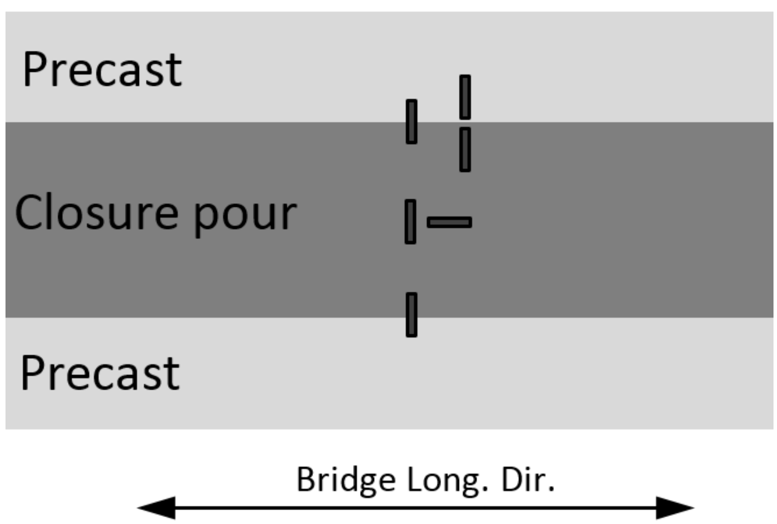


Figure 3.10 Concrete Strain Gage Arrangement

In addition to the closure pour strain gages, the girders were also instrumented on each side of the bulbs on the interior girders. In Figure 3.11 the blue circles indicate the bulbs which were instrumented with strain gages. The red indicates the approximate location for each strain gage. These gages were placed to calibrate and verify the Finite Element model which was created to replicate the actual conditions occurring at the bridge.

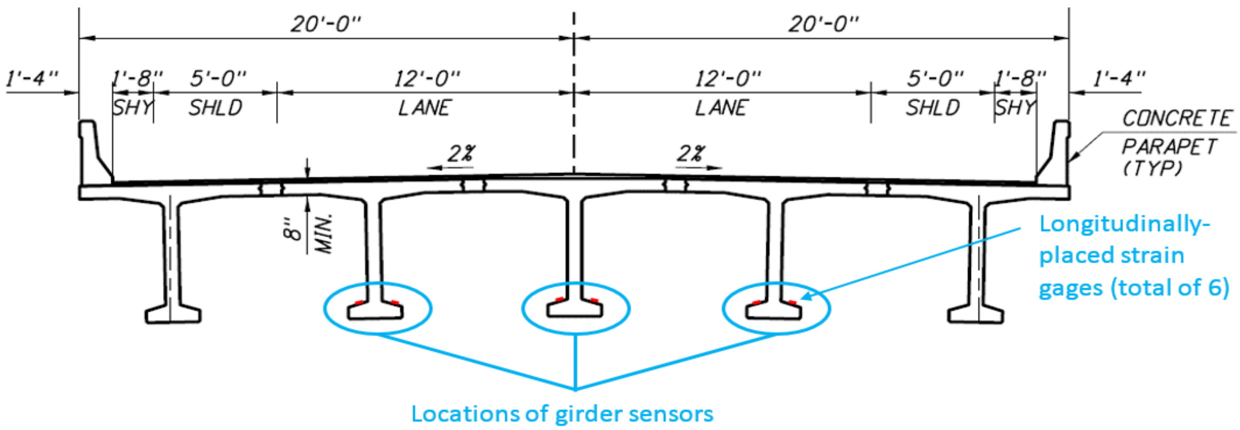


Figure 3.11 Location of Bulb Strain Gages

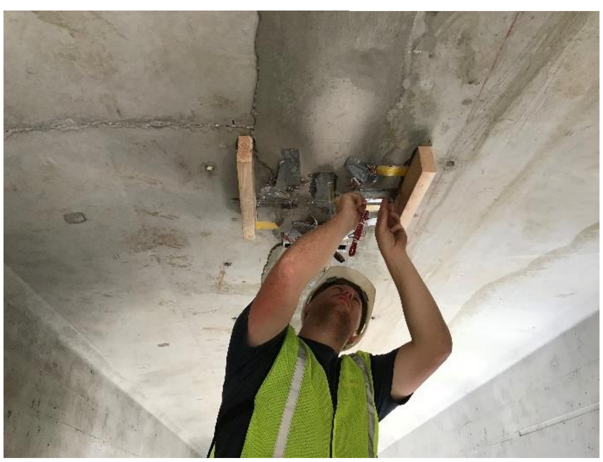
The process of instrumenting a concrete surface is similar to a steel surface but has a few differences. The installation of concrete gages was also different due to them having to be installed upside down underneath the bridge. The first step involved marking the concrete surfaces at the locations where strain gages were to be installed. Then an electric grinder was used to remove any surface irregularities. To clean the surface, degreaser was sprayed onto the concrete and wiped off with gauze pads. For final cleaning, the conditioner and neutralizer from Micro-Measurements was used to clean the surface. For installation of concrete gages an extra step of preparation is needed to assure the strain gage completely bonds to the concrete surface. The two-part epoxy which is used to attach the strain gages is used to fill in the pores on the surface of the concrete. This was done by creating a large patch of gage installation tape and putting the epoxy over the sticky side of the tape and taping the large patch over the areas to be instrumented. The tape was strong enough to keep the epoxy held up on the concrete surface until it was fully cured. This procedure is shown in Figure 3.12.

Figure 3.12 Filling Pores on Concrete Surface

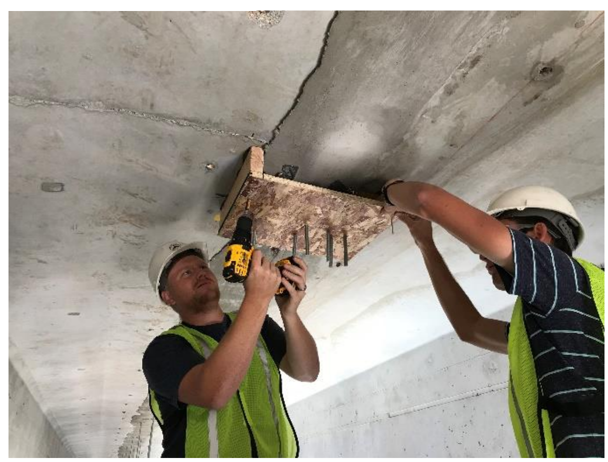
After the epoxy cured the tape was removed and the surface was ground down to the concrete surface, so the final bonding surface was the concrete with the pores filled in with epoxy. The surface was again cleaned with conditioner and neutralizer in preparation for gage installation. The next step involved placing strain gages on the surfaces using the gage installation tape. Once the gages were all placed, a two-part epoxy was prepared and placed underneath the gages and the gages were taped back onto the concrete surface for clamping.

The clamping of the strain gages was difficult due to the inverted surface the gages were being installed on and the lack of another surface to use for leverage. In order to overcome this challenge a device was designed to apply the proper amount of pressure on the strain gages. The clamping devices consisted of a threaded rod approximately 4 inches in length with a spring epoxied to one end. The other end of the spring had a small metal plate epoxied to it which was slightly larger than the size of the strain gages. On top of the plate was a piece of rubber used to distribute the pressure evenly to the strain gages. The threaded rod was then run down through plywood at the locations of the strain gages and the plywood was secured to 2 by 4's, which were epoxied to the girders, with screws. Nuts were used to force the threaded rods upwards thus applying force through the springs and onto the strain gages. The springs were necessary to make sure all six gages had pressure applied to them. Figure 3.13 shows one of the spring devices used in a typical clamping mechanism. The circular steel plate in Figure 3.13 represents the plywood and the rod can be forced upwards by turning the nut at the steel plate clockwise. The spring clamps were left in place for a minimum of 24 hours to ensure proper curing of the epoxy was achieved. Once the appropriate amount of time passed, the spring devices were removed, and the gages were checked for proper bonding to the concrete and a multi-meter was used to confirm each gage maintained a resistance of 350 ohms. Once all gages were checked, the plywood was reinstalled without the clamps for protection of the strain gages.

Figure 3.13 Spring Clamping Device



(a)



(b)

Figure 3.14 Concrete Gage Clamping Mechanism: (a) 2 by 4 Supports, and (b) the Plywood Supporting the Six Spring Loaded Clamps

3.4 Wiring and Protection

Wiring of strain gages was done in November and December to complete the instrumentation of the bridge. Each strain gage installed came with ten feet of pre-attached wire, so no soldering was needed. For ease of access in the future, two large junction boxes were placed ten feet off the southwest abutment in the two interior closure pours. The first step was to extend all wires from the strain gages to the junction boxes. The amount of wire needed to extend all wires to the junction boxes was measured and proper lengths of wire were cut and spliced into the existing wires. Each strain gage comes with three lead wires color coded red, black, and white which are used to record strain. Each splice consisted of individual splicing of each of the three-color coded wires. The protection from the strain gage lead wire and the wire to be spliced to it was stripped down by roughly one inch. The color corresponding leads were then twisted together and taped using electrical tape. Once each of the three-color coded wires were spliced together, all three wires were taped back together to keep the connections from getting caught on other wires while running them through the protective PVC conduit system. Once the wires were spliced, a multi-meter was used to test all strain gages for a resistance of 350 ohms. This ensures all splices and connections of wires to the gages are still reliable. After all wires were tested, each one was relabeled at the end of the spliced wire using a label maker so they could be identified in the junction box. The next step was to bundle the sets of wires coming from each closure pour using electrical tape to prevent wires from getting caught on others while running them through the PVC conduit. Figure 3.15 shows part of the PVC conduit system used in this project.

Figure 3.15 PVC Conduit Protection for Strain Gage Wires

The PVC conduit system used consisted of ¾ and 1 ½ inch PVC pipe. The ¾ inch PVC pipe was used for conduit where only one set of closure pour wires were run. The 1 ½ inch PVC pipe was used in locations where multiple bundles of closure pour gages were run. Figure 3.16 shows a diagram of the PVC conduit system used to protect strain gage wires. All strain gage wires were run through the PVC conduit to the locations marked in red. At these two locations the wires were then run an additional 10 feet closer to the southwest abutment so the wires could be accessed after construction of the bridge is complete.

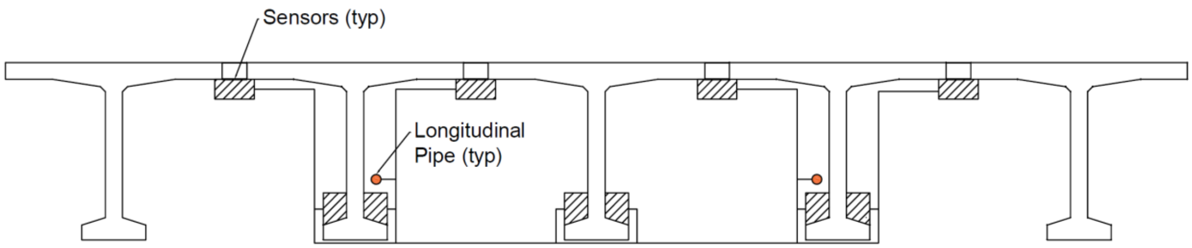


Figure 3.16 Instrumentation Protection System

Another important aspect of the wiring of the bridge was knowing which wires were connected to which strain gage. In order to stay organized, a notation was used for all rebar strain gages and another was used for the concrete strain gages. The bridge girders which were instrumented were labeled 101 through 105 from North to South on the West span. The closure pours which were instrumented were labeled 1 through 4 starting from the downstream (South) side. The bulb strain gages (see Figure 3.11) were located only on the interior girders and labeled 1 through 6 starting on the downstream side. The labeling system which was used is in Table 3.1 and Table 3.2.

Table 3.1 Rebar Strain Gage Labeling System

Girder Number	East or West	North or South	Interface or Head	Top or Bottom
101-	E=East	N=North	I=Interface	T=Top
105	W=West	S=South	H=Head	B=Bottom

Table 3.2 Concrete Strain Gage Labeling System

Label	Description
Longitudinal	Located in the middle of the closure pour material in the longitudinal direction
Transverse	Located in the middle of the closure pour in the transverse direction

CP (Closure Pour)	Located completely on the closure pour material right next to the interface in the transverse direction
Girder	Located completely on the girder right next to the interface in the transverse direction
Interface East	Located directly on the East interface in the transverse direction
Interface West	Located directly on the West interface in the transverse direction

Chapter 4 Bridge Loading

Load testing of the SH-36 Bridge was conducted from December 2018 through March 2019. The loading consisted of both static and dynamic loading. The static loading was done with known truck loads provided by the Idaho Department of Transportation and the dynamic loading was done by both known and unknown loads. The unknown loads consisted of commercial vehicle traffic with more than two axles.

4.1 Static Loading

Static loading of the bridge was done using trucks with known axle weights placed in various positions on the bridge. The trucks are bridge inspection trucks known as “Under Bridge Inspection Trucks” (UBIT). Two separate UBIT trucks were provided on separate days for the purpose of testing the bridge under known load. The purpose of using two trucks to conduct testing was to obtain more than one set of data for determining the response of each directly loaded closure pour and for use in refining the computer model of the bridge. Having two separate loads to compare with the computer model ensures that the model is behaving similar to the actual bridge under various loads. The first truck provided was the smaller of the two trucks and the load testing took place on January 29th, 2019. The loading consisted of 12 different truck locations for static testing. Figure 4.1 shows a diagram of the smaller UBIT with the approximate axle weights for the vehicle. The truck was weighed at a nearby weigh station before testing and the axle weights were close to the values provided in the diagram.

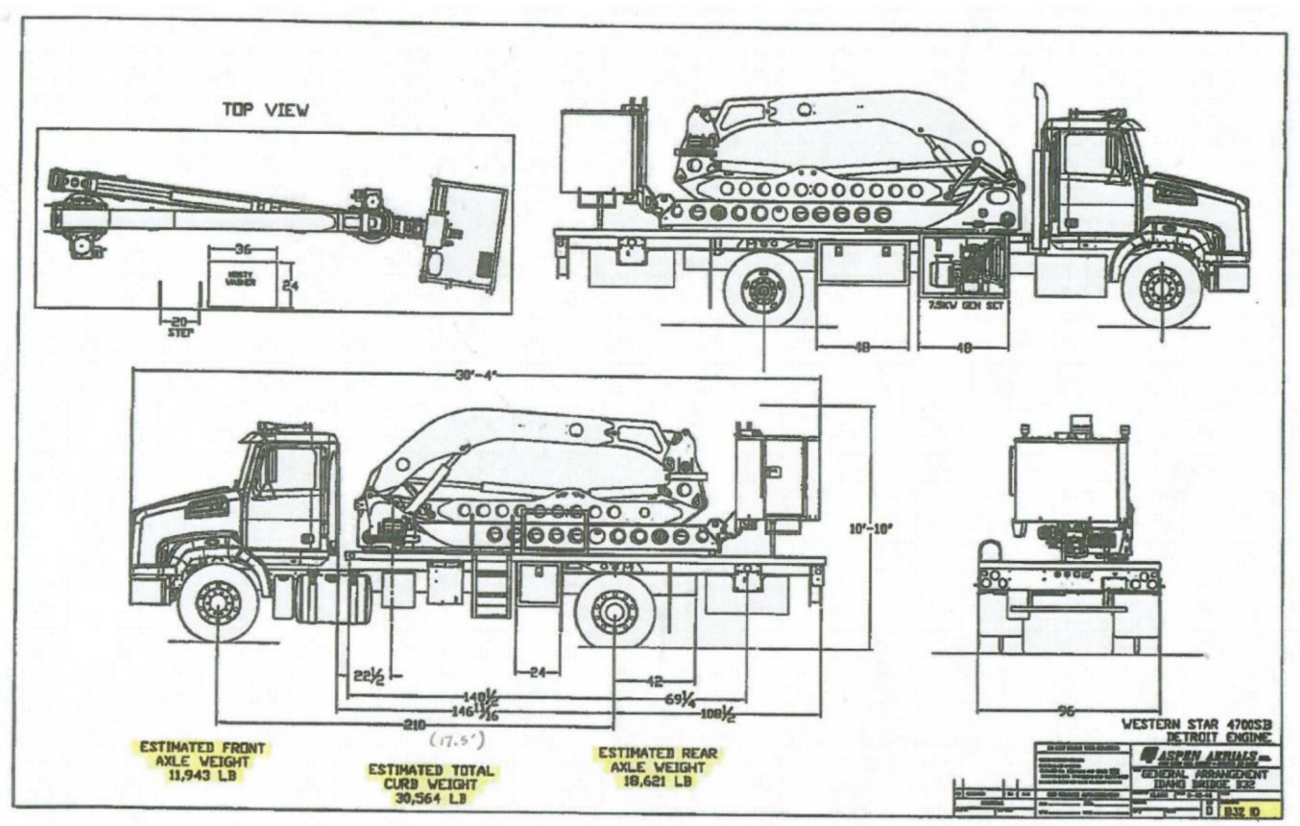


Figure 4.1 Small UBIT Diagram

The static loading arrangements can be easily described by breaking the 12 load positions into 2 groups of 6 positions. The first group of positions consisted of placing a front tire directly on top of the closure pours at the location where the closure pours were instrumented. The line of instrumentation is located approximately 20 ft. from the southwest abutment.

The direct loading of the closure pours consisted of 6 positions. Each of the interior closure pours were loaded with both the driver and passenger tires. The exterior closure pours were only able to be loaded by one of the two tires due to size restrictions. Figure 4.2 shows the UBIT with the front passenger side tire directly loaded on Closure Pour 2. The loading process consisted of the truck slowly driving onto the bridge and parking directly over the instrumentation for approximately 15 seconds to allow any dynamic effects to settle out. After 15 seconds the truck backed off the bridge in order to zero the data acquisition system before the next loading position. The positioning of the static UBIT loads can be seen in Figure 4.3.

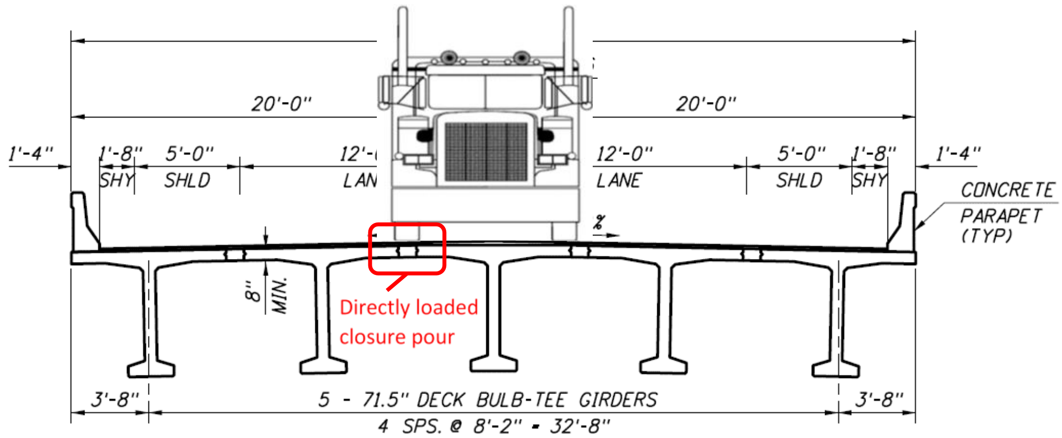


Figure 4.2 Loading of Closure Pour

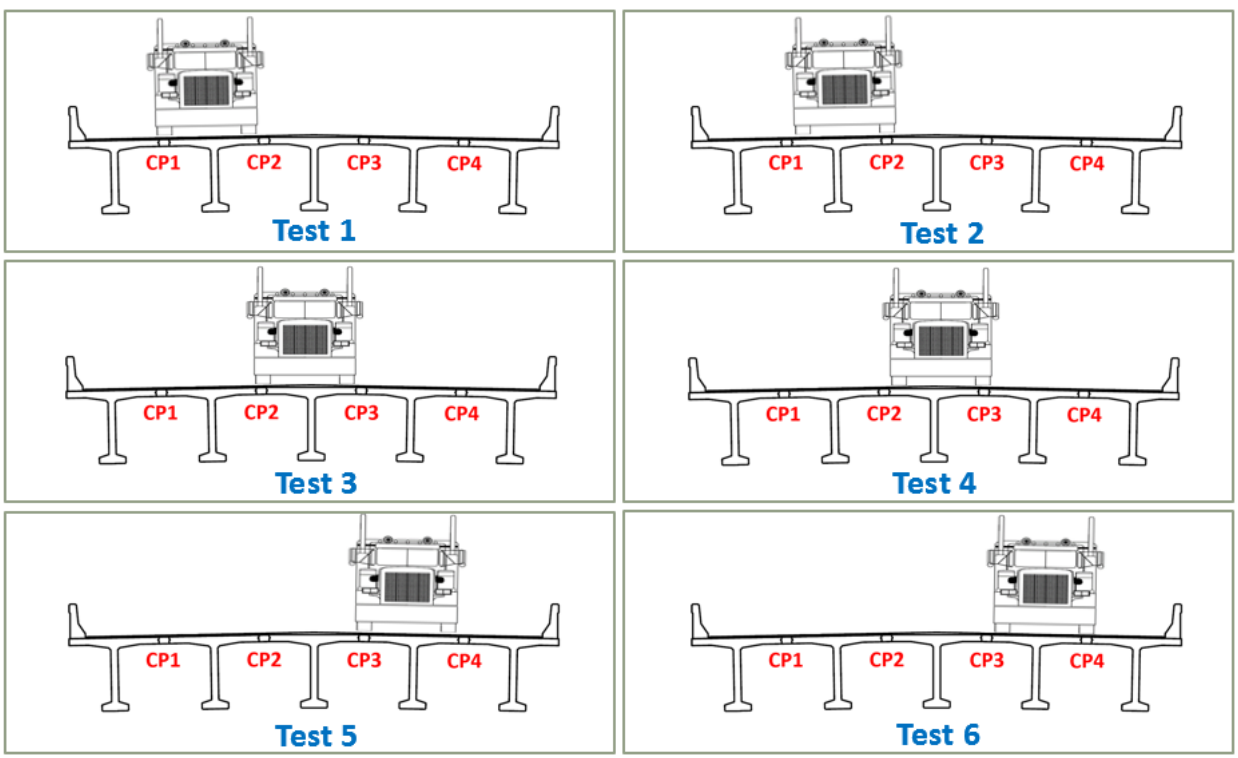


Figure 4.3 Static UBIT Load Positions

The second set of 6 static loading positions consisted of parking the truck at the ¼, ½, and ¾ span locations on the instrumented span of the bridge. The truck was parked with the driver tires directly over the center line of the bridge in the transverse direction. These three tests were labeled Tests 2.1, 2.2, and 2.3, respectively. The second set of 3 tests were repeats of the first set except the passenger side tires were placed in the same positions as the previous 3 tests. These three tests were labeled Tests 2.4, 2.5, and 2.6, respectively.

Figure 4.4 shows the loading position where the truck is at the ½ span location and the driver side wheels are located on the centerline of the bridge. These six positions were performed the same way as the closure pour direct loading where the truck slowly pulled onto the bridge and parked in the proper position for approximately 15 seconds. Static loading for the larger UBIT took place on March 12th, 2019 and the same static loading positions were used. The only difference between the small and large UBIT loadings were the static loadings for the large UBIT were performed twice for repeatability. Figure 4.5 is a diagram of the large UBIT and includes the axle weights for each axle. The drop axle was down during all tests performed with the large UBIT.

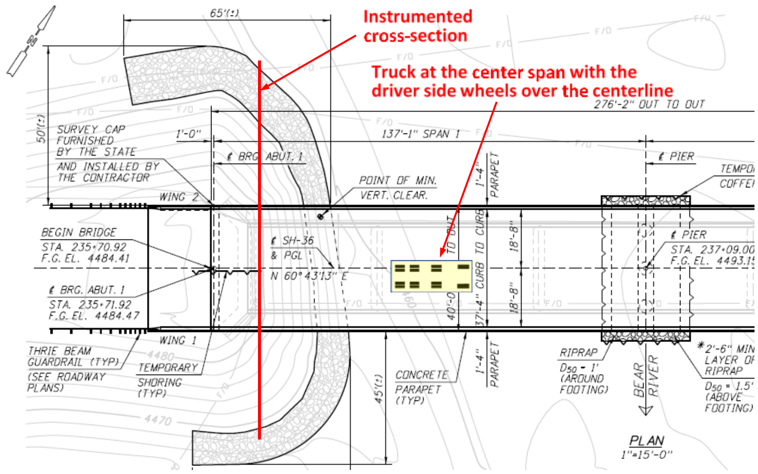


Figure 4.4 UBIT at Center Span Location

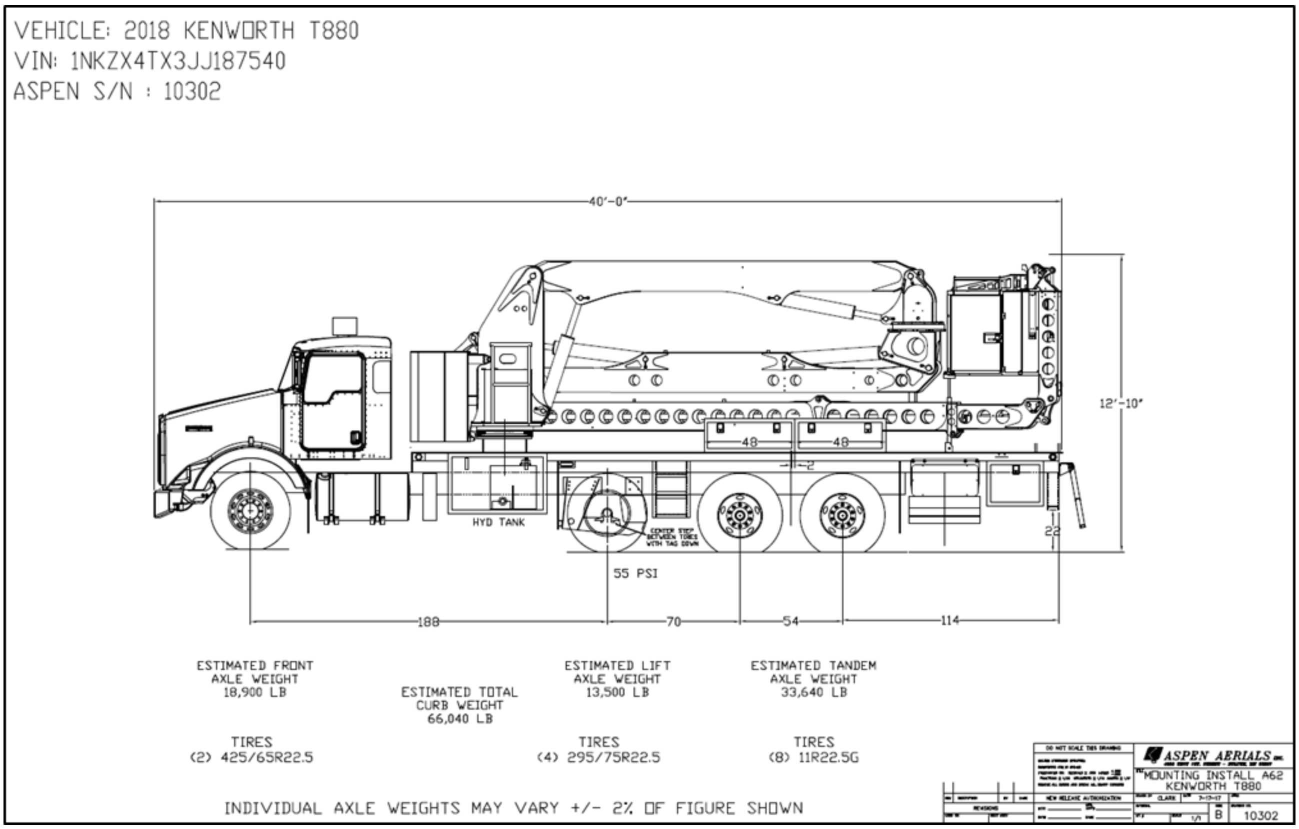


Figure 4.5 Large UBIT Diagram with Drop Axle Down

4.2 Dynamic Loading

Dynamic loading of the bridge consisted of loading the bridge with both known and unknown loads. Dynamic loading was included in this research to observe the average stresses in the closure pour material during normal traffic conditions.

Dynamic loading which consisted of known load was performed with the small and large UBITs. Four dynamic tests were performed with each of the UBITs. The first test consisted of the UBIT traveling over the bridge at a crawl speed (approximately 3 mph) with the driver side tires on the centerline of the bridge. The next test involved the truck traveling the same speed in the same direction with the passenger side tires on the centerline of the bridge. These two tests can then be combined to observe the reaction of two truck traveling over the bridge simultaneously along the center line. The final two tests were performed in the same manner as the previous two but at a speed of 10 mph. Figure 4.6 shows the large UBIT performing a dynamic test with the driver side tires on the centerline of the bridge. The data for these tests (Tests 3.1 through 3.4) can be found in Appendix D.

Figure 4.6 Large UBIT Dynamic Test

Dynamic tests involving unknown loads were performed over multiple days and on various days of the week to obtain an average sample of traffic. A total of 20 hours of truck traffic data was obtained to analyze the average strains seen in the bridge. Individual events where a vehicle consisting of more than 2 axles were recorded during this time. For each event, the time, type of vehicle, number of axles, direction of travel, and any pertinent notes were taken. Pictures for most of the events were also taken from the end of the bridge to determine where the vehicle passed over the instrumentation in the transverse direction. Figure 4.7 shows an example of a data sheet used to record the individual events.

Time (Hour:Minute)	Type of Vehicle	# of Axles	Direction of Travel East	Direction of Travel West	Picture of Vehicle	Notes
11:04	PICK UP TRAILER	4	✓		✓	HORSE TRAILER
11:09	Pickup trailer	4		✓	✓	empty trailer
11:15	PICK UP TRAILER	4		✓	✓	EMPTY HORSE TRAILER
11:17	PICK UP TRAILER	4	✓		✓	EMPTY TRAILER
11:26	PICK UP TRAILER	4	✓		✓	TRAILER CARRYING HAY BALES
12:03	dump truck	3	✓		✓	
12:11	Pickup trailer	4	✓		✓	Trailer carrying hay Bales
12:34	PICK UP TRAILER	4		✓		UHAUL TRAILER

Figure 4.7 Commercial Vehicle Data Sheet

Chapter 5 Data Collection

Data collection for this project consisted of collecting readings from 94 strain gage sensors at a rate of 33 samples per second. The data collection system used is a product of Campbell Scientific, Inc. and consisted of a CR6 Datalogger, six analog input modules (CDMs), and 94 Terminal Input Modules (TIMs). The system was required to operate at its upper limit due to the sampling rate and number of sensors required in this project.

5.1 Data Collection Hardware

The data collection system consisted of four main hardware components: strain gages, TIMs, CDMs, and a CR6. Each of these components will be discussed in this section. A schematic of how each of the hardware components were arranged in the data collection system can be seen in Figure 5.1.

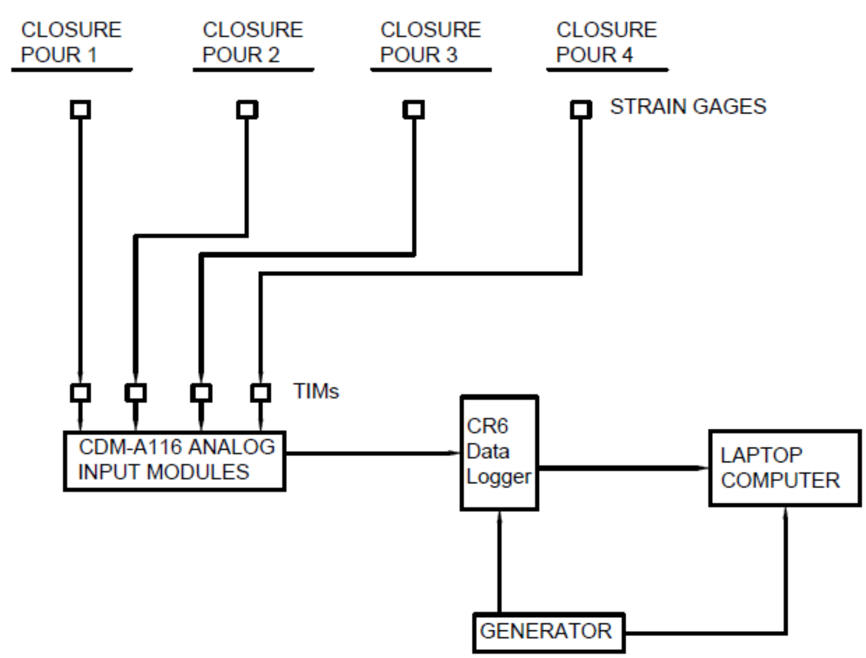


Figure 5.1 Data Collection Schematic

The strain gages are the instruments which are attached to the steel and concrete surfaces on the bridge and record strain by means of a change in voltage. A specified voltage is sent through the strain gage and the change which is observed across the strain gage is recorded and used to determine the amount of strain the gage and material it is attached to is experiencing. For more information on the specific strain gages used in this project please refer to Chapter 3 and Appendix A.

The strain gages were connected to the Terminal Input Modules (TIMs) using three wires which were color coded red, white, and black. The red wire is used for excitation where the voltage enters the strain gage. The other two wires are used to measure the voltage that leaves the strain gages. Figure 5.2 shows the wires for four strain gages correctly connected to the TIMs. All strain gages used in this project were 350 ohm gages and the TIMs used in this project were specific to 350 ohm strain gages.

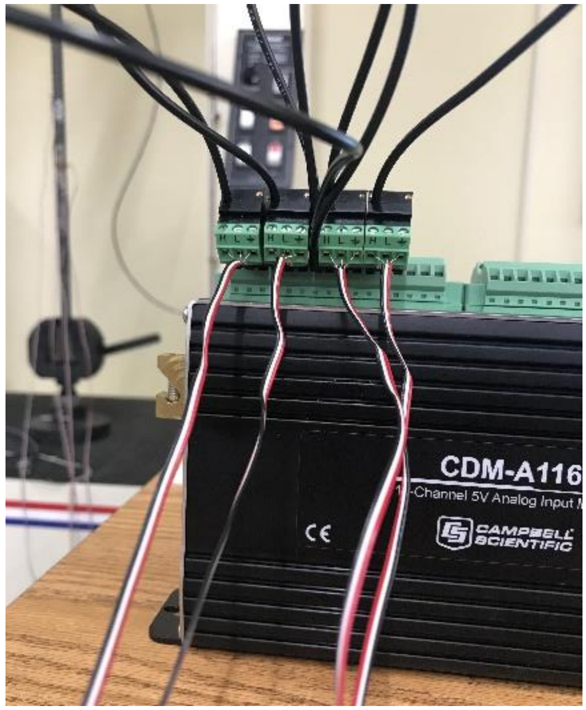


Figure 5.2 Strain Gage Wiring to TIM

The TIMs used were supplied by Campbell Scientific and were used to complete the Wheatstone bridge for accurate strain measurements. The data sheet for the TIMs (4WFBS350) can be found in Appendix A. A typical TIM used in this project can be seen in Figure 5.3. Figure 5.3 also shows proper installation of a TIM on a CDM terminal block. The high, low, and ground prongs on the TIMs each inserted into the port corresponding with the same symbol on the CDMs terminal block. The black wire which comes out of the TIM is connected to the port labeled X which stands for excitation. For this project, four TIMs were required to share one excitation port since each CDM only has four total excitation ports.

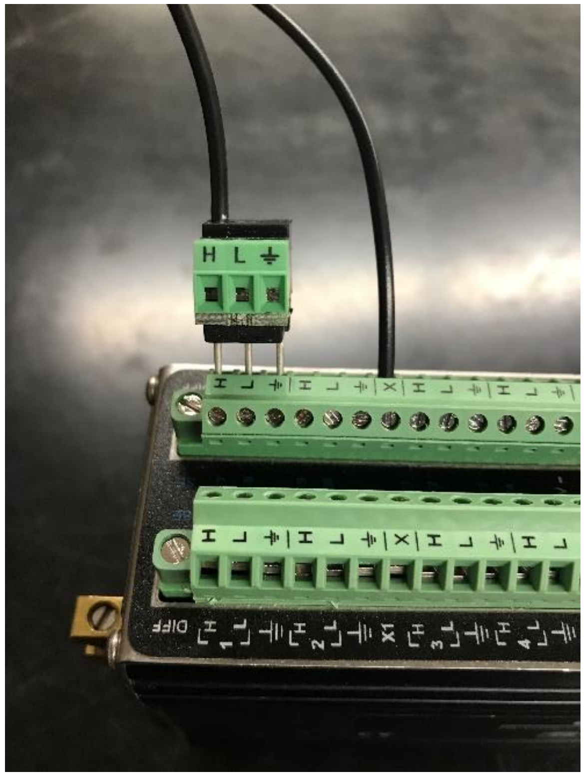


Figure 5.3 Terminal Input Module (TIM)

The CDMs were also provided by Campbell Scientific and are analog input modules that increase the number of channels in the data acquisition system. The CDMs used in this project were each able to add an additional 16 channels to the data collection system. A total of six CDMs were used in order to record data from all 94 strain gages at one time. The CDMs also work as an analog to digital converter. Converting the data from an analog signal to a digital signal prevents outside sources from interfering with the data. For this reason, it was decided to locate the CDMs closer to the strain gages to limit the length of wire that an analog signal would be transmitting through. A typical CDM used in this project is shown in Figure 5.4.

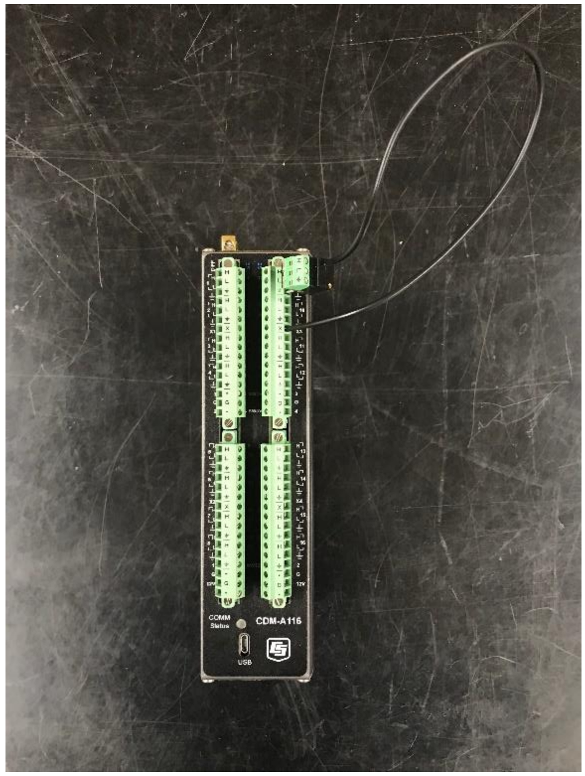


Figure 5.4 Analog Measurement Module (CDM-A116)

All six CDMs were connected to a CR6 by means of Ethernet cables. The data which was converted from analog to digital was sent to the CR6 where it was then written to a file on a connected computer. The CR6 was the central location of the data collection system where all data was sent to be recorded. The data sheets for all hardware components of the data collection system can be found in Appendix A. A picture of the CR6 used in this project is shown in Figure 5.5.

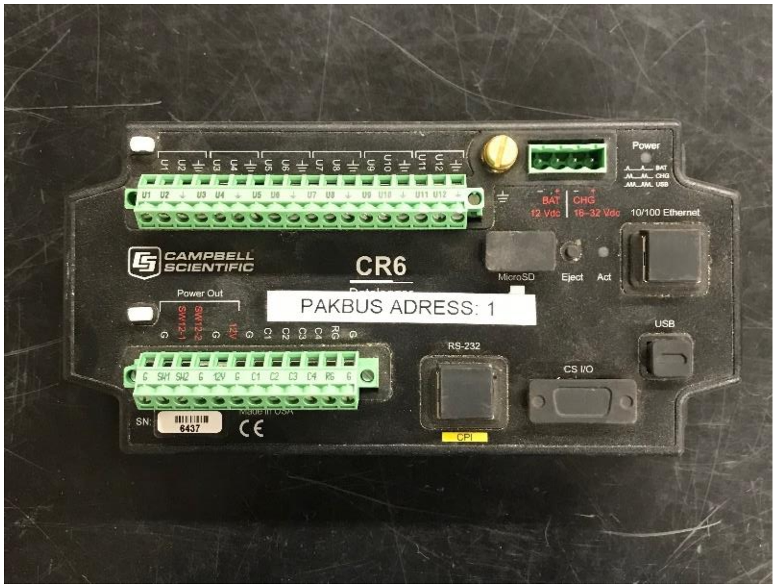


Figure 5.5 CR6 Datalogger

5.2 Data Collection Software

The software used in this project is a product of Campbell Scientific called Loggernet. Loggernet uses a programming language called CRBasic to manipulate the data collection system. Campbell Scientific also provides a user-friendly way to create a CRBasic program through their Shortcut application. Shortcut allows for a new user to easily step through the process of creating a program without having to know the commands associated within it. For this project, the Shortcut application was used to build an initial program which provided the large majority of the program that was needed. Once the initial program was built using shortcut, it was opened in Campbell Scientifics CRBasic program editor for further refining. Due to the large number of strain gages (94) and the sampling rate (33 Hz), the data collection system was operating at its upper limit. Therefore, many of the generic battery voltage and temperature measurements that are typically used to monitor the CDMs and CR6 needed to be removed from the program to allow for a sampling rate of 33 Hertz. A step by step tutorial of how to build the program and the final code used for this project can be found in Appendix C.

When testing was in progress the data collection system was collecting readings from all 94 strain gage sensors at a rate of 33 samples per second. Due to the large amount of data being continuously collected the data collection system needed to continuously write data to a file on a laptop connected to the system. The file was written in a binary data format during the testing to allow the system to keep pace with the speed of the strain gage sampling rate. Once testing was completed, an application in the Campbell Scientific software called Card Convert was used to convert the binary file into an ASCII file which could then be imported into Microsoft Excel for post processing.

Chapter 6 Finite Element Modeling

The finite element model of the SH-36 Bridge over Bear River is presented in this chapter. Unlike the first phase of the project in which one span of this bridge was modeled, the revised model includes both spans, the cap beam, and the three columns at the center pier. The commercial finite element analysis software ANSYS was used to model the bridge. (“ANSYS Mechanical APDL” n.d.) The input data on bridge dimensions and materials were obtained either from the bridge structural plans or obtained at the bridge site.

6.1 Introduction

Finite element analysis is a method of simulation based on the Finite Element Method (FEM) founded in the 1940s. One of the first individuals to contribute to the development of FEM in structural engineering was Dr. Ray William Clough. FEM was created as a numerical technique to find approximate solutions for partial differential equations. This method is based on breaking a problem into smaller pieces called finite elements. The main capability of FEM is the ability for detailed visualization of bending and torsion for a structure. For developing and simulating the finite element models in this project, ANSYS 18.1, a general-purpose FE software was used. The model consisted of replicating four main components of the bridge. The four main bridge components are the deck, girders, columns, and cap beam. These components were modeled using two different types of elements. These elements are beam and shell elements.

6.2 Shell Elements

Shell element 181 was used to model the deck structure on the SH-36 bridge. According to ANSYS, SHELL 181 is suitable for analyzing thin to moderately thick shell structures and is a four-node element with six degrees of freedom at each node: translations in the x, y, and z directions, and rotations about the x, y, and z-axes. SHELL 181 is well-suited for linear, large rotation, and/or large strain nonlinear applications. (“Shell 181 Element Description” 2019)

Shell elements are used in this project to model the concrete overlay and deck portion of bridge girders. The thickness of the shell elements vary in both the transverse and longitudinal direction. The data for the thickness was obtained through survey data of the bridge. Due to the variations of thickness in both the transverse and longitudinal directions 72 different sections were introduced into the model to account for all the different shell elements. The size of the shell elements used in this project are 4 in. in the transverse direction by 6 in. in the longitudinal direction. Figure 6.1 shows the cross section of the modeled bridge and the variations in deck thickness across the width of the bridge.

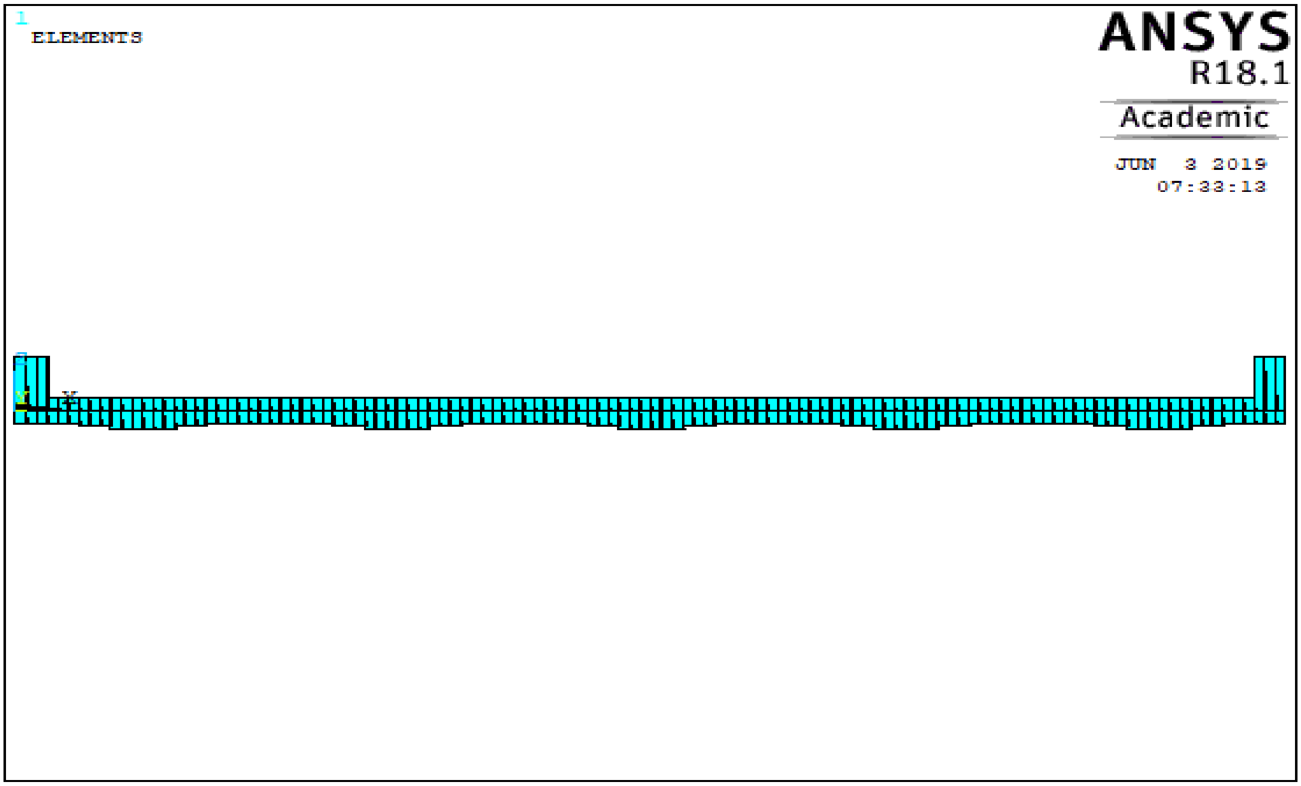


Figure 6.1 Cross Section of Modeled Bridge Deck

6.3 Beam Elements

For this project, the BEAM188 element was used to model the web and bottom bulb of the bridge girders. BEAM188 is suitable for analyzing slender to moderately stubby/thick beam structures. The element is based on Timoshenko beam theory which includes shear-deformation effects. The element provides options for unrestrained warping and restrained warping of cross-sections. The element is a linear, quadratic, or cubic two-node beam element in 3-D. BEAM188 has six or seven degrees of freedom at each node. These include translations in the x, y, and z directions and rotations about the x, y, and z directions. A seventh degree of freedom (warping magnitude) is optional. This element is well-suited for linear, large rotation, and/or large strain nonlinear applications. (“Beam 188 Element Description”)

Figure 6.2 shows the element summary for the beams used to model the girders in this project. The beam elements were placed below the deck at the centroid location of the girders. The dimensions given to the beam elements in this model are the dimensions in the plans and confirmed at the precast plant where the girders were made. Figure 6.3 shows the cross section of the modeled deck and girders.

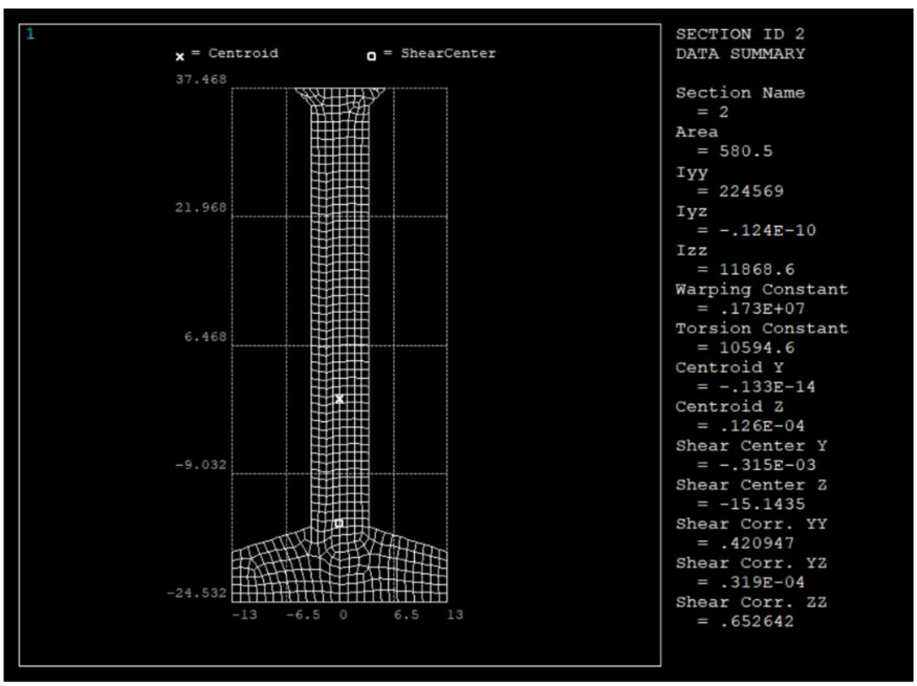


Figure 6.2 Beam Element Summary

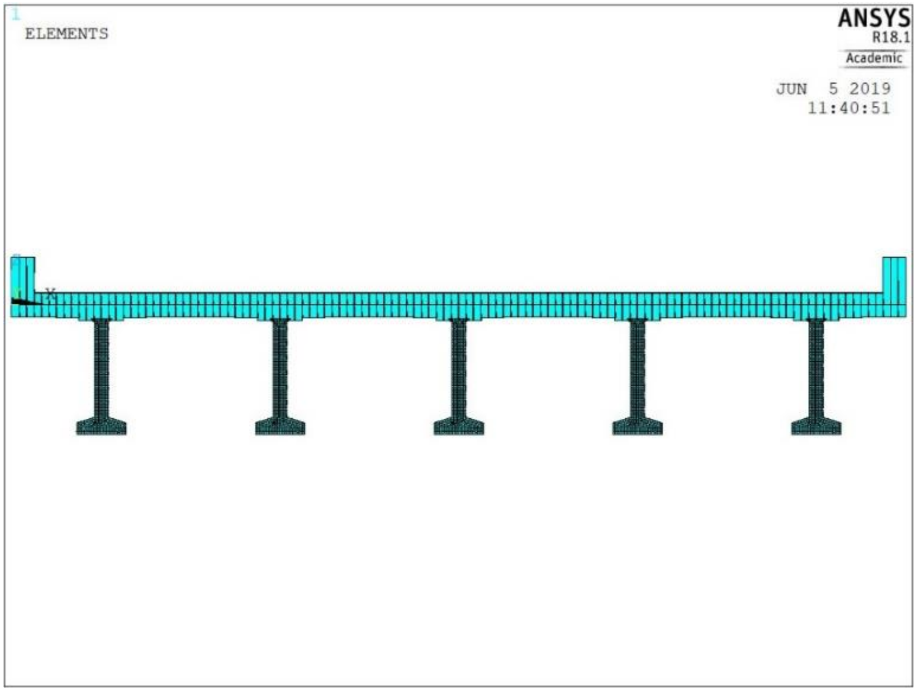


Figure 6.3 Cross Section of Modeled Deck and Girders

The final step in creating the model was to model the columns and cap beam. These were modeled by using the beam elements as well. The SH-36 bridge consisted of three columns and one cap beam at the center of the bridge. Figure 6.4 shows the model including the columns and cap beam. The bridge supports were assumed to be fixed at the base of all columns and at the two ends of the bridge for one test and fixed at the base of all columns and roller supports at the ends of the bridge for the second test.

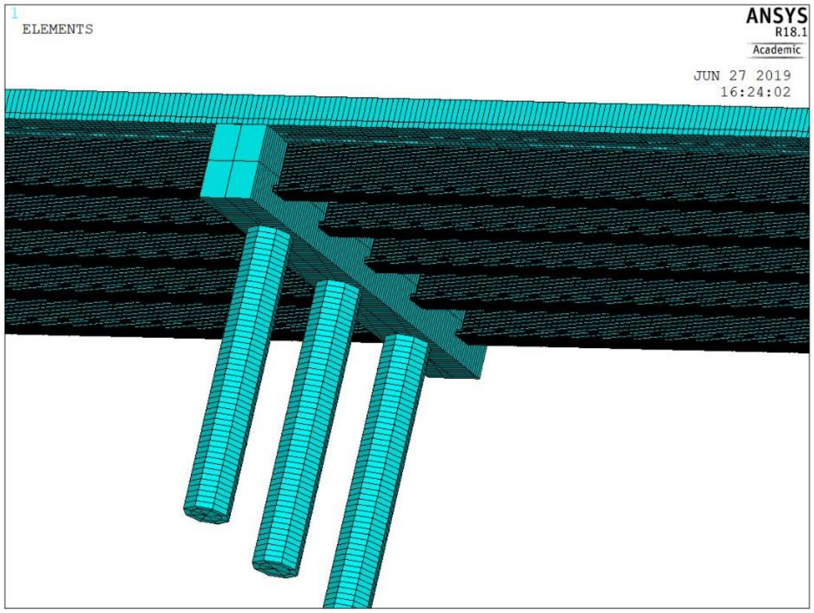


Figure 6.4 Columns and Cap Beam

6.4 Model Assumptions

The analysis of the model consisted of linear elastic materials. This was done since no part of the bridge was to see any permanent (nonlinear) deformation. The modulus of elasticity used for the bridge girders in this analysis was calculated using American Association of State Highway and Transportation Officials (AASHTO) equation for concrete with compressive strengths greater than 5,000 psi since the girders had a compressive strength of 10.7 ksi. The equation is shown below.

$$E_c = 33{,}000 * (0.14 + 0.001 * f_c')^{1.5} * \sqrt{f_c'} \tag{6.1}$$

where:

$E_c - Modulus\ of\ Elasticity\ of\ Concrete\ (ksi)$

$f_c' - Concrete\ Compressive\ Strength\ (ksi)$

The cap beam and columns have compressive strengths of 5 ksi or less so the following AASHTO equation was used to determine the modulus of elasticity.

$$E_c = 33{,}000 * 0.145^{1.5} * \sqrt{f_c'} \tag{6.2}$$

The Poisson ratio used for this model was assumed to be 0.2. The Loading of the bridge in ANSYS was done at the same locations as in load testing with the UBIT vehicles. For the FE model, only load tests 1.1 through 1.6 and 2.1 through 2.6 were analyzed. The weights of the axles for each UBIT was used for load testing of the FE model. The only issue with loading the model bridge in this project was that the tire loads were not able to be placed at the same location as the field tests. The tires were offset two inches due to the arrangements of the elements. To fix this issue, two simulations were run; one with tire offsets upstream of the instrumented area, and one downstream. Then by averaging the data from the two, a more realistic strain is obtained for the actual loading conditions. Another issue that was the strain gage locations on the model were located inside elements and not on the border of elements where results are calculated. So, in order to obtain data for the location where the strain gages were, linear interpolation was used between the edges nearest to the strain gage locations to obtain more accurate results. The results of FE modeling can be found in Chapter 7.

Chapter 7 Results

This chapter reviews the results from load testing and computer modeling of the SH-36 Bridge over Bear River. There are three main sections: static loading results, dynamic loading results, and computer modeling results. Load tests were performed with vehicles of both known and unknown weights. Tables and graphs have been produced to summarize and simplify the results.

7.1 Static Loading Results

Static Loading consisted of using ITD Under Bridge Inspection Trucks (UBIT) of known weight in various positions on the bridge. Further information on the load positions used in this project can be found in Chapter 4. For each load position the data collection system was zeroed, the vehicle would then drive onto the bridge and park in several locations. The truck would remain parked for about 15 seconds to allow any dynamic effects to settle out and then the truck would pull off the bridge to complete the test. For the duration of each load case, traffic would be stopped so the only strain observed would be the strain caused by the UBIT vehicles.

Figure 7.1 Static Loading

For each test, all 94 strain gages recorded at a rate of 33 samples per second. After testing was completed for each day, the data would be exported from the data collection system in a text file. The text file would then be imported into Microsoft™ Excel. Once the data was imported into Excel, the rebar strain gages which are located on top and bottom of the rebar at the same location along the length of the rebar were averaged to obtain an average strain at that location on each instrumented rebar. Once the appropriate strain gages were averaged, individual Excel sheets were made for each load case. This was done to reduce the amount of data and organize each load case onto its own Excel sheet. For each load case, eight graphs were made to show the rebar and concrete strain occurring in each closure pour. For each closure pour, two graphs were made. One for the eight rebar gage averages and one for the six concrete gages. Figures 7.1 and 7.2 show the graphs for Closure Pour 1 for load Test 1.1. The naming convention used for these graphs start with the UBIT vehicle which was used for the test, followed by which load case was being performed. The next part identifies the closure pour which is graphed and finishes with either the rebar or concrete gages. All phases of the load test can be seen in these graphs. The data collection system was zeroed at record number 500, the small UBIT then travelled onto the bridge and parked on the designated location from approximately record number 2000 to 2500, the truck then backed off the bridge to complete the Load Test 1.1. A total of 12 different static loading cases were conducted. Six tests were for the small UBIT and six tests for the large UBIT.

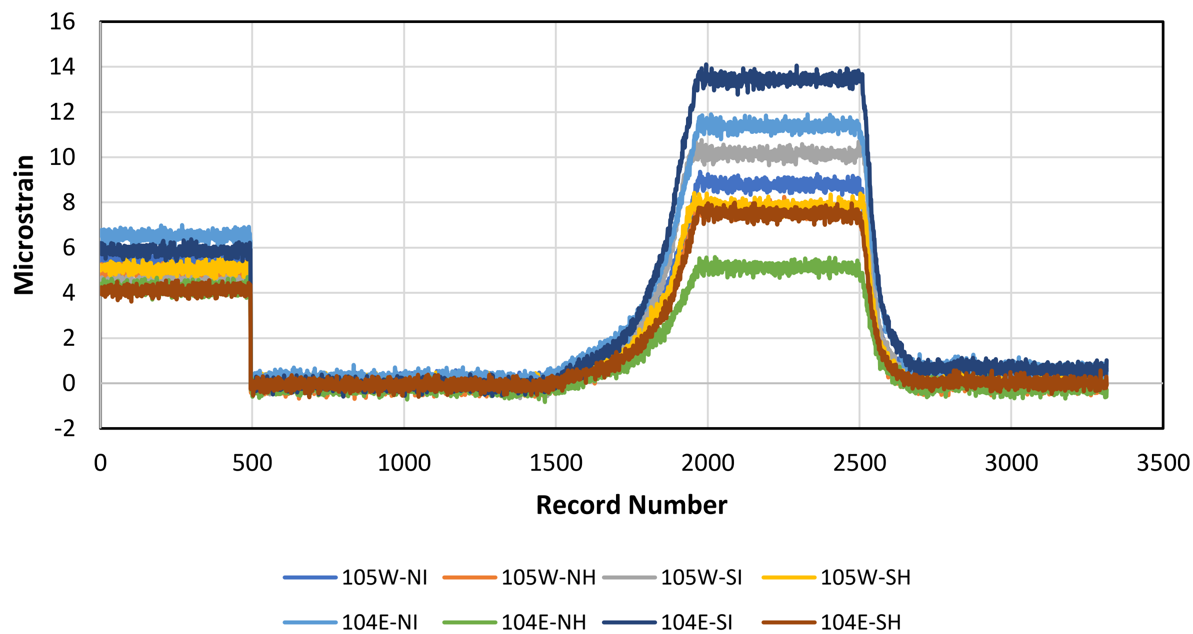


Figure 7.2. Rebar Strain Data in Closure Pour 1 for Test 1.1 (Small UBIT)

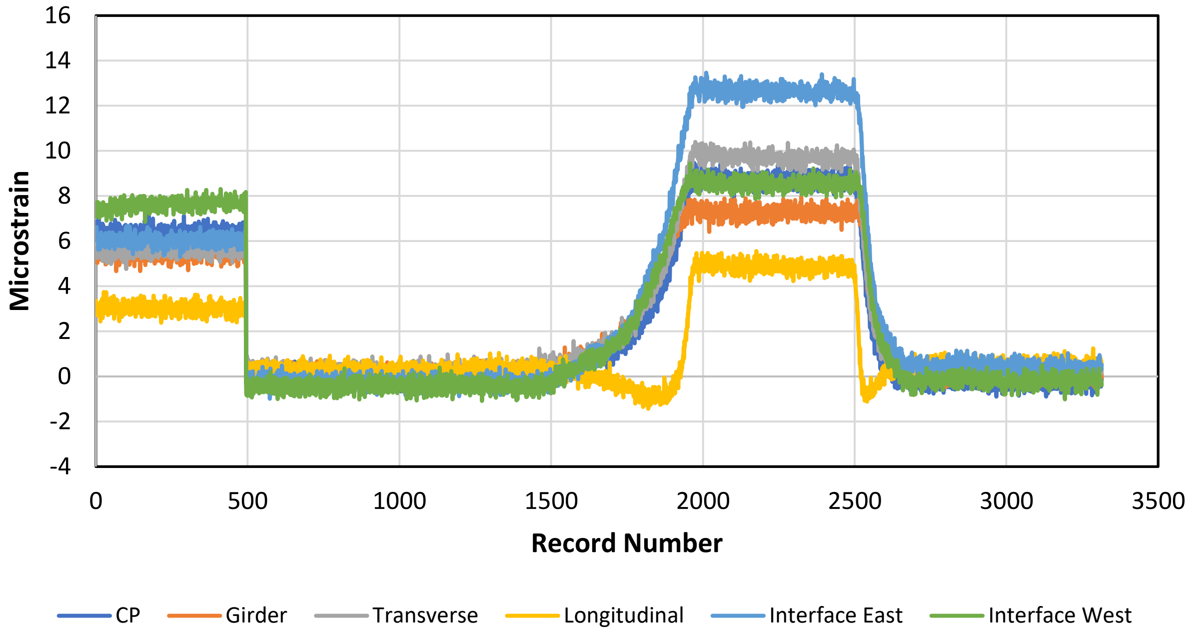


Figure 7.3. Concrete Strain Data in Closure Pour 1 for Test 1.1 (Small UBIT)

After all graphs were made for the UBIT loadings, Tables D.1 and D.2 in Appendix D were prepared to summarize the strain data from the UBIT loadings. One table was made to summarize the concrete strain gages and the other summarizes the rebar strain gages. The 16 rebar strain gages in each closure pour were averaged to get four values. Figure 3.2 shows the location where the rebar strain gages were installed on each rebar. In each closure pour there were four instrumented rebars of which two are from each girder. The four rebar strain gages closest to the rebar head on one girder were averaged and the four closest to the interface were also averaged. The same was done with the other girder in the same closure pour connection to get the four values of interface east, head east, interface west, head west. The concrete gages were reported individually. From Tables D.1 and D.2 it can be observed that strain in Closure Pour 2 is much larger than the other closure pour connections. This trend was observed throughout the project for both static and dynamic loads.

The next step in summarizing the static loading consisted of summarizing the maximum values of strain from the concrete strain gages in each closure pour for each load test. Along with noting the maximum concrete strain in each closure pour, the location of the largest concrete strain was also noted. In Tables D.3 and D.4 of Appendix D the maximum rebar strain of all instrumented rebars was also included along with the corresponding rebar stress and the location where the maximum rebar strain was observed.

After the maximum values were summarized, the next step involved creating graphs of the front wheel force versus strain to compare the effects of the small and large UBIT vehicles which is shown in Figures 7.3 and 7.4. Figure 7.4 shows the bilinear graph created using the maximum values observed in the concrete strain gages. Figure 7.5 shows the bilinear force versus strain graph created for the rebar strain gages. This was done to determine if a linear trend could be observed between the strain of the small and large UBIT vehicles. To do this, two graphs were made; one for concrete gages and one for rebar strain gages. For each graph, only the interface strain gages were considered since the interface was the area which saw the most strain. As noted earlier, it was also observed throughout the data analysis process that Closure Pour 2 had significantly higher strains than the other three closure pours so it was decided to graph data for Closure Pour 2 separately on the same graph. It was also observed that, in each closure pour, one interface had larger strains in both the rebar and concrete gages than the other closure pour. It can be argued that the strains at the two interfaces of a closure pour connection are not independent of each other and reporting both values would not be conservative. For this reason, it was decided to include the mean and the standard deviation of the larger interface concrete and rebar strains for the comparisons shown in Figure 7.3 and 7.4.

Each graph consists of four data points. Two data points correspond to the small UBIT; one for Closure Pour 2, and one for Closure Pours 1, 3, and 4. The other two data points correspond to the large UBIT loading in the same way as the small UBIT. Each of these four points is an average of the six maximum values observed in the interface strain gages while the corresponding closure pours were directly loaded by the UBIT vehicles during the six direct loading positions. The points were then connected with lines to determine if a linear trend is observed between the two UBIT vehicles. Error bars were also included which represent one population standard deviation on each side of the data point.

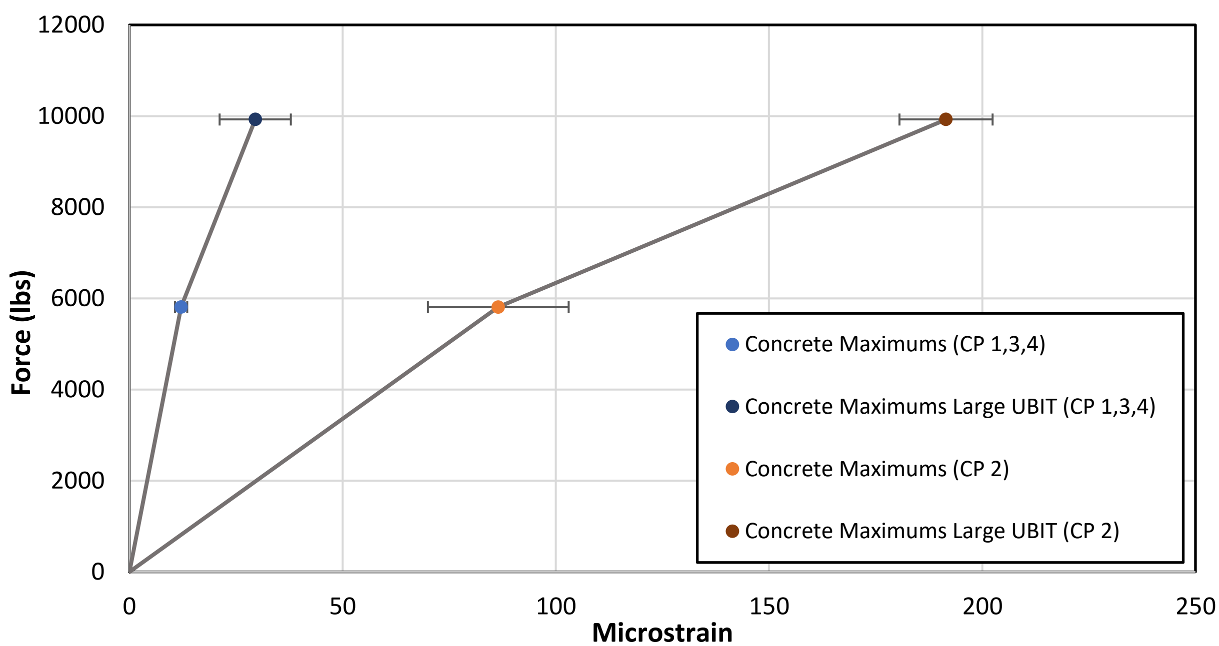


Figure 7.4 Bilinear Front Wheel Force vs Strain for UBIT Loading (Concrete Strain Gages at the Interface)

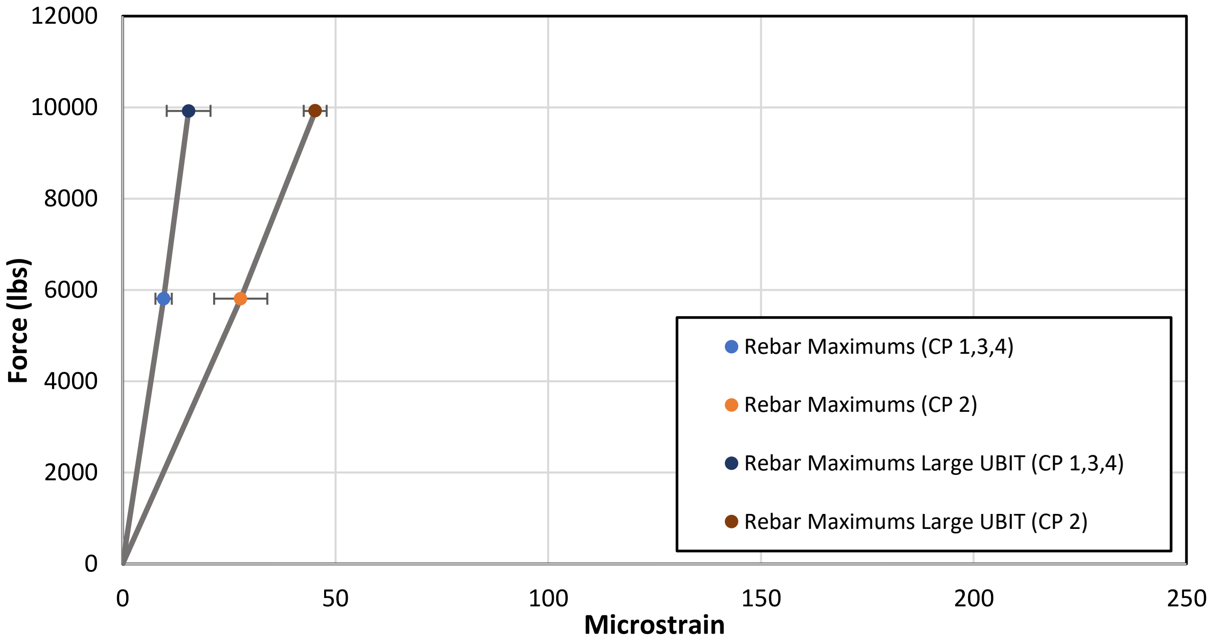


Figure 7.5 Bilinear Front Wheel Force vs Strain for UBIT Loading (Rebar Strain Gages at the Interface)

The rebar behaved linearly between the Small UBIT and the Large UBIT vehicles. The concrete strain gages did not behave in the same linear fashion. This could be partially due to the nonlinear behavior of concrete. Figure 7.6 shows a typical stress vs strain graph for concrete. In Figure 7.6, the line representing the concrete deviates from the initial tangent modulus at very small stress values compared to the concrete's ultimate strength. This continuous softening of the concrete in Figure 7.6 is a possible reason for the nonlinear behavior seen in Closure Pours 1, 3, and 4. Closure Pour 2 shows much higher strain values than the other three closure pours for the concrete strain gages. More conclusions on the nonlinearity are discussed in the next chapter.

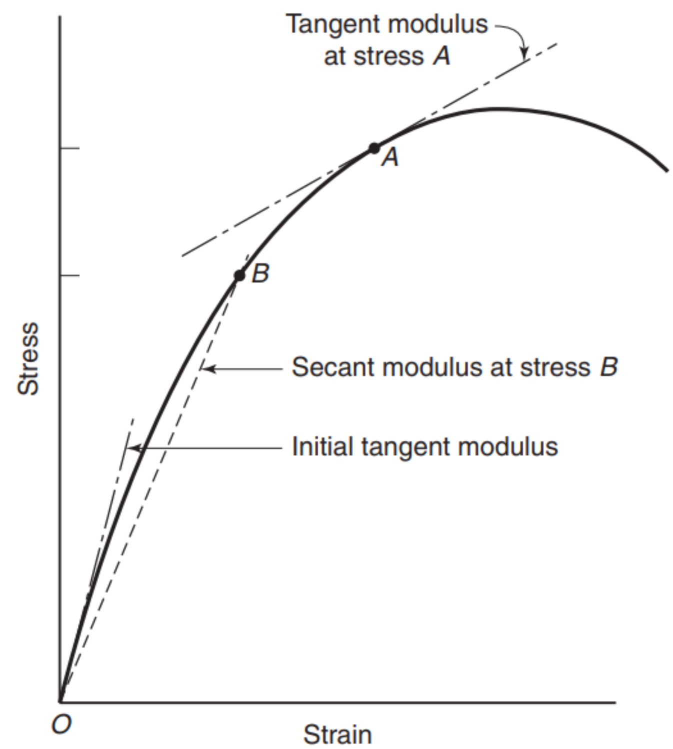


Figure 7.6 Stress vs Strain Curve for Concrete (Wight 2016)

7.2 Dynamic Loading Results

Dynamic loading of the bridge consisted of both UBIT vehicles and commercial traffic. For the UBIT vehicles, the dynamic load tests consisted of a 10 mph and a crawl speed (approximately 3 mph) test. Figures 7.7, 7.8, 7.9, and 7.10 show dynamic loading strain data for the small and large UBIT trucks. Figures 7.7 and 7.8 show data for Closure Pour 2 whereas Figures 7.9 and 7.10 show strain data for Closure Pour 3. The concrete strain data is the strain from the larger of the two concrete interface strain gages. The rebar strain data is the data from the rebar that corresponds to the larger concrete interface. It can be seen in these figures that there is not much of a difference in strain between the different travel speeds in this project. The results of this project show that the strain observed throughout the load tests were all within the approximate yield strain of 140 microstrain for concrete except for Closure Pour 2. Closure Pour 2 went above this threshold at times but no visible cracks appeared under the bridge during controlled load testing. Also, the rebar strain data was all within the yield strain of 2,069 microstrain for the steel reinforcement.

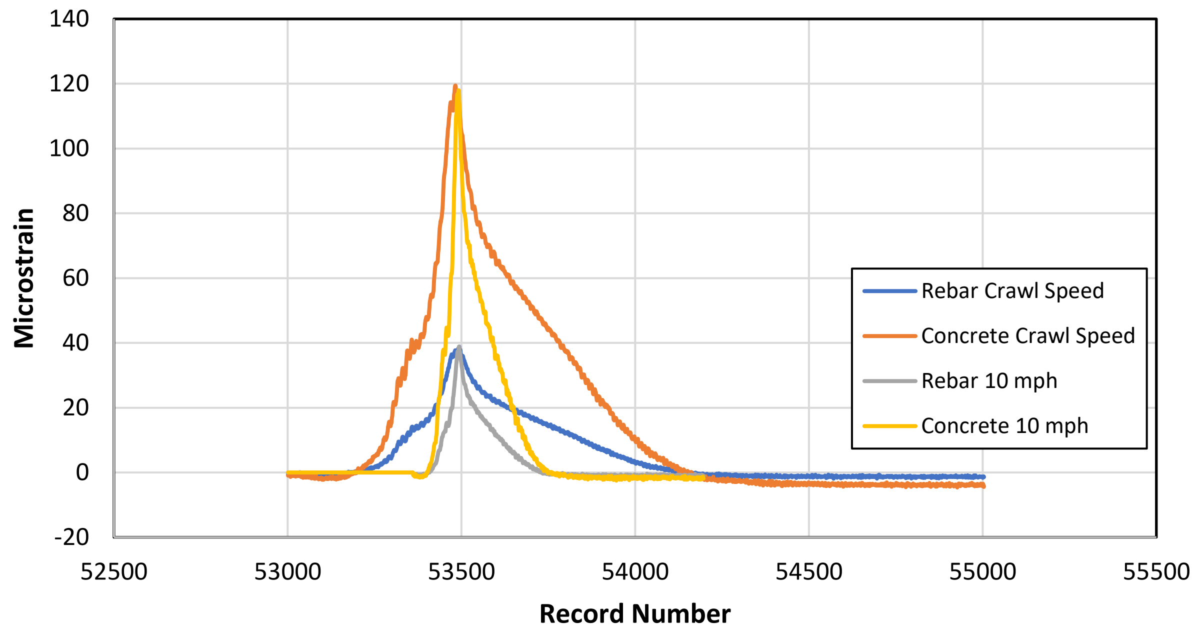


Figure 7.7 Dynamic Interface Maximum Strain Data in Closure Pour 2 for the Small UBIT

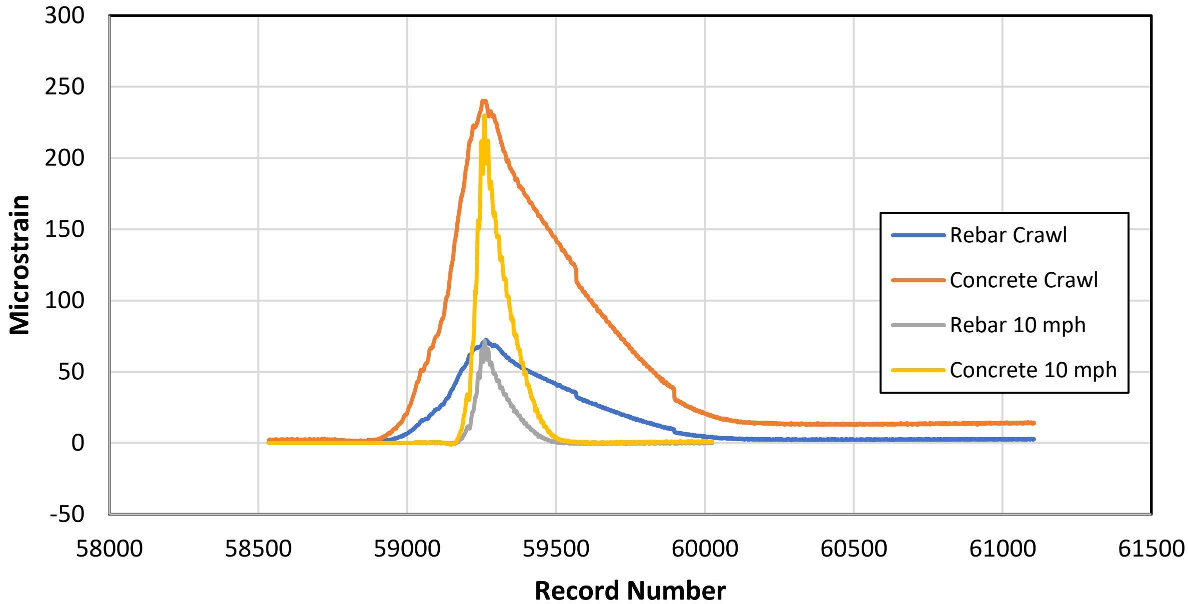


Figure 7.8 Dynamic Interface Maximum Strain Data in Closure Pour 2 for the Large UBIT

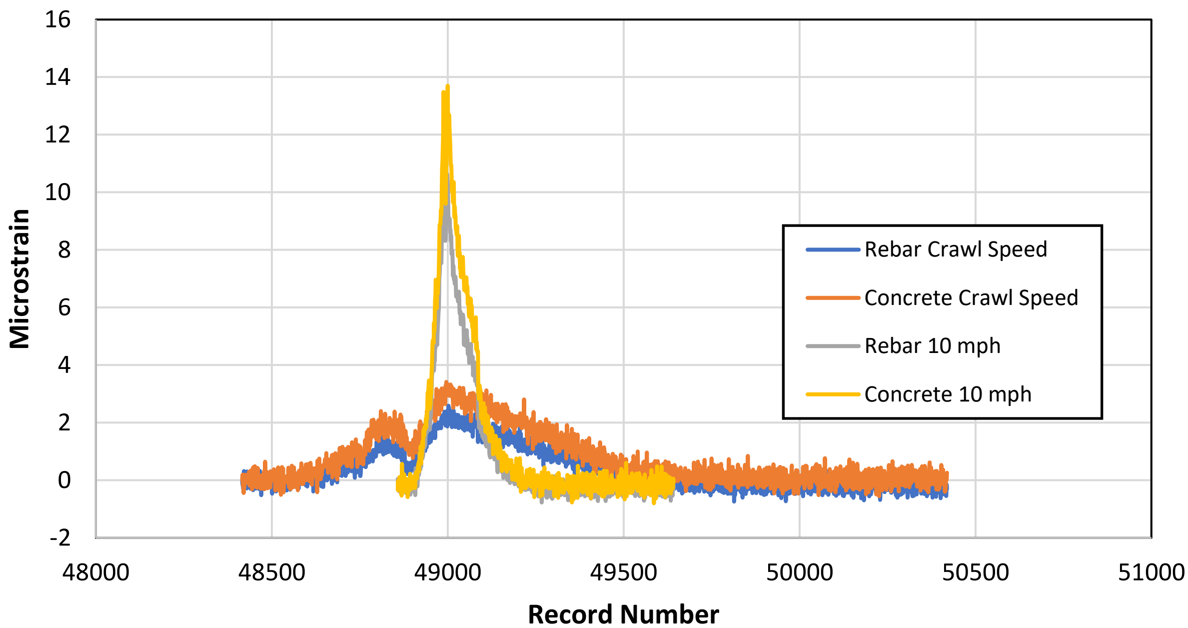


Figure 7.9 Dynamic Interface Maximum Strain Data in Closure Pour 3 for the Small UBIT

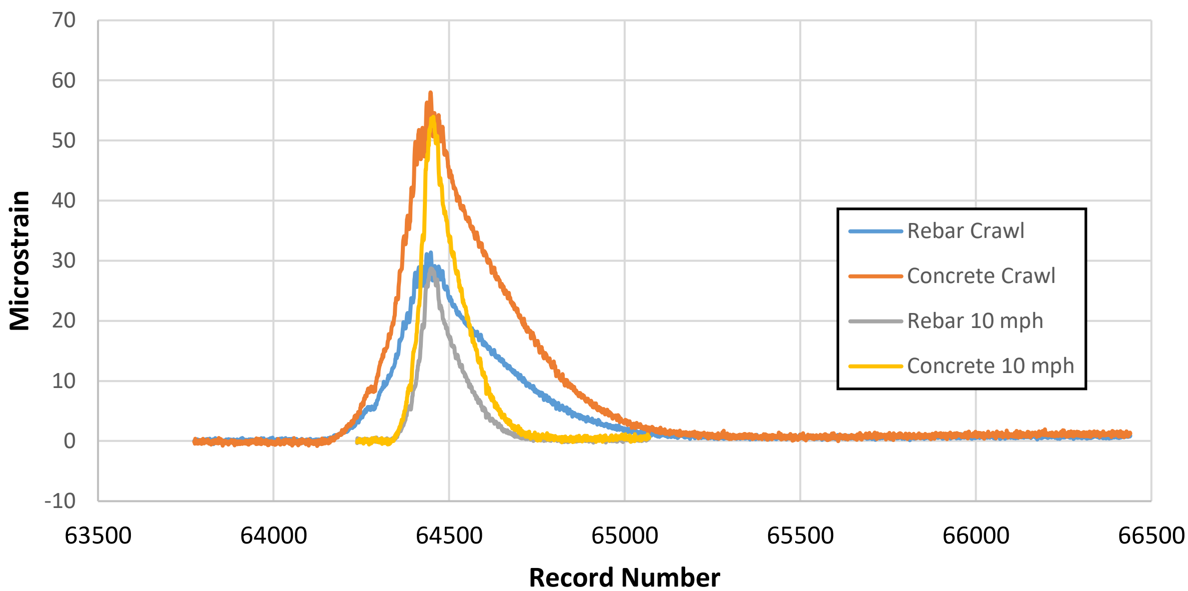


Figure 7.10 Dynamic Interface Maximum Strain Data in Closure Pour 3 for the Large UBIT

Commercial traffic loading consisted of 20 hours of data collection where vehicles with more than two axles were recorded. The purpose of the commercial loading is to observe strain in the bridge during normal vehicle traffic. Once data was collected for each day, it was imported into Excel where the rebar strain data could be averaged in the same way as was done for the static loading data. After the averaging, the data could then be separated so the data for each event was analyzed separately. Once the data was separated into individual events, two graphs were made for each closure pour; one for rebar gages and one for concrete strain gages. This gave a total of eight graphs for each individual event. After all graphs were made, the maximum value of strain for the concrete strain gages for each closure pour was recorded into a table along with the location of the largest concrete strain observed throughout all the concrete strain gages. The maximum rebar strain which was observed and the location where it was recorded at was also noted in the table along with the corresponding stress in the rebar. This information can be found in Appendix D in Table D.5. The final graphs which were made consisted of graphing the maximum strain in each closure pour for each truck event. A total of eight graphs were made; four for rebar strain gages (one for each closure pour), and four for the concrete strain gages (one for each closure pour). The graphs show the strain vs the number of axles for each individual event. Different symbols were given to eastbound and westbound traffic to show the trend each direction of travel has on each closure pour. Figure 7.11 shows the completed graph for the concrete strain gage maximums in Closure Pour 3 for the commercial traffic. Figure 7.12 shows the rebar strain maximums in Closure Pour 3 for commercial traffic. The remaining graphs for commercial traffic can be found in Appendix D.

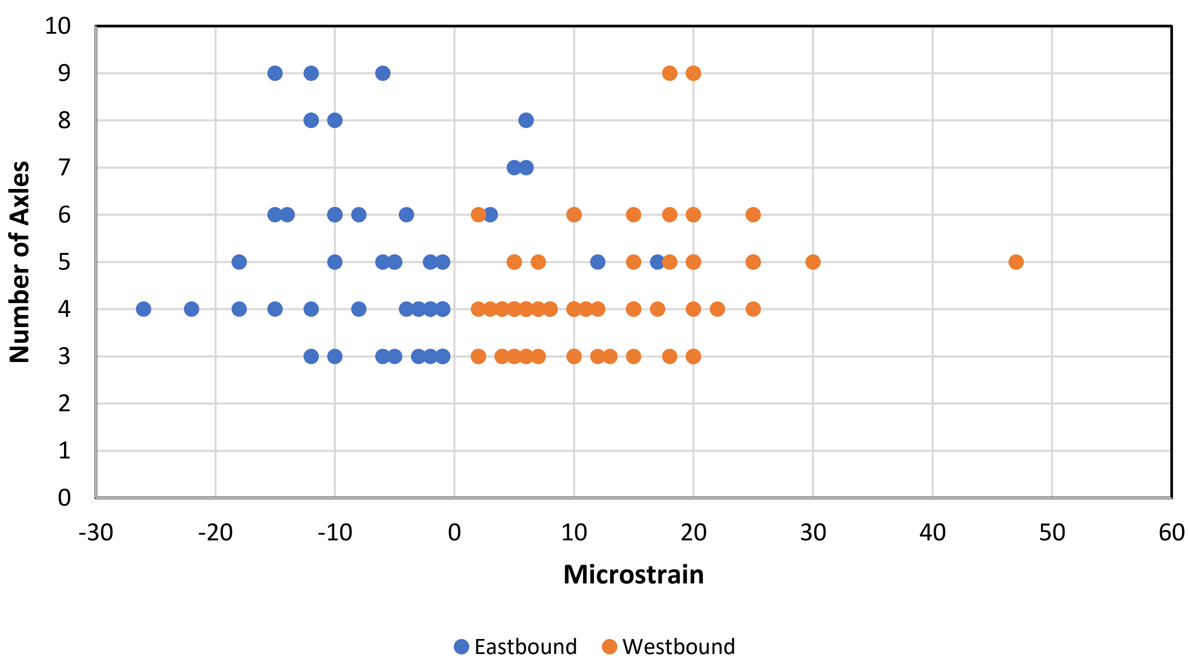


Figure 7.11 Maximum Concrete Strain in Closure Pour 3 Versus Number of Axles for Commercial Traffic

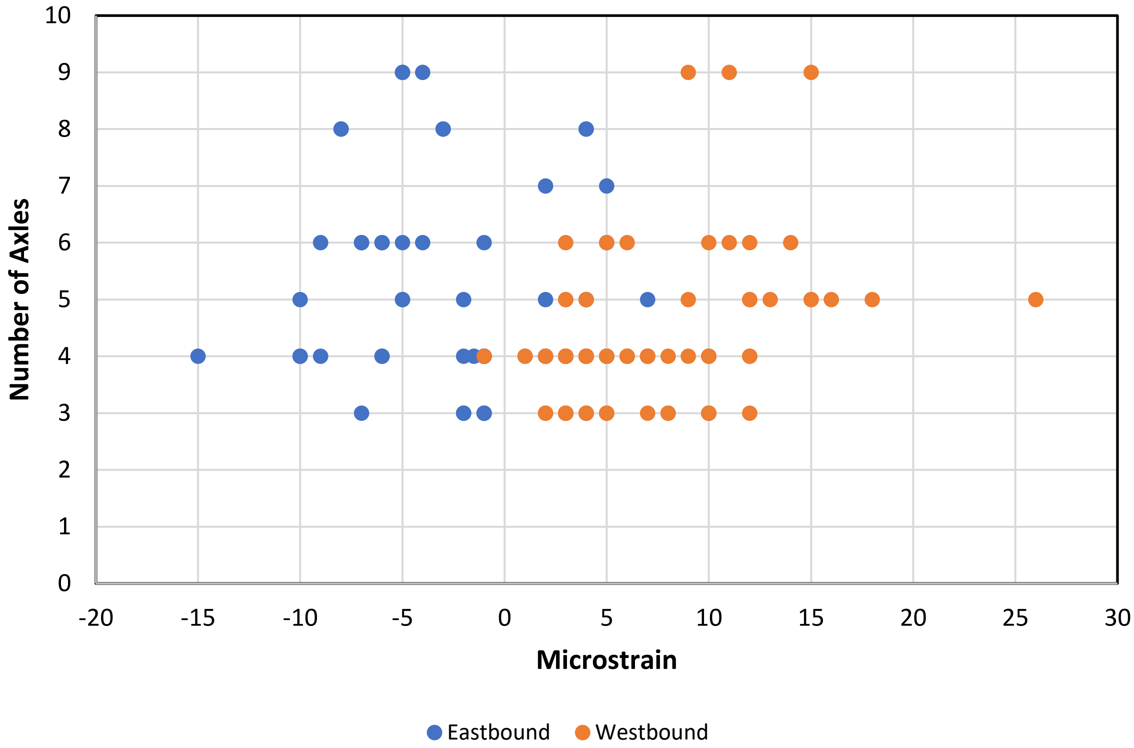


Figure 7.12 Maximum Rebar Strain in Closure Pour 3 Versus Number of Axles for Commercial Traffic

7.3 Finite Element Results

For the finite element analysis done in this project, Load Cases 1 and 2 were analyzed. For Load Case 1, the front tires loads were applied using pressures with the same area as the UBIT truck tires. The rear tires were then applied as point loads as the rear tires are not located near the instrumented area and applying pressures is not required at such distances. For Load Case 2, all loads from tires were applied using point loads as they were further away from the instrumented area.

Table 7.1 shows the results for Load Case 1 where the closure pours were directly loaded at the location of instrumentation. The numerical results match up with the experimental data well except at Closure Pour 2 which was expected.

Table 7.1 FE Results for Load Case 1

	Small UBIT		Large UBIT	
Load Case	Experimental Average Strain at Interface	Numerical Average Strain at Interface	Experimental Average Strain at Interface	Numerical Average Strain at Interface
1.1	11.0	9.9	18.3	17.3
1.2	45.0	9.5	172.5	16.9
1.3	84.5	11.0	171.3	18.8
1.4	11.5	10.2	19.5	18.5
1.5	11.0	10.1	17.5	18.0
1.6	8.5	9.4	19.0	17.2

Table 7.2 and Table 7.3 show the small and large UBIT experimental and finite element results for Load Case 2. The values represent the average of two girder bulb strains. As previously stated, the model was run twice with different support conditions. The first condition was to assume that all supports were rigid or fixed. The second condition was assuming that only the column base connections were fixed and to have roller connections at the ends of the bridge. From the following tables it can be seen that the actual support conditions of the bridge are somewhere between the two assumptions. Some results for Load Case 2 are not as close to the experimental as Load Case 1. This could be due to the load being applied further away from the instrumented area. Since the load is located further away there are more factors that can influence the results. Even with some of the data being a little off, most of the numerical modeling showed good results and are well within range of the

experimental results to be considered accurate. More detailed tables on the finite element model and results can be found in Appendix D.

Table 7.2 Experimental and FE Bulb Strain Results for Load Case 2 (Small UBIT)

	Experimental			Numerical (All Supports Fixed)			Numerical (Columns Fixed, Rollers at Ends of Bridge)		
Load Case	Girder 102	Girder 103	Girder 104	Girder 102	Girder 103	Girder 104	Girder 102	Girder 103	Girder 104
2.1	3	6.5	6	0.34	2.61	2.10	9.68	13.69	13.71
2.2	1	-1	-1	-5.74	-7.63	-7.79	6.83	6.41	7.28
2.3	-1	-2	-2	-4.85	-5.71	-6.01	3.21	3.07	3.42
2.4	6	7	3	2.10	2.61	0.34	13.71	13.69	9.68
2.5	-1	-1	0.5	-7.79	-7.63	-5.74	7.28	6.41	6.83
2.6	-2	-2	-1	-6.01	-5.71	-4.85	3.42	3.07	3.21

Table 7.3 Experimental and FE Bulb Strain Results for Load Case 2 (Large UBIT)

	Experimental			Numerical (All Supports Fixed)			Numerical (Columns Fixed, Rollers at Ends of Bridge)		
Load Case	Girder 102	Girder 103	Girder 104	Girder 102	Girder 103	Girder 104	Girder 102	Girder 103	Girder 104
2.1	5	13	12.5	0.54	3.26	2.54	17.20	23.24	23.55
2.2	2.5	-1.5	-1.5	-10.90	-15.15	-15.41	16.15	15.33	17.31
2.3	-2	-5	-5	-11.16	-13.30	-13.97	7.77	7.42	8.29
2.4	12	12	5	2.54	3.26	0.54	23.55	23.24	17.20
2.5	0	-1.5	2	-15.41	-15.15	-10.90	17.31	15.33	16.15
2.6	-4.5	-5	-1.5	-13.97	-13.30	-11.16	8.29	7.42	7.77

Chapter 8 Summary, Conclusions, and Future Work

The purpose of this research project was to determine the adequacy of high early strength (HES) concrete for use in closure pour connections between bridge girders. Specifically, the objectives were to assess the performance of HES concrete used in the connection detail of SH-36 Bridge over Bear River and create a finite element model of the bridge for confirmation of some of the experimentally obtained data. This chapter summarizes the experimental and numerical results of this research. The conclusions reached from this research project will also be discussed as well as the possibility of future work on the long-term performance of the connections.

8.1 Static Loading Summary

The static loading done in this project consisted of using Under Bridge Inspection Trucks (UBIT) vehicles of known weight to induce direct loads on the closure pours at the location of instrumentation. These same vehicles were also used to load the bridge at ¼, ½, and ¾ span locations to observe the global behavior of the closure pour connection. The goal of using two different UBIT vehicles was to observe the change between the two vehicles and determine if the strain observed in the bridge increased linearly between the two vehicles. It was also observed that the concrete strain data was all under the modulus of rupture strain threshold of approximately 140 microstrain except for Closure Pour 2 which was expected. The strain data for rebar was all under the yield strain for steel reinforcement.

8.2 Dynamic Loading Summary

Dynamic loading in this project consisted of using the same UBIT vehicles from the static loading as well as the dynamic load caused by normal traffic on the bridge for larger vehicles. The UBIT dynamic loads performed involved the UBIT vehicles traveling across the bridge on the centerline at both a crawl (approximately 3 mph) and 10 mph speed. Results were obtained and recorded and graphs showed that there were minimum dynamic effects present between the different travel speeds used in this project. Similar to the static strain results, the UBIT and normal traffic strain data for the concrete strain gages only exceeded the modulus of rupture strain threshold at Closure Pour 2. All rebar strain gages stayed within the yield strain threshold.

8.3 Finite Element Summary

For this project a finite element model was created to replicate the SH-36 bridge. Shell and beam elements were used to model the deck, girders, cap beam, and columns of the bridge. All supports were assumed to be fixed in the first analysis whereas only the columns were fixed and the ends of the bridge were assumed to be roller supports for the second analysis. Both analyses were done under the assumption of linear elastic behavior. The model was analyzed using Load Cases 1 and 2 from the experimental portion of this research. Results were obtained and compared to the experimental results for confirmation of experimental testing.

8.4 Conclusions

In this research project it was determined that the use of HES concrete is feasible for use in connections between deck bulb tee girders. The levels of strain observed in this project are all within the linear elastic range of concrete except for the material in the instrumented location of Closure Pour 2. There were a few reasons for why Closure Pour 2 may not have performed as well as the other closure pours. Closure Pour 2 was the last to be placed sometime in November so the cold weather could have influenced the bond between the two concrete surfaces. When the bridge deck was poured there were heaters used underneath the bridge to help provide warmth to cure the concrete properly, but no heaters were present for the closure pour connections. It was also observed during construction that the exposed aggregate surfaces were not wetted before placement of new concrete against the surface. Research done by Casanova et al. (2018) found that wetting the exposed aggregate surface before placement of new concrete makes a significant difference in the bond strength between the two surfaces. Also, Idaho Transportation Department (ITD) Standard Specification for Highway Construction states in Subsection 501.03 G states that the contractor should clean the construction joint surface and saturate it with water immediately prior to concrete placement (*Idaho Transportation Department Standard Specifications for Highway Construction* 2018). Construction deviation could be another potential source. Finite element analysis further confirmed the results obtained experimentally. The finite element results for the strains at the closure pour concrete to precast interface under directly loaded closure pours matched closely with the experimentally obtained data except for Closure Pour 2. The matching results between experimental and numerically obtained data confirms the conclusion that HES concrete is an acceptable and cost saving alternative to UHPC for use in connections between deck bulb tee girders, provided that the closure pour material installation is done properly.

8.5 Future Work

Future research may be conducted on the SH-36 bridge using the existing instrumentation. This future work consists of replacing strain gages on the concrete surface underneath the bridge to install new strain gages using a method which will increase the expected life span of the instrumentation. The future project will use the same UBIT vehicles to perform load testing multiple times a year on the bridge to observe the long-term performance of the closure pour material.

References

"4WFBS120, 4WFBS350, 4WFBS1K 4-Wire Full-Bridge Terminal Input Modules (TIMs)." (2017). <https://s.campbellsci.com/documents/us/manuals/4wfbs.pdf>.

"ANSYS Mechanical APDL." (n.d.). Canonsburg, PA.

Barr, P. J., Woodward, C. B., Najera, B., and Amin, M. N. (2006). "Long-term structural health monitoring of the San Ysidro Bridge." *Journal of Performance of Constructed Facilities*, 20(1), 14–20.

"Beam 188 Element Description." (n.d.). <https://ansyshelp.ansys.com/account/secured?returnurl=/Views/Secured/corp/v190/ans_elem/Hlp_E_BEAM188.html?q=Beam188>.

Bell, E. S., Lefebvre, P. J., Sanayei, M., Brenner, B., Sipple, J. D., and Peddle, J. (2013). "Objective Load Rating of a Steel-Girder Bridge Using Structural Modeling and Health Monitoring." *Journal of Structural Engineering*, 139(10).

Cardini, A. J., and DeWolf, J. T. (2009). "Long-term structural health monitoring of a multi-girder steel composite bridge using strain data." *Structural Health Monitoring*, 8(1), 47–58.

Casanova, M. (2018). "Mechanical Behavior of High Early Strength Concrete With Polypropylene Fibers for Field-Cast Connections of Bridge Precast Elements." Idaho State University.

Chajes, M. J., and Shenton, H. W. (2006). "Using diagnostic load tests for accurate load rating of typical bridges." *Bridge Structures*, 2(1), 13–23.

Hedegaard, B. D., French, C. E. W., Shield, C. K., Stolarski, H. K., and Jilk, B. J. (2013). "Instrumentation and Modeling of I35W St. Anthony Falls Bridge." *Journal of Bridge Engineering*, 18(6), 476–485.

Idaho Transportation Department Standard Specifications for Highway Construction. (2018). Boise, ID.

Jáuregui, D. V., and Barr, P. J. (2004). "Nondestructive Evaluation of the I-40 Bridge over the Rio Grande River." *Journal of Performance of Constructed Facilities*, 18(4), 195–204.

"Leadwire Selection." (2010). <http://www.vishaypg.com/docs/11174/VMM-11.pdf> (Dec. 10, 2018).

"M-Coat F Application Instructions." (2014). <http://www.vishaypg.com/docs/11134/11134B134.pdf> (Dec. 10, 2018).

"Noise Control in Strain Gage Measurements." (2013). <http://www.vishaypg.com/docs/11051/tn501.pdf> (Dec. 10, 2018).

"Preventing and Attacking Measurement Noise Problems." (2001). <https://s.campbellsci.com/documents/us/technical-papers/mnoise.pdf> (Dec. 10, 2018).

Provines, J. T., Connor, R. J., and Sherman, R. J. (2014). "Development of Load Rating Procedure for Railroad Flatcar Bridges through Use of Field Instrumentation. I: Data Collection and Analysis." *Journal of Bridge Engineering*, 19(5).

Rutz, F. R., Asce, M., and Rens, K. L. (2008). "Wind Pressure and Strain Measurements on Bridges. I: Instrumentation/Data Collection System." *Journal of Performance of Constructed Facilities*, 22(1), 2–11.

Sanayei, M., Phelps, J. E., Sipple, J. D., and Bell, E. S. (2012). "Instrumentation, nondestructive testing, and finite-element model updating for bridge evaluation using strain measurements." *Journal of Bridge Engineering*, 17(1), 130–138.

"Shell 181 Element Description." (n.d.). <https://ansyshelp.ansys.com/account/secured?returnurl=/Views/Secured/corp/v190/ans_elem/Hlp_E_SHELL181.html?q=Shell181>.

"Strain Gage Clamping Techniques." (2015). <http://www.vishaypg.com/docs/11090/tt610.pdf> (Dec. 10, 2018).

"Strain Gage Installations for Concrete Structures." (2015). <http://www.vishaypg.com/docs/11091/tt611.pdf> (Nov. 10, 2018).

"Strain Gage Selection: Criteria, Procedures, Recommendations." (2018). <http://www.vishaypg.com/docs/11055/tn505.pdf> (Nov. 10, 2018).

"U.S. Department of Transportation: Federal Highway Administration." (2019). .

Wight, J. K. (University of M. (2016). *Reinforced Concrete: Mechanics and Design*. Pearson, Harlow.

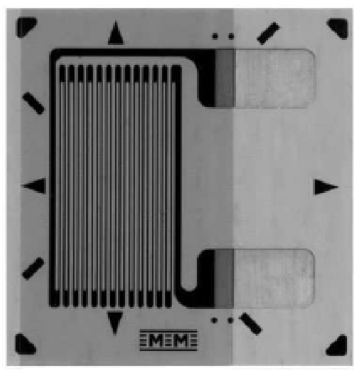
Appendix A Material Data Sheets

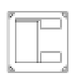
MICRO MEASUREMENTS
A VPG Brand

250UB

General Purpose Strain Gages—Linear Pattern

GAGE PATTERN DATA





actual size

GAGE DESIGNATION See Note 1	RESISTANCE (OHMS) See Note 2	OPTIONS AVAILABLE See Note 3
CEA-XX-250UB-350	350 ± 0.3%	**P2**, SP35

DESCRIPTION

General-purpose gage. Exposed solder tab area is 0.10 x 0.07 in (2.5 x 1.8 mm).

GAGE DIMENSIONS

Legend
ES = Each Section
S = Section (S1 = Section 1)
CP = Complete Pattern
M = Matrix

inch / millimeter

Gage Length	Overall Length	Grid Width	Overall Width	Matrix Length	Matrix Width
0.250	0.310	0.160	0.320	0.42	0.42
6.35	7.87	4.06	8.130	10.7	10.7

GAGE SERIES DATA — See Gage Series datasheet for complete specifications

Series	Description	Strain Range	Temperature Range
CEA	Universal general-purpose strain gages.	±5%	–100° to +350°F (–75° to +175°C)

Note 1: Insert desired S-T-C number in spaces marked XX.

Note 2: Tolerance is increased when Option W, E, SE, LE, P, or SP35 is specified.

Note 3: Products with designations and options shown in **bold** are not RoHS compliant.

Document No.: 11156
Revision: 29-Aug-2016

For technical questions, contact
mm@vpgsensors.com

www.micro-measurements.com
1

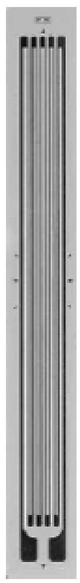
Figure A.1 Rebar Strain Gage Data Sheet

20CLW

MICRO MEASUREMENTS
A VPG Brand

General Purpose Strain Gages—Linear Pattern

GAGE PATTERN DATA



actual size

GAGE DESIGNATION See Note 1	RESISTANCE (OHMS)	OPTIONS AVAILABLE
C2A-XX-20CLW-120	120 ± 0.6%	SP20
C2A-XX-20CLW-350	350 ± 0.6%	SP20

DESCRIPTION

For use on concrete and for strain integration on large specimens.

RoHS COMPLIANT

GAGE DIMENSIONS

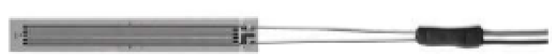
Legend
ES = Each Section
S = Section (S1 = Section 1)
CP = Complete Pattern
M = Matrix

inch / millimeter

Gage Length	Overall Length	Grid Width	Overall Width	Matrix Length	Matrix Width
2.000	2.155	0.175	0.175	2.232	0.235
50.80	54.740	4.450	4.450	56.692	5.969

GAGE SERIES DATA — See Gage Series datasheet for complete specifications

Series	Description	Strain Range	Temperature Range
C2A	Encapsulated constantan gages with preattached ready-to-use cables.	±3%	–60° to +180°F (–50° to +80°C)



Example of a
C2A Construction

Note 1: Insert desired S-T-C number in spaces marked XX.

www.micro-measurements.com
56

For technical questions, contact
mm@vpgsensors.com

Document No.: 11256
Revision: 27-Apr-2017

Figure A.2 Concrete Strain Gage Data Sheet

General Information and Selection

MATERIALS LIST

- Solvent cleaners
- Water-based cleaners
- Surface-abrasion materials
- Special-purpose materials

DESCRIPTION

For proper bonding of strain gages and temperature sensors, the workpiece surface must be chemically clean and totally free of contaminants before applying the adhesive. Recommended surface cleaning procedures for all common structural materials are described in Instruction Bulletin B-129, "Surface Preparation for Strain Gage Bonding".

In the case of steel and aluminum parts with finish-machined or formed surfaces, the surface cleaning procedure can be summarized briefly as follows:

1. Removal of oily contaminants with a solvent cleaner. Note: Immersion of the workpiece in a degreaser is, by itself, inadequate; and, if done as a preliminary step, must be followed by cleaning with an uncontaminated solvent (one which is never returned to the container or otherwise reapplied after contact with the workpiece).
2. Light abrasion in the presence of a mildly acidic wash, to dislodge and remove oxides and mechanically bound contaminants.
3. Thorough surface scrubbing with an alkaline solution, to finish the cleaning process and leave the surface at the appropriate pH level for optimum bonding.

When the cleaning procedure is performed strictly according to the instructions in Instruction Bulletin B-129, and when the proper high-quality cleaning agents are used, the surface will be left in a condition best suited for bonding.

Following is a complete assortment of cleaning supplies, selected specifically for surface preparation in the installation of strain gages and bondable temperature sensors.

SOLVENT CLEANERS	
MODEL/PART NO.	**TYPE/DESCRIPTION**
CSM-3	**Degreaser:** A powerful environmentally friendly degreaser. Readily attacks general-purpose lubricating and hydraulic oils. 20-oz (0.56-kg) pressured spray can. Dispensing solvents from "one way" containers prevents contamination buildup.
GC-6	**Isopropyl Alcohol:** Frequently used as a solvent degreaser where other solutions are restricted, such as with most plastics. Flammable. 4-oz (120-ml) bottle.

WATER-BASED CLEANERS	
Final surface preparation for most materials is accomplished with M-Prep Conditioner A immediately followed by M-Prep Neutralizer 5A.	
MODEL/PART NO.	**TYPE/DESCRIPTION**
CONDITIONER A: A mild phosphoric-acid compound. Acts as a mild etchant and accelerates the cleaning process. Shelf Life: 1 year at +75°F (+24°C).	
MCA-1	2-oz* (60-ml) plastic squeeze bottle with on/off dispenser nozzle cap.
MCA-2	Same as MCA-1 except 16 oz (0.5 l).
NEUTRALIZER 5A: An ammonia-based material. Neutralizes any chemical reaction introduced by Conditioner A, and produces optimum surface conditions for most strain gage adhesives. Shelf Life: 1 year at +75°F (+24°C).	
MN5A-1	2-oz* (60-ml) plastic squeeze bottle with on/off dispenser nozzle bottle cap.
MN5A-2	Same as MN5A-1 except 16 oz (0.5 l).

***Note:** The 2-oz (60-ml) size is recommended for bench use and is easily refilled from the 16-oz (0.5-l) bottle.

Figure A.3 Surface Cleaning Materials (a)

Surface Cleaning Supplies

MICRO MEASUREMENTS A VPG Brand

General Information and Selection

SURFACE-ABRASION MATERIALS

Abrading is often necessary to dislodge contaminants and to remove rust, scale, etc. When grit-blasting is necessary, use fine alumina powder and high-quality filters, and never recycle used grit. In general, wet-or-dry silicon-carbide paper is most suitable.

MODEL/PART NO.	TYPE/DESCRIPTION
SCP-1	**220-grit Wet-or-Dry Silicon-Carbide Paper:** Suited to most steels. 1 in x 100 ft (25 mm x 30 m) roll.
SCP-2	**320-grit Wet-or-Dry Silicon-Carbide Paper:** Suited to most steels. Also suited to aluminum alloys and other soft metals. 1 in x 100 ft (25 mm x 30 m) roll.
SCP-3	**400-grit Wet-or-Dry Silicon-Carbide Paper:** Suited to aluminum alloys and other soft metals. 1 in x 100 ft (25 mm x 30 m) roll.
GC-5	**Pumice Powder:** Produces a dull, matte finish. Recommended for minimal removal of surface material. 1/2 oz (15 ml) bottle.

SPECIAL-PURPOSE MATERIALS

MODEL/PART NO.	TYPE/DESCRIPTION
TEC-1	**Tetra-Etch® Compound:** Used for etching Teflon® to render the surface bondable. Shelf life 3 months at +32°F (0°C). 2 oz (60 ml) can.
CSP-1	**Cotton Tip Applicators:** 100 single-ended applicators per package [6 in (150 mm) long, wooden stick].
GSP-1	**Gauze Sponges:** 200 sponges [3 x 3 in (75 x 75 mm)] per package.

TetraEtch is a Registered Trademark of W. L. Gore.
Teflon is a Registered Trademark of DuPont.

Figure A.4 Surface Cleaning Materials (b)

MICRO MEASUREMENTS
A VPG Brand

Installation Tools and Accessories

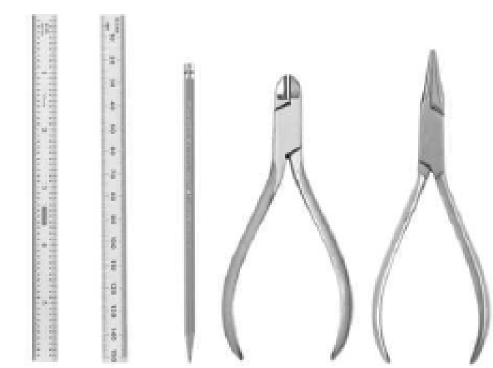
General Information and Selection

There is a strong element of craftsmanship involved in making consistently successful strain gage installations. As for any other field, this craft has its own special tools and working materials—found by seasoned professionals to be most effective for achieving the desired results. The installation accessories described on this and the following pages represent the distillation of many years' experience in determining the most appropriate tool or material for each task in the gage installation process.

Every accessory item listed here has been thoroughly tested and evaluated in the Micro-Measurements Applications Engineering Laboratory for quality and reliability, for ease of use, and for compatibility with all other Micro-Measurements products. It should be noted that the instruction bulletins supplied for gages, adhesives, protective coatings, etc. assume the availability of these accessories to the user, since such is generally the case for an experienced practitioner in a well-equipped laboratory.

TOOLS

SSH-1 STW-1 BTW-1 DPR-1 SSC-1



SSS-1 SSS-2 DP-1 DWC-1 NNP-1

SSH-1 SURGICAL SHEARS:
Chromium steel, 4-1/2 in (115 mm) long, with one sharp pointed blade and one blunt-end blade.

STW-1 TWEEZERS:
Stainless steel, 4-1/2 in (115 mm) long. Rugged, precision ground sharp ends. Primarily used for handling leadwires.

BTW-1 TWEEZERS:
Stainless steel, 4-1/2 in (115 mm) long. Antimagnetic; acid and corrosion resistant. Thin, flat blunt ends ideal for safe handling of strain gages.

DPR-1 DENTAL PROBE:
Stainless steel "pick". Flexible 75° pointed tip.

SSC-1 SURGICAL SCALPEL AND BLADE:
Stainless steel, uses SSC-2 snap-in replacement blade.

SSC-2 REPLACEMENT SCALPEL BLADES:
Five blades per package. Not shown.

SSS-1 STEEL SCALE:
6 in (150 mm) long, satin-chromed finish. Graduated in inches (1/32, 1/64, 1/10, 1/100).

SSS-2 STEEL SCALE:
6 in (150 mm) long, satin-chromed finish. Graduated in inches (1/10, 1/100) and millimeters (0.5, 1).

DP-1 4-H DRAFTING PENCIL:
For gage layout.

DWC-1 DIAGONAL CUTTERS:
Stainless steel, 4-1/2 in (115 mm) long, precision cutter for wire up to AWG No. 18 (1 mm diameter).

NNP-1 NEEDLE-NOSED PLIERS:
Nickel-chrome plated, 4-1/2 in (115 mm) long, with serrated needle-nosed jaws.

ATS-2 GAGE APPLICATION TOOL SET:
Includes one of each item plus one additional DPR-1 Dental Probe. Durable, polypropylene box. Not shown.

Document No.: 11021
Revision: 02-Feb-2018

For technical questions, contact mm@vpgsensors.com

www.micro-measurements.com
1

Figure A.5 Installation Tools and Accessories (a)

General Information and Selection

TOOLS

GT-11

SPT-1

SPT-2

GT-11 CAMEL'S HAIR BRUSH
3/8 in (9.5 mm).

SPT-1 STAINLESS STEEL MIXING SPATULA
Double blade. Overall length 8 in (200 mm).

SPT-2 STAINLESS STEEL MIXING SPATULA:
Single blade. Overall length 7-3/4 in (195 mm). Wooden handle.

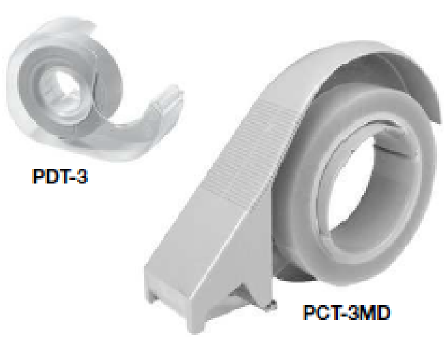
MHG-1

MHG-1 MASTER MITE HEAT GUN:
Lightweight, compact, perfectly balanced. 2 lb (0.9 kg) with nozzle attached. 8-7/8 x 7 in (225 x 180 mm). Quiet, brush- less-type shaded pole motor rated for continuous duty. Three interchangeable nozzle heating elements control average outlet temperature 1/2 in (13 mm) from nozzle at +500°F (+260°C), +650°F (+345°C), or +800°F (+425°C). Air- cooled barrel. Three-conductor grounded linecord. Slip-on deflector completely surrounds shrinkable tubing (HST-1) with heat. Pinpoint adapter directs heat without affecting adjacent areas. 120Vac, 60Hz. Maximum current draw 5.4 amps.

MHG-2 MASTER MITE HEAT GUN:
Same as above, except 220 Vac.

GENERAL-PURPOSE TAPES AND MATERIALS

PLY-001



PDT-3

PCT-3MD

PCT-3M GAGE INSTALLATION TAPE:
For gage handling. Compatible with the cure temperature ranges of all MM adhesives up to 400°F (204°C). 3/4 in x 72 yd (19 mm x 65 m).
Three ordering options:
PCT-3M: Tape only.
PCT-3MD: Tape and hand dispenser*.
PCT-3D: Hand dispenser* only.
*This portable, high impact, durable plastic hand-held tape dispenser features a hand brake in the core.

PDT-3 PAPER DRAFTING TAPE:
For soldering mask, and lead positioning. 0.75 in x 400 in (19 mm x 10.1 m).

PLY-001 Kapton® Film:
For electrical insulation, 4 x 10 x 0.001 in thick (100 x 250 x 0.02 mm thick).

Store all at or near +75°F (+24°C).

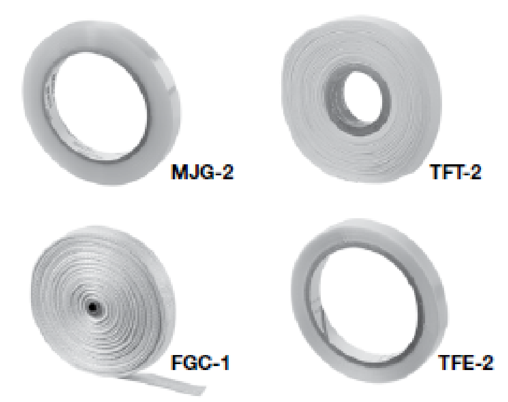
Figure A.6 Installation Tools and Accessories (b)

MICRO MEASUREMENTS
A VPG Brand

Installation Tools and Accessories

General Information and Selection

HIGH-TEMPERATURE TAPES AND MATERIALS



MJG-2 MYLAR® TAPE:
For gage handling with heat-curing resin systems. Compatible with the cure temperature ranges of all MM adhesives up to 400°F (204°C).
1/2 in x 216 ft (13 mm x 66 m).

TFT-2 THERMOSETTING [+340°F (+170°C)] FIBERGLASS TAPE:
For electrical insulation at high temperatures.
1/2 In x 180 ft (13 mm x 55 m).

FGC-1 WOVEN FIBERGLASS CLOTH:
Bound edges. For lead anchoring when used in conjunction with M-Bond adhesives and M-Coat protective coatings. 0.015 in x 1 in x 50 yd (0.4 mm x 25 mm x 46 m).

TFE-2 HIGH MODULUS TFE TEFLON® WITH SILICONE MASTIC:
1/2 in x 108 ft (13 mm x 33 m).

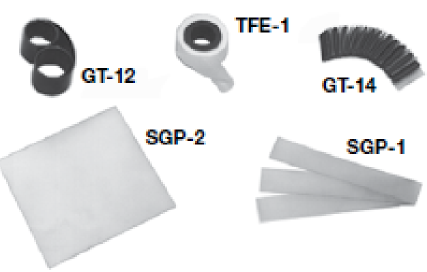
Store all at or near +75°F (+24°C).

CLAMPING SUPPLIES

HSC-1 SPRING CLAMP:
Maximum Opening: 1 in (25 mm).
Maximum Recommended Opening: 1/2 in (13 mm).
Nominal Clamp Force at Recommended Opening: 20 lbf (89 N).

HSC-2 SPRING CLAMP:
Maximum Opening: 2 in (51 mm).
Maximum Recommended Opening: 1 in (25 mm).
Nominal Clamp Force at Recommended Opening: 24 lbf (107 N).

HSC-3 SPRING CLAMP:
Maximum Opening: 3 in (76 mm).
Maximum Recommended Opening: 1-1/2 in (38 mm).
Nominal Clamp Force at Recommended Opening: 30 lbf (133 N).



GT-12 NEG'ATOR CONSTANT FORCE EXTENSION SPRING CLAMP:
1 x 0.006 x 38 in (25 mm x 0.4 mm x 0.97 m) stainless steel band, drum I.D. 1.16 in (30 mm), 10.6 lb (47 N) load.

TFE-1 TEFLON FILM:
0.003 in x 1 in x 50 ft (0.08 mm x 25 mm x 15 m).

GT-14 PRESSURE PADS AND BACKUP PLATES:
Kit of 12 Silicone Rubber Pads 3/32 x 1/2 x 1-1/4 in (2.5 x 13 x 32 mm), and 12 aluminum plates, 1/8 x 1/2 x 1-1/4 in (3 x 13 x 32 mm).

SGP-1 SILICONE RUBBER:
Three pieces, each 3/32 x 1 x 6 in (2.5 x 25 x 150 mm).

SGP-2 SILICONE RUBBER:
One piece, 3/32 x 6 x 6 in (2.5 x 150 x 150 mm).

Document No.: 11021
Revision: 02-Feb-2018
For technical questions, contact mm@vpgsensors.com
www.micro-measurements.com
3

Figure A.7 Installation Tools and Accessories (c)

MICRO MEASUREMENTS
A VPG Brand

M-Bond AE-10

Strain Gage Adhesive

OTHER ACCESSORIES USED IN AN M-BOND AE-10 INSTALLATION:

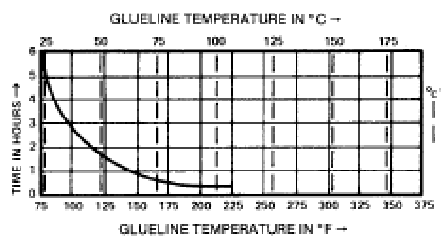
- CSM Degreaser or GC-6 Isopropyl Alcohol
- Silicon-Carbide Paper
- M-Prep Conditioner A
- M-Prep Neutralizer 5A
- GSP-1 Gauze Sponges
- CSP-1 Cotton Tip Applicators
- PCT-2M Gage Installation Tape
- HSC Spring Clamp
- GT-14 Pressure Pads and Backup Plates

RoHS COMPLIANT

DESCRIPTION

Two-component, 100%-solids epoxy system for generalpurpose stress analysis. Transparent, medium viscosity. Cure time as low as six hours at +75°F (+24°C) may be used. Elevated-temperature postcure is recommended for maximum stability, and/or tests above room temperature.

Highly resistant to moisture and most chemicals, particularly when postcured. For maximum elongation, bonding surface must be roughened. Cryogenic applications require very thin gluelines.

CHARACTERISTICS	
PARAMETER	**DETAILS**
OPERATING TEMPERATURE RANGE	**Long Term:** –320° to +200°F (–195° to +95°C)
ELONGATION CAPABILITIES	1% at –320° (–195°C), 6% to 10% at +75°F (+24°C), 15% at +200°F (+95°C).
SHELF LIFE	Minimum 12 months at +75°F (+24°C); or 18 months at +40°F (+5°C). If crystals form in resin jar, heat to +120°F (+50°C) for 30 minutes. Cool before mixing. Refer to product label for most recent information.
POT LIFE	15 to 20 minutes at +75°F (+24°C). Can be extended by cooling jar or by spreading adhesive on clean aluminum plate.
CLAMPING PRESSURE	5 to 20 psi (35 to 140 kN/m²).
CURE REQUIREMENTS*	**Preferred Room-Temperature Cure:** 24 to 48 hours at +75°F (+24°C). **Recommended Postcure:** 2 hours at 25°F (15°C) above maximum operating temperature. 

PACKAGING	
KIT	**BULK**
6 mixing jars (10 g ea) Resin 1 bottle (15 ml) Curing Agent 10 6 calibrated pipettes 6 stirring rods	200 g Resin 40 g Curing Agent 10 3 calibrated pipettes

* **Reference:** Instruction Bulletin B-137, "Strain Gage Applications with M-Bond AE-10, AE-15, and GA-2 Adhesive Systems", included in each kit.

Document No.: 11011
Revision: 17-May-2017

For technical questions, contact mm@vpgsensors.com

www.micro-measurements.com
21

Figure A.8 M-Bond AE-10

M-Coat A

MICRO MEASUREMENTS
A VPG Brand

Protective Coating

FEATURES

- Easy to use
- Transparent
- Good general-purpose coating for laboratory use

DESCRIPTION

Air-drying solvent-thinned (xylene) polyurethane. Transparent. Moderate hardness; good flexibility. Can be removed with *M-LINE* Rosin Solvent or toluene. Film thickness 0.005–0.01 in (0.1–0.25 mm) per coat.

General-purpose coating for lab use, and as base coating for field applications. Must be fully cured before addition of other coatings. Fair moisture resistance. Not readily attacked by many solvents. Convenient to use.

RoHS COMPLIANT

CHARACTERISTICS

PARAMETER	DETAILS
CURE REQUIREMENTS	Dries tack-free at room temperature in 20 minutes. Completely dry in 2 hours. Normal cure 24 hours at room temperature. Chemical resistance and coating hardness increase for 6 to 7 days.
OPERATING TEMPERATURE RANGE	**Short Term:** –100° to +300°F (–75° to +150°C). **Long Term:** –100° to +250°F (–75° to +120°C).
SHELF LIFE	Minimum 1 year at +75°F (+24°C). Refer to product label for most recent information.

PACKAGING OPTIONS

KIT	BULK
4 brush-cap bottles [1 oz (30 ml) ea].	Quart container.

www.micro-measurements.com
66

For technical questions, contact
mm@vpgsensors.com

Document No.: 11026
Revision: 18-Apr-2017

Figure A.9 M-Coat A

M-Coat F

Protective Coating

FEATURES

- Excellent for outdoor applications
- No cure required
- Versatile

DESCRIPTION

Kit of selected materials easily applied in various combinations. Provides environmental and mechanical protection. Particularly well-suited to field applications where conditions are not ideal. Typical applications include pipelines, tunnels, bridges, reinforcement bars in concrete structures, heavy machinery, ships, aircraft, motor vehicles, and pressure vessels.

CHARACTERISTICS

PARAMETER	DETAILS
CURE REQUIREMENTS	No mixing or curing required.
OPERATING TEMPERATURE RANGE	**Short Term:** –70° to +250°F (–55° to +120°C). **Long Term:** –20° to +175°F (–30° to +80°C).
SHELF LIFE	Minimum 1 year at +75°F (+24°C). Refer to product label for most recent information.

PACKAGING OPTIONS

KIT	BULK
12 pieces [4-1/2 in x 3-3/4 in x 1/8 in ±1/32 in (115 x 95 x 3.2 mm ±0.8 mm)] each: • M-Coat FB Butyl Rubber Sealant • M-Coat FN Neoprene Rubber Sheets 1 roll [0.003 in x 2 in x 20 ft (0.08 mm x 50 mm x 6 m)] M-Coat FA Aluminum Foil Tape 2 brush-cap bottles [1/2 oz (15 ml) ea] M-Coat B Air-Drying Nitrile Rubber Coating M-Coat FT Teflon® Tape	25 pieces M-Coat FB-2 Butyl Rubber Sealant 25 pieces M-Coat FN-2 Neoprene Rubber Sheets 1 roll [20 ft (6 m)] M-Coat FA-2 Aluminum Foil Tape 4 brush-cap bottles [1 oz (30 ml) ea] M-Coat B Air-Drying Nitrile Rubber Coating 10 pieces [1 x 20 x 0.003 in (25 x 500 x 0.08 mm) ea] M-Coat FT Teflon® Tape

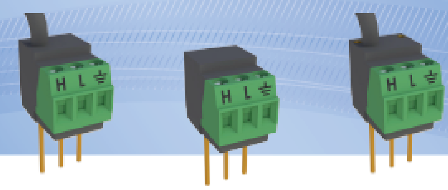
Teflon is a Registered Trademark of DuPont.

Figure A.10 M-Coat F

COMPONENT CATEGORY

TIMS

Terminal Input Modules



Rugged, Reliable, and Ready for any Application

Terminal input modules (TIMs) are small peripherals that provide completion resistors for resistive bridge measurements, or act as voltage dividers or precision current shunts. The modules attach directly to the datalogger's input terminals. Each module provides circuitry to connect one sensor, except for the voltage dividers which allow connection of two single-ended sensors.

The legs of our TIMs do not fit on the CR7 datalogger's connectors.

MAJOR SPECIFICATIONS

	Used With	Resistor	Tolerance @ 25°C	Power Rating	Maximum Temperature Coefficient
CURS100 | Current Shunt Module	Sensors that output a current signal (4 to 20 mA)	Shunt (bulk metal foil): 100 Ω	±0.01%	0.25 W	±0.8 ppm/°C
VDIV10:1 | 10-to-1 Voltage Divider	Sensors with a high voltage output (up to 50 V)	10 kΩ and 90 kΩ	Ratio: ±0.02%	per Element: 0.1 W @ 70°C	Ratio (0° to 70°C): 2 ppm/°C
VDIV2:1 | 2-to-1 Voltage Divider	Sensors with a high voltage output	10 kΩ and 10 kΩ	Ratio: ±0.02%	per Element: 0.1 W @ 70°C	Ratio (0° to 70°C): 2 ppm/°C
4WFBS120 | 120 Ω, 4-Wire Full Bridge Module	4-wire strain gages or other full bridge measurements that have a 120 Ω nominal resistance.	2:1 Resistive Divider 1 kΩ/1 kΩ Completion 120 Ω	2:1 Resistive Divider Ratio: ±0.01% Completion ±0.01%	2:1 Resistive Divider per Element: 0.1 W @ 70°C Completion 0.25 W @ 70°C	2:1 Resistive Divider Ratio (-55° to 85°C): 0.5 ppm/°C Completion 0.8 ppm/°C
4WFBS350 | 350 Ω, 4-Wire Full Bridge Module	4-wire strain gages or other full bridge measurements that have a 350 Ω nominal resistance.	2:1 Resistive Divider 1 kΩ/1 kΩ Completion 350 Ω	2:1 Resistive Divider Ratio: ±0.01% Completion ±0.01%	2:1 Resistive Divider per Element: 0.1 W @ 70°C Completion 0.25 W @ 70°C	2:1 Resistive Divider Ratio (-55° to 85°C): 0.5 ppm/°C Completion 0.8 ppm/°C
4WFBS1K | 1 kΩ, 4-Wire Full Bridge Module	4-wire strain gages or other full bridge measurements that have a 1 kΩ nominal resistance.	2:1 Resistive Divider 1 kΩ/1 kΩ Completion 1 kΩ	2:1 Resistive Divider Ratio: ±0.01% Completion ±0.01%	2:1 Resistive Divider per Element: 0.1 W @ 70°C Completion 0.25 W @ 70°C	2:1 Resistive Divider Ratio (-55° to 85°C): 0.5 ppm/°C Completion 0.8 ppm/°C

More info: **435.227.9120**
campbellsci.com/tims

Figure A.11 Terminal Input Module

COMPONENT

CAMPBELL SCIENTIFIC
WHEN MEASUREMENTS MATTER

CR6 Series

Measurement and Control Datalogger

One Datalogger, Countless Applications

Featuring advanced vibrating-wire technology

Overview

The CR6-series measurement and control datalogger is a powerful core component for your data-acquisition system. We combined the best features of all our dataloggers and added faster communications, low power requirements, built in USB, compact size, and improved analog input accuracy and resolution. The CR6 series also introduces our new universal (U) terminal—an ingenious way for allowing virtually any sensor (analog, digital, or smart) to be connected to any U terminal. This is also our first multipurpose datalogger capable of doing static vibrating-wire measurements.

Benefits and Features

- Powerfully versatile, multi-tool of data acquisition
- U terminals configurable to what you want them to be: analog or digital, input, or output
- Static vibrating wire measurements using our patented spectral analysis
- Surge ESD and over-voltage protection on all terminals
- Flexible power input from solar panel, dc power supply, 12 V battery, USB
- Onboard communication options include Ethernet, Wi-Fi, and spread spectrum radios
- CR6-WIFI ideal for short-range, wireless IP communication
- CR6-RF407/412/422 ideal for low power medium range license-free radio communication
- CR6-RF451 ideal for long-range, license-free radio communication
- Wiring made easy through removable terminal block
- Two non-isolated current input channels included for directly connecting sensors with 0-to-20 mA or 4-to-20 mA current outputs[a]
- MicroSD card drive for extended memory requirements
- Serial sensors support with RS-232 and RS-485 native
- CPI for hosting Campbell high speed sensors and distributed modules (CDM)
- Programmable with CRBasic or SCWin program generator, completely PakBus compatible

General Specifications

- **CPU:** 32 bit with hardware FPU, running at 100 MHz
- **Internal Memory[b]:** 128 MB flash and 4 MB battery-backed SRAM
- **MicroSD Drive** for extended data storage (Campbell Scientific offers 2 GB and 8 GB microSD cards)
- **Clock Accuracy:** ±3 min per year, optional GPS correction to 10 µs
- **USB micro B** for direct connection to PC (limited power source during configuration), 2.0 full speed, 12 Mbps
- **CS I/O Port** for connection to Campbell Scientific modems and displays
- **10/100 Ethernet RJ45** for LAN connection
- **CPI Port** for terminal expansion using Campbell Distributed modules (CDM)
- **Battery Terminal Pair** for regulated 12 V power input or rechargeable 12 V VRLA for UPS mode

[a] *Capability was added to revision 19 boards. CR6 dataloggers with revision 19 or higher boards have a blue strip on their label.*
[b] *Internal memory is for CR6s with rev 19 or higher boards.*

More info: **435.227.9120**
www.campbellsci.com/cr6

Figure A.12 CR6 Datalogger (a)

General Specifications Continued

- **Charge Terminal Pair** for 16 to 32 V from dc power converter or 12 or 24 V solar panel
- **Two Switched 12 V Terminals** for powering sensors or communication devices, 1100 mA @ 20°C
- **Continuous 12 V Terminal**
- **Twelve Universal (U) Terminals:** U terminals are software configurable for analog or digital functions
  - Analog functions consist of:
    - Analog inputs: 12 single-ended or 6 differential with ±5000 mV, ±1000 mV, ±200 mV ranges 24 bit ADC
    - Analog outputs: ±2.5 V or ±2.5 mA ranges for bridge measurements 12 bit DAC
    - Static frequency-analyzed vibrating wire: terminal pair both excites to 12 V p-p and 100 Hz to 6.5 kHz and reads vibrating-wire transducers using our patented spectral-analysis technology (VSPECT™)
    - Thermistor: completion resistor internal 5 kΩ
    - Period average: up to 200 kHz, amplitude dependent
  - Digital I/O functions consist of 5 V or 3.3 V logic levels for:
    - General status/control
    - Voltage source: 5 V, 3.3 V, 20 mA @ 3.5 V
    - Low level ac: up to 20 kHz, amplitude dependent
    - Switch closure (150 Hz) or high frequency counter (1 MHz)
    - Pulse width modulation
    - Interrupts and timer input
    - SDI-12 and SDM
    - Serial asynchronous communication Tx/Rx pairs
- **Four Control (C) Terminals:** C terminals are software configurable for digital functions
  - Digital I/O functions consist of 5 or 3.3 V logic levels for:
    - RS-232/RS-485: half or full duplex
    - General status/control
    - Voltage source 5 V, 3.3 V: 10 mA @ 3.5 V
    - Switch closure (150 Hz) or high frequency counter (1 MHz)
    - Pulse width modulation
    - Interrupts and timer input
    - SDI-12 and SDM
    - Serial asynchronous communication Tx/Rx pairs
- **Best Analog Accuracy:** ±(0.04% of reading + 2 µV), 0° to 40°C
- **Best Effective Resolution:** 50 nV (±200 mV range, differential measurement, input reversal, 5 Hz f_{NI})
- **Operating Temperature Range**
  - Standard: -40° to +70°C
  - Extended: -55° to +85°C (not available for communication options)
- **Compliance Information:**
  - View the EU Declaration of Conformity for the CR6, CR6-WIFI, and CR6-RF422 at: www.campbellsci.com/cr6
  - Shock: MIL-STD 810G method 516.6
  - Vibration: MIL-STD 810G method 514.6
  - Protection: IP50
- **Weight**
  - CR6: 0.42 kg (0.92 lb)
  - CR6-WIFI: 0.50 kg (1.10 lb)
  - CR6-RF451: 0.52 kg (1.15 lb)
  - CR6-RF407/412/422: 0.51 kg (1.13 lb)
- **Dimensions:** 21 cm x 10.2 x 5.7 cm (8.3 in x 4.0 x 2.2 in)

Terminal Functions

Twelve U terminals and four C terminals are programmable as pairs for the following functions.

Analog Input Function	C1	C2	C3	C4	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	U11	U12	RG1	RG2	Max
Single Ended					✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			12
Differential					H	L	H	L	H	L	H	L	H	L	H	L			6
Period Average					✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			12
Vibrating Wire					✓		✓		✓		✓		✓		✓				6
Current Loop																	✓	✓	2
Thermistor					✓		✓		✓		✓		✓		✓				6
Analog Output Function	**C1**	**C2**	**C3**	**C4**	**U1**	**U2**	**U3**	**U4**	**U5**	**U6**	**U7**	**U8**	**U9**	**U10**	**U11**	**U12**	**RG1**	**RG2**	**Max**
Switched-Voltage Excitation					✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			12
Switched-Current Excitation					✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			12
Digital I/O Function	**C1**	**C2**	**C3**	**C4**	**U1**	**U2**	**U3**	**U4**	**U5**	**U6**	**U7**	**U8**	**U9**	**U10**	**U11**	**U12**	**RG1**	**RG2**	**Max**
RS-232	Tx	Rx	Tx	Rx															2
RS-485 (Half Duplex)	A(-)	B(+)	A(-)	B(+)															2
RS-485 (Full Duplex)	Tx-	Tx+	Rx-	Rx+															1
RS-232 TTL	Tx	Rx	Tx	Rx	Tx	Rx	Tx	Rx	Tx	Rx	Tx	Rx	Tx	Rx	Tx	Rx			8
SDI-12	✓		✓		✓		✓		✓		✓		✓		✓				8
SDM	DATA	CLK	ENABLE		DATA	CLK	ENABLE		DATA	CLK	ENABLE		DATA	CLK	ENABLE				1
General I/O Pair	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			16
5 V or 3.3 V Source	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			16
Pulse-Width Modulation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			16
Timer I/O	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			16
Interrupt	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			16
Pulse Counting Function	**C1**	**C2**	**C3**	**C4**	**U1**	**U2**	**U3**	**U4**	**U5**	**U6**	**U7**	**U8**	**U9**	**U10**	**U11**	**U12**	**RG1**	**RG2**	**Max**
Switch Closure	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			16
High Frequency	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			16
Low Level AC						✓		✓		✓		✓		✓		✓			6

Terminal Use Examples and Notes

1. If U1 is programmed for analog input or output, its associated pair, U2, may only be used as an analog input or output.

2. Triggering conflicts can occur when companion ports are used for different triggering instructions (TimerInput, PulseCount, SDI12Recorder, WaitDigTrig). For example, if U3 is used for the SDI12Recorder instruction, U4 cannot be used in the TimerInput, PulseCount, or WaitDigTrig instructions.

3. Only one trio of channels can be programmed as an SDM connection. For example, if channels C1–C3 are used for an SDM connection, you cannot connect another SDM on any of the other channels.

Figure A.13 CR6 Datalogger (b)

CR6-WIFI Specifications

Wireless Local Area Network (WLAN)

- **Supported Technologies:** 802.11 b/g/n, WPA/WPA2-Personal, WPA/WPA2-Enterprise Security, WEP
- **Client Mode:** WPA/WPA2-Personal and Enterprise, WEP
- **Access Point Mode:** WPA2-Personal
- **Communication Rate**
  - 802.11b: up to 11 Mbps
  - 802.11g: up to 54 Mbps
  - 802.11n: up to 72 Mbps
- **Frequency:** 2.4 GHz
- **Antenna Connector:** RPSMA
- **Antenna:** pn 16005 unity gain (0 dBd), 1/2 wave whip, omnidirection-al with articulating knuckle joint for vertical or horizontal orientation.
- **Transmit Power:** 7 to 18 dBm
- **Rx Sensitivity:** -97 dBm

WLAN Power Requirements (@ 12 Vdc)

- **Client Mode:** 7 mA idle, 70 mA communicating
- **Access Point Mode:** 62 mA idle, 65 mA communicating
- **Sleep (disabled using IPNetPower() or DevConfig setting):** <0.1 mA

Compliance Information

- **United States FCC ID:** XF6-RS9113SB
- **Industry Canada (IC):** 8407A-RS9113SB

Note: The user is responsible for emissions if changing the antenna type or increasing the gain.

CR6-RF407, CR6-RF412 Specifications

Frequency Hopping Spread Spectrum Radios (FHSS)

- **Transmit**
  - Output Power: 5 to 250 mW, user selectable
  - Frequency
    - RF407: 902 to 928 MHz (US, Canada)
    - RF412: 915 to 928 MHz (Australia, New Zealand)
  - Channel Capacity
    - RF407: Eight 25-channel hop sequences sharing 64 available channels
    - RF412: Eight 25-channel hop sequences sharing 31 available channels
  - RF Data Rates: 200 kbps
- **Receive Sensitivity:** -101 dBm
- **Antenna Connector:** RPSMA (external antenna required; see www.campbellsci.com/order/cr6 for Campbell Scientific antennas)

Average Additional Current Contribution @ 12 Vdc

- **Transmit:** < 80 mA
- **Idle On:** 12 mA
- **Idle 0.5 s Power Mode:** 4 mA
- **Idle 1 s Power Mode:** 3 mA
- **Idle 4 s Power Mode:** 1.5 mA

Compliance Information

- **CR6-RF407**
  - United States: FCC Part 15.247: MCQ-XB900HP
  - Industry Canada (IC): 1846A-XB900HP
  - Mexico IF: RCPDIXB15-0672-A1
- **CR6-RF412**
  - ACMA RCM
  - United FCC Part 15.247: MCQ-XB900HP
  - Industry Canada (IC): 1846A-XB900HP

CR6-RF422 Specifications

F868 MHz SRD 860 Radio with Listen Before Talk (LBT) and Automatic Frequency Agility (AFA)

- **Transmit**
  - Output Power: 2 to 25 mW, user selectable
  - Frequency: 863 to 870 MHz (European Union)
  - Channel Capacity: 30 channels (default), software configurable for meeting local regulations; 10 sequences for reducing interference through channel hop
  - RF Data Rates: 10 kbps
- **Receive Sensitivity:** -106 dBm
- **Antenna Connector:** RPSMA (external antenna required)

Average Additional Current Contribution @ 12 Vdc

- **Transmit:** 20 mA
- **Idle On:** 9.5 mA
- **Idle 0.5 s Power Mode:** 3.5 mA
- **Idle 1 s Power Mode:** 2.5 mA
- **Idle 4 s Power Mode:** 1.5 mA

Figure A.14 CR6 Datalogger (c)

CR6-RF451 Specifications

Frequency Hopping Spread Spectrum Radio (FHSS)

- **Transmit**
  - Output Power: 10 mW to 1 W, user selectable
  - Frequency: 902 to 928 MHz
  - Modulation: 2 level GFSK
  - RF Data Rates: 115.2 or 153.6 kbps, selectable speeds
- **Receive Sensitivity**
  - -108 dBm at 115.2 kbps for 10^{-4} BER
  - -103 dBm at 153.6 kbps for 10^{-4} BER
- **Antenna Connector:** RPSMA female (external antenna required; see www.campbellsci.com/order/cr6 for Campbell Scientific antennas)

Average Additional Current Contribution @ 12 Vdc

- **Transmit:** 650 mA, maximum
- **Receive:** 40 mA
- **Idle:** 15 mA
- **Sleep:** 6 mA

Compliance Information

- **United States FCC ID:** KNYAMM0921TT
- **Industry Canada (IC):** 2329B-AMM0921TT

Figure A.15 CR6 Datalogger (d)

COMPONENTS

CAMPBELL SCIENTIFIC
WHEN MEASUREMENTS MATTER

CDM-A108 and CDM-A116

Analog Measurement Modules

24-Bit Resolution

Greatly Increases Sensor Capacity

Overview

The CDM-A108 and CDM-A116 are 24-bit analog input modules that significantly increase the number of analog channels in a datalogger system. The CDM-A108 has eight differential channels and the CDM-A116 has 16 differential channels.

The CDM-A108 and CDM-A116 feature a 24-bit, analog-to-digital converter and a low-noise, analog front-end to provide superior analog measurements. They also can make simultaneous measurements, support period average measurements, and include both current and voltage excitation channels.

Benefits and Features

- 8 differential or 16 single-ended inputs on the CDM-A108
- 16 differential or 32 single-ended inputs on the CDM-A116
- Ability to make simultaneous measurements
- 3.0 kHz maximum multiplexed sample rate using fast (100 µs) input settling
- 30 kHz maximum burst sample rate
- 24-bit sigma-delta ADC with 16 user programmable notch frequencies from 30000 Hz to 2.5 Hz, including 50 and 60 Hz. Previous generations of dataloggers could notch out 50 or 60 Hz
- ±5000 mV, ±1000 mV, and ±200 mV input ranges

Specifications

Power Requirements

- Voltage: 9.6 to 32 Vdc

Estimated Accuracy

- ±(0.04% of reading + offset), 0° to 40°C
- ±(0.06% of reading + offset), -40° to 70°C
- ±(0.08% of reading + offset), -55° to 85°C

Voltage/Current Excitation Outputs

- Voltage Excitation: ±5 V @ 50 mA
- Current Excitation: ±2.5 mA; ±5 V compliance voltage
- Number of Voltage/Current Excitation Outputs: 2 (CDM-A108), 4 (CDM-A116)

General Purpose Outputs for AM16/32B Control or Sensor Power

SW5V Outputs

- Number of Outputs: 2 (CDM-A108), 4 (CDM-A116)
- Output Resistance: 40 Ω

SW12V Outputs

- Number of Outputs: 1 (CDM-A108), 2 (CDM-A116)
- Typical Limit: 200 mA
- Minimum Limit: 180 mA

12V Outputs

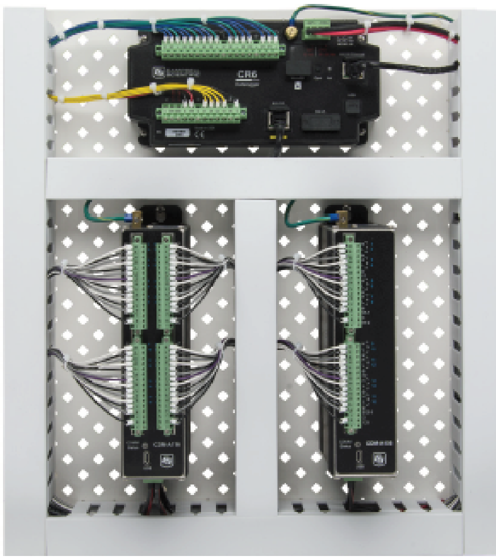
- Number of Outputs: 1 (CDM-A108), 2 (CDM-A116)
- Typical Limit: 200 mA
- Minimum Limit: 180 mA

questions & quotes: **435.227.9120**

www.campbellsci.com/cdms

Figure A.16 CDM-A116 (a)

Specifications Continued



The CR6 (shown above) and CR1000X measure CDM devices natively, and therefore do not require an SC-CPI.

Period Averaging

- Traditional period averaging on analog input channels

Communication

- CPI: For datalogger connection. Baud rate selectable from 50 kbps to 1 Mbps. Allowable cable length varies depending on baud rate, number of nodes, cable quality, and noise environment, but can be as long as 700 m under proper conditions.
- USB: USB 2.0 full speed connection available for attaching to a PC. Port is used to configure the module and download updates via our Device Configuration Utility.

Physical

- Dimensions: 20.3 x 12.7 x 5.1 cm (8 x 5 x 2 in.)
- Mounting: Standard 1-in. grid; DIN rail mounting available
- Operating Temperature: -40° to +70°C (standard), -55° to +85°C (extended)

Typical Measurement Performance

Analog Voltage Measurement Range and Resolution

f_{N1} [1] (Hz)	Range[2] (mV)	Typical Effective Resolution: Differential w/Input Reversal[3] RMS µV	Differential w/Input Reversal[3] bits	Differential w/o Input Reversal[3] RMS µV	Differential w/o Input Reversal[3] bits
30000	±5000	10.350	20.0	14.756	19.5
	±1000	2.239	19.9	3.148	19.4
	±200	0.799	19.0	1.121	18.5
60	±5000	0.769	23.7	1.140	23.2
	±1000	0.162	23.6	0.261	23.0
	±200	0.056	22.9	0.113	21.8
50	±5000	0.732	23.8	1.112	23.2
	±1000	0.161	23.7	0.254	23.0
	±200	0.053	22.9	0.111	21.9
2.5	±5000	0.447	24.5	0.564	24.2
	±1000	0.095	24.4	0.144	23.8
	±200	0.020	24.3	0.077	22.4

[1] First notch frequency
[2] Range overhead of ~6% on all ranges guarantees that full-scale values will not cause overrange.
[3] Effective resolution (ER) in bits is computed from ratio of full-scale range to RMS noise.

Analog Voltage Measurement Speed[1]

f_{N1} (Hz)	Multiplexed[2] Measurement: With Input Reversal Time (ms)	With Input Reversal Rate (Hz)	Without Input Reversal[3] Time (ms)	Without Input Reversal[3] Rate (Hz)
30000	1.46	698.49	0.75	1394.05
60	34.73	28.82	17.38	57.63
50	41.50	24.18	20.72	48.35
2.5	801.40	1.25	400.72	2.50

[1] Default settling time of 500 µs.
[2] Refers to multiplexing circuitry internal to the CDM-A100 series.

EU Declaration of Conformity

- www.campbellsci.com/cdm-a108
- www.campbellsci.com/cdm-a116

Warranty

- One year against defects in materials and workmanship.

Figure A.17 CDM-A116 (b)

Appendix B Instrumentation Installation Instructions

MICRO MEASUREMENTS A VPG Brand

Instruction Bulletin B-129-8

Surface Preparation for Strain Gage Bonding

1.0 Introduction

Strain gages can be satisfactorily bonded to almost any solid material if the material surface is *properly* prepared. While a properly prepared surface can be achieved in more than one way, the specific procedures and techniques described here offer a number of advantages. To begin with, they constitute a carefully developed and thoroughly proven system; and, when the instructions are followed precisely (along with those for gage and adhesive handling), the consistent result will be strong stable bonds. The procedures are simple to learn, easy to perform, and readily reproducible. Furthermore, the surface preparation materials used in these procedures are, unless otherwise noted, generally low in toxicity, and do not require special ventilation systems or other stringent safety measures. Of course, as with any materials containing solvents or producing vapors, adequate ventilation is necessary.

The importance of attention to detail, and precise adherence to instructions, cannot be overstressed in surface preparation for strain gage bonding. Less thorough, or even casual, approaches to surface preparation may sometimes yield satisfactory gage installations; but for *consistent* success in achieving high-quality bonds, the methods given here can be recommended without qualification. Fundamental to the Micro-Measurements system of surface preparation is an understanding of *cleanliness* and *contamination*. All open surfaces not thoroughly and freshly cleaned must be considered contaminated, and require cleaning immediately prior to gage bonding. Similarly, it is imperative that the materials used in the surface preparation be fresh, clean, and uncontaminated. It is worth noting that strain gages as received from Micro-Measurements are chemically clean, and specially treated on the underside to promote adhesion. Simply touching the gages with the fingers (which are always contaminated) can be detrimental to bond quality.

The Micro-Measurements system of surface preparation includes five basic operations. These are, in the usual order of execution:

1. *Solvent degreasing*
2. *Abrading (dry and wet)*
3. *Application of gage layout lines*
4. *Conditioning*
5. *Neutralizing*

These five operations are varied and modified for compatibility with different test material properties, and exceptions are introduced as appropriate for certain special materials and situations.

The surface preparation operations are described individually in ***Section 2.0***, following a summary of the general principles applicable to the entire process. ***Section 3.0*** discusses special precautions and considerations which should be borne in mind when working with unusual materials and/or surface conditions.

The various surface preparation and installation accessories referred to throughout this Application Note are Micro-Measurements Accessories, listed in Strain Gage Accessories Data Book and available directly from Micro-Measurements.

As a convenience to the gage installer in quickly determining the specific surface preparation steps applicable to any particular test material, ***Section 4.0*** includes a chart listing approximately 75 common (and uncommon) materials and the corresponding surface preparation treatments.

2.0 Basic Surface Preparation Operations and Techniques

2.1 General Principles of Surface Preparation for Strain Gage Bonding

The purpose of surface preparation is to develop a chemically clean surface having a roughness appropriate to the gage installation requirements, a surface alkalinity corresponding to a pH of 7 or so, and visible gage layout lines for locating and orienting the strain gage. It is toward this purpose that the operations described here are directed.

As noted earlier, cleanliness is vital throughout the surface preparation process. It is also important to guard against recontamination of a once-cleaned surface. Following are several examples of surface recontamination to be avoided:

a. Touching the cleaned surface with the fingers.
b. Wiping back and forth with a gauze sponge, or reusing a once-used surface of the sponge (or of a cotton swab).
c. Dragging contaminants into the cleaned area from the uncleaned boundary of that area.
d. Allowing a cleaning solution to evaporate on the surface.
e. Allowing a cleaned surface to sit for more than a few minutes before gage installation, or allowing a partially prepared surface to sit between steps in the cleaning procedure.

Beyond the above, it is good practice to approach the surface preparation task with freshly washed hands, and to wash hands as needed during the procedure.

2.2 Solvent Degreasing

Degreasing is performed to remove oils, greases, organic contaminants, and soluable chemical residues. Degreasing should always be the first operation. This is to avoid having subsequent abrading operations drive surface contaminants into the surface material. Porous materials such as titanium,

Figure B.1 Surface Preparation for Strain Gage Bonding (a)

cast iron, and cast aluminum may require heating to drive off absorbed hydrocarbons or other liquids.
Degreasing can be accomplished using a hot vapor degreaser, an ultrasonically agitated liquid bath, aerosol type spray cans of CSM-2 Degreaser, or wiping with GC-6 Isopropyl Alcohol. One-way applicators, such as the aerosol type, of cleaning solvents are always preferable because dissolved contaminants cannot be carried back into the parent solvent. Whenever possible, the entire test piece should be degreased. In the case of large bulky objects which cannot be completely degreased, an area covering 4 to 6 in [100 to 150mm] on all sides of the gage area should be cleaned. This will minimize the chance of contamination in subsequent operations, and will provide an area adequately large for applying protective coatings in the final stage of gage installation.

2.3 Surface Abrading

General — In preparation for gage installation, the surface is abraded to remove any loosely bonded adherents (scale, rust, paint, galvanized coatings, oxides, etc.), and to develop a surface texture suitable for bonding. The abrading operation can be performed in a variety of ways, depending upon the initial condition of the surface and the desired finish for gage installation. For rough or coarse surfaces, it may be necessary to start with a grinder, disc sander, or file. (***Note:*** *Before performing any abrading operations, see* ***Section 3.1*** *for safety precautions*.) Finish abrading is done with silicon-carbide paper of the appropriate grit, and recommended grit sizes for specific materials are given in ***Section 4.0***.
If grit blasting is used instead of abrading, either clean alumina or silica (100 to 400 grit) is satisfactory. In any case, the air supply should be well filtered to remove oil and other contaminant vapors coming from the air compressor.
The grit used in blasting should not be recycled or used again in surface preparation for bonding strain gages.
The optimum surface finish for gage bonding depends somewhat upon the nature and purpose of the installation. For general stress analysis applications, a relatively smooth surface (in the order of 100µin [2.5µm] rms) is suitable, and has the advantage over rougher surfaces that it can be cleaned more easily and thoroughly. Smoother surfaces, compatible with the thin "gluelines" required for minimum creep, are used for transducer installations. In contrast, when very high elongations must be measured, a rougher (and preferably cross-hatched) surface should be prepared. The recommended surface finishes for several classes of gage installations are summarized in Table I, below.

TABLE I

CLASS OF INSTALLATION	SURFACE FINISH, rms	
	µin	µm
General stress analysis	63-125	1.6-3.2
High elongation	>250	>6.4
	cross-hatched	
Transducers	16-63	0.4-1.6

Wet Abrading — Whenever *M-Prep* Conditioner A is compatible with the test material (see ***Section 4.0***), the abrading should be done while keeping the surface wet with this solution, if physically practicable. Conditioner A is a mildly acidic solution which generally accelerates the cleaning process and, on some materials, acts as a gentle etchant. It is not recommended for use on magnesium, synthetic rubber, or wood.

2.4 Gage-Location Layout Lines

The normal method of accurately locating and orienting a strain gage on the test surface is to first mark the surface with a pair of crossed reference lines at the point where the strain measurement is to be made. The lines are made perpendicular to one another, with one line oriented in the direction of strain measurement. The gage is then installed so that the triangular index marks defining the longitudinal and transverse axes of the grid are aligned with the reference lines on the test surface.
The reference, or layout, lines should be made with a tool that *burnishes*, rather than scores or scribes, the surface. A scribed line may raise a burr or create a stress concentration. In either case, such a line can be detrimental to strain gage performance and to the fatigue life of the test part. On aluminum and most other nonferrous alloys, a 4H drafting pencil is a satisfactory and convenient burnishing tool. However, graphite pencils should never be used on high temperature alloys, where the operating temperature might cause a carbon embrittlement problem. On these and other hard alloys, burnished alignment marks can be made with a ballpoint pen or a round-pointed brass rod. Layout lines are ordinarily applied following the abrading operation and before final cleaning. All residue from the burnishing operation should be removed by scrubbing with Conditioner A as described in the following section.

2.5 Surface Conditioning

After the layout lines are marked, Conditioner A should be applied repeatedly, and the surface scrubbed with cotton tipped applicators until a clean tip is no longer discolored by the scrubbing. During this process the surface should be kept constantly wet with Conditioner A until the cleaning is completed. *Cleaning solutions should never be allowed to dry on the surface*. When clean, the surface should be dried by wiping through the cleaned area with a single slow stroke of a gauze sponge. The stroke should begin inside

Figure B.2 Surface Preparation for Strain Gage Bonding (b)

the cleaned area to avoid dragging contaminants in from the boundary of the area. Then, with a fresh sponge, a single slow stroke is made in the opposite direction. The sponge should never be wiped back and forth, since this may redeposit the contaminants on the cleaned surface.

2.6 Neutralizing

The final step in surface preparation is to bring the surface condition back to an optimum alkalinity of 7.0 to 7.5pH, which is suitable for all Micro-Measurements strain gage adhesive systems. This should be done by liberally applying *M-Prep* Neutralizer 5A to the cleaned surface, and scrubbing the surface with a clean cotton-tipped applicator. The cleaned surface should be kept completely wet with Neutralizer 5A throughout this operation. When neutralized, the surface should be dried by wiping through the cleaned area with a *single* slow stroke of a clean gauze sponge.
With a fresh sponge, a *single* stroke should then be made in the opposite direction, beginning with the cleaned area to avoid recontamination from the uncleaned boundary.
If the foregoing instructions are followed precisely, the surface is now properly prepared for gage bonding, and the gage or gages should be installed as soon as possible.

3.0 Special Precautions and Considerations

3.1 Safety Precautions

As in any technical activity, safety should always be a prime consideration in surface preparation for strain gage bonding. For example, when grinding, disc sanding, or filing, the operator should wear safety glasses and take such other safety precautions as specified by his organization or by the Occupational Safety and Health Administration (OSHA).
When dealing with toxic materials such as beryllium, lead, uranium, plutonium, etc., all procedures and safety measures should be approved by the safety officer of the establishment before commencing surface preparation.

3.2 Surfaces Requiring Special Treatment

Concrete — Concrete surfaces are usually uneven, rough, and porous. In order to develop a proper substrate for gage bonding, it is necessary to apply a leveling and sealing precoat of epoxy adhesive to the concrete. Before applying the precoat, the concrete surface must be prepared by a procedure which accounts for the porosity of this material. Contamination from oils, greases, plant growth, and other soils should be removed by vigorous scrubbing with a stiff-bristled brush and a mild detergent solution. The surface is then rinsed with clean water. Surface irregularities can be removed by wire brushing, disc sanding, or grit blasting, after which all loose dust should be blown or brushed from the surface.

The next step is to apply Conditioner A generously to the surface in and around the gaging area, and scrub the area with a stiff-bristled brush. Contaminated Conditioner A should be blotted with gauze sponges, and then the surface should be rinsed thoroughly with clean water. Following the water rinse, the surface acidity must be reduced by scrubbing with Neutralizer 5A, blotting with gauze sponges, and rinsing with water. A final thorough rinse with distilled water is useful to remove the residual traces of water-soluble cleaning solutions. Before precoating, the cleaned surface must be thoroughly dried. Warming the surface gently with a propane torch or electric heat gun will hasten evaporation.
Micro-Measurements M-Bond AE-10 room-temperature-curing epoxy adhesive is an ideal material for precoating the concrete. For those cases in which the test temperature may exceed the specified maximum operating temperature of AE-10 (+200°F [+95°C]), it will be necessary to fill the surface with a higher temperature resin system such as M-Bond GA-61.
In applying the coating to the porous material, the adhesive should be worked into any voids, and leveled to form a smooth surface. When the adhesive is completely cured, it should be abraded until the base material begins to be exposed again. Following this, the epoxy surface is cleaned and prepared conventionally, according to the procedure specified in ***Section 4.0*** for bonding gages to epoxies.
Plated Surfaces — In general, plated surfaces are detrimental to strain gage stability, and it is preferable to remove the plating at the gage location, if this is permissible. Cadmium and nickel plating are particularly subject to creep, and even harder platings may creep because of the imperfect bond between the plating and the base metal. When it is not permissible to remove the plating, the surface should be prepared according to the procedure given in ***Section 4.0*** for the specific plating involved. Note that it may be necessary to adjust testing procedures to minimize the effects of creep.
Use of Solvents on Plastics — Plastics vary widely in their reactivity to solvents such as those employed in the surface preparation procedures described here. Before applying a solvent to any plastic, ***Section 4.0***, which includes most common plastics, should be referred to for the recommended compatible solvent. For plastics not listed in ***Section 4.0***, the manufacturer of the material should be consulted, or tests should be performed to verify nonreactivity between the solvent and the plastic.
Dimensional or Mechanical Changes Due to Surface Preparation— For most materials, strain measurement results are usually not significantly changed by the surface preparation procedures described in this Application Note. Even with appreciable material removal, effects on the static mechanical properties of the test part are generally negligi-ble compared to other error sources in the experiment. It

Figure B.3 Surface Preparation for Strain Gage Bonding (c)

should be understood, however, that removal of a plated or hardened surface layer, or of a surface layer with significant residual stresses, may noticeably affect the fatigue life or the wear characteristics of the part when operated under dynamic service conditions.

Silicone Contamination —The properties of silicones which make them excellent lubricants and mold-release agents also make them the enemies of adhesion, and therefore potentially the most serious of contaminants to be encountered in the practice of bonding strain gages. The problem is compounded by the high natural affinity of the silicones for most materials, and by their tendency to migrate. Furthermore, since silicones are relatively inert chemically, and unaffected by most solvents, they are among the most difficult surface contaminants to remove.

The best practice is to keep the gage-bonding area free of silicones. This may not be as easy as it sounds, since the widely used silicones can be introduced from a variety of sources. For instance, many hand creams and cosmetics contain silicones, and these should not be used by persons involved in gage installation. Some of the machining lubricants also contain silicones, and such lubricants should be avoided when machining parts that are to have strain gages installed. Similarly, silicone-saturated cleaning tissues for eyeglasses should not be used in the gage-bonding area or by gage-installation personnel.

Regardless of efforts to avoid silicones, contamination may still occur. Light contamination can sometimes be removed by cleaning with Conditioner A, preferably heated to +200°F [+95°C]. More severe cases may require special cleaning solutions and procedures, recommendations for which should be obtained from the manufacturer of the silicone compound involved in the contamination.

4.0 Index of Test Materials and Surface Preparation Procedures

In this section, the specific step-by-step surface preparation procedures are given for approximately 75 different materials. For compactness, and convenient, quick access to the procedure for any particular material, the information is presented in chart form in Table II. The test materials are listed alphabetically, from ABS Plastics to Zirconium; and the complete procedure for each material is defined by one or more digits in each of the applicable operations columns of the table. Each digit identifies the required operation and specifies the step number for that operation in the complete procedure.

For example, assume that the necessity arises for bonding one or more strain gages to a brass test specimen. Reading down the *Specimen Material* column of Table II to Brass, and following that row across the table to the right, the first step in surface preparation consists of degreasing the specimen with CSM-2 Degreaser. The symbol (1) in the *Isopropyl Alcohol* column indicates that this is a suitable substitute degreasing operation. Continuing across the row, the second operation calls for abrading the specimen surface with 320-grit silicon-carbide paper. In the third operation the specimen is reabraded with 400-grit silicon-carbide paper, wet lapping with Conditioner A if feasible. The fourth and fifth operations consist of applying layout lines for locating the gages, and scrubbing the surface clean with Conditioner A. Cleaning with isopropyl alcohol is the final operation in the procedure.

In the *Remarks* column, it is recommended that the gages be installed within 20 minutes after completing the surface preparation, because the freshly bared brass surface tends to oxidize rapidly. In addition, in the *Grit Blast* column, the gage installer is specifically advised not to substitute grit blasting for other surface abrading methods, in order to avoid significantly altering the surface condition of this relatively soft material. Surface preparation procedures for other materials are defined similarly in the table, and, in many cases, accompanied by special warnings or recommendations in the *Remarks* column. When an operation not included in the first ten column headings is required, it is indexed in the *Other* column, with an arrow pointing to the *Remarks* column where the operation is specified.

Additional References

For additional information, refer to Instruction Bulletins listed below:

B-127, "Strain Gage Installations with M-Bond 200 Adhesive".
B-130, "Strain Gage Installations with M-Bond 43-B, 600, and 610 Adhesives".
B-137, "Strain Gage Applications with M-Bond AE-10, AE-15, and GA-2 Adhesive Systems".

Important Notice

Figure B.4 Surface Preparation for Strain Gage Bonding (d)

Instruction Bulletin B-137

Strain Gage Applications with M-Bond AE-10, AE-15 and GA-2 Adhesive Systems

GENERAL DESCRIPTION

The three adhesives described in this bulletin, M-Bond AE- 10, AE-15, and GA-2, are all 100%-solids epoxy systems for use with strain gages and special-purpose sensors. The gage installation procedure described is appropriate for each adhesive, the primary differences in the systems being in mixing instructions, pot life, cure cycles, and, to some extent, elongation properties. Each system is effective from the cryogenic region to +200°F [+95°C].

For proper results, the procedures and techniques presented in this bulletin should be used with qualified Micro-Measurements installation accessory products (refer to Micro-Measurements Strain Gage Accessories Data Book). Accessories used in this procedure are:

- CSM Degreaser or GC-6 Isopropyl Alcohol
- CSP-1 Cotton Applicators
- PCT Gage Installation Tape
- Silicon-Carbide Paper
- MJG-2 Mylar Tape
- M-Prep Conditioner A
- HSC Spring Clamp
- M-Prep Neutralizer 5A
- GT-14 Pads and Backup Plate
- GSP-1 Gauze Sponges

Handling Precautions

While these bonding agents are considered relatively safe to handle, contact with skin and inhalation of their vapors should be avoided. Immediate washing with ordinary soap and water is effective in cleansing should skin contact occur. For eye contact, rinse thoroughly with a copious amount of water and consult a physician. For additional health and safety information, consult the Safety Data Sheet, which is available upon request.

MIXING INSTRUCTIONS AND ADHESIVE CHARACTERISTICS

A. General

1. Each kit contains materials for mixing six batches of adhesive. Mixing instructions for M-Bond AE-10 and M-Bond AE-15 Bulk are included below.

2. Any resin removed from refrigeration must be allowed attain room-temperature equilibrium before being opened.

3. Mix adhesives thoroughly for five minutes according to instructions. If a room-temperature cure is used, allow the freshly mixed adhesive to stand an additional five minutes before use.

4. The pot life for Systems AE-10 and GA-2 can be prolonged by occasionally stirring to prevent localized exotherm in the center of the resin system, or by pouring it out onto a chemically clean metal plate.

Note: During storage, crystals may form in the Resin AE. These crystals do not affect adhesive performance, but should be reliquefied prior to mixing by warming the resin jar to +120°F [+50°C] for approximately one-half hour. Allow the resin to return to room temperature before adding curing agent; excess heat will shorten mixed pot life.

B. M-Bond AE-10 Adhesive Kit

AE-10 will cure at +70°F [+20°C] in 6 hours, with approximately 6% elongation capability and essentially creep-free performance. Elongation capability of approximately 10% can be obtained by extending the cure time to 24 to 48 hours at +75°F [+24°C].* To mix, fill one of the calibrated droppers with Curing Agent 10 exactly to the number 10 and dispense the contents into the center of the jar of Resin AE. Immediately cap the bottle of Curing Agent 10 to avoid moisture absorption. Mix thoroughly for 5 minutes, using one of the plastic stirring rods. The pot life or working time after mixing is 15 to 20 minutes. Discard the dropper after use.

M-Bond AE-10 Bulk is packaged with 200 grams of resin, 40 grams of Curing Agent 10, and three calibrated pipettes. The mix ratio is 10.0 parts by weight of AE Resin to 1.5 parts by weight of Curing Agent 10. Mix thoroughly for five minutes, then allow the mixture to stand for an additional five minutes before use. When mixing quantities greater than 10 grams of AE Resin, the normal pot life of 15-20 minutes will be shortened accordingly.

*Refer to Instruction Bulletin B-129 and Application Note TT-605 for discussions of high-elongation strain measurements.

C. M-Bond AE-15 Adhesive Kit

AE-15 requires moderately elevated curing temperatures, and is recommended for critical installations, such as

Figure B.5 M-Bond AE-10 Installation Instructions (a)

strain gage transducers, where zero shift and hysteresis must be minimized. The AE-15 system is also useful with high elongation strain gages at strain levels up to approximately 10% to 15% at +70°F [+20°C], and at strain levels up to 15% at +200°F [+95°C]. To mix, fill one of the calibrated droppers with Curing Agent 15 exactly to the number 15 and dispense the contents into the center of the jar of Resin AE. Immediately cap the bottle of Curing Agent 15 to avoid moisture absorption. Mix the Resin AE and the Curing Agent 15 thoroughly for 5 minutes, using one of the plastic stirring rods. The pot life is approximately 1-1/2 hours at +70°F [+20°C]. Discard the dropper after use.

M-Bond AE-15 Bulk is packaged with 200 grams of resin, 25 grams of Curing Agent 15, and three calibrated pipettes. The mix ratio is 10.0 parts by weight of AE Resin to 0.8 parts by weight of Curing Agent 15. Mix thoroughly for five minutes, then allow the mixture to stand for an additional five minutes before use. When mixing quantities greater than 10 grams of AE Resin, the normal pot life of 15-20 minutes will be shortened accordingly.

D. M-Bond GA-2 Kit

GA-2 is a partially filled 100%-solids epoxy adhesive. Resin GA-2 with Curing Agent 10-A will have approximately 10% to 15% elongation capabilities when cured for 40 hours at +70°F [+20°C], and approximately 6% elongation capabilities when cured for 6 hours at +70°F [+20°C]. To mix, fill one of the calibrated droppers with Curing Agent 10-A exactly to the number 10, and dispense the contents into the jar of Resin GA-2. Immediately cap the bottle of Curing Agent 10-A to prevent moisture absorption. Mix the Resin GA-2 and the Curing Agent 10-A thoroughly for 5 minutes using one of the plastic stirring rods. Pot life is approximately 15 minutes at +70°F [+20°C]. Discard the dropper after use.

GAGE INSTALLATION PROCEDURE

Step 1

The surface preparation technique used is the same basic cleaning procedure described in Micro-Measurements Instruction Bulletin B-129, *"Surface Preparation for Strain Gage Bonding"*. The initial step is to thoroughly degrease with solvents such as CSM Degreaser or GC-6 Isopropyl Alcohol. CSM Degreaser is preferred whenever possible since this is a very active degreaser. The substitution of GC-6 as a degreasing agent should be considered for materials that may be sensitive to strong solvents. Any degreasing should be done with clean solvents. Thus the use of a "one-way" container, such as the aerosol can, is highly advisable.

Step 2

Dry-abrade the gaging area with 220- or 320-grit silicon-carbide paper to remove any scale or oxides on the base material. Apply M-Prep Conditioner A and wet-abrade the gage area. Keep the surface wet while abrading. Remove the residue and Conditioner by slowly wiping through the gaging area with a gauze sponge. The wet-abrade and wiping procedure should then be repeated with 400-grit silicon-carbide paper. With a 4H (hard) drafting pencil on aluminum or a ballpoint pen on steel, burnish whatever alignment marks are needed on the specimen. Rewet the surface with Conditioner A and scrub with cotton tipped applicators until a clean applicator is no longer discolored by the scrubbing. Remove the residue and Conditioner by slowly wiping through the gaging area with a gauze sponge. Do not wipe back and forth over the gage area since this may allow contaminants to be redeposited on the cleaned area.

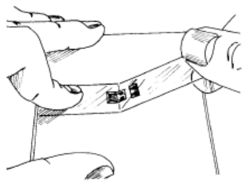
Step 3

Apply a liberal amount of M-Prep Neutralizer 5A to the gage area. Keeping the surface wet, scrub with cotton tipped applicators. Do not allow evaporation of the cleaning material on the specimen surface since this would leave a thin, unwanted film between the adhesive and the specimen. Remove the Neutralizer by slowly wiping through the gage area, allowing the gauze sponge to absorb the Neutralizer. Do not wipe back and forth over

Figure B.6 M-Bond AE-10 Installation Instructions (b)

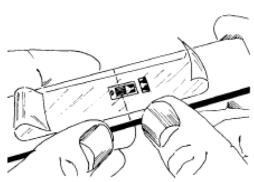
the gage area since this may allow contaminants to be redeposited on the cleaned area.

Step 4



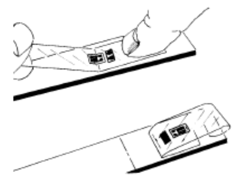
Remove the gage from its transparent envelope by grasping the edge of the gage backing with tweezers, and place bonding side down on a chemically clean glass plate or empty gage box. If a solder terminal is to be incorporated, position it on the plate adjacent to the gage as shown. A space of approximately 1/16 in [1.6 mm] should be left between the gage backing and terminal. Use 4 to 6 in [100 to 150 mm] of PCT Gage Installation tape as a carrier to aid in positioning the strain gage and terminal. [When cure temperatures exceed +175°F [+80°C], MJG-2 mylar tape must be substituted for the gage installation tape.] Tack one end of the tape to the glass plate behind the gage and terminal, and wipe forward onto the terminal and gage. Carefully lift the tape at a shallow angle (about 45 degrees to the glass plate), bringing the gage up with it.

Step 5



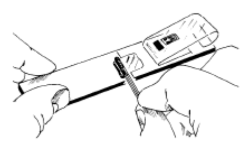
Position the gage/tape assembly so the triangle alignment marks on the gage are over the layout lines on the specimen. Holding the tape at a shallow angle, wipe the assembly onto the specimen surface. If the assembly appears to be misaligned, lift one end of the tape at a shallow angle until the assembly is free of the specimen. Realign properly and firmly anchor down at least one end of the tape to the specimen. This realignment can be done without fear of contamination by the tape mastic if the recommended gage installation tape is used. This tape will retain the mastic when removed.

Step 6



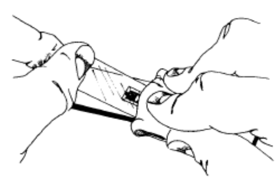
Lift one end of the tape at a shallow angle to surface (about 45 degrees) until gage and terminal are free of specimen surface. Tuck the loose end of the tape under and press to the surface so the gage lies flat with the bonding side exposed. In some cases this may be difficult because of space limitations. If this situation occurs, leave enough slack in the tape to allow a finger to be slipped behind the gage to support it while applying the adhesive.

Step 7



Coat the specimen, back of the gage, and terminal strip with the prepared adhesive. The mixing rod can be used to apply a thin layer of adhesive over each surface. Be careful not to pick up any unmixed components of the adhesive. To ensure this, it is advisable to wipe the mixing rod clean and then pick up a very small amount of the adhesive from the center area of the adhesive jar. Immediately after coating the gage and specimen with adhesive, proceed without delay to Step 8. This will limit the absorption of moisture by the uncured adhesive, and the gage installation tape will serve as a temporary moisture barrier during curing.

Step 8

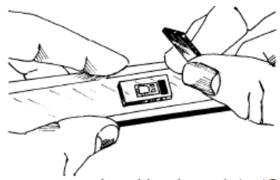


Lift the tucked-over end of tape and bridge it over the adhesive at approximately a 30-degree angle. With a piece of gauze, slowly make a single wiping stroke over the gage/tape assembly, bringing the gage back down over the alignment marks on the specimen. Use firm

Figure B.7 M-Bond AE-10 Installation Instructions (c)

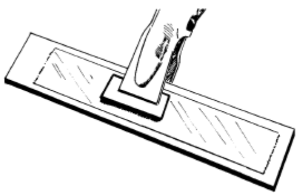
pressure with your fingers when wiping over the gage, since the adhesive is quite viscous. A very thin layer of adhesive is desired for optimum bond performance.

Step 9



Place a silicone gum pad and backup plate (GT-14) over the gage installation. The silicone gum should be soft (Durometer A40-60) and at least 3/32 in [2.5 mm] thick. This will allow the clamping force to be exerted evenly over the gage. The area of the silicone gum pad should be used to compute the final clamping pressure.

Step 10



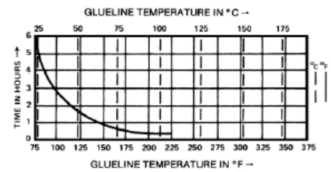
Apply force by spring clamp or dead weight until a clamping pressure of 5 to 20 psi [35 to 135 kN/m2] is attained. Take special care in making sure the clamping pressure is equal over the entire gage. Unequal clamping pressure may result in an irregular glueline. Take steps to ensure that the clamps will not slide out of position during cure. A few strips of tape to assist in holding the clamps or backup plate in place during cure may be helpful. Cure the installation in accordance with the recommended cure schedule below.

Step 11

The gage and terminal strip are now solidly bonded in place. To remove the tape, pull it back directly over itself, peeling it slowly and steadily off the surfaces. This technique will prevent possible lifting of the foil on open-faced gages or otherwise damaging the installation. It is not necessary to remove this tape immediately after gage installation. The tape will offer mechanical protection for the grid surface, and may be left in place until it is removed for gage wiring.

RECOMMENDED CURE SCHEDULES

M-Bond AE-10 and GA-2

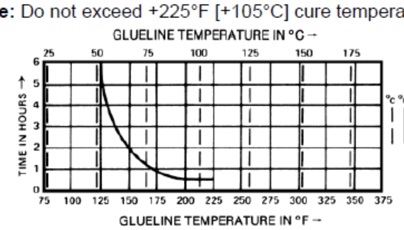


Caution: These systems may not cure properly below +70°F [+20°C]. Postcuring the installation for two hours at least +25°F [+15°C] above the maximum operating temperature with the clamping fixture removed will provide essentially creep-free performance.

M-Bond AE-15

Caution: To ensure proper polymerization, the cure cycle should start within 1.5 hours after mixing.

Note: Do not exceed +225°F [+105°C] cure temperature.



FINAL INSTALLATION PROCEDURE

1. Select appropriate solder and attach leadwires. Remove solder flux with RSK Rosin Solvent. See Micro-Measurements Strain Gage Accessories Data Book for these materials.

2. Select and apply protective coating. See Micro-Measurements Strain Gage Accessories Data Book.

3. Micro-Measurements gages have been treated for optimum bonding conditions and require no precleaning before use unless contaminated during handling. If contaminated, the back of any gage may be cleaned with a cotton applicator slightly moistened with Neutralizer 5A.

Figure B.8 M-Bond AE-10 Installation Instructions (d)

Strain Gage Installations for Concrete Structures

Introduction

The installation of strain gages for concrete structures presents several unique challenges to the installer, whether measurements are made on the concrete surface or within the concrete, or on reinforcement bars within the structure. For example, special preparation is required to ensure that strains on the irregular surface of the concrete are fully transmitted to the strain gage; and when gages are bonded to reinforcement bars, provisions are necessary to protect the installation from mechanical damage during fabrication and from the hostile environment of the concrete itself. This Tech Tip outlines recommendations for gage, leadwire and protective coating selections and installations under these conditions. The surface preparation materials and installation accessories referenced throughout are described in detail in the Micro-Measurements Strain Gage Accessories Data Book.

Installing Strain Gages on Concrete and Other Irregular Surfaces

Strain gages can be satisfactorily bonded to almost any solid material — including concrete — if the surface is properly prepared. For smooth surfaces on nonporous materials, only the basic operations of solvent degreasing, abrading, application of layout lines, conditioning and neutralizing are required. For concrete and other materials with an uneven, rough and porous surface, an extra operation must be added to fill the voids and seal the surface with a suitable precoating before the gage is bonded.

Degreasing

Use a stiff-bristled brush and a mild detergent (Figure 1) to remove any loose soil or plant growth. Rinse with clean water. A degreaser such as CSM may be needed if oils and greases are present. Remove surface irregularities with a wire brush, disc sander, or grit blaster. Blow or brush all loose dust from the surface.

Conditioning

Generously apply *M-Prep* Conditioner A, a mildly acidic solution, to the surface in and around the gaging area. Scrub with a stiff-bristled brush. Blot contaminated Conditioner A with gauze sponges. Rinse the area thoroughly with clean water. Reduce the surface acidity by scrubbing with *M-Prep* Neutralizer 5A. Blot with gauze sponges and rinse with water. Dry the surface thoroughly. Warming the surface gently with a propane torch or heat gun will hasten evaporation.

Filling

Application of a 100%-solids adhesive to the gaging area (Figure 2) will provide a suitable gage-bonding surface. For test temperatures up to +200°F (*+95°C*), M-Bond AE-10 is normally used. At higher temperatures, M-Bond GA-61 is recommended. In applying the adhesive as a sealer to the surface, work the adhesive into any voids, and level to form a smooth surface. After the adhesive is cured, it should be abraded with 320-grit abrasive paper until the

Figure 1 – Conditioning the surface for gage installation.

Figure 2 – Filling of the surface.

Figure B.9 Strain Gage Installations for Concrete Structures (a)

Strain Gage Installations for Concrete Structures

base material is exposed. (If a thin adhesive, like M-Bond 200, will be used to bond the gage, the base material should not be exposed.)

Layout Lines

Using a ballpoint pen or round-pointed metal rod, burnish layout lines. Scrub them with Conditioner A, apply Neutralizer 5A, and dry as before. Supplemental layout lines may be drawn with ink on the concrete outside the gaging area.

Gage Bonding

Normal procedures should be followed for bonding the gage to the prepared gaging surface. Special notice should be paid to several points, however. First, the gage length of strain gages used on concrete should be at least 5 times the diameter of the largest aggregate in the concrete. This often results in the use of patterns with gage lengths of 1 in (*25 mm*) or more. N2A-Series or encapsulated EA-Series gages, which tend to lie flatter during handling, are highly recommended for their ease of installation under these circumstances. Further, bonding with a quick-curing adhesive, like M-Bond 200, is not recommended, even when test conditions may warrant its use. Accurate gage alignment and an even application of pressure as the adhesive is cured are more difficult when bonding longer gages. A slower curing adhesive, like M-Bond AE-10 shown in Figures 3 and 4, will allow time for realigning the gage, if necessary. It will also enable the use of a suitable pressure pad and clamping fixture as outlined in Micro-Measurements Tech Tip TT-610.

Soldering

Concrete and adhesive fillers are relatively poor heat conductors. Accordingly, care should be taken when soldering leads directly to the strain gage. Excessive heating of the tabs can be eliminated by using gages with Option W (integral printed circuit terminal), or Option P (preattached leadwires), which is shown in Figure 5.

Attention to these procedures will help ensure successful installations of strain gages on the surface of concrete and other similar solids. If you have any questions about your particular applications, contact our Applications Engineering Department for recommendations.

Strain Measurement Within Concrete Structures

Micro-Measurements EGP-Series Embedment Strain Gages (Figure 6) are specially designed for measurement of mechanical strains within concrete structures. The sensing grid has an active gage length of 4 in (*100 mm*) to average

Figure 3 – Adhesive application.

Figure 4 – Application.

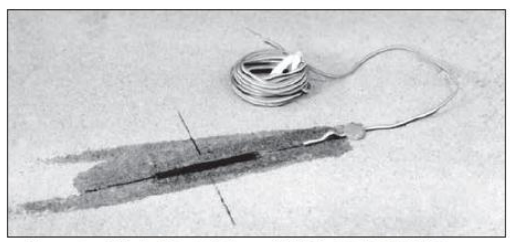


Figure 5 – Finished installation with N2A-06-40CBY-120 gage with Option P (preattached leadwires).

Figure 6 – EGP-Series Embedment Gage.

Figure B.10 Strain Gage Installation for Concrete Structures (b)

Strain Gage Installations for Concrete Structures

strains in aggregate materials, and is fully encapsulated in a polymer concrete material to closely match the mechanical properties of typical structural concrete, guard against mechanical damage, and to protect against moisture and corrosive attack. EGP-Series Gages incorporate a 10-ft (*3-m*), jacketed, three-conductor cable for ease of use in field installations, and are compatible with conventional strain measurement instrumentation.

Gage Installation

No preparation of the gage itself is required; however, as with bonded or welded strain gages, EGP-Series Gages must be accurately aligned along the intended strain measurement direction during the installation process. Care should be taken to secure the gage in the desired location and orientation, and to tie the leadwire cable to any available support, before the concrete is poured. While the Embedment Gage must be completely encapsulated in concrete to ensure complete strain transfer from the structure, normal pouring techniques are usually all that are required.

Cable Splices

EGP-Series Gages are provided with a 10-ft (*3-m*) cable to allow for making cable splices outside the concrete structure. When splices are required, all connections should be soldered and then protected from moisture and other contamination with a suitable cable splice sealant.

Strain Gage Installation On Concrete Reinforcement

Strain gage installation on reinforcing rods follows the same general procedure recommended for most steel specimens. These rods are, however, subjected to mechanical abrasion and a moist, corrosive environment. Accordingly, the following special attention is required:

Surface Preparation

1. Degrease with a degreaser (CSM) over at least a 6-in (*150-mm*) length of the bar at the proposed gage location.
2. Descale and smooth the rebar around its circumference with a grinder wheel. (Aluminum oxide or silicon carbide abrasive of approximately 50 mesh is preferred.) A 3-in (*75-mm*) length generally provides a sufficiently large descaled area for gage and protective coating installations. Surface finish after this operation should be about 180 microinches (*5 µm*) rms.
3. Wet abrade with Conditioner A and 220-grit silicon carbide wet-or-dry paper (SCP-1). Use sufficient Conditioner A to prevent material from drying on the rebar surface while abrading.
4. Wipe dry with a clean gauze sponge (GSP-1), then repeat Step 3 (with 320-grit paper) and dry again.
5. Surface finish should be 63 to 125 microinch (*1.6 to 3.2 µm*) rms at the completion of the second wet-abrading operation.
6. Lay out the gage locations.
7. Scrub the installation area with Conditioner A and a cotton applicator (CSP-1). Wipe dry with gauze sponges.
8. Scrub the area thoroughly with Neutralizer 5A and a cotton applicator and wipe dry with a gauze sponge as previously noted. This step must be accomplished thoroughly to neutralize all traces of Conditioner A used in Steps 3 through 7.
9. Mask an area with PCT-2M gage installation tape (or MJG-2 Mylar®) tape at the gage location to minimize flow-out of adhesive for subsequent protective coating application.

Adhesive Selection

M-Bond AE-10 adhesive is a good selection when a room-temperature cure of a field application is required. This adhesive will cure in 6 hours at +75°F (*+24°C*). Other adhesives that may be used, depending upon the test environment, are M-Bond AE-15, M-Bond 600/610, or GA-61 adhesive. Application of the adhesive should follow the specific instructions accompanying it.

Gage Selection

CEA-Series gages are the most popular choice when the cross section of the bar is 1/8 in (*3mm*) or larger in diameter. Where very stable installations are required (e.g., for tests in excess of one year) on 1/4 in (*6 mm*) or larger diameter rebar rod, WK-Series gages are recommended. When conditions are not favorable for bonding gages, CEA- and LWK-Series Weldable Gages (Figure 7) may be used.

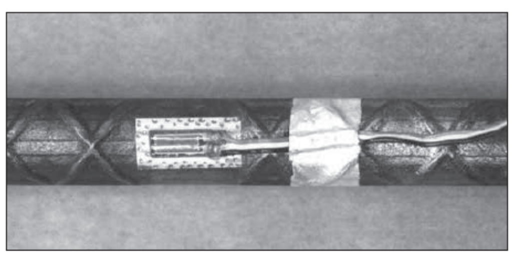


Figure 7 – CEA-Series Weldable Gage.

Figure B.11 Strain Gage Installations for Concrete Structures (c)

Strain Gage Installations for Concrete Structures

Leadwire Considerations

When utilizing one active strain gage (quarter-bridge configuration), it is good practice to use a three-leadwire system. Micro-Measurements EA- and CEA-Series strain gages can be supplied with a preattached three-leadwire cable (Options P and P2, respectively) to eliminate the need for attaching leadwires at the job site, and to reduce installation time.

Alternately, leadwires may be soldered to the strain gage tabs after gage bonding. If a parallel or twisted cable is used, separate the individual (leadwire) conductors for a distance of about 1 in (*25 mm*) from the cable end and, if Teflon®-insulated cable is used, etch the insulation with Tetra-Etch® compound; if vinyl-insulated cable is used, prime the insulation with thinned M-Coat B. These materials should not be allowed to flow onto the bare strands of the conductors.

After allowing the M-Coat B to air dry for at least two hours at room temperature [about +75° (*+24°*)], thermally strip the leadwire ends and tin and solder the wires to the strain gage tabs. For most rebar installations, 361A-20R solder will give excellent results. Carefully remove all rosin flux from the soldered connections using rosin solvent (RSK-1) before applying the protective coating.

Environmental Protection

Apply M-Coat J to the gage installation carefully following the procedures outlined in Micro-Measurements Instruction Bulletin B-147. The coating should be built up to provide approximately ¼ in (*6 mm*) thickness completely surrounding the rebar (Figure 8) at the gage location, and should be carried back far enough to cover the leadwire area previously primed with M-Coat B. Allow this coating to cure 24 hours at +75°F (*+24°C*), or 4 hours at +125°F (*+50°C*).

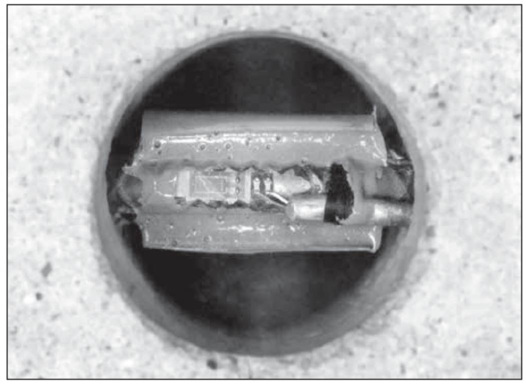


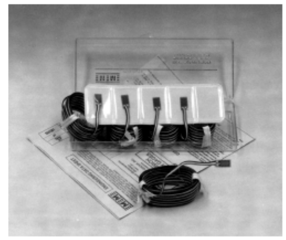
Figure 8 – Cut-away view of installation.

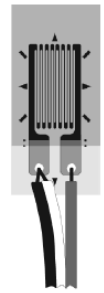
As a final step, the instrumentation leads extending from the gage, out through the concrete, should be placed in conduit to prevent mechanical damage to the leadwire system. Of course, the complete installations should be thoroughly checked with a Model 1300 Gage Installation Tester before and after the concrete is poured. A properly installed and protected strain gage is capable of many years of service on embedded reinforcing bars, providing data about load effects throughout the life of a concrete structure — from initial construction forces to unexpected severe loading conditions.

Figure B.12 Strain Gage Installations for Concrete Structures (d)

Installing Gages with Option P2

CEA-Series gages supplied with Option P2 can be installed in a wide variety of applications. General gage installation procedures provided in Micro-Measurements technical literature and training programs provide a sound foundation; however, the need for leadwire attachment after gage bonding is eliminated by Option P2. Although application conditions may dictate certain installation procedures, the following guidelines are recommended for maximum performance. They supplement any standard procedures when installing gages with preattached leadwires.





SURFACE PREPARATION

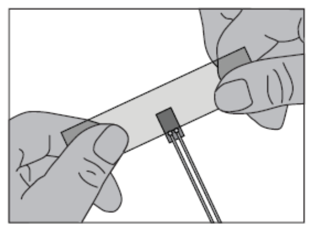
Surface preparation for bonding is described in Application Note B-129, *Surface Preparation for Strain Gage Bonding*, for gages with preattached leadwires.

GAGE HANDLING AND CABLE SUPPORT

After removing the gage and its protective window from the pouch in the plastic box, hold the gage/cable assembly by the cable bundle. Release a comfortable working length of cable and place the gage on a chemically clean surface. Temporarily secure the remainder of the bundle before removing the gage from its protectivle window with a pair of BTW-1 Blunt-nosed Tweezers.

Apply a strip of PCT-2M Cellophane Tape to the gage face. This transfer tape should be applied in the direction transverse to the leadwires.

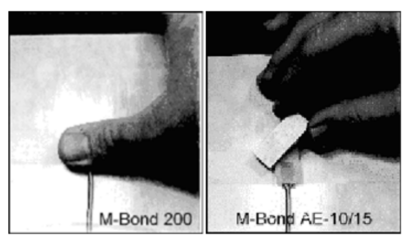
When ready to bond the gage, carefully lift the tape from the surface at a shallow angle. Unsecure the cable bundle and hold the gage/tape assembly by the bundle when moving it to the installation site.



GAGE BONDING

To preclude damage to the cable insulation, the adhesive selected should be curable at a temperature of no more than +180°F (+80°C).

Lift the gage end of the gage/tape assembly at a shallow angle to the specimen surface (less than 45 degrees) until the gage is no longer in contact with the surface. Continue lifting the tape until it is free from the surface about 1/2 in (13mm) beyond the gage. Tuck the loose end of the tape under itself and apply the adhesive according to the instructions provided. Since Option P2 leadwires are attached directly to the gage, a cushion may be used over the grid area to promote uniform pressure over the entire gage area. With M-Bond 200 , a folded gauze sponge can be used as a cushion. However, the thumb by itself is sufficient when placed transverse to the leadwires. When M-Bond AE-10 / 15 is used, the silicone gum pad should be placed over the gage grids and butted to the ends of the leadwire on the solder tabs. M-Bond 600 and 610 should not be used on gages with Option P2 because their elevated curing temperatures are excessive for the vinyl cable insulation.



After the adhesive has cured, remove the transfer tape by pulling it back directly over itself, peeling it slowly and steadily off the surface. An application of M-LINE Rosin Solvent will quickly soften the mastic and ease tape removal.

Figure B.13 Installing Gages with Option P2 (a)

Installing Gages with Option P2

PROTECTIVE COATINGS

Option P2 provides electrical insulation of the gage grids, but not the solder joints. Therefore, an additional protective coating is recommended when the gage installation is exposed to moisture, chemical attack, or potential for mechanical damage. When applying coatings, pay particular attention to the junction between the solder tabs and cable leadwires. Apply an appropriate coating in this area before the cable is permanently anchored to the specimen.

STRAIN RELIEF

Before loosening the cable bundle, it is recommended that strain relief loops be provided in the cable. Form these loops over the handle of a M-LINE DPR-1 Dental Probe or rod of similar diameter. The jumper-wire loop, which should lie in the plane of the specimen, is usually held in place by the protective coating. The cable loop, which should remain upright, is usually located outside the coated area. M-LINE 3145 RTV silicone rubber can be used as a cable anchor.

After the cable has been properly anchored, the remainder of the bundled cable can be loosened and routed to the strain gage instrumentation. If a cable extension is added, remember that it should be attached by soldering. Alligator clips, twist caps, and most other mechanical connections should be avoided when making electrical connections within strain gage circuits.

Gages supplied with Option P2 can be installed readily with these techniques in most applications. Should you have any questions about your particular application, our Applications Engineering staff is always ready to assist you. Don't hesitate to give them a call.

Figure B.14 Installing Gages with Option P2 (b)

Strain Gage Clamping Techniques

Introduction

All organic strain gage adhesives require that some form of clamping pressure be applied and maintained throughout the curing stage. In the case of the fast-curing M-Bond 200 adhesive, clamping pressure is applied with the thumb or finger, and maintained for a minimum of one minute. However, M-Bond 200 is not recommended for elevated-temperature or long-term strain measurements. For these applications, or when gages must be installed in confined areas such as inside tubing or bored holes, epoxy or epoxy-phenolic adhesives are commonly selected.

With epoxy-based adhesives it is always necessary to maintain a specified uniform clamping pressure while the adhesive is curing. The instruction bulletins accompanying all Micro-Measurements strain gage adhesives include, in each case, the recommended clamping pressure and curing cycle. Since the curing process usually takes several hours and may involve elevated temperatures, it is important that the clamping device be physically stable and capable of holding the specified force for the required time.

This Tech Tip describes several popular, and some unusual, gage clamping methods and hardware.

Clamping Hardware

The mechanical arrangement used to obtain a steady, non-shifting clamping force obviously depends on the nature of the test object and the gage installation. Sometimes a simple spring clamp will suffice. In other cases, it may be necessary to devise a more elaborate clamping fixture. For any type of clamp, the assembly generally consists of four components:

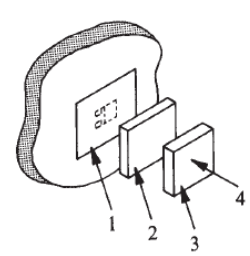


Figure 1

1. A release film is used between the gage/adhesive and the pressure pad. It prevents the pressure pad from adhering to the adhesive layer. For low-temperature-curing epoxies [<+150°F (+*66°C*)] such as AE-10/15 and GA-2, this film is usually gage installation tape (PCT-2M). For higher-temperature-curing epoxies, such as 600, 610, 43-B and GA-61, it is usually a sheet of Teflon® film (TFE-1) or Mylar tape (MJG-2).
2. A resilient rubber pressure pad is used to provide a uniform clamping pressure over the gage area. It should be soft enough to conform to slightly irregular surfaces but not so soft as to extrude from under the clamping plate. Recommended hardness is durometer A40-60. Silicone gum or silicone rubber are preferred because of their high-temperature capability.
3. A metal clamping plate serves to distribute the clamping force over the entire area of the pressure pad. It should be formed to match the contour of the pressure pad or test part and should have sufficient thickness to prevent deformation under normal clamping force.
4. A force application device is used to apply steady force on the metal clamping plate. It could range from simple dead weights to sophisticated vacuum pads with integral heaters.

Calculating Clamping Pressure

All Micro-Measurements instruction bulletins for epoxy adhesives specify a recommended clamping pressure. Specified in pounds per square inch (psi) or kilonewtons per square meter (kN/m^2), clamping pressure is calculated by dividing the applied force by the surface area of the rubber pad in contact with the strain gage and specimen surface. Normally the desired clamping pressure is known from the instruction bulletin, and the proposed pressure pad area can be measured. Therefore, the necessary quantity to be determined is clamping force.

® Registered trademark of DuPont.

Figure B.15 Strain Gage Clamping Techniques (a)

Strain Gage Clamping Techniques

As an example, the gage shown in Figure 1 is to be bonded with M-Bond 610 adhesive at a recommended clamping pressure of 45 psi (312 kN/m^2). The gage pattern selected can be conveniently covered with one of the clamping pads from the GT-14 pad kit. These pads measure 0.5 x 1.25 in (*13 x 32 mm*). The necessary clamping force can be computed by multiplying the required clamping pressure by the pad area:

clamping force = clamping pressure x pad area
= 45 psi x 0.625 in^2 ($312\,kN/m^2 \times 0.0004\,m^2$)
= 28 lbs (*125 N*)

Thus a 28-lb (*125-N*) clamping force for the example in Figure 1 would yield the recommended 45 psi ($312\,kN/m^2$) clamping pressure.

Clamping Techniques

A selection of gage clamping techniques is shown in the sketches that follow. Whether one of these or another clamping scheme is used, there are two precautions that need to be observed in every case. The first is to always apply the clamping force through some form of spring (preferably low-rate). Rigid clamps (C-clamps, hose clamps, etc.), such as those shown in Figures 4 and 5, should not be used without a spring in series with the clamping force. The spring is necessary to ensure that the force does not vary significantly with small dimensional changes which may occur as the adhesive flows and cures, or as the temperature changes. The second is to always provide a means for determining the actual clamping force, thus making certain that it is within the range specified by the supplier. This can be done by precalibrating the spring for force versus deflection, or by direct measurement on the clamping assembly with an inexpensive spring scale (e.g., a "fish scale"). The latter technique is particularly appropriate for arrangements such as those shown in Figures 2 and 7.

The selection of additional clamping methods is limited only by the imagination of the gage installer. Following the guidelines provided in this Tech Tip, there should be very few applications where adequate gage clamping pressure cannot be achieved.

For further assistance in applying the clamping techniques illustrated, contact our Applications Engineering Department.

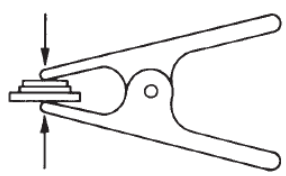


Figure 2 – Common spring clamp available in various sizes. Clamping force exerted should be checked at different jaw openings, as force may vary.

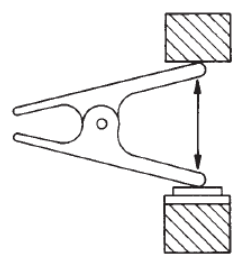


Figure 3 – Spring clamp used in a reverse (pushing) mode. Force can be checked by pressing handles down on platform or bathroom scale.

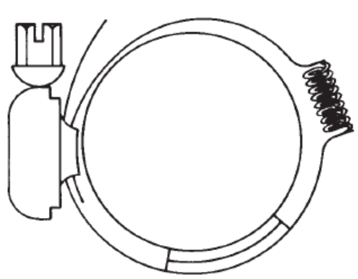


Figure 4 – Hose clamp with spring in series to provide constant and measurable force.

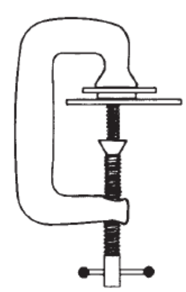


Figure 5 – C-clamp with compression spring that can be removed and checked for force versus deflection.

Figure B.16 Strain Gage Clamping Techniques (b)

Strain Gage Clamping Techniques

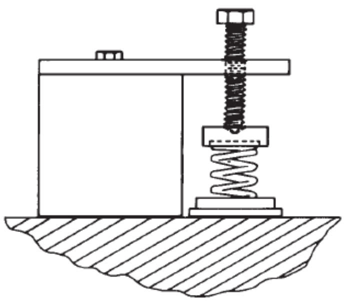


Figure 6 – Magnetic or metal block that can be attached to structure with dental cement or M-Bond 200. Spring can be calibrated separately.

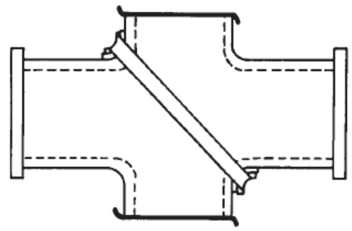


Figure 7 – Rubber-band clamp (usually surgical tubing) wrapped tightly around structure can be force-calibrated with spring scale.

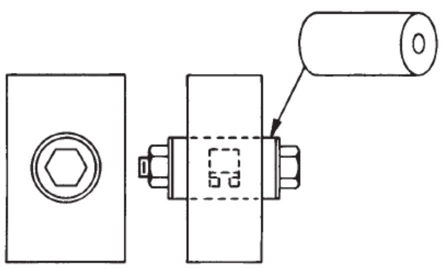


Figure 8 – Silicone rubber plug expands to provide clamping force to gage inside hole. Difficult to calibrate.

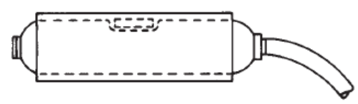


Figure 9 – Silicone rubber tubing has both ends plugged and fitted with air hose. Under pressure, tube expands to provide clamping force for gage inside pipe. Gage can also be prewired and temporarily installed upside down on tubing before insertion in pipe. Adhesive is then applied to gage bonding surface and assembly slid into pipe to the proper position and inflated.

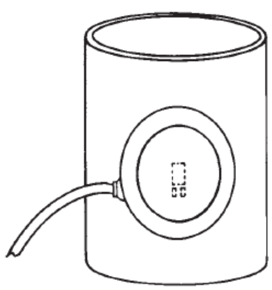


Figure 10 – Commercially available vacuum pads adhere to surface through suction. Internally heated models are available.

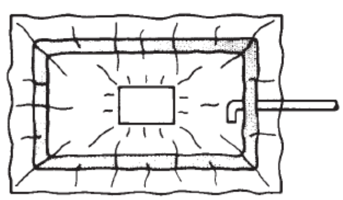


Figure 11 – Homemade vacuum clamping fixture. Putty is formed into a shallow box shape with vacuum hose molded into side. After gage placement, a plastic film (usually mylar) is placed over putty frames, and the vacuum is applied. Normally heat lamps are used to cure elevated-temperature-curing epoxies.

Figure B.17 Strain Gage Clamping Techniques (c)

MICRO MEASUREMENTS A VPG Brand

Instruction Bulletin B-134

M-Coat F Application Instructions

INTRODUCTION

The M-Coat F Protective Coating Kit is designed to fit a wide variety of both bondable and weldable strain gage application requirements. Because M-Coat F is easily applied and requires no mixing or curing, it is particularly suited for use where working conditions are not ideal. Typical applications include pipelines, tunnels, bridges, reinforcement bars in concrete, heavy machinery, ships, aircraft, motor vehicles, and pressure vessels.

This kit contains all materials necessary for installation under general laboratory conditions or in hostile field environments. Contents include self-adhering Teflon® tape; a soft, pliable butyl rubber sealant; neoprene rubber sheets; aluminum foil tape; and M-Coat B (an air-drying nitrile rubber coating). These materials can be applied to vertical and inverted surfaces without flowing.

Application of M-Coat F consists of pressing a small piece of Teflon tape onto the exposed gage foil and lead connections. This is followed by a layer of M-Coat FB butyl rubber to immediately seal against moisture. For mechanical protection, a layer of M-Coat FN neoprene rubber is pressed onto the layer of FB sealant. In applications exposed to solvents, petroleum products, or flowing air or water, FA aluminum tape is installed over the entire installation and sealed with M-Coat B. This forms a smooth contour and provides additional protection against moisture and solvents.

The normal operating temperature range of M-Coat F is -20° to +175°F [-30° to +80°C]. Operation in an extended range of -70° to +250°F [-55° to +120°C] will not damage the coating, but may result in softening or reduction in bond strength. All kit components have flash points above +110°F [+45°C]. Shelf life is a minimum of one year.

HANDLING PRECAUTIONS
All components of the M-Coat F Kit are safe to use when reasonable care is observed; however, the user is cautioned to: (1) Avoid direct contact with M-Coat B; (2) Avoid prolonged or repeated breathing of its vapors; (3) Use M-Coat B only in well-ventilated areas. If skin contact with M-Coat B does occur, thoroughly flush the contaminated area with warm water. Obtain medical attention in cases of ingestion or extreme exposure. For additional health and safety information, consult the safety data sheet.

INSTALLATION PROCEDURES

Leadwire Preparation and Priming

Step 1

Using the brush provided, prime vinyl-insulated leadwires with a layer of M-Coat B and allow to air dry. It may be desirable to thin the M-Coat B by mixing it 50:50 with methyl ethyl ketone (MEK). Etch untreated Teflon-insulated leadwires with a Teflon etchant such as Micro-Measurements TEC-1 Tetra-Etch® compound. Separate the individual conductors of flat multi-conductor cables prior to priming or etching.

Step 2

Strip and tin each leadwire. Stripping and tinning after priming or etching prevents the primer/etchant from touching bare conductors.

Step 3

Attach the leadwires and remove all soldering fluxes according to recommended procedures for the materials used. (Refer to Micro-Measurements Strain Gage Accessories Data Book.)

Note: When splicing lengths of leadwire, protect and water proof the splice joints with a heat-shrinkable sealant (Micro-Measurements HST-1).

Figure B.18 M-Coat F Application Instructions (a)

Instruction Bulletin B-134

Application of M-Coat FT Teflon Tape, FB Butyl Rubber, and FN Neoprene Rubber

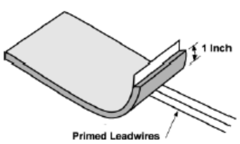
Step 1

Clean the gage installation area with a suitable degreasing agent to ensure a tenacious bond of the coating. The cleaned area should be slightly larger than the space to be covered with M-Coat F. If the surface of the specimen is below +40°F [+5°C], warm with a heat gun, heat lamp, etc., for best results.

Step 2

Cut a piece of M-Coat FT Teflon tape large enough to cover all exposed electrical surfaces on the gage installation. On open-faced gages this would include all foil areas and solder connections. On encapsulated gages, only the solder connections need to be covered. The tape should extend 1/16 in [1.5 mm] beyond bare foil and electrical connections. Press in place.

Step 3

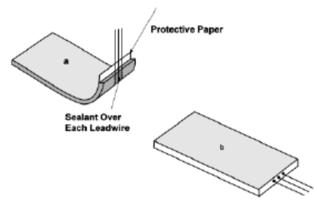


Cut a patch of M-Coat FB butyl rubber sealant large enough to extend 1/2 in [13 mm] beyond the three open sides of the gage (or Teflon tape), and at least 1-1/4 in [30 mm] beyond the end of the gage or terminal strip from which the leadwires exit. If the gage-bonding adhesive extends beyond this area, increase the size of the patch accordingly. This is particularly important with M-Bond 200 cyanoacrylate adhesive.

Step 4
Remove the protective paper from one side of the M-Coat FB patch. Press this exposed area to the surface of the installation, beginning at the end opposite the leadwires and stopping 1/4 in [6 mm] past the solder connections. Leave 1 in [25 mm] of the sealant exposed as shown above.

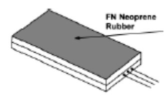
Teflon is a registered trademark of DuPont. Tetra-Etch is a registered trademark of W.L. Gore.

Step 5



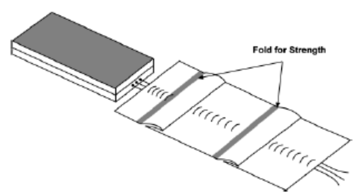
Using tweezers, raise each lead and tack to the coating. Use a dental probe to form the sealant around each lead, being careful not to puncture the sealant. Firmly press the remainder of the patch onto the specimen surface.

Step 6



For mechanical protection, cut a patch of M-Coat FN neoprene rubber to the same size as the butyl rubber sealant. Remove the protective paper from the butyl rubber, and press the neoprene in place.

Step 7



M-Coat FA aluminum tape can serve as a convenient leadwire restraint. For maximum strength, fold as shown above.

Teflon is a registered trademark of DuPont.
Tetra-Etch is a registered trademark of W.L. Gore.

Figure B.19 M-Coat F Application Instructions (b)

MICRO MEASUREMENTS A VPG Brand

Instruction Bulletin B-134

M-Coat F Installation with Aluminum Tape

In applications exposed to solvents, petroleum products, flowing water or air, installation of aluminum tape and sealing with M-Coat B offers increased protection. The aluminum tape contours the installation and leadwire routing; application of M-Coat B seals the edges.

Steps 1 through 5

Follow procedures in Steps 1 through 5 for M-Coats FT, FB, and FN.

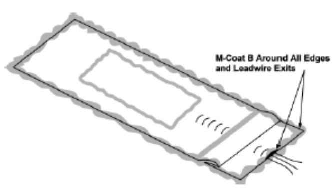
Step 6

For mechanical protection, cut a patch of M-Coat FN neoprene rubber approximately 1/4 in [6 mm] smaller (on all sides) than the butyl rubber. This technique minimizes the otherwise steep edge over which the aluminum tape is installed.

Step 7

Cut the aluminum tape to a length at least 1 in [25 mm] longer than the installation, and long enough to cover the desired length of leadwire. Press the foil firmly into place around the installation and leadwires. Smooth the tape edges with a blunt instrument.

Step 8



Apply two coats of M-Coat B to the tape edges paying particular attention to the lead exit area. Allow the first coat to dry to the touch before applying the second. A completed installation is shown above.

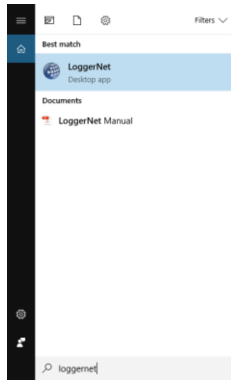
Note: When a low-profile installation is desired, the FN neoprene sheet can be eliminated from the assembly. However, caution must be exercised with this method since it provides less mechanical protection.

Figure B.20 M-Coat F Application Instructions (c)

Appendix C How to Setup a Program in Loggernet

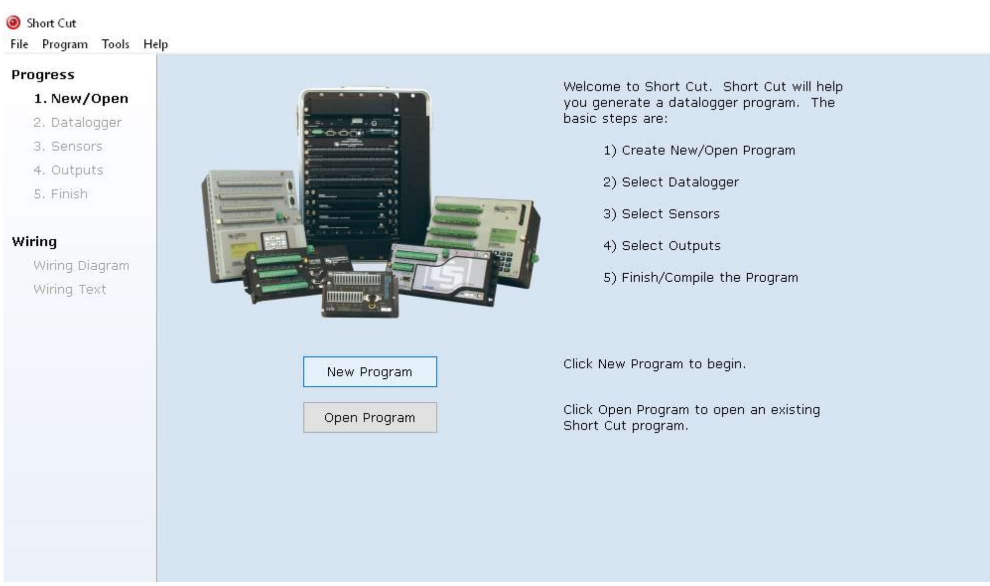
How to create a program in Loggernet

1. Open the Loggernet software.

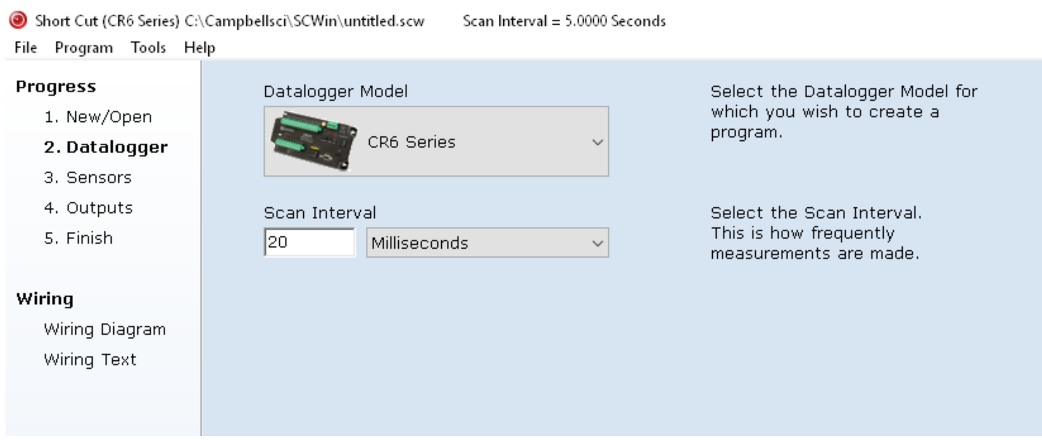


2. Under the program menu choose shortcut to create a basic program. More editing will need to be done to the code in CRBasic editor in future steps.

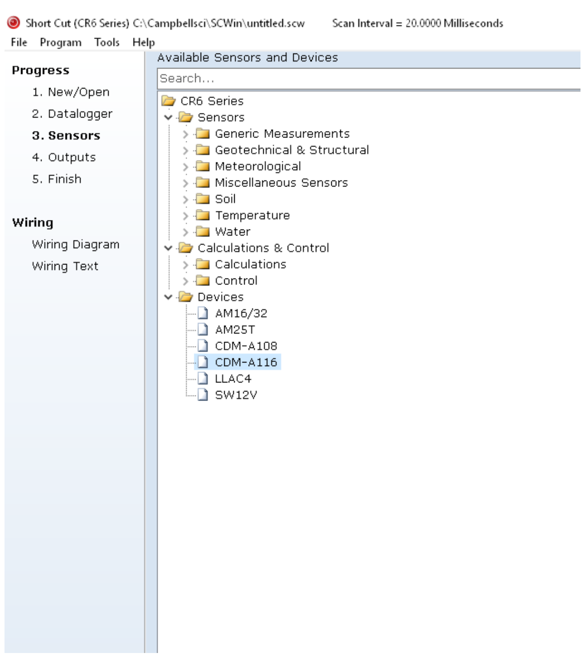
3. Choose new program

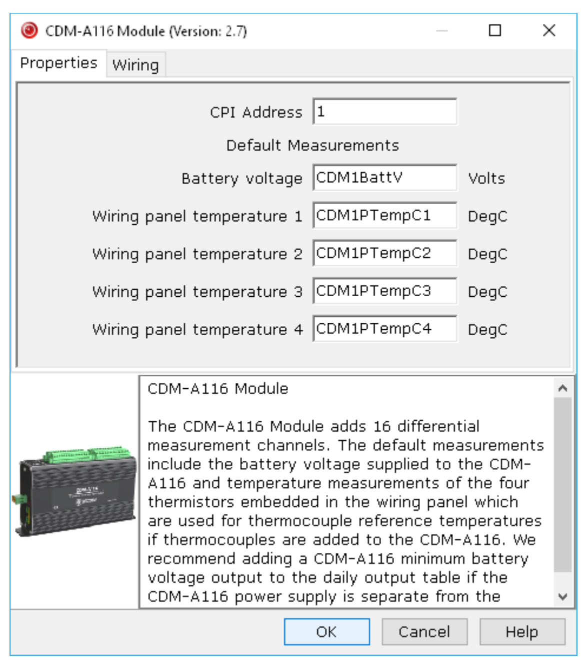


4. Choose CR6 for the Data-logger and select the scan interval desired for the test. The scan interval is the amount of time between each recorded sample on every measurement device used in the experiment. The scan interval for this project is 30 milliseconds. Then click “next”. With the newer version of shortcut the scan interval box is located on the output setup tab. If this is the case, wait to define the scan interval until at the output setup tab.

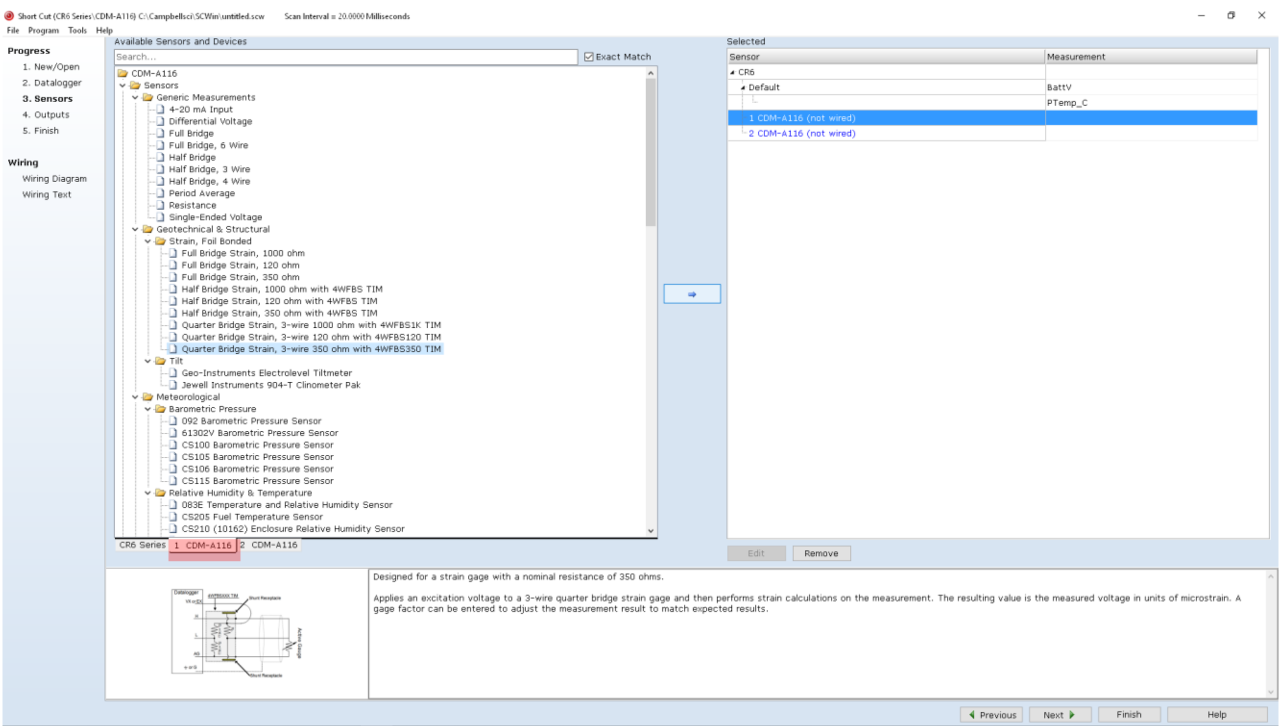


5. In this step we will add all of the measurement devices used in the experiment. Under devices double click CDM-A116. A dialog box will appear, the only label of concern is the CPI Address. Each data-logger and analog input module (CDM-A116) has its own CPI address assigned to it. These addresses can be determined and changed by connecting the device to the computer via USB and going to the device configuration utility. This is located under utilities which is shown in the figure under step 2. Once the correct CPI address is entered click “ok” in the dialog box. For this project there were six CDMs used so the CPI addresses used were one through six.

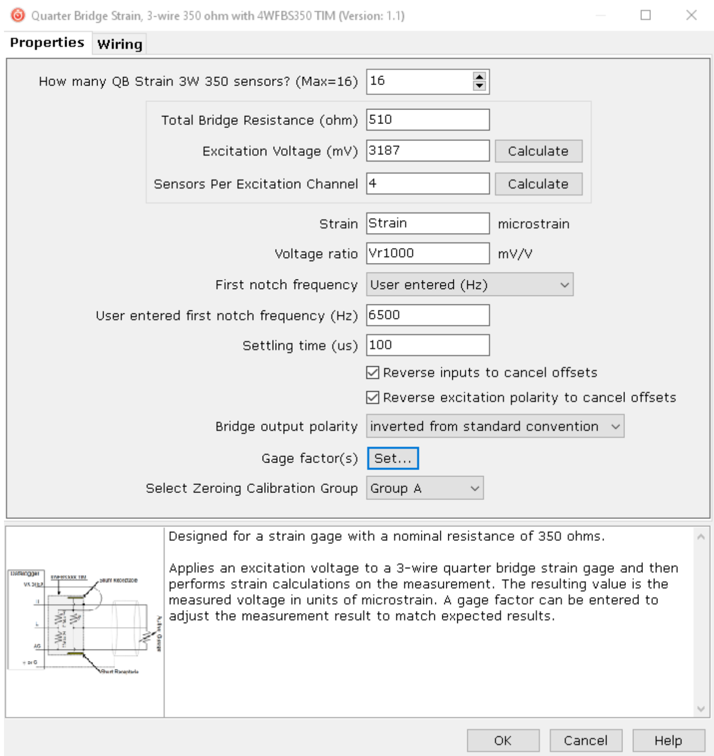


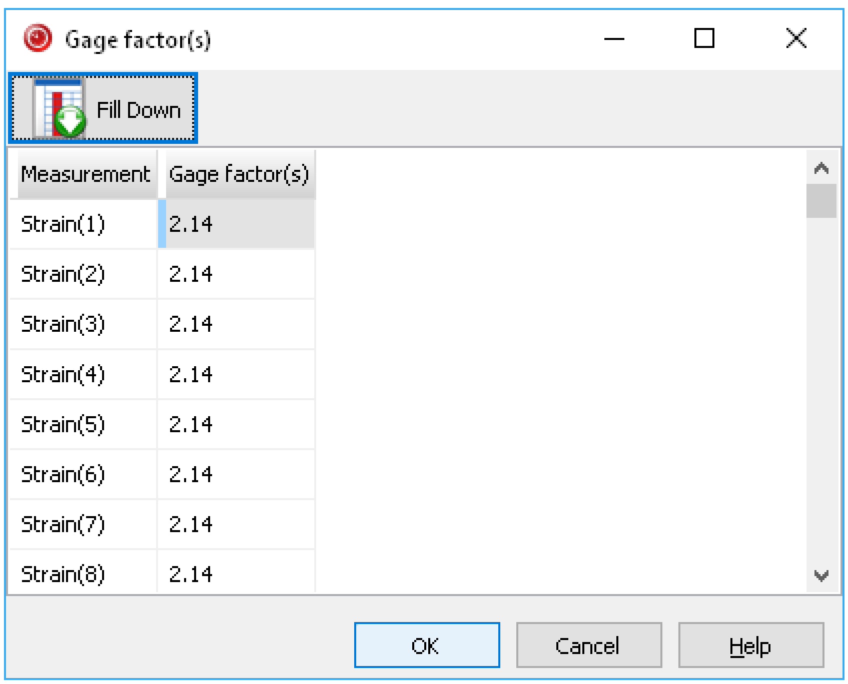


6. Once the correct number of CDMs are added, the CDM tabs can be found in the figure below in red. Make sure to click on the 1st CDM tab and add the appropriate sensors for the test. In this project, quarter bridge 350 ohm gages were used with the Terminal Input Modules (TIM) which are located in the Geotechnical and Structural folder and also in the Strain, Foil Bonded folder. The gage selected is also highlighted in light blue.

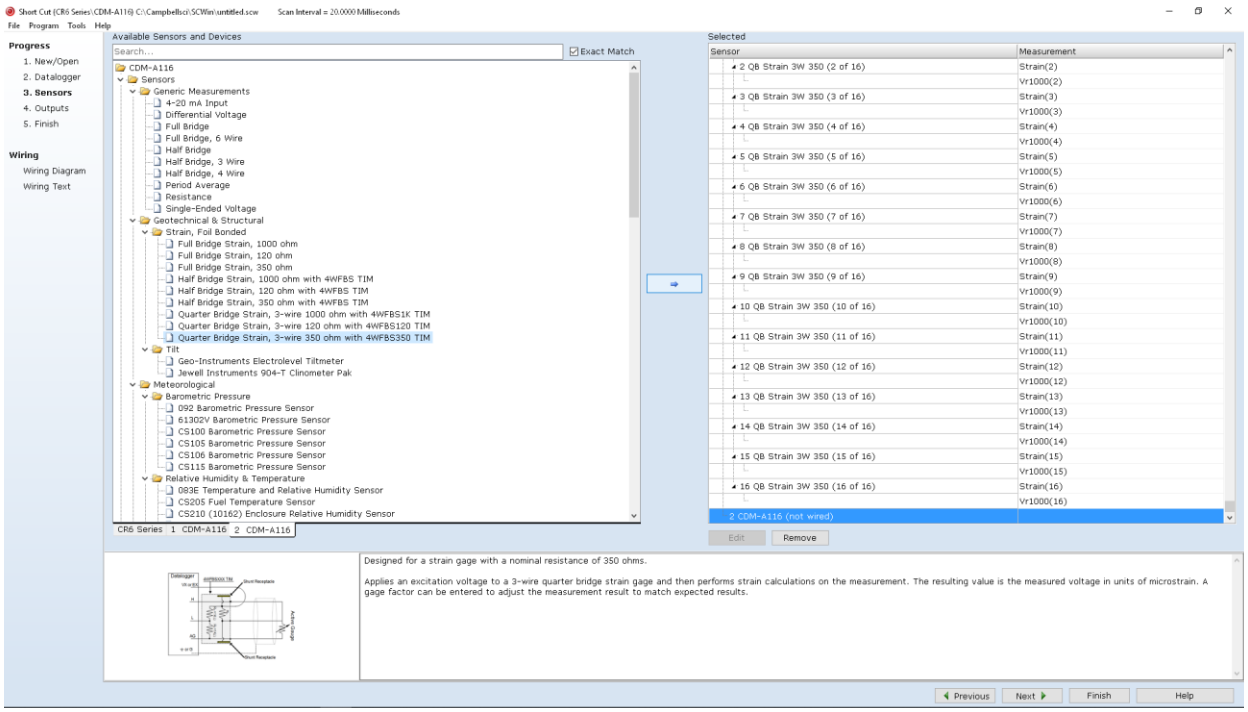


7. Once the sensor is selected a dialog box will open like in the following figure. The first step is to change the number of sensors per excitation channel. There are only four excitation channels on one CDM and 16 channels for strain gages so the value of sensors per excitation can vary from one to four. In this case we will be using all 16 strain gage channels on the CDM so we need to set the sensors per excitation channel value to 4. Once this is done the max value for how many sensors will change to 16. Input 16 for how many sensors (the top input box). The total bridge resistance is the resistance of the completed Wheatstone bridge. The inputs used for this project can be found in the following diagram. After all boxes have been filled out the gage factors for the strain gages need to be entered. To do this, click on the set gages box and fill in the appropriate gage factors. For this project the strain gages attached to rebar had a gage factor of 2.14 and the strain gages attached to the concrete had a gage factor of 2.15. After all gage factors have been entered click ok on the gage factor dialog box and the sensor dialog box. Repeat step 6 and 7 for each CDM that is being used in the project.

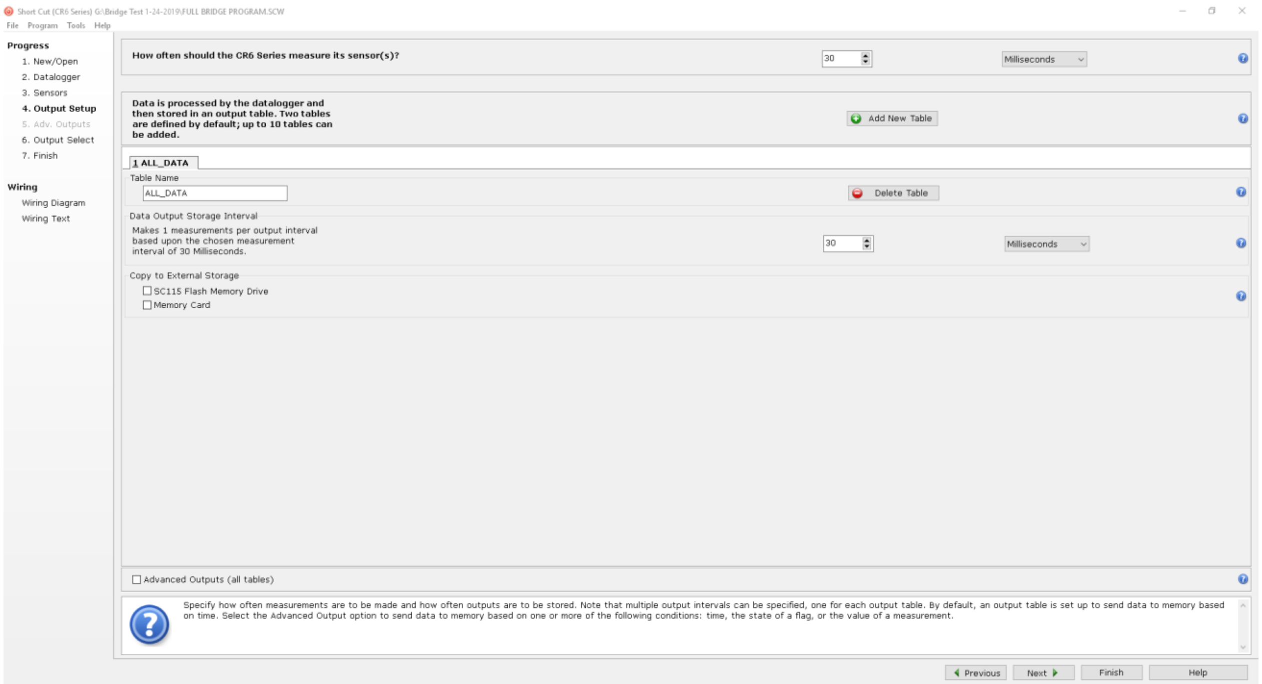

Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM (Version: 1.1)
Properties
Wiring
How many QB Strain 3W 350 sensors? (Max=16)
16
Total Bridge Resistance (ohm)
510
Excitation Voltage (mV)
3187
Calculate
Sensors Per Excitation Channel
4
Calculate
Strain
Strain
microstrain
Voltage ratio
Vr1000
mV/V
First notch frequency
User entered (Hz)
User entered first notch frequency (Hz)
6500
Settling time (us)
100
Reverse inputs to cancel offsets
Reverse excitation polarity to cancel offsets
Bridge output polarity
inverted from standard convention
Gage factor(s)
Set...
Select Zeroing Calibration Group
Group A
Designed for a strain gage with a nominal resistance of 350 ohms.
Applies an excitation voltage to a 3-wire quarter bridge strain gage and then performs strain calculations on the measurement. The resulting value is the measured voltage in units of microstrain. A gage factor can be entered to adjust the measurement result to match expected results.
OK
Cancel
Help


Gage factor(s)
Fill Down
Measurement
Gage factor(s)
Strain(1)
2.14
Strain(2)
2.14
Strain(3)
2.14
Strain(4)
2.14
Strain(5)
2.14
Strain(6)
2.14
Strain(7)
2.14
Strain(8)
2.14
OK
Cancel
Help

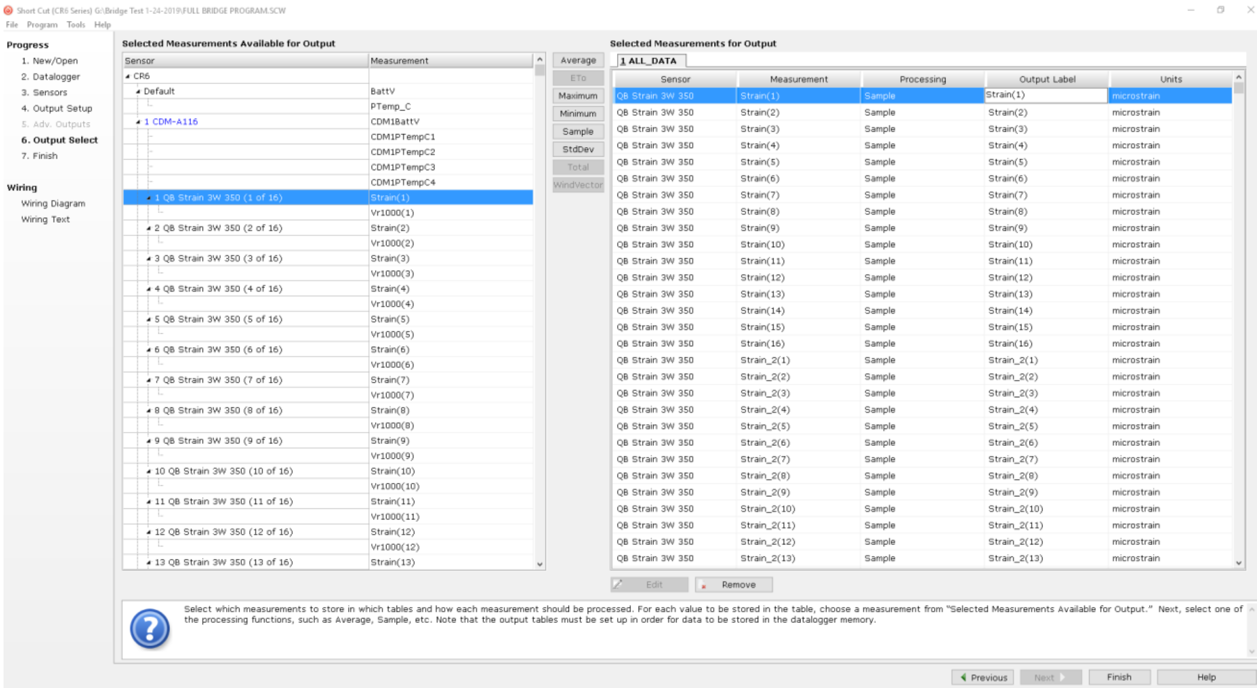
8. Once all CDMs and sensors are added click “next” to designate the output requirements.



9. The output setup tab and output select tab is where the data to be collected is specified. Multiple tables can be made to group certain sensors. Due to the large amount of sensors for this project it was decided to group all sensors together and separate them during post processing of the data. If the newer version of shortcut is being used, the scan interval should be defined at this time. As previously mentioned, the scan interval used for this project is 30 milliseconds. The next step is to create tables in the output setup tab. At this point, the name of the tables can be defined. Also the interval that you would like to keep data that is being recorded can also be defined. Usually the data output storage interval will be the same as the scan interval. Once the tables that are desired are created, click on “next”.



10. The next step is to tell the program what sensors are to be in each of the table which were created in the last step. Since all of the sensors in this project are to be grouped in one table, all sensors were selected on the left list (one sensor highlighted in dark blue) and then the "sample" button was clicked to tell the program to collect the sample of that gage. Once all gages appear on the right hand side (side with light blue highlighting), the "Finish" button can be clicked. This will generate the program. Once the program has been generated it may say that there are some errors associated with the scan rate. Click "ok" on the error message and save the program to the desired destination. The errors will be fixed during manipulation in the CRBasic Program Editor.



11. The next step involves changing the program in the CRBasic Editor. Click on CRBasic Editor when Logger Net is open. Find where the previously saved Shortcut program was saved and open the program with the file extension .CR6.

12. The code for this project can be found after this tutorial for use as a reference for the following steps. As can be seen in lines 1-4 of the code, using an apostrophe before any line of code makes that line commentary only and changes the color of the text to green. Comment lines have no effect on what the program does while running. To fix the scan rate errors, some of the commands which are not used for results in this project need to be commented out of the program. From the program below the following lines need to be commented out to allow for the scan rate of 30 milliseconds to work: 317, 319, 321, 323, 336, 338, 351, 353, 366,368, 381, 383, 396, and 398. Once all of these commands are commented out of the program, save the

program and compile the program by clicking “compile” under the compile drop down list. After the program is finished compiling, the results will be shown on the lower part of the screen and it will show some warnings about variables being declared but not used. Ignore these warnings as they are a result of commenting out the specified lines of code. Once the program is saved and compiled it can be sent to the CR6 for use.

Program Used in Project

```
'CR6 Series
'Created by Short Cut (4.0)

'Declare Variables and Units
Public BattV
Public FCLoaded
Public PTemp_C
Public CDM1BattV
Public CDMPTempC(4)
Public CReps
Public QBSSMode
Public CIndex
Public CAvg
Public LCount
Public Strain(16)
Public Vr1000(16)
Public GFAdj(16)
Public BrZero(16)
Public CKnown(16)
Public Group_A
Public CDM2BattV
Public CDM2PTempC(4)
Public CReps_2
Public QBSSMode_2
Public CIndex_2
Public CAvg_2
Public LCount_2
Public Strain_2(16)
Public Vr1000_2(16)
Public GFAdj_2(16)
Public BrZero_2(16)
Public CKnown_2(16)
Public CDM3BattV
Public CDM3PTempC(4)
Public CReps_3
Public QBSSMode_3
Public CIndex_3
Public CAvg_3
Public LCount_3
Public Strain_3(16)
Public Vr1000_3(16)
Public GFAdj_3(16)
Public BrZero_3(16)
Public CKnown_3(16)
Public CDM4BattV
Public CDM4PTempC(4)
```

```
Public CReps_4
Public QBSSMode_4
Public CIndex_4
Public CAvg_4
Public LCount_4
Public Strain_4(16)
Public Vr1000_4(16)
Public GFAdj_4(16)
Public BrZero_4(16)
Public CKnown_4(16)
Public CDM5BattV
Public CDM5PTempC(4)
Public CReps_5
Public QBSSMode_5
Public CIndex_5
Public CAvg_5
Public LCount_5
Public Strain_5(16)
Public Vr1000_5(16)
Public GFAdj_5(16)
Public BrZero_5(16)
Public CKnown_5(16)
Public CDM6BattV
Public CDM6PTempC(4)
Public CReps_6
Public QBSSMode_6
Public CIndex_6
Public CAvg_6
Public LCount_6
Public Strain_6(14)
Public Vr1000_6(14)
Public GFAdj_6(14)
Public BrZero_6(14)
Public CKnown_6(14)
Public GFsRaw(16)={2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14}
Public GFsRaw_2(16)={2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14}
Public GFsRaw_3(16)={2.15,2.15,2.15,2.15,2.15,2.15,2.15,2.15,2.15,2.15,2.15,2.15,2.15,2.15,2.15,2.15}
Public GFsRaw_4(16)={2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14}
Public GFsRaw_5(16)={2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14,2.14}
Public GFsRaw_6(14)={2.15,2.15,2.15,2.15,2.15,2.15,2.15,2.15,2.15,2.15,2.15,2.15,2.15,2.15}

Alias CDMPTempC(1)=CDM1PTempC1
Alias CDMPTempC(2)=CDM1PTempC2
Alias CDMPTempC(3)=CDM1PTempC3
Alias CDMPTempC(4)=CDM1PTempC4
Alias CDM2PTempC(1)=CDM2PTempC1
Alias CDM2PTempC(2)=CDM2PTempC2
Alias CDM2PTempC(3)=CDM2PTempC3
Alias CDM2PTempC(4)=CDM2PTempC4
Alias CDM3PTempC(1)=CDM3PTempC1
```

```
Alias CDM3PTempC(2)=CDM3PTempC2
Alias CDM3PTempC(3)=CDM3PTempC3
Alias CDM3PTempC(4)=CDM3PTempC4
Alias CDM4PTempC(1)=CDM4PTempC1
Alias CDM4PTempC(2)=CDM4PTempC2
Alias CDM4PTempC(3)=CDM4PTempC3
Alias CDM4PTempC(4)=CDM4PTempC4
Alias CDM5PTempC(1)=CDM5PTempC1
Alias CDM5PTempC(2)=CDM5PTempC2
Alias CDM5PTempC(3)=CDM5PTempC3
Alias CDM5PTempC(4)=CDM5PTempC4
Alias CDM6PTempC(1)=CDM6PTempC1
Alias CDM6PTempC(2)=CDM6PTempC2
Alias CDM6PTempC(3)=CDM6PTempC3
Alias CDM6PTempC(4)=CDM6PTempC4

Units BattV=Volts
Units PTemp_C=Deg C
Units CDM1BattV=Volts
Units Strain=microstrain
Units Vr1000=mV/V
Units GFAdj=unitless
Units BrZero=mV/V
Units CDM2BattV=Volts
Units Strain_2=microstrain
Units Vr1000_2=mV/V
Units GFAdj_2=unitless
Units BrZero_2=mV/V
Units CDM3BattV=Volts
Units Strain_3=microstrain
Units Vr1000_3=mV/V
Units GFAdj_3=unitless
Units BrZero_3=mV/V
Units CDM4BattV=Volts
Units Strain_4=microstrain
Units Vr1000_4=mV/V
Units GFAdj_4=unitless
Units BrZero_4=mV/V
Units CDM5BattV=Volts
Units Strain_5=microstrain
Units Vr1000_5=mV/V
Units GFAdj_5=unitless
Units BrZero_5=mV/V
Units CDM6BattV=Volts
Units Strain_6=microstrain
Units Vr1000_6=mV/V
Units GFAdj_6=unitless
Units BrZero_6=mV/V
Units CDM1PTempC1=DegC
Units CDM1PTempC2=DegC
Units CDM1PTempC3=DegC
Units CDM1PTempC4=DegC
Units CDM2PTempC1=DegC
Units CDM2PTempC2=DegC
Units CDM2PTempC3=DegC
```

```
Units CDM2PTempC4=DegC
Units CDM3PTempC1=DegC
Units CDM3PTempC2=DegC
Units CDM3PTempC3=DegC
Units CDM3PTempC4=DegC
Units CDM4PTempC1=DegC
Units CDM4PTempC2=DegC
Units CDM4PTempC3=DegC
Units CDM4PTempC4=DegC
Units CDM5PTempC1=DegC
Units CDM5PTempC2=DegC
Units CDM5PTempC3=DegC
Units CDM5PTempC4=DegC
Units CDM6PTempC1=DegC
Units CDM6PTempC2=DegC
Units CDM6PTempC3=DegC
Units CDM6PTempC4=DegC

'Define Data Tables
DataTable(ALL_DATA,True,-1)
DataInterval(0,30,mSec,10)
Sample(1,Strain(1),IEEE4)
Sample(1,Strain(2),IEEE4)
Sample(1,Strain(3),IEEE4)
Sample(1,Strain(4),IEEE4)
Sample(1,Strain(5),IEEE4)
Sample(1,Strain(6),IEEE4)
Sample(1,Strain(7),IEEE4)
Sample(1,Strain(8),IEEE4)
Sample(1,Strain(9),IEEE4)
Sample(1,Strain(10),IEEE4)
Sample(1,Strain(11),IEEE4)
Sample(1,Strain(12),IEEE4)
Sample(1,Strain(13),IEEE4)
Sample(1,Strain(14),IEEE4)
Sample(1,Strain(15),IEEE4)
Sample(1,Strain(16),IEEE4)
Sample(1,Strain_2(1),IEEE4)
Sample(1,Strain_2(2),IEEE4)
Sample(1,Strain_2(3),IEEE4)
Sample(1,Strain_2(4),IEEE4)
Sample(1,Strain_2(5),IEEE4)
Sample(1,Strain_2(6),IEEE4)
Sample(1,Strain_2(7),IEEE4)
Sample(1,Strain_2(8),IEEE4)
Sample(1,Strain_2(9),IEEE4)
Sample(1,Strain_2(10),IEEE4)
Sample(1,Strain_2(11),IEEE4)
Sample(1,Strain_2(12),IEEE4)
Sample(1,Strain_2(13),IEEE4)
Sample(1,Strain_2(14),IEEE4)
Sample(1,Strain_2(15),IEEE4)
Sample(1,Strain_2(16),IEEE4)
Sample(1,Strain_3(1),IEEE4)
Sample(1,Strain_3(2),IEEE4)
```

```
Sample(1,Strain_3(3),IEEE4)
Sample(1,Strain_3(4),IEEE4)
Sample(1,Strain_3(5),IEEE4)
Sample(1,Strain_3(6),IEEE4)
Sample(1,Strain_3(7),IEEE4)
Sample(1,Strain_3(8),IEEE4)
Sample(1,Strain_3(9),IEEE4)
Sample(1,Strain_3(10),IEEE4)
Sample(1,Strain_3(11),IEEE4)
Sample(1,Strain_3(12),IEEE4)
Sample(1,Strain_3(13),IEEE4)
Sample(1,Strain_3(14),IEEE4)
Sample(1,Strain_3(15),IEEE4)
Sample(1,Strain_3(16),IEEE4)
Sample(1,Strain_4(1),IEEE4)
Sample(1,Strain_4(2),IEEE4)
Sample(1,Strain_4(3),IEEE4)
Sample(1,Strain_4(4),IEEE4)
Sample(1,Strain_4(5),IEEE4)
Sample(1,Strain_4(6),IEEE4)
Sample(1,Strain_4(7),IEEE4)
Sample(1,Strain_4(8),IEEE4)
Sample(1,Strain_4(9),IEEE4)
Sample(1,Strain_4(10),IEEE4)
Sample(1,Strain_4(11),IEEE4)
Sample(1,Strain_4(12),IEEE4)
Sample(1,Strain_4(13),IEEE4)
Sample(1,Strain_4(14),IEEE4)
Sample(1,Strain_4(15),IEEE4)
Sample(1,Strain_4(16),IEEE4)
Sample(1,Strain_5(1),IEEE4)
Sample(1,Strain_5(2),IEEE4)
Sample(1,Strain_5(3),IEEE4)
Sample(1,Strain_5(4),IEEE4)
Sample(1,Strain_5(5),IEEE4)
Sample(1,Strain_5(6),IEEE4)
Sample(1,Strain_5(7),IEEE4)
Sample(1,Strain_5(8),IEEE4)
Sample(1,Strain_5(9),IEEE4)
Sample(1,Strain_5(10),IEEE4)
Sample(1,Strain_5(11),IEEE4)
Sample(1,Strain_5(12),IEEE4)
Sample(1,Strain_5(13),IEEE4)
Sample(1,Strain_5(14),IEEE4)
Sample(1,Strain_5(15),IEEE4)
Sample(1,Strain_5(16),IEEE4)
Sample(1,Strain_6(1),IEEE4)
Sample(1,Strain_6(2),IEEE4)
Sample(1,Strain_6(3),IEEE4)
Sample(1,Strain_6(4),IEEE4)
Sample(1,Strain_6(5),IEEE4)
Sample(1,Strain_6(6),IEEE4)
Sample(1,Strain_6(7),IEEE4)
Sample(1,Strain_6(8),IEEE4)
Sample(1,Strain_6(9),IEEE4)
```

```
Sample(1,Strain_6(10),IEEE4)
Sample(1,Strain_6(11),IEEE4)
Sample(1,Strain_6(12),IEEE4)
Sample(1,Strain_6(13),IEEE4)
Sample(1,Strain_6(14),IEEE4)
EndTable

'Calibration history table
DataTable(CalHist,NewFieldCal,10)
SampleFieldCal
EndTable

'Main Program
BeginProg
'Initialize calibration variables for
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000()' on CDM-A116 with CPI address 1
CIndex=1 : CAvg=1 : CReps=16
For LCount = 1 To 16
GFAdj(LCount)=GFsRaw(LCount)
Next
'Initialize calibration variables for
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000_2()' on CDM-A116 with CPI address 2
CIndex_2=1 : CAvg_2=1 : CReps_2=16
For LCount_2 = 1 To 16
GFAdj_2(LCount_2)=GFsRaw_2(LCount_2)
Next
'Initialize calibration variables for
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000_3()' on CDM-A116 with CPI address 3
CIndex_3=1 : CAvg_3=1 : CReps_3=16
For LCount_3 = 1 To 16
GFAdj_3(LCount_3)=GFsRaw_3(LCount_3)
Next
'Initialize calibration variables for
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000_4()' on CDM-A116 with CPI address 4
CIndex_4=1 : CAvg_4=1 : CReps_4=16
For LCount_4 = 1 To 16
GFAdj_4(LCount_4)=GFsRaw_4(LCount_4)
Next
'Initialize calibration variables for
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000_5()' on CDM-A116 with CPI address 5
CIndex_5=1 : CAvg_5=1 : CReps_5=16
For LCount_5 = 1 To 16
GFAdj_5(LCount_5)=GFsRaw_5(LCount_5)
Next
'Initialize calibration variables for
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000_6()' on CDM-A116 with CPI address 6
CIndex_6=1 : CAvg_6=1 : CReps_6=14
For LCount_6 = 1 To 14
GFAdj_6(LCount_6)=GFsRaw_6(LCount_6)
```

```
Next
'Load the most recent calibration values from the CalHist table
FCLoaded=LoadFieldCal(True)
'Main Scan
Scan(30,mSec,66,0)
'Default CR6 Datalogger Battery Voltage measurement 'BattV'
'Battery(BattV)
'Default CR6 Datalogger Wiring Panel Temperature measurement 'PTemp_C'
'PanelTemp(PTemp_C,60)
'Default Battery Voltage measurement 'CDM1BattV' on CDM-A116 with CPI address 1
'CDM_Battery(CDM_A116,1,CDM1BattV)
'Default Wiring Panel Temperature measurements 'CDMPTempC()' on CDM-A116 with CPI address
1
'CDM_PanelTemp(CDM_A116,1,CDMPTempC(),4,1,60)
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000()' on CDM-A1
16 with CPI address 1
CDM_BrFull(CDM_A116,1,Vr1000(),16,mV200,1,1,4,3187,True,True,100,6500,1,0)
'Calculated strain result 'Strain()' for
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000()' on CDM-A1
16 with CPI address 1
StrainCalc(Strain(),16,Vr1000(),BrZero(),-1,GFAdj(),0)
'Quarter bridge strain shunt calibration for
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000()' on CDM-A1
16 with CPI address 1
FieldCalStrain(13,Strain(),1,GFAdj(),0,QBSSMode,CKnown(),CIndex,CAvg,GFsRaw(),0)
'Zeroing calibration for
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000()' on CDM-A1
16 with CPI address 1
FieldCalStrain(10,Vr1000(),CReps,0,BrZero(),Group_A,0,CIndex,CAvg,0,Strain())
'Default Battery Voltage measurement 'CDM2BattV' on CDM-A116 with CPI address 2
'CDM_Battery(CDM_A116,2,CDM2BattV)
'Default Wiring Panel Temperature measurements 'CDM2PTempC()' on CDM-A116 with CPI addres
s 2
'CDM_PanelTemp(CDM_A116,2,CDM2PTempC(),4,1,60)
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000_2()' on CDMA116
with CPI address 2
CDM_BrFull(CDM_A116,2,Vr1000_2(),16,mV200,1,1,4,3187,True,True,100,6500,1,0)
'Calculated strain result 'Strain_2()' for
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000_2()' on CDMA116
with CPI address 2
StrainCalc(Strain_2(),16,Vr1000_2(),BrZero_2(),-1,GFAdj_2(),0)
'Quarter bridge strain shunt calibration for
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000_2()' on CDMPage
A116 with CPI address 2
FieldCalStrain(13,Strain_2(),1,GFAdj_2(),0,QBSSMode_2,CKnown_2(),CIndex_2,CAvg_2,GFsRaw_2
(),0)
'Zeroing calibration for
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000_2()' on CDMA116
with CPI address 2
FieldCalStrain(10,Vr1000_2(),CReps_2,0,BrZero_2(),Group_A,0,CIndex_2,CAvg_2,0,Strain_2())
'Default Battery Voltage measurement 'CDM3BattV' on CDM-A116 with CPI address 3
'CDM_Battery(CDM_A116,3,CDM3BattV)
'Default Wiring Panel Temperature measurements 'CDM3PTempC()' on CDM-A116 with CPI addres
s 3
'CDM_PanelTemp(CDM_A116,3,CDM3PTempC(),4,1,60)
```

```
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000_3()' on CDMA116
with CPI address 3
CDM_BrFull(CDM_A116,3,Vr1000_3(),16,mV200,1,1,4,3187,True,True,100,6500,1,0)
'Calculated strain result 'Strain_3()' for
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000_3()' on CDMA116
with CPI address 3
StrainCalc(Strain_3(),16,Vr1000_3(),BrZero_3(),-1,GFAdj_3(),0)
'Quarter bridge strain shunt calibration for
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000_3()' on CDMA116
with CPI address 3
FieldCalStrain(13,Strain_3(),1,GFAdj_3(),0,QBSSMode_3,CKnown_3(),CIndex_3,CAvg_3,GFsRaw_3
(),0)
'Zeroing calibration for
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000_3()' on CDMA116
with CPI address 3
FieldCalStrain(10,Vr1000_3(),CReps_3,0,BrZero_3(),Group_A,0,CIndex_3,CAvg_3,0,Strain_3())
'Default Battery Voltage measurement 'CDM4BattV' on CDM-A116 with CPI address 4
'CDM_Battery(CDM_A116,4,CDM4BattV)
'Default Wiring Panel Temperature measurements 'CDM4PTempC()' on CDM-A116 with CPI addres
s 4
'CDM_PanelTemp(CDM_A116,4,CDM4PTempC(),4,1,60)
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000_4()' on CDMA116
with CPI address 4
CDM_BrFull(CDM_A116,4,Vr1000_4(),16,mV200,1,1,4,3187,True,True,100,6500,1,0)
'Calculated strain result 'Strain_4()' for
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000_4()' on CDMA116
with CPI address 4
StrainCalc(Strain_4(),16,Vr1000_4(),BrZero_4(),-1,GFAdj_4(),0)
'Quarter bridge strain shunt calibration for
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000_4()' on CDMA116
with CPI address 4
FieldCalStrain(13,Strain_4(),1,GFAdj_4(),0,QBSSMode_4,CKnown_4(),CIndex_4,CAvg_4,GFsRaw_4
(),0)
'Zeroing calibration for
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000_4()' on CDMA116
with CPI address 4
FieldCalStrain(10,Vr1000_4(),CReps_4,0,BrZero_4(),Group_A,0,CIndex_4,CAvg_4,0,Strain_4())
'Default Battery Voltage measurement 'CDM5BattV' on CDM-A116 with CPI address 5
'CDM_Battery(CDM_A116,5,CDM5BattV)
'Default Wiring Panel Temperature measurements 'CDM5PTempC()' on CDM-A116 with CPI addres
s 5
'CDM_PanelTemp(CDM_A116,5,CDM5PTempC(),4,1,60)
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000_5()' on CDMA116
with CPI address 5
CDM_BrFull(CDM_A116,5,Vr1000_5(),16,mV200,1,1,4,3187,True,True,100,6500,1,0)
'Calculated strain result 'Strain_5()' for
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000_5()' on CDMA116
with CPI address 5
StrainCalc(Strain_5(),16,Vr1000_5(),BrZero_5(),-1,GFAdj_5(),0)
'Quarter bridge strain shunt calibration for
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000_5()' on CDMA116
with CPI address 5
FieldCalStrain(13,Strain_5(),1,GFAdj_5(),0,QBSSMode_5,CKnown_5(),CIndex_5,CAvg_5,GFsRaw_5
(),0)
'Zeroing calibration for
```

```
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000_5()' on CDMA116 with CPI address 5
FieldCalStrain(10,Vr1000_5(),CReps_5,0,BrZero_5(),Group_A,0,CIndex_5,CAvg_5,0,Strain_5())
'Default Battery Voltage measurement 'CDM6BattV' on CDM-A116 with CPI address 6
'CDM_Battery(CDM_A116,6,CDM6BattV)
'Default Wiring Panel Temperature measurements 'CDM6PTempC()' on CDM-A116 with CPI address 6
'CDM_PanelTemp(CDM_A116,6,CDM6PTempC(),4,1,60)
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000_6()' on CDMA116 with CPI address 6
CDM_BrFull(CDM_A116,6,Vr1000_6(),14,mV200,1,1,4,3187,True,True,100,6500,1,0)
'Calculated strain result 'Strain_6()' for
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000_6()' on CDMA116 with CPI address 6
StrainCalc(Strain_6(),14,Vr1000_6(),BrZero_6(),-1,GFAdj_6(),0)
'Quarter bridge strain shunt calibration for
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000_6()' on CDMA116 with CPI address 6
FieldCalStrain(13,Strain_6(),1,GFAdj_6(),0,QBSSMode_6,CKnown_6(),CIndex_6,CAvg_6,GFsRaw_6(),0)
'Zeroing calibration for
'Quarter Bridge Strain, 3-wire 350 ohm with 4WFBS350 TIM measurement 'Vr1000_6()' on CDMA116 with CPI address 6
FieldCalStrain(10,Vr1000_6(),CReps_6,0,BrZero_6(),Group_A,0,CIndex_6,CAvg_6,0,Strain_6())
'Call Data Tables and Store Data
CallTable ALL_DATA
CallTable CalHist
NextScan
EndProg
```

Appendix D Strain Data

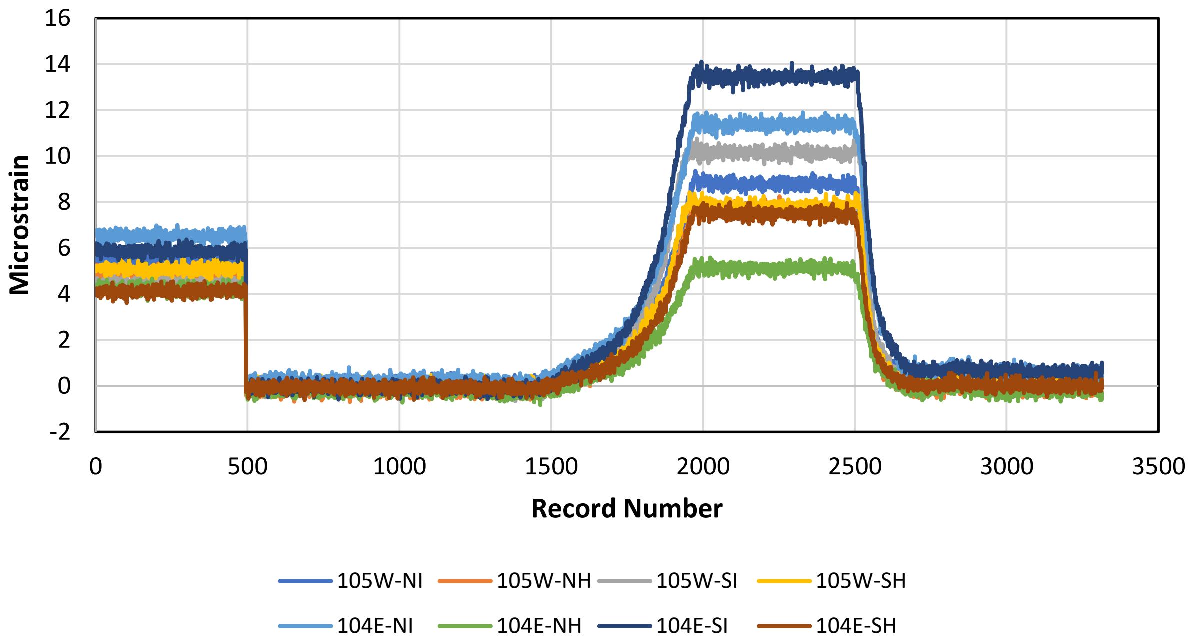


Figure D.1 Small UBIT Test 1.1 CP 1 (Rebar Gages)

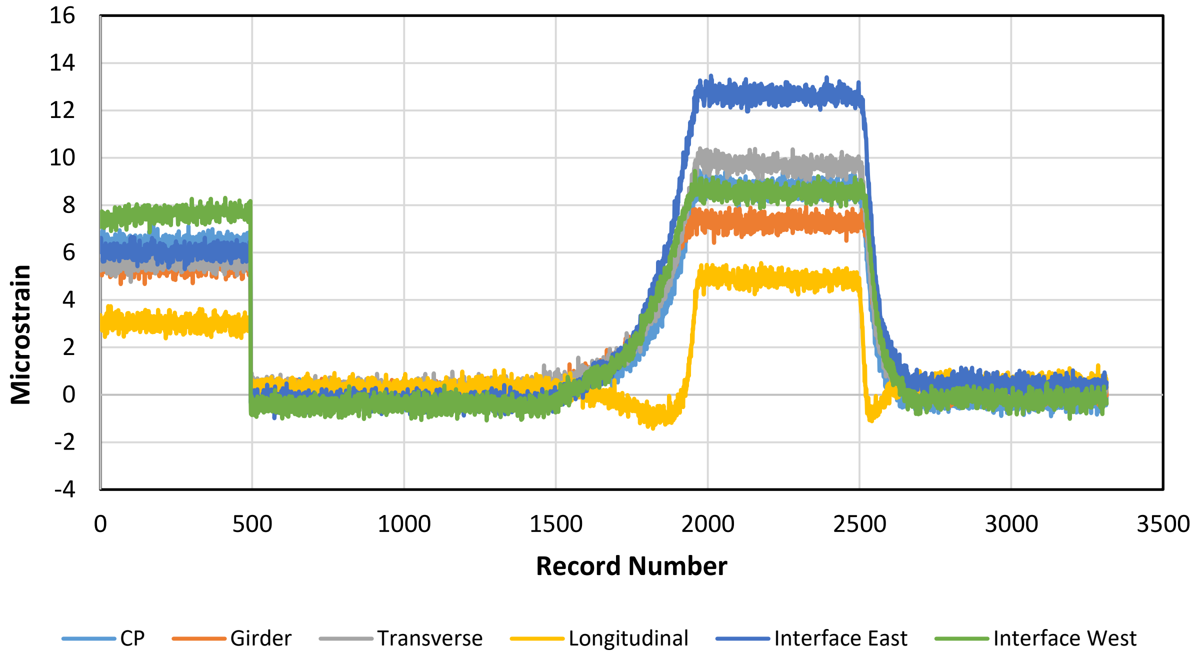


Figure D.2 Small UBIT Test 1.1 CP 1 (Concrete Gages)

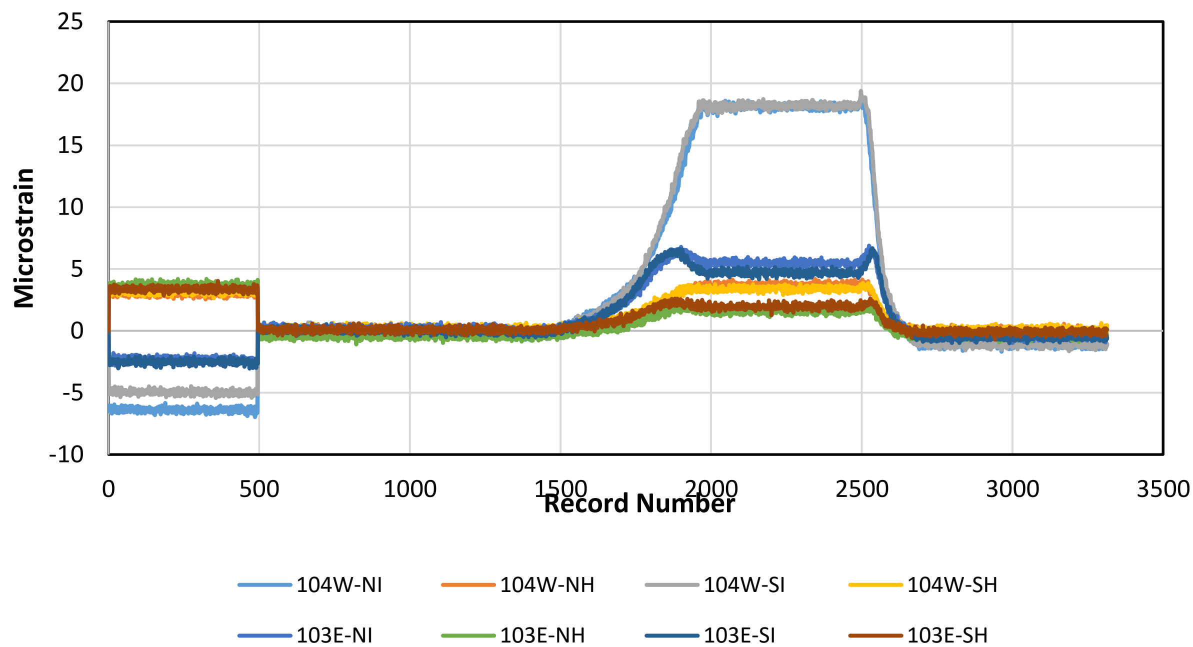


Figure D.3 Small UBIT Test 1.1 CP 2 (Rebar Gages)

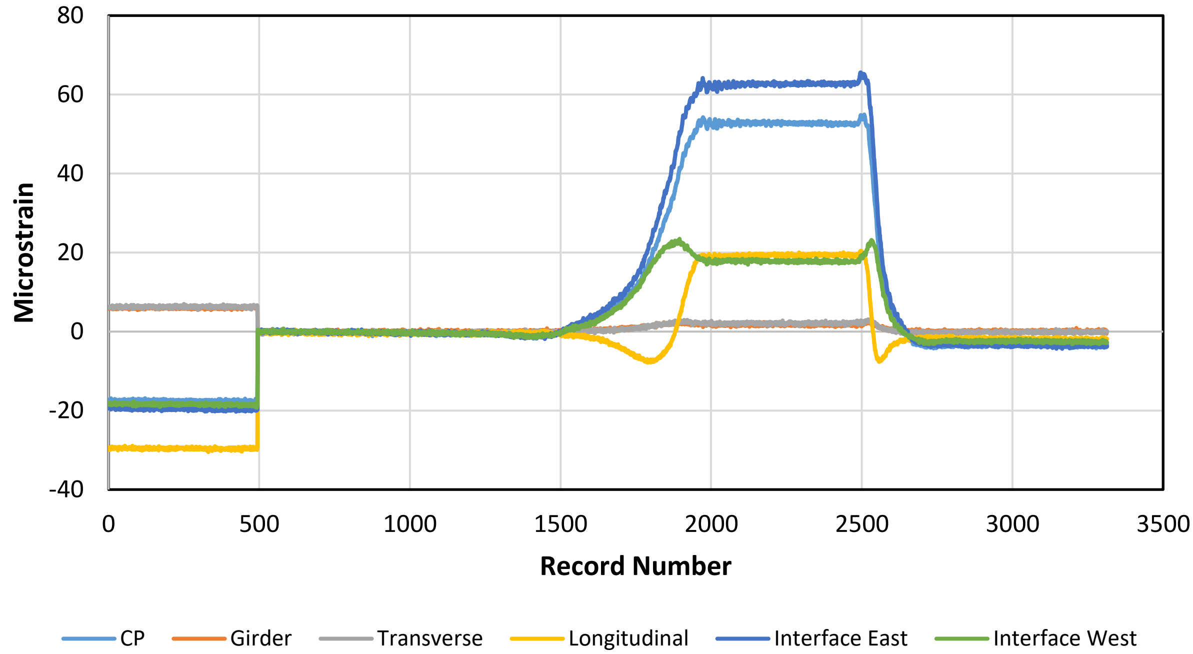


Figure D.4 Small UBIT Test 1.1 CP 2 (Concrete Gages)

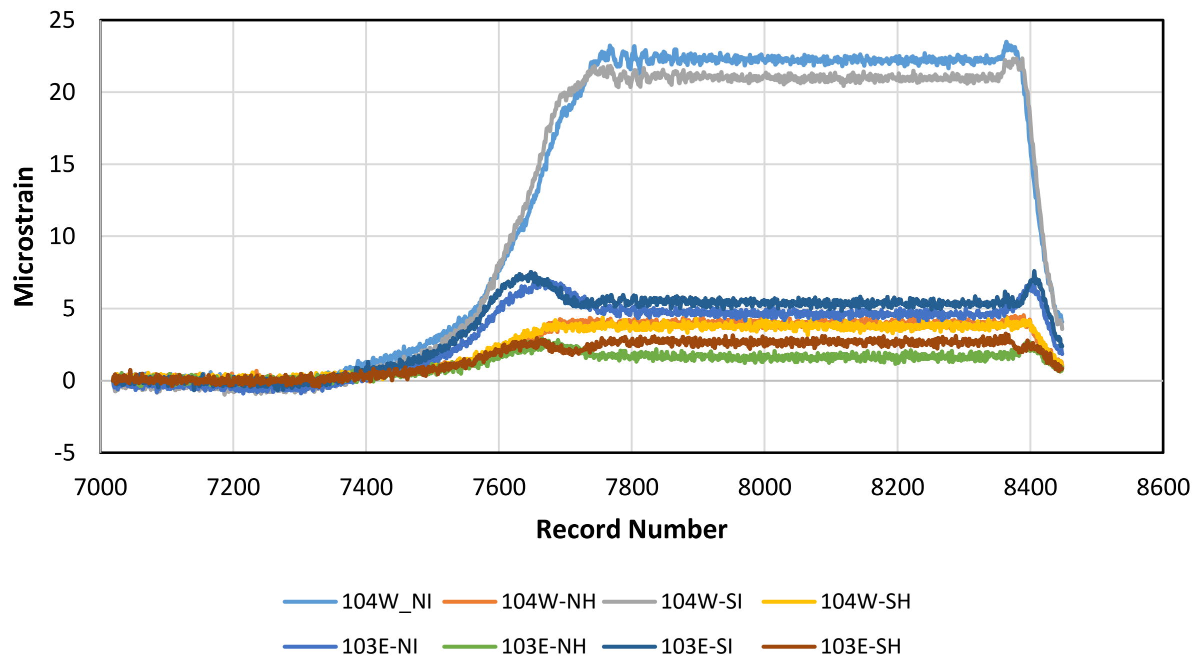


Figure D.5 Small UBIT Test 1.2 CP 2 (Rebar Gages)

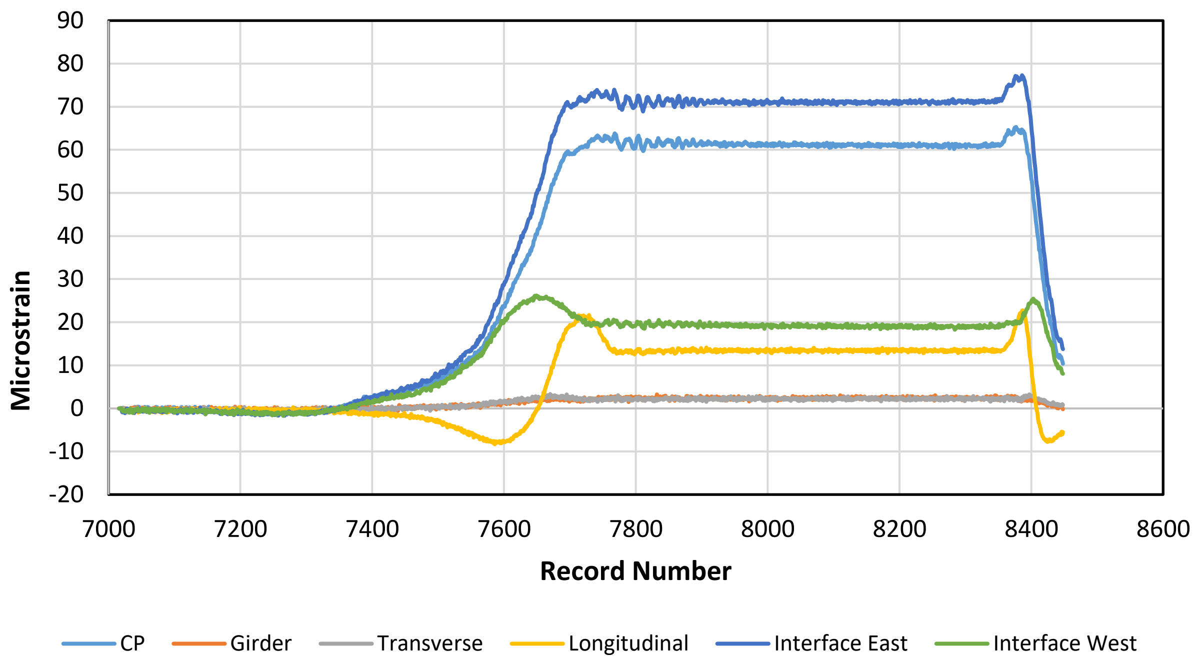


Figure D.6 Small UBIT Test 1.2 CP 2 (Concrete Gages)

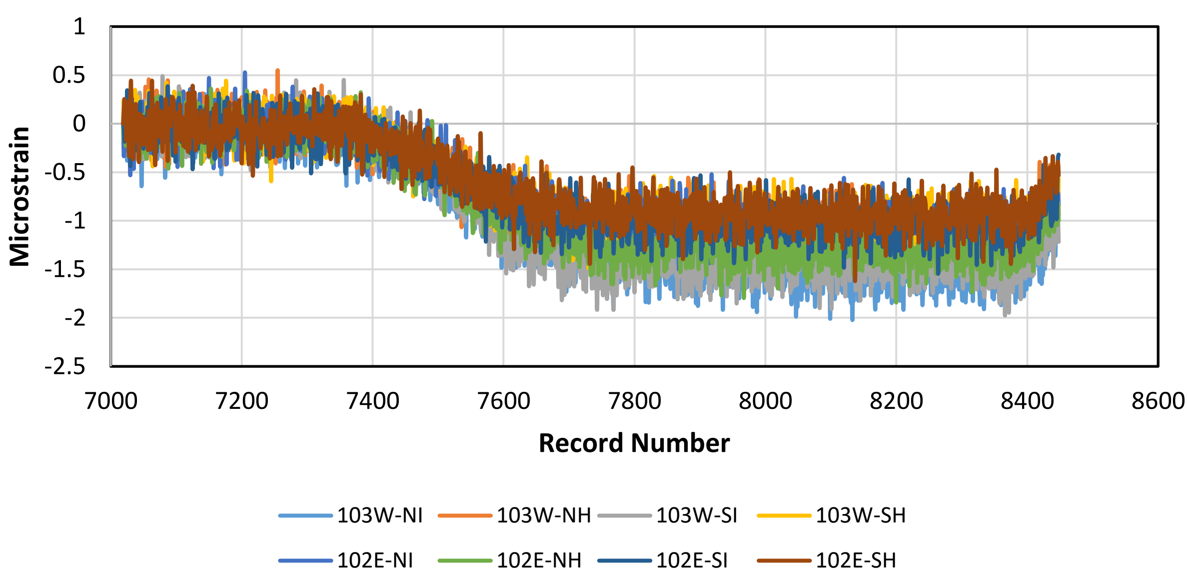


Figure D.7 Small UBIT Test 1.2 CP 3 (Rebar Gages)

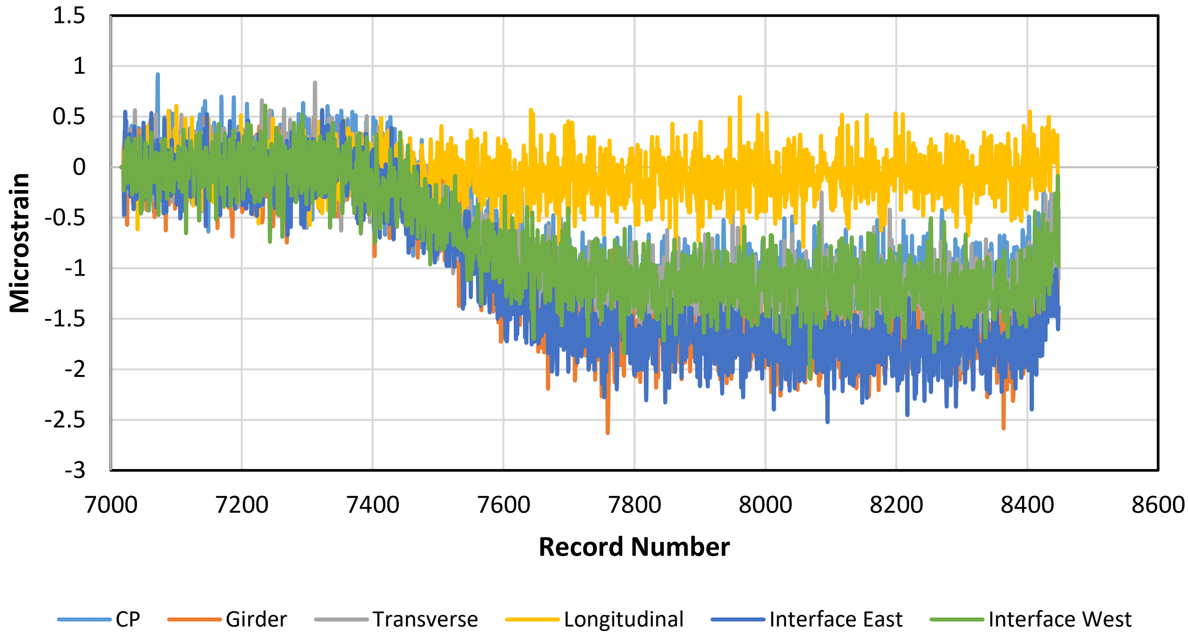


Figure D.8 Small UBIT Test 1.2 CP 3 (Concrete Gages)

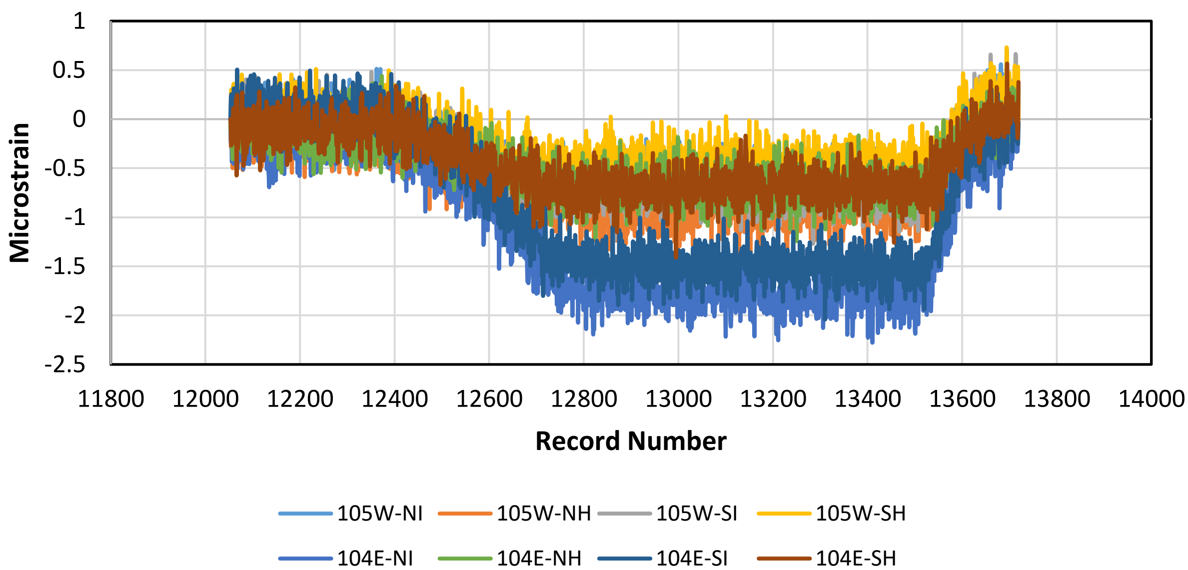


Figure D.9 Small UBIT Test 1.3 CP 1 (Rebar Gages)

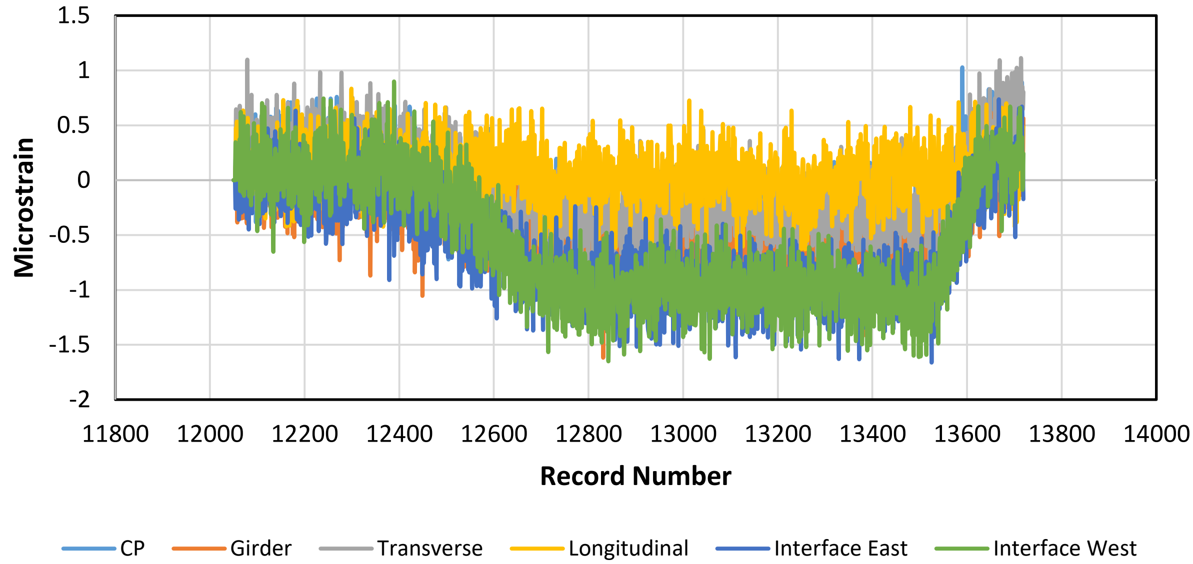


Figure D.10 Small UBIT Test 1.3 CP 1 (Concrete Gages)

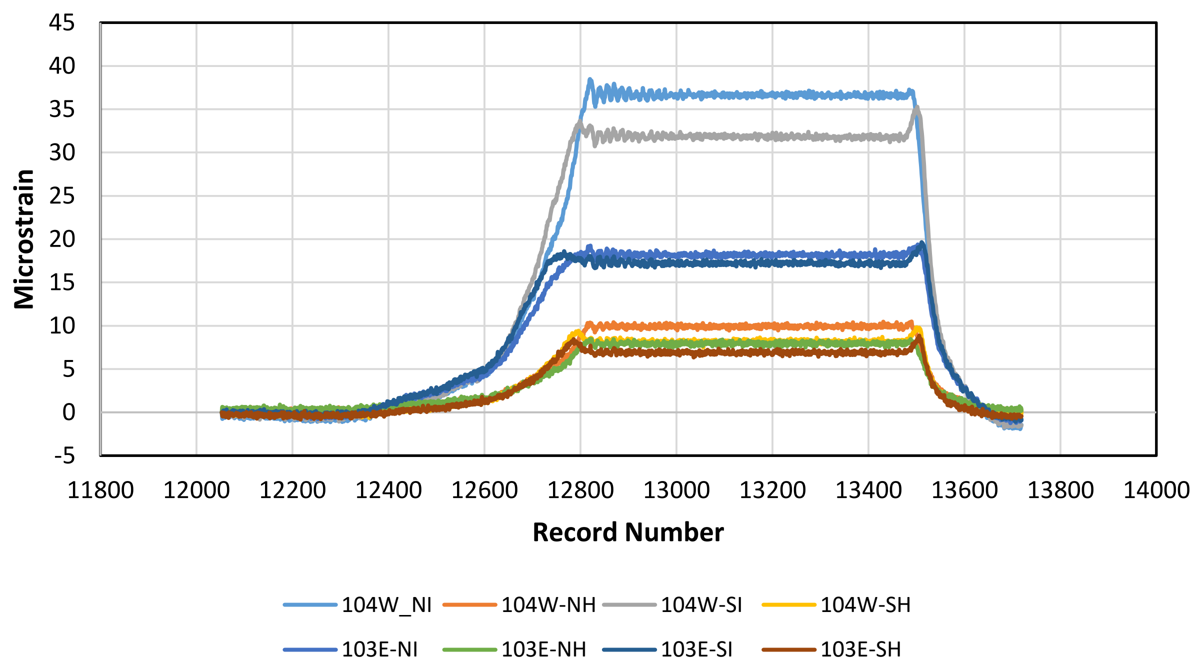


Figure D.11 Small UBIT Test 1.3 CP 2 (Rebar Gages)

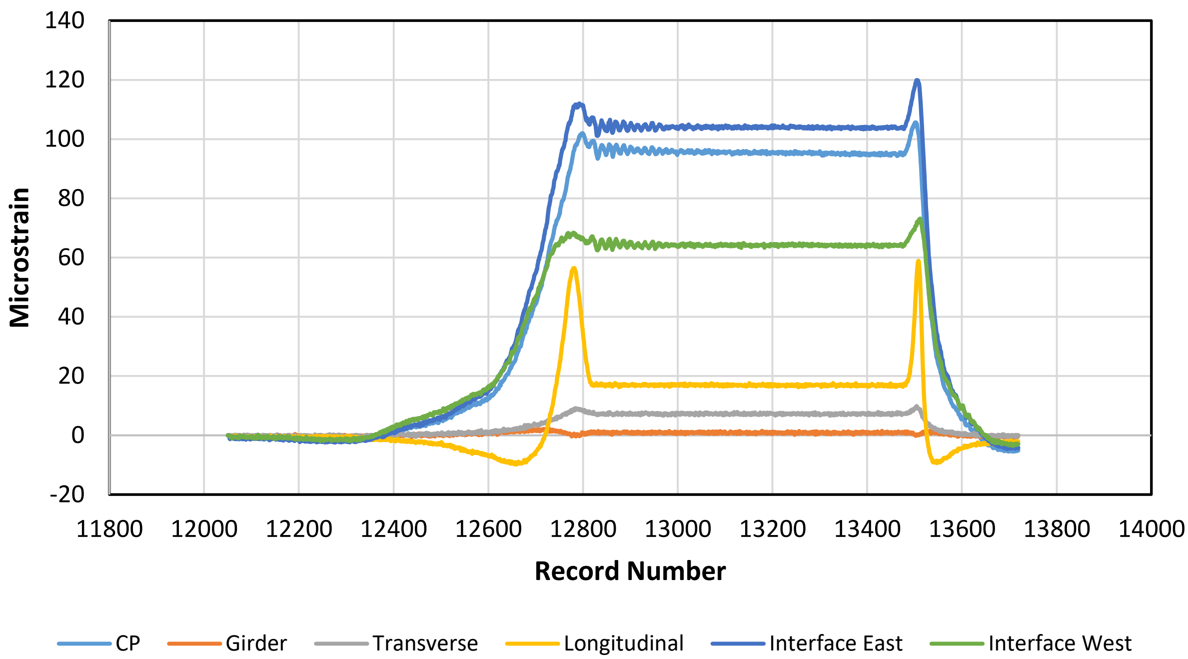


Figure D.12 Small UBIT Test 1.3 CP 2 (Concrete Gages)

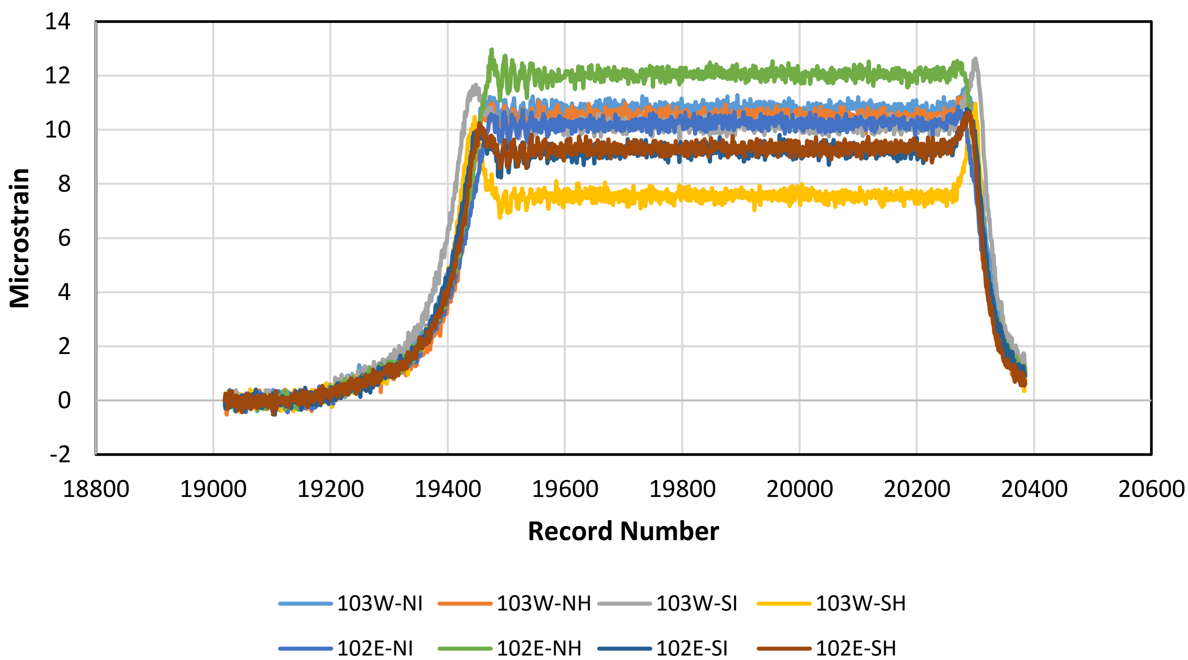


Figure D.13 Small UBIT Test 1.4 CP 3 (Rebar Gages)

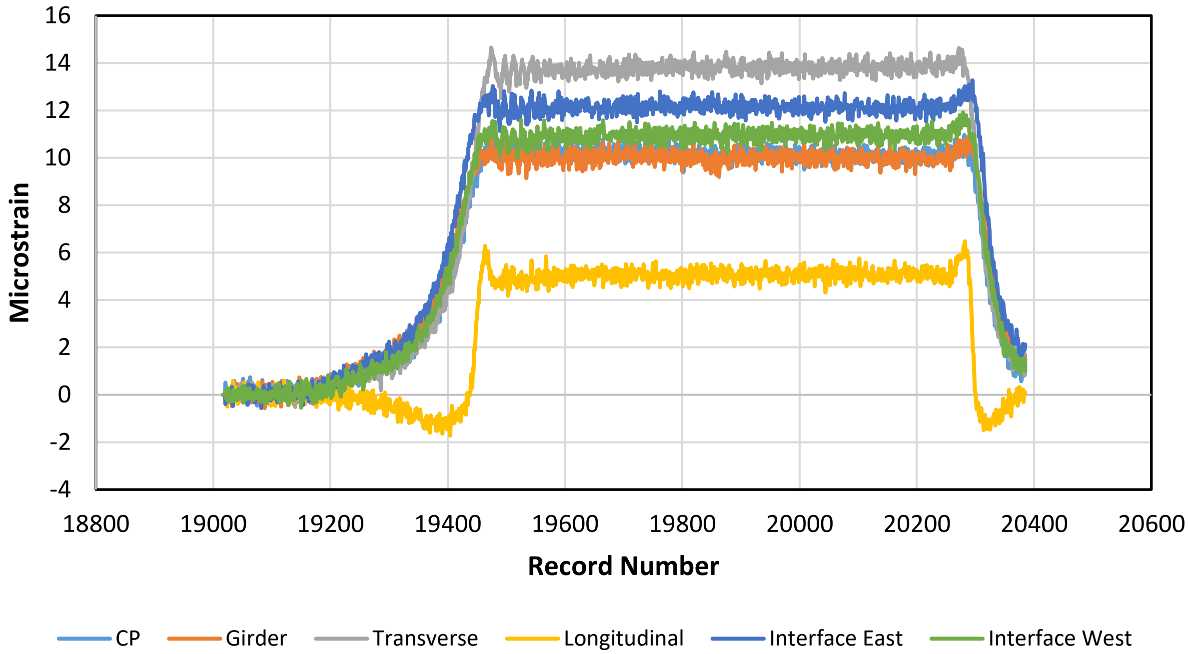


Figure D.14 Small UBIT Test 1.4 CP 3 (Concrete Gages)

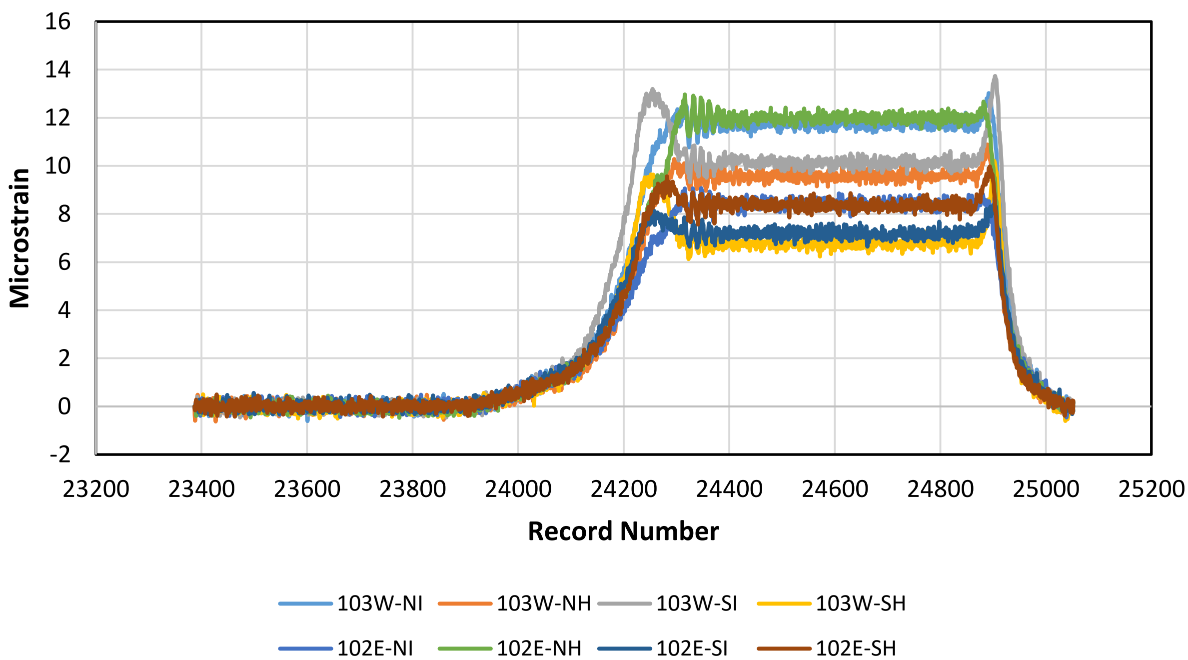


Figure D.15 Small UBIT Test 1.5 CP 3 (Rebar Gages)

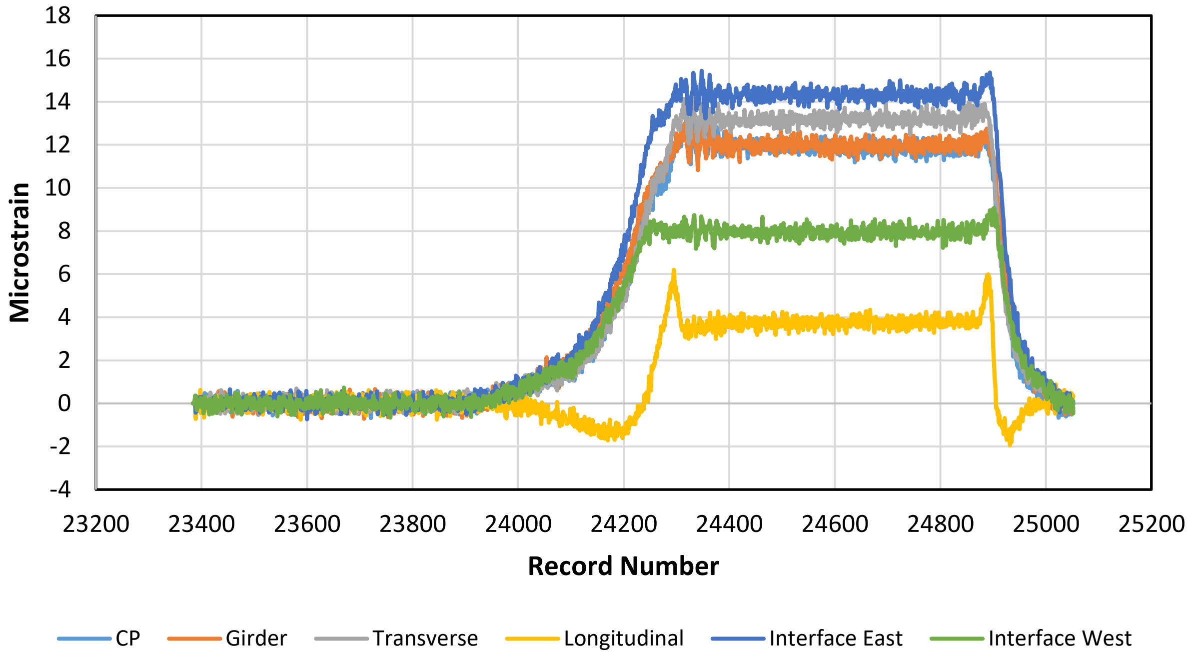


Figure D.16 Small UBIT Test 1.5 CP 3 (Concrete Gages)

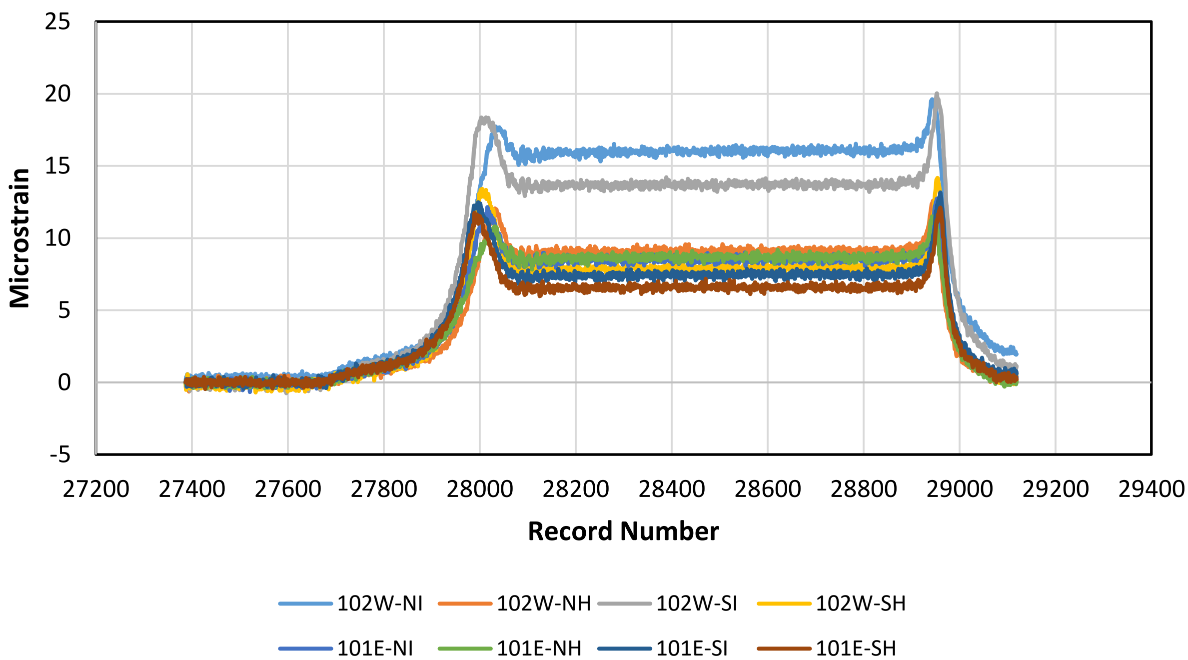


Figure D.17 Small UBIT Test 1.6 CP 4 (Rebar Gages)

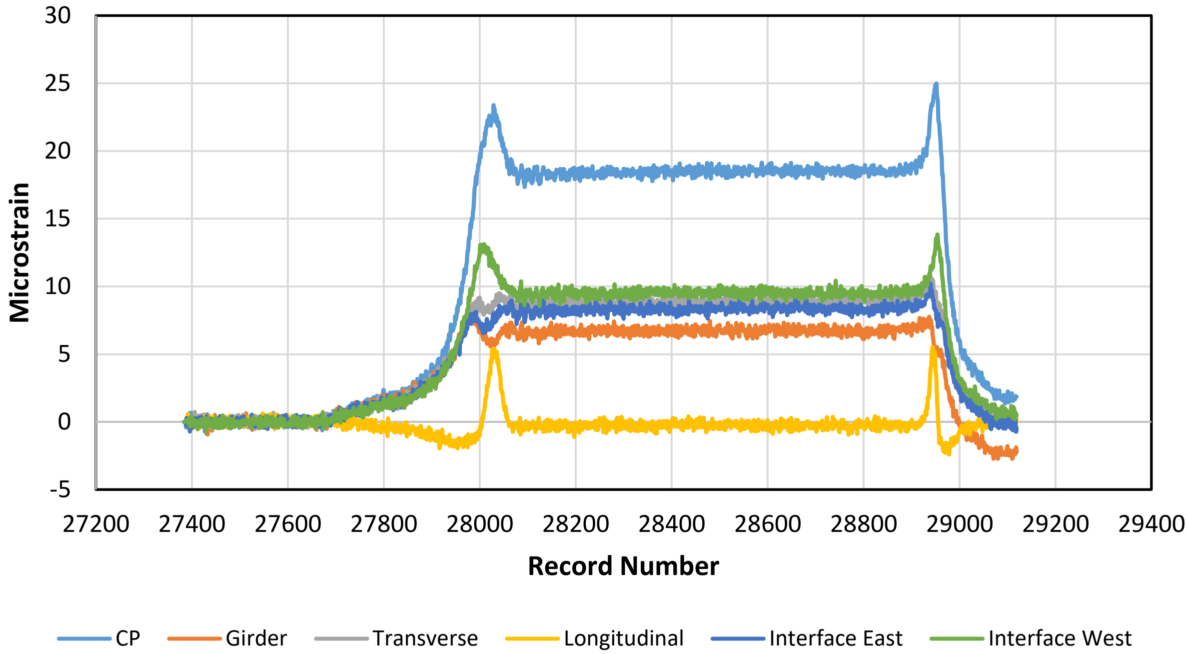


Figure D.18 Small UBIT Test 1.6 CP 4 (Concrete Gages

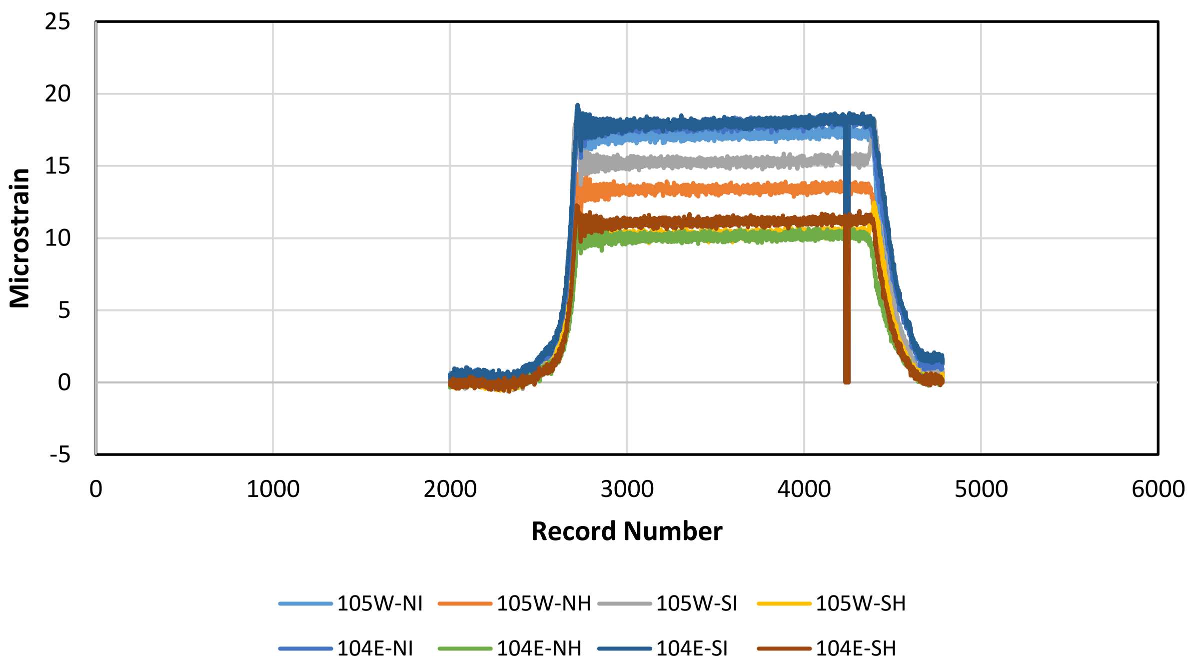


Figure D.19 Large UBIT Test 1.1 CP 1 (Rebar Gages)

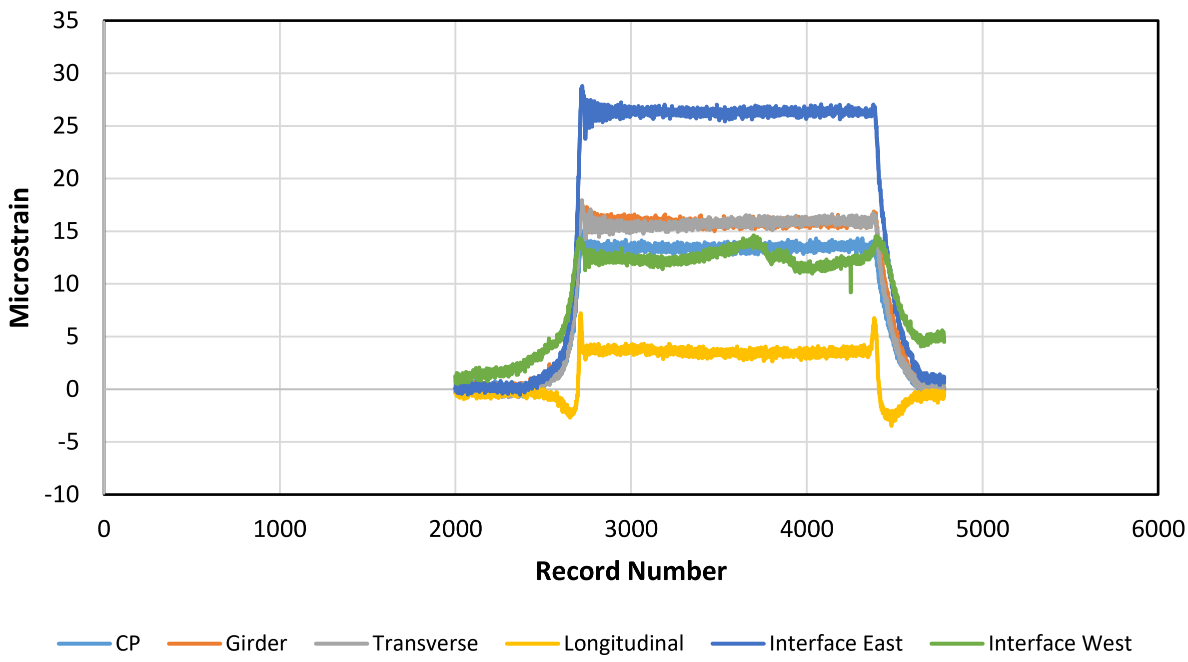


Figure D.20 Large UBIT Test 1.1 CP 1 (Concrete Gages)

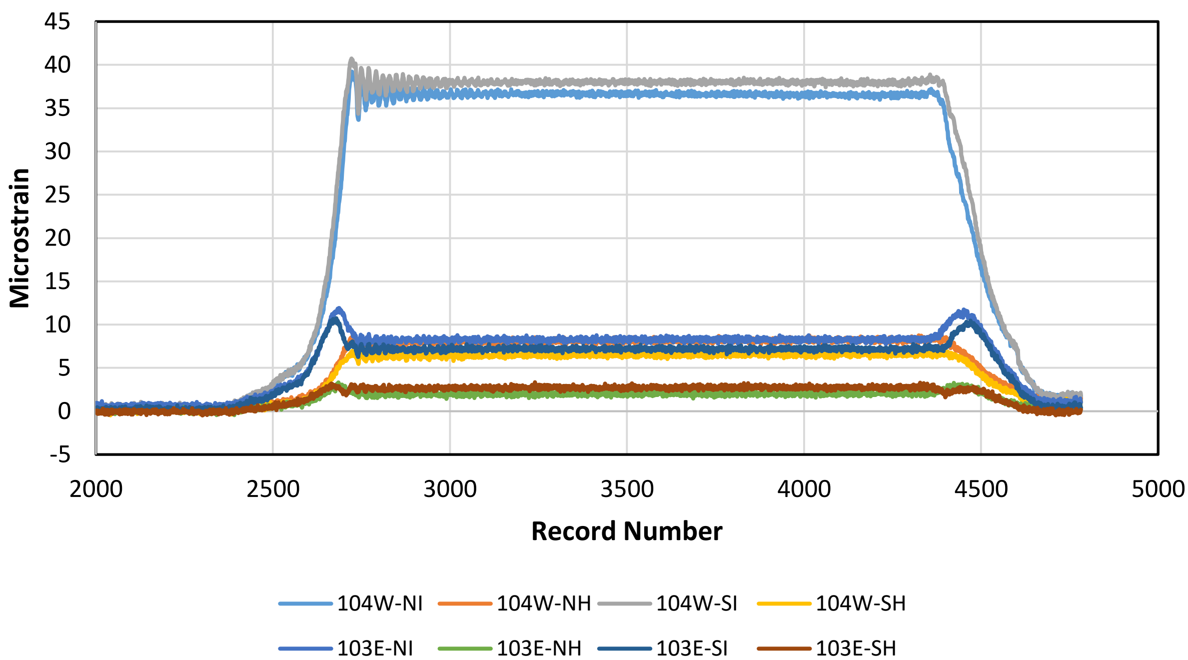


Figure D.21 Large UBIT Test 1.1 CP 2 (Rebar Gages)

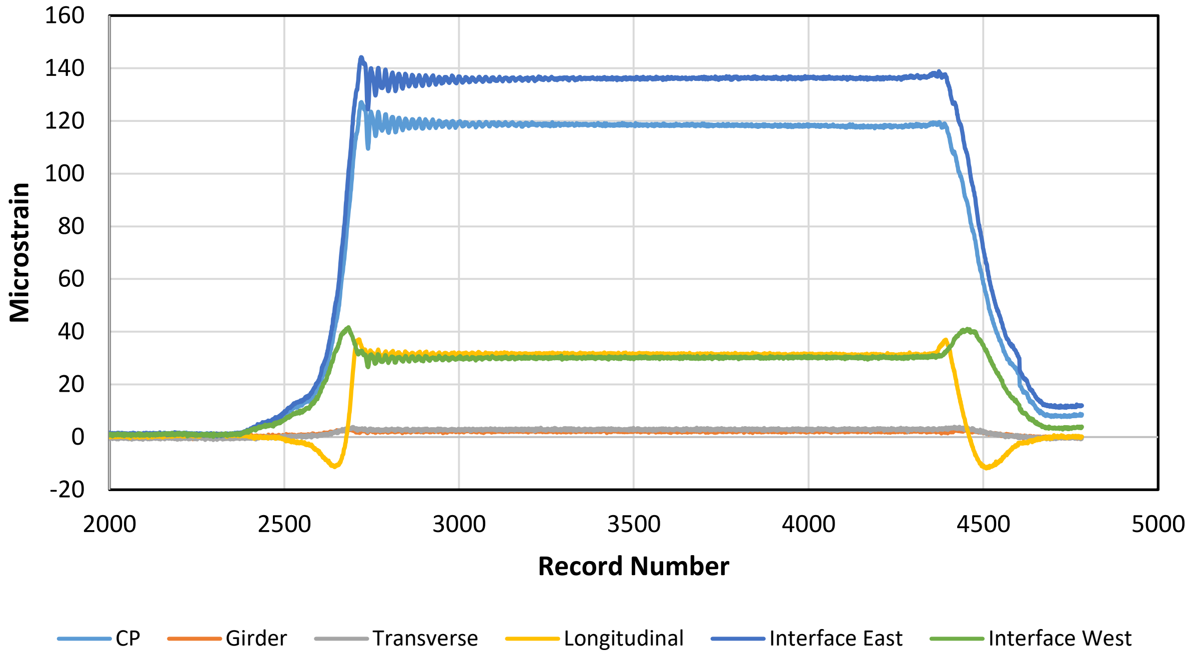


Figure D.22 Large UBIT Test 1.1 CP 2 (Concrete Gages)

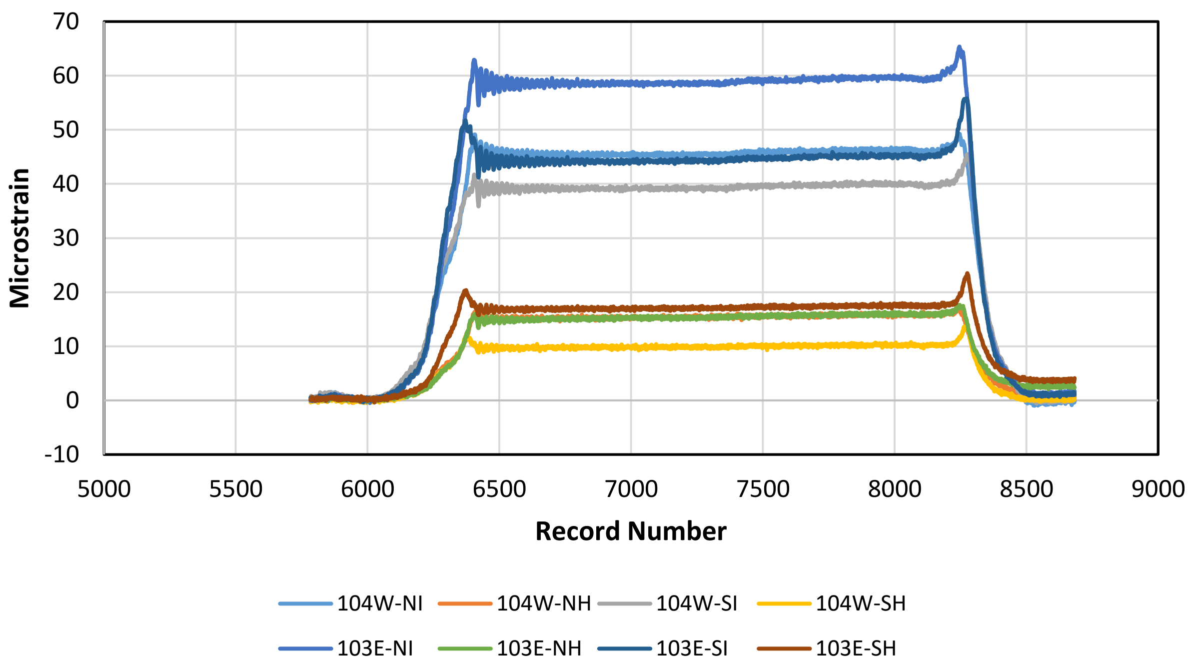


Figure D.23 Large UBIT Test 1.2 CP 2 (Rebar Gages)

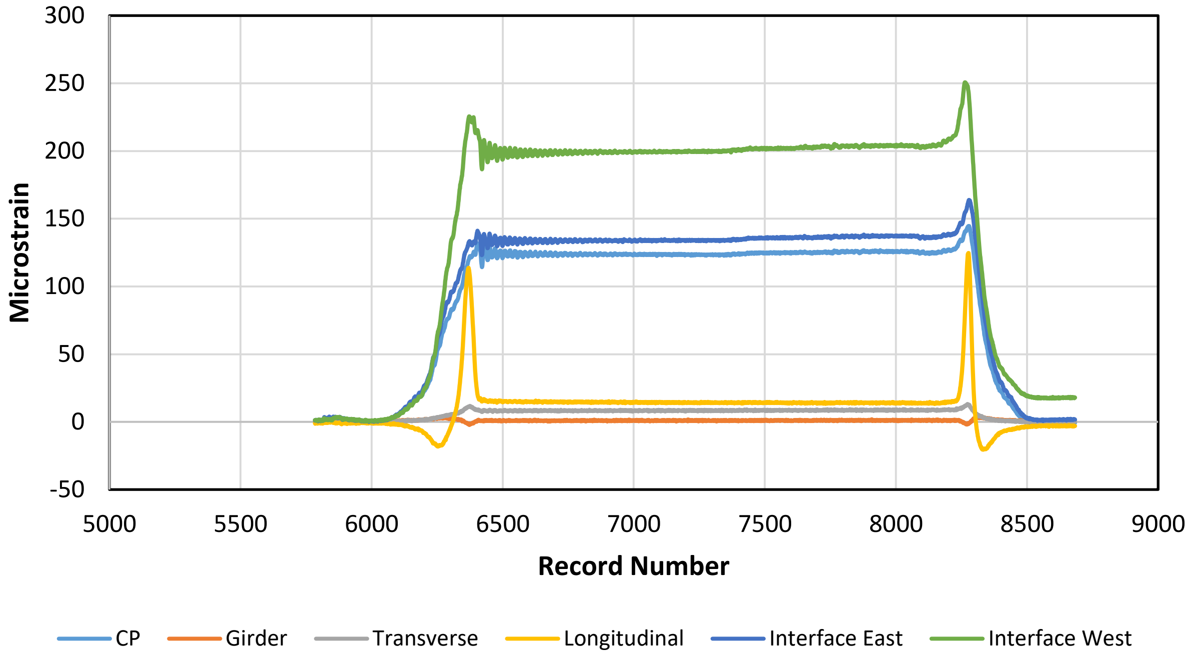


Figure D.24 Large UBIT Test 1.2 CP 2 (Concrete Gages)

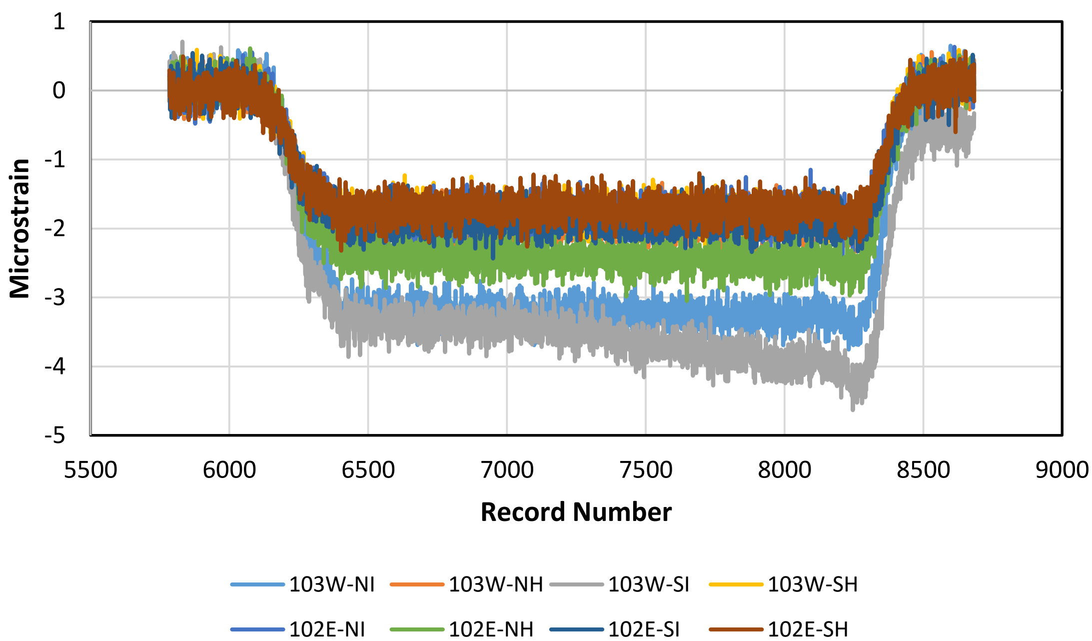


Figure D.25 Large UBIT Test 1.2 CP 3 (Rebar Gages)

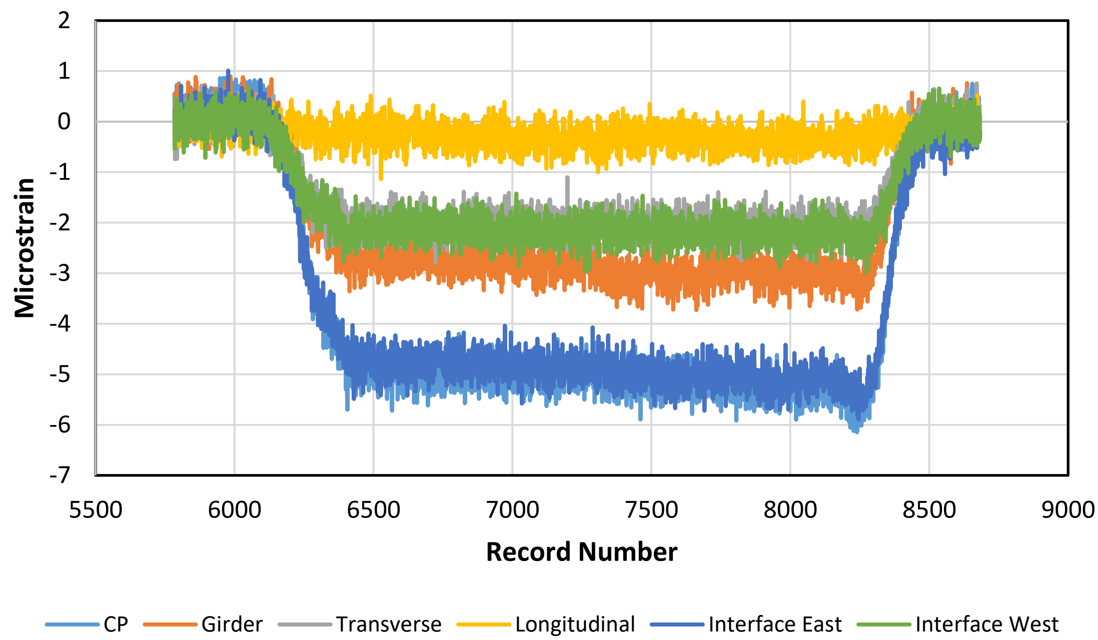


Figure D.26 Large UBIT Test 1.2 CP 3 (Concrete Gages)

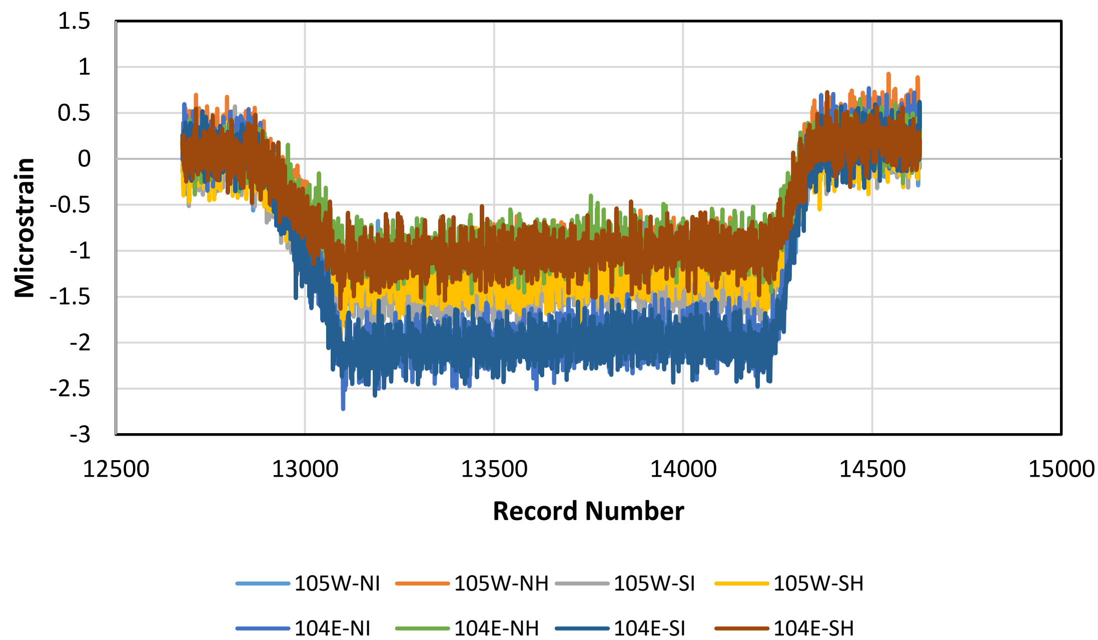


Figure D.27 Large UBIT Test 1.3 CP 1 (Rebar Gages)

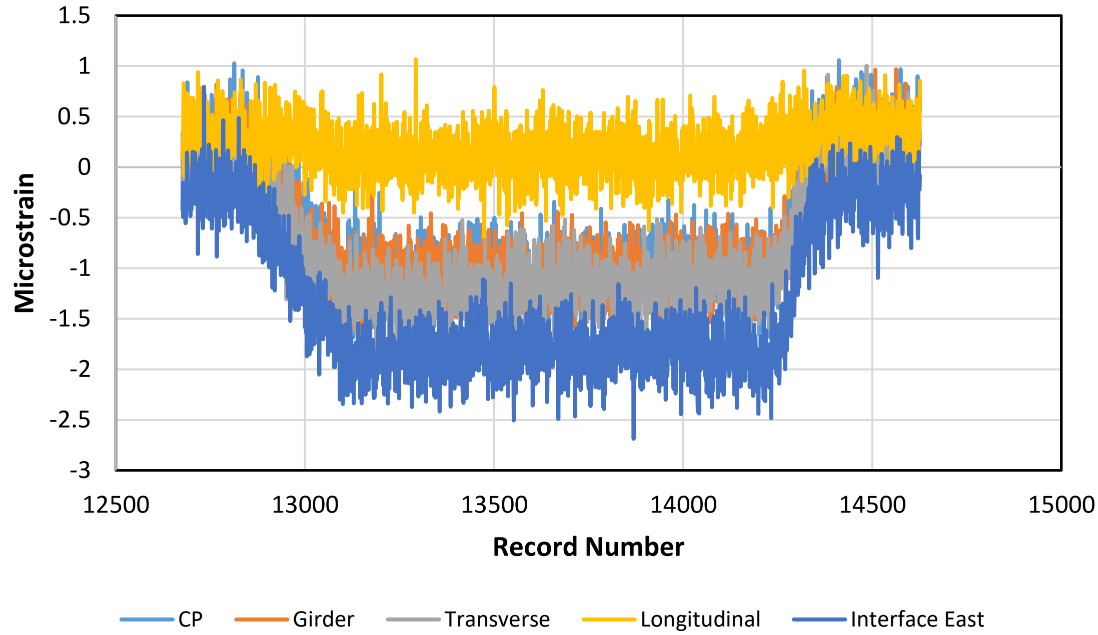


Figure D.28 Large UBIT Test 1.3 CP 1 (Concrete Gages)

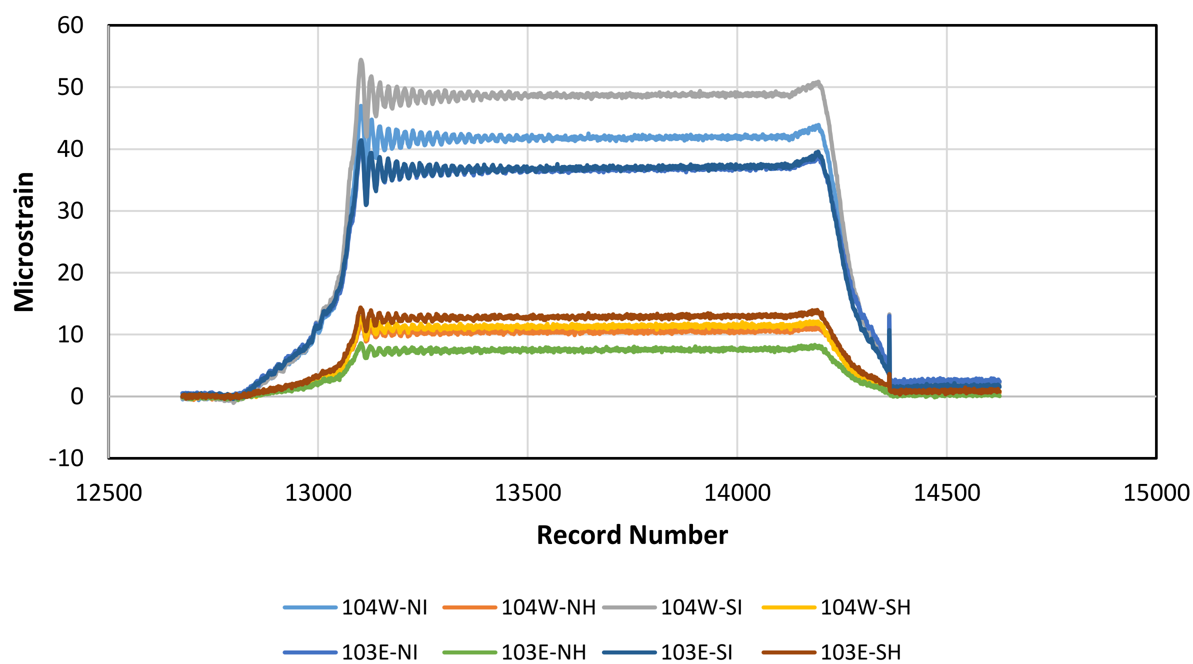


Figure D.29 Large UBIT Test 1.3 CP 2 (Rebar Gages)

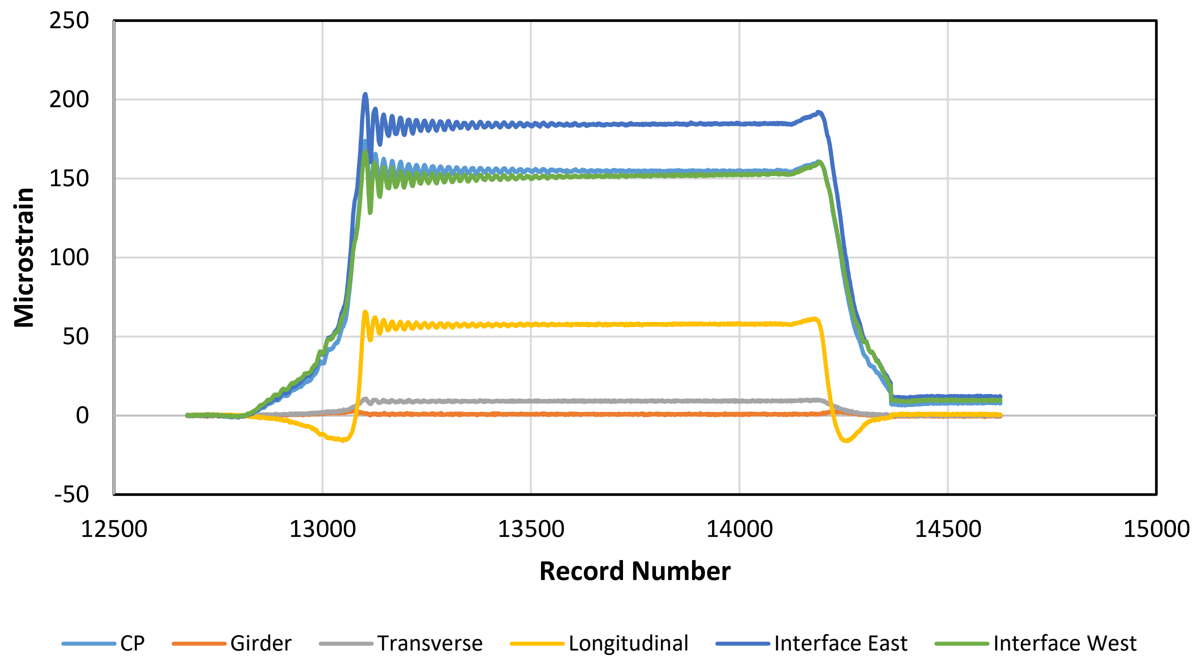


Figure D.30 Large UBIT Test 1.3 CP 2 (Concrete Gages)

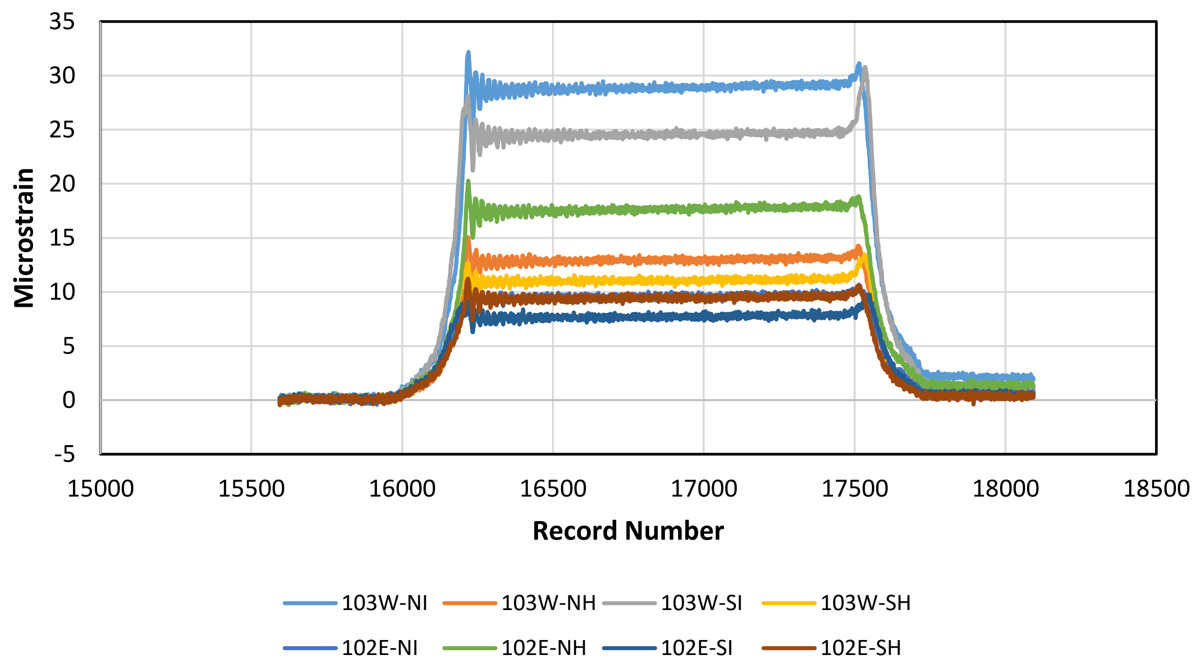


Figure D.31 Large UBIT Test 1.4 CP 3 (Rebar Gages)

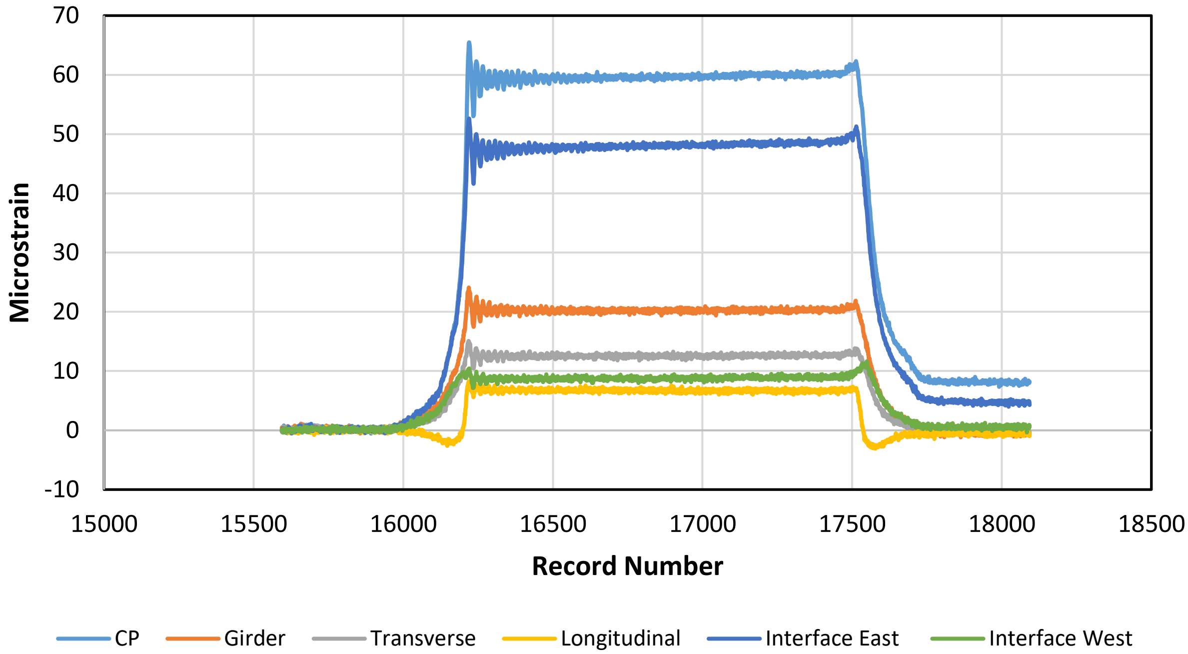


Figure D.32 Large UBIT Test 1.4 CP 3 (Concrete Gages)

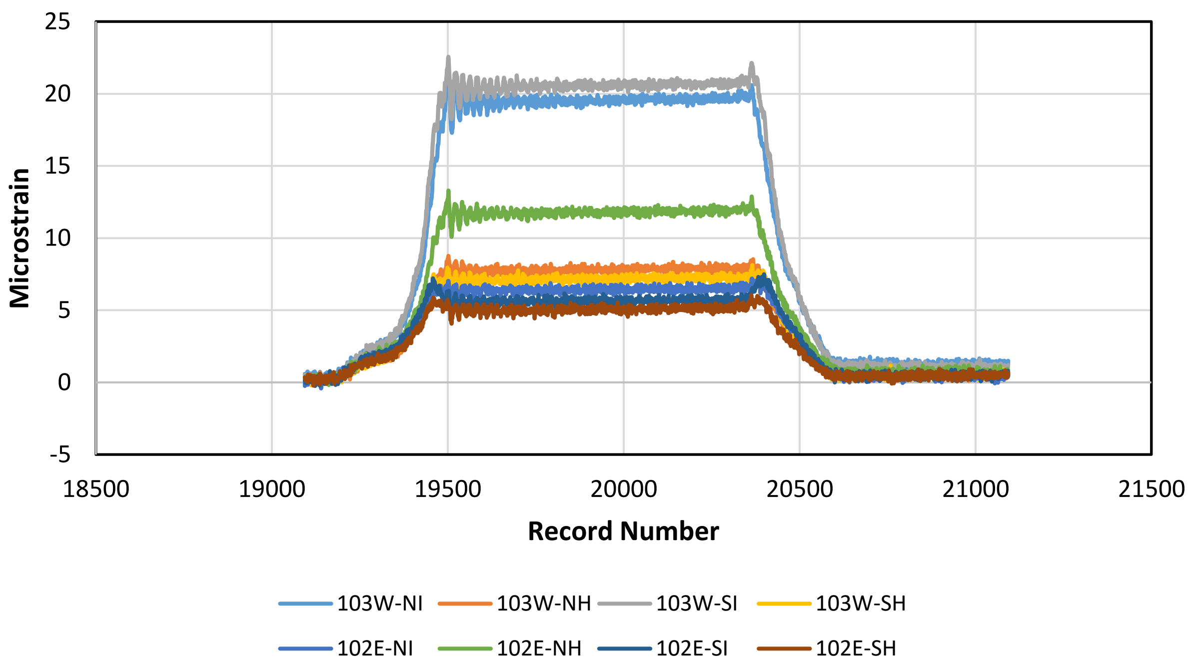


Figure D.33 Large UBIT Test 1.5 CP 3 (Rebar Gages)

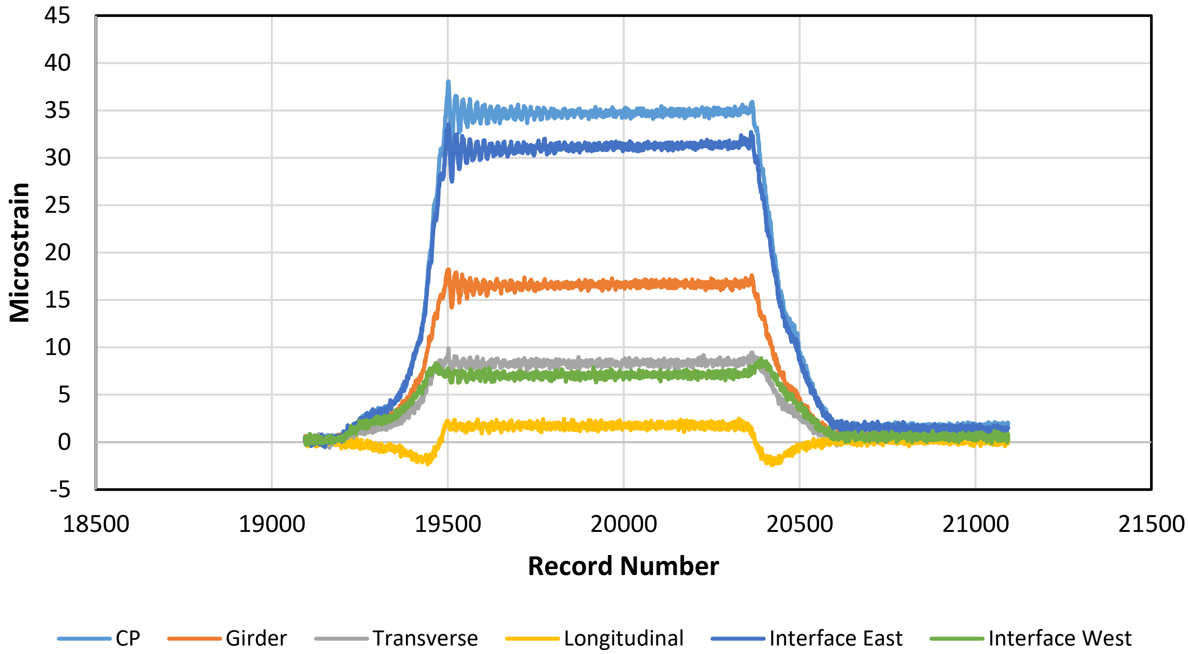


Figure D.34 Large UBIT Test 1.5 CP 3 (Concrete Gages)

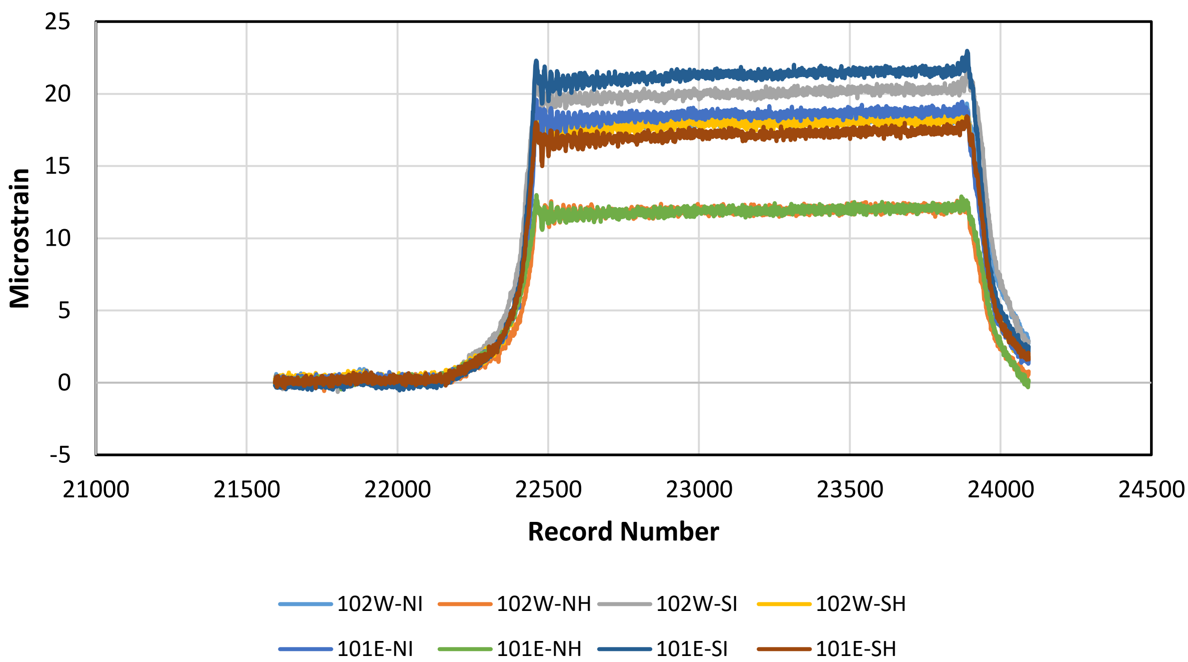


Figure D.35 Large UBIT Test 1.6 CP 4 (Rebar Gages)

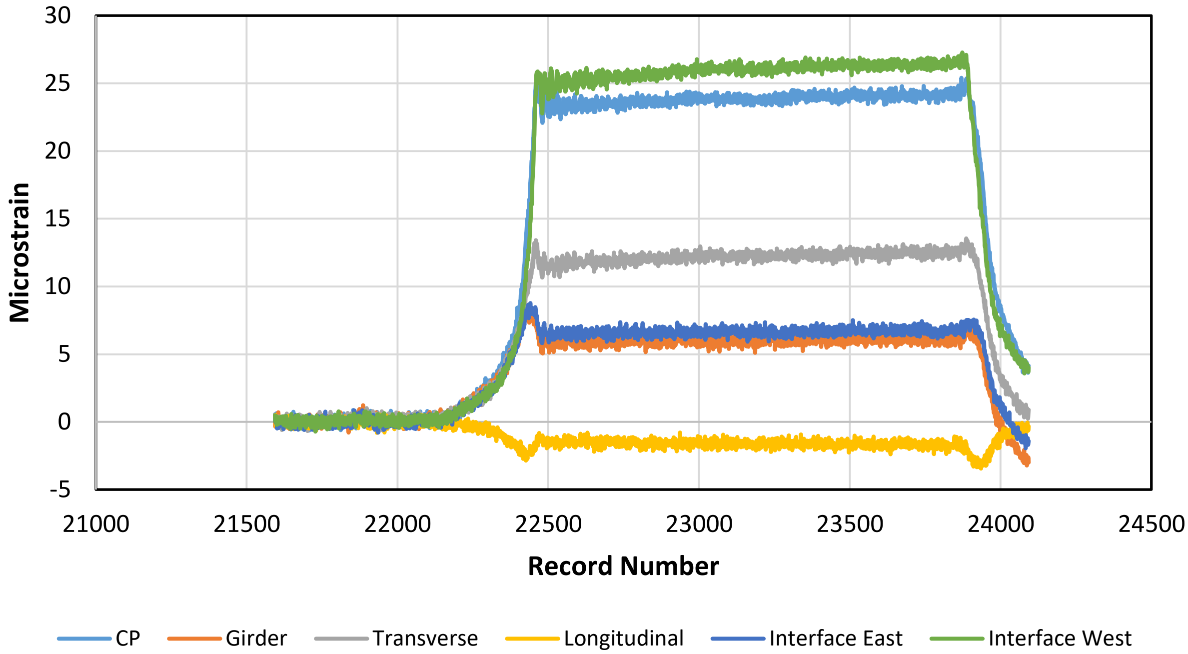


Figure D.36 Large UBIT Test 1.6 CP 4 (Concrete Gages)

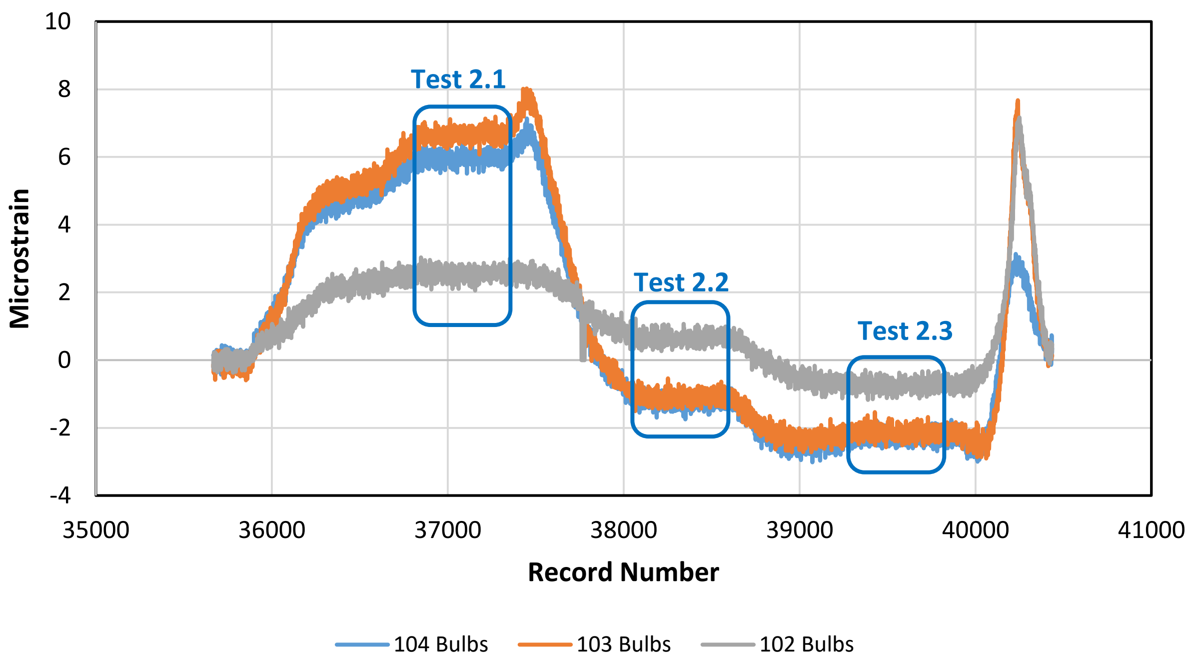


Figure D.37 Small UBIT Test 2.1, 2.2, and 2.3 (Bulb Gages)

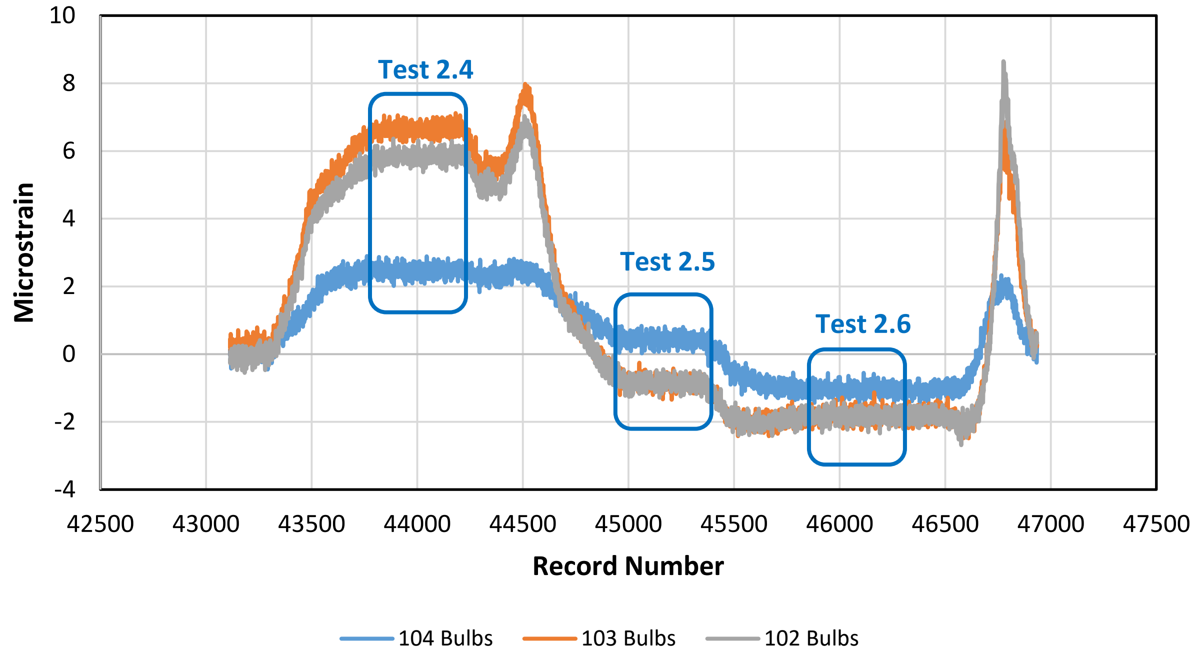


Figure D.38 Small UBIT Test 2.4, 2.5, and 2.6 (Bulb Gages)

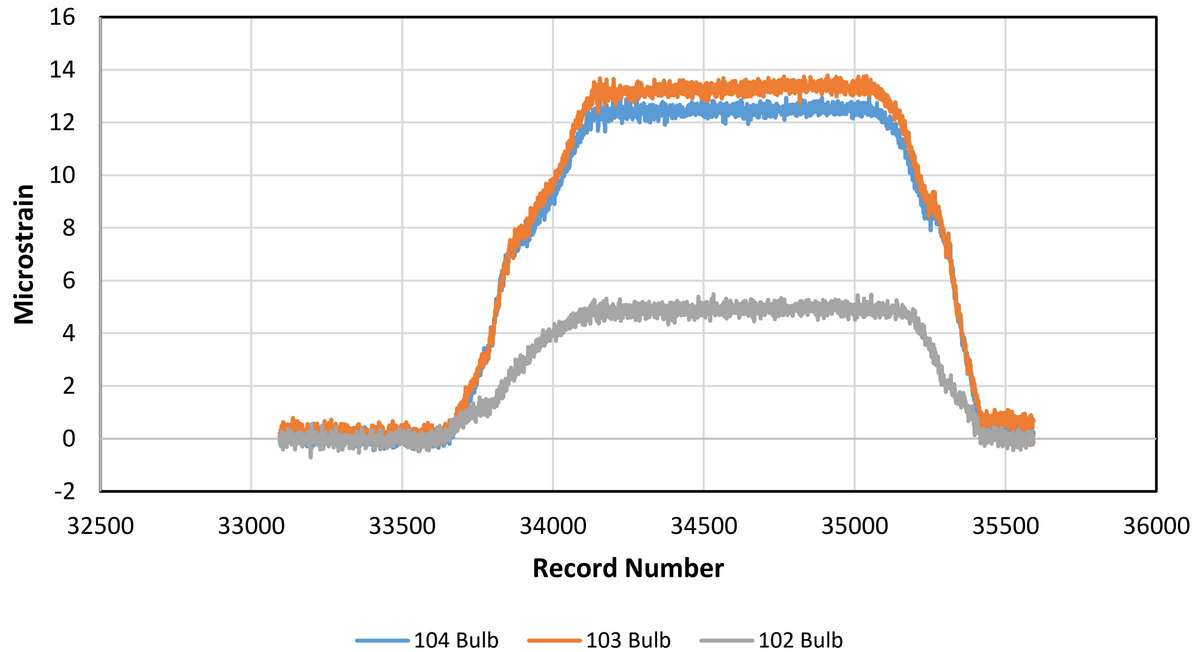


Figure D.39 Large UBIT Test 2.1 (Bulb Gages)

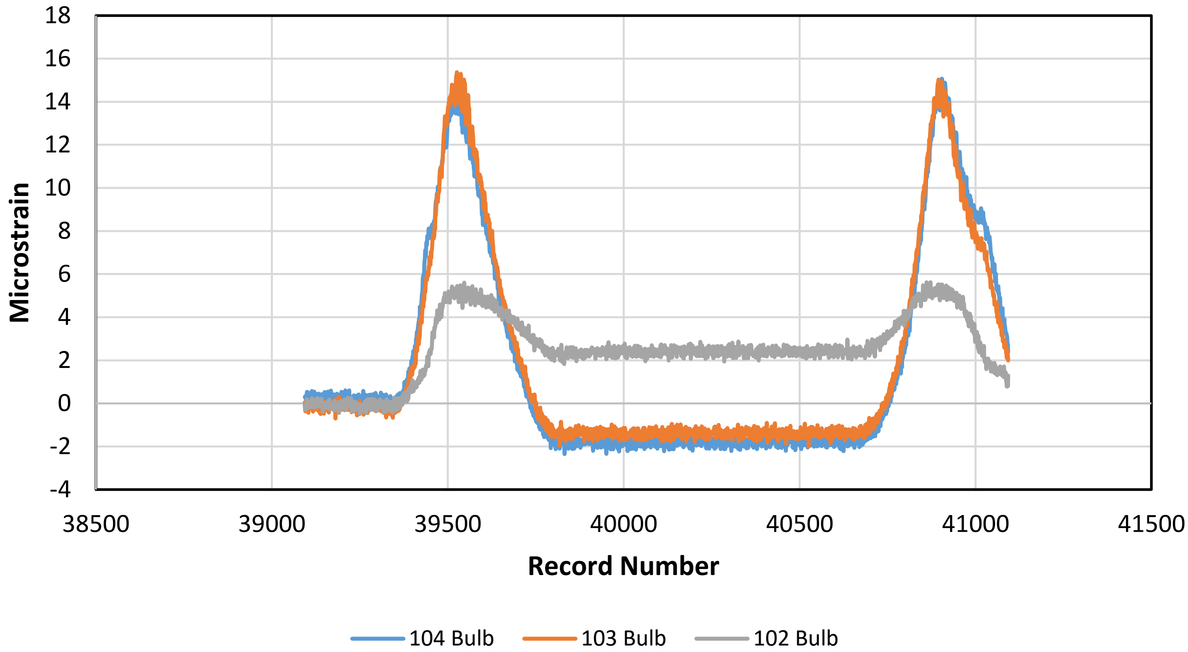


Figure D.40 Large UBIT Test 2.2 (Bulb Gages)

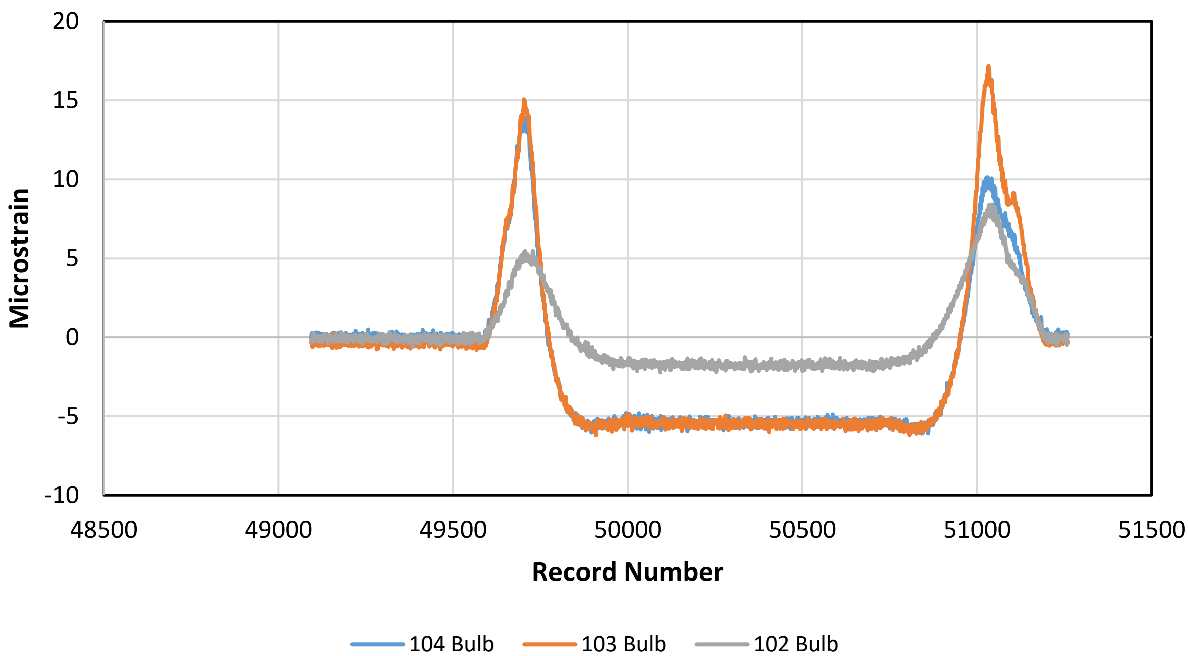


Figure D.41 Large UBIT Test 2.3 (Bulb Gages)

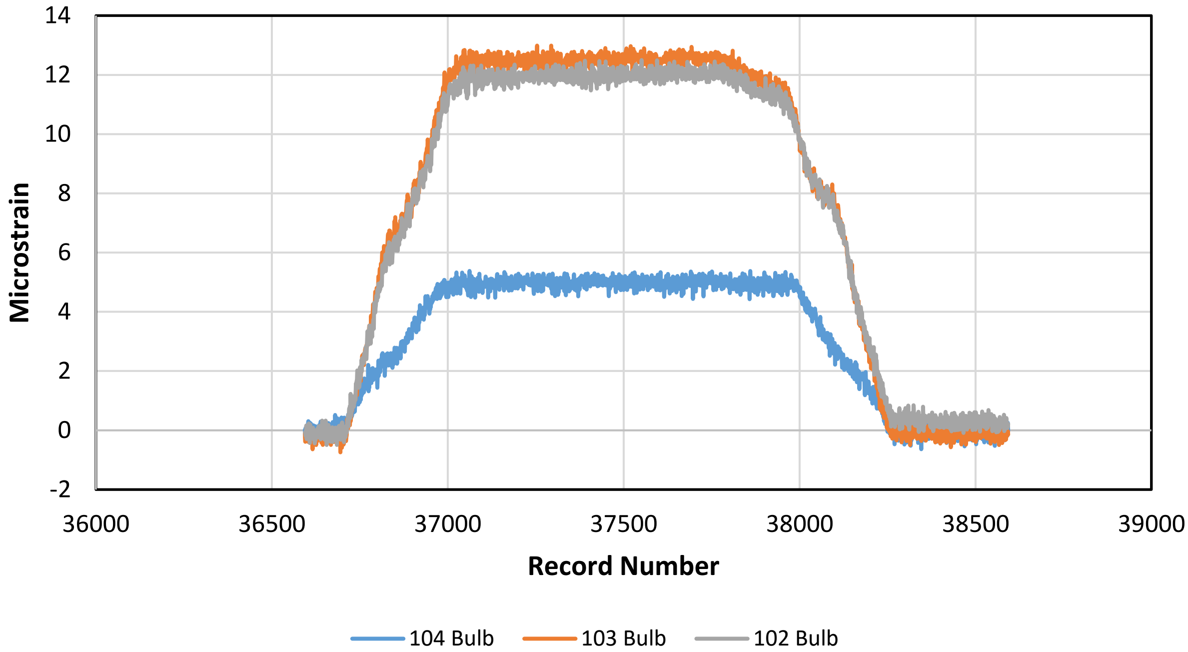


Figure D.42 Large UBIT Test 2.4 (Bulb Gages)

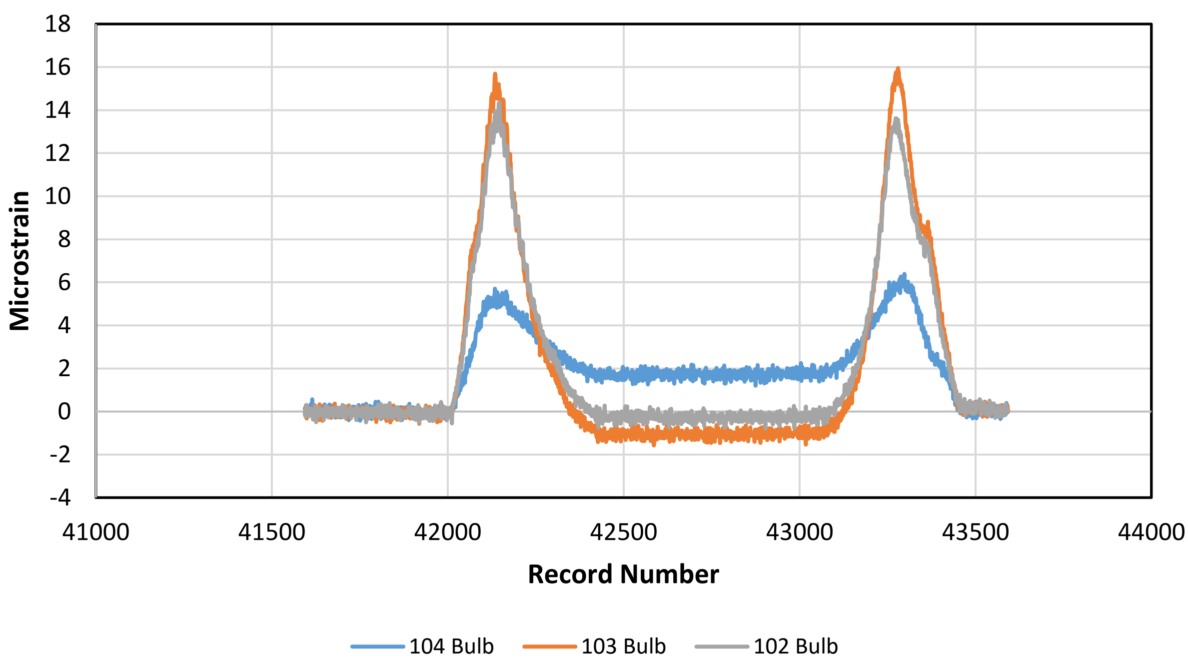


Figure D.43 Large UBIT Test 2.5 (Bulb Gages)

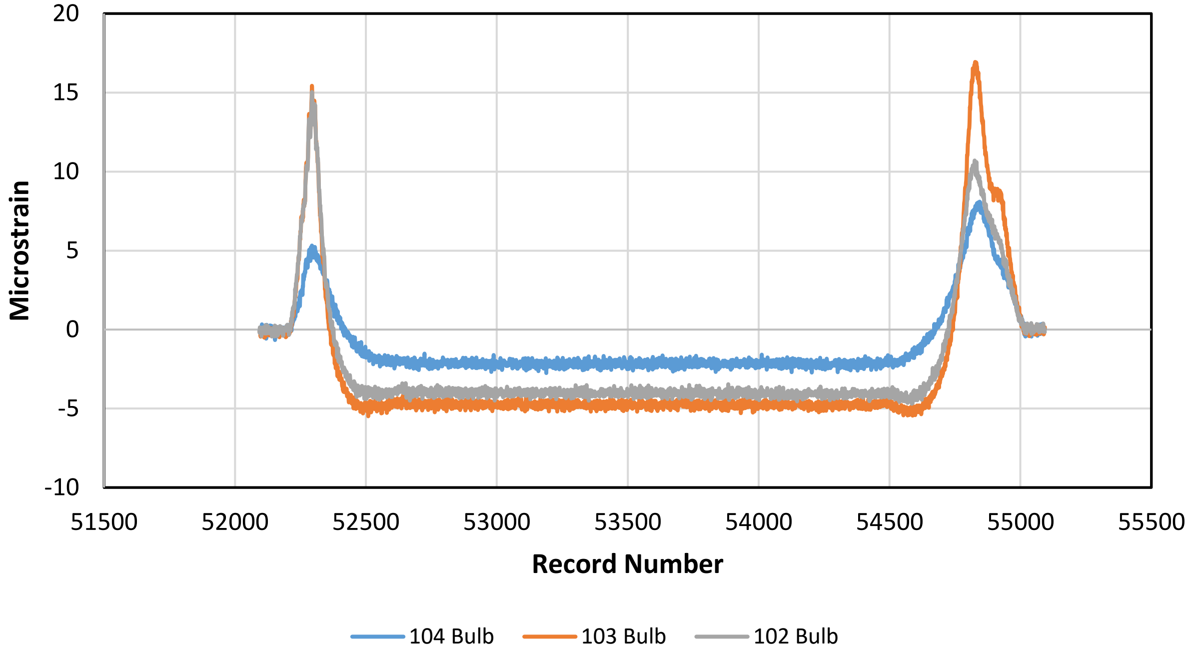


Figure D.44 Large UBIT Test 2.6 (Bulb Gages)

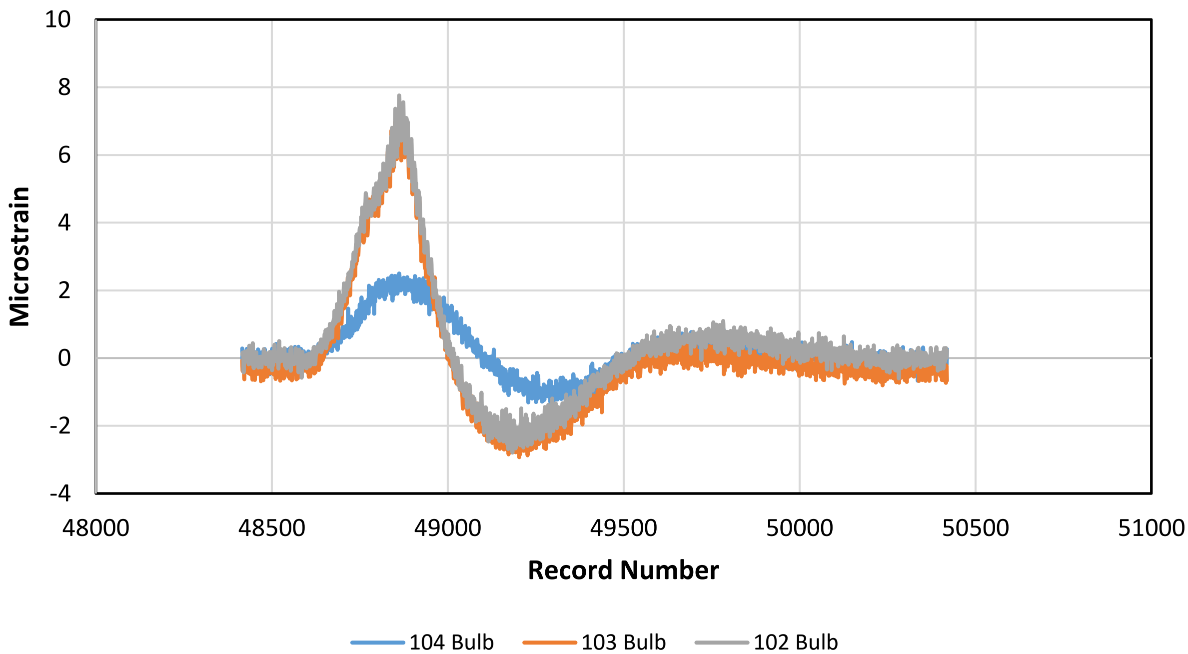


Figure D.45 Small UBIT Test 3.1 (Bulb Gages)

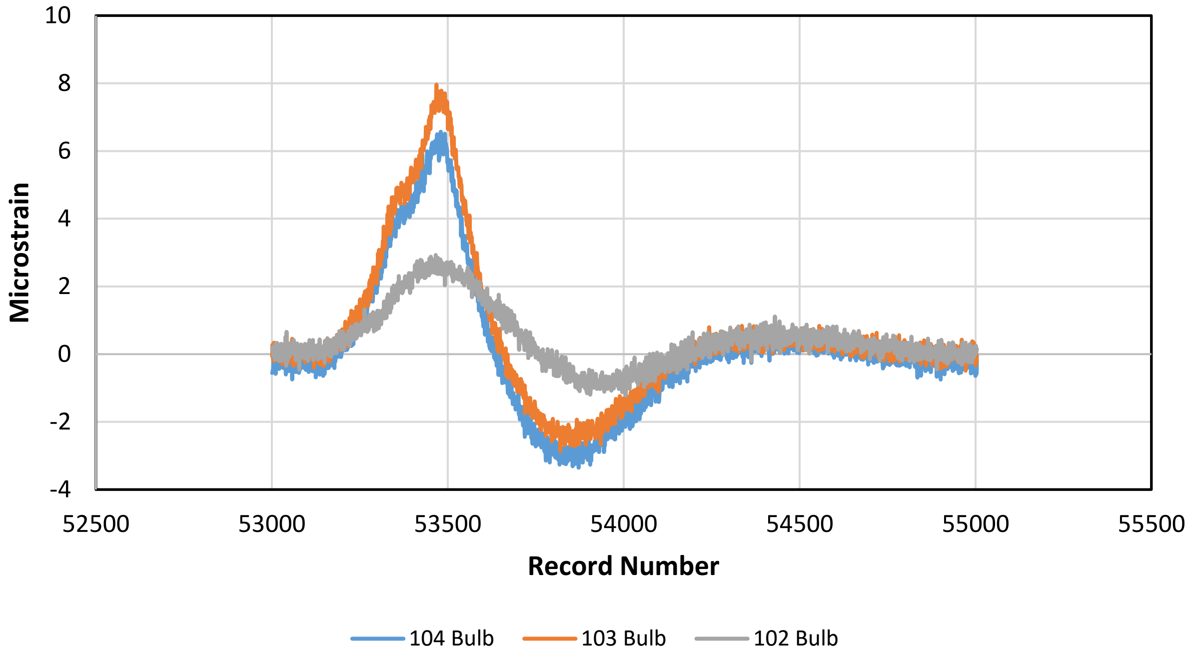


Figure D.46 Small UBIT Test 3.2 (Bulb Gages)

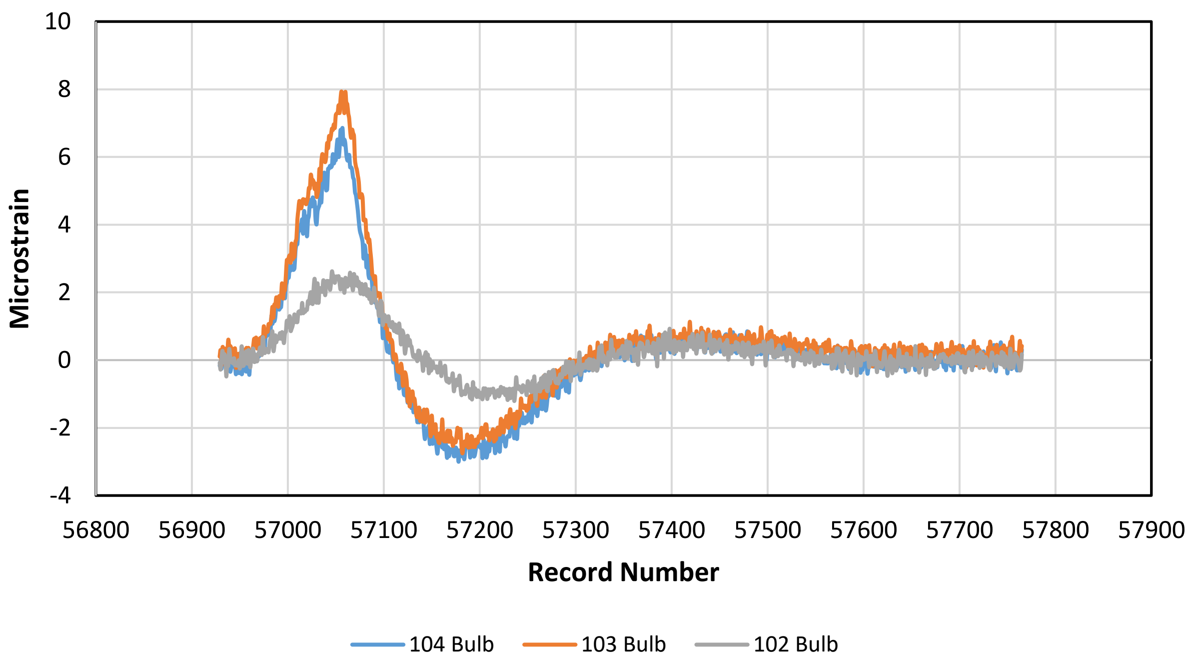


Figure D.47 Small UBIT Test 3.3 (Bulb Gages)

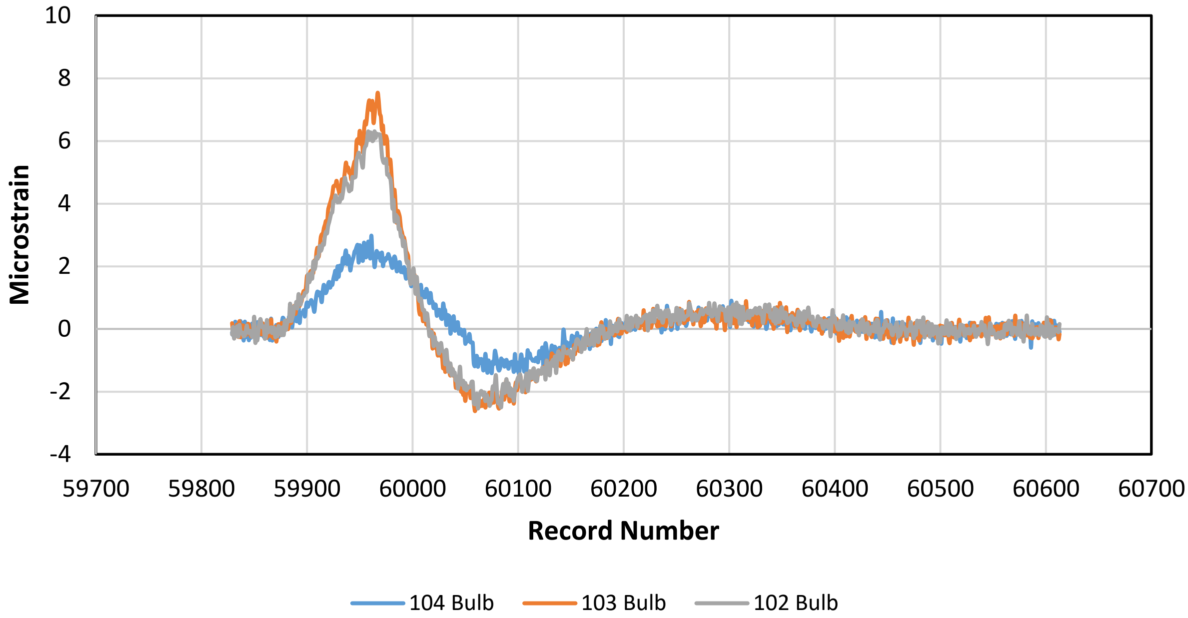


Figure D.48 Small UBIT Test 3.4 (Bulb Gages)

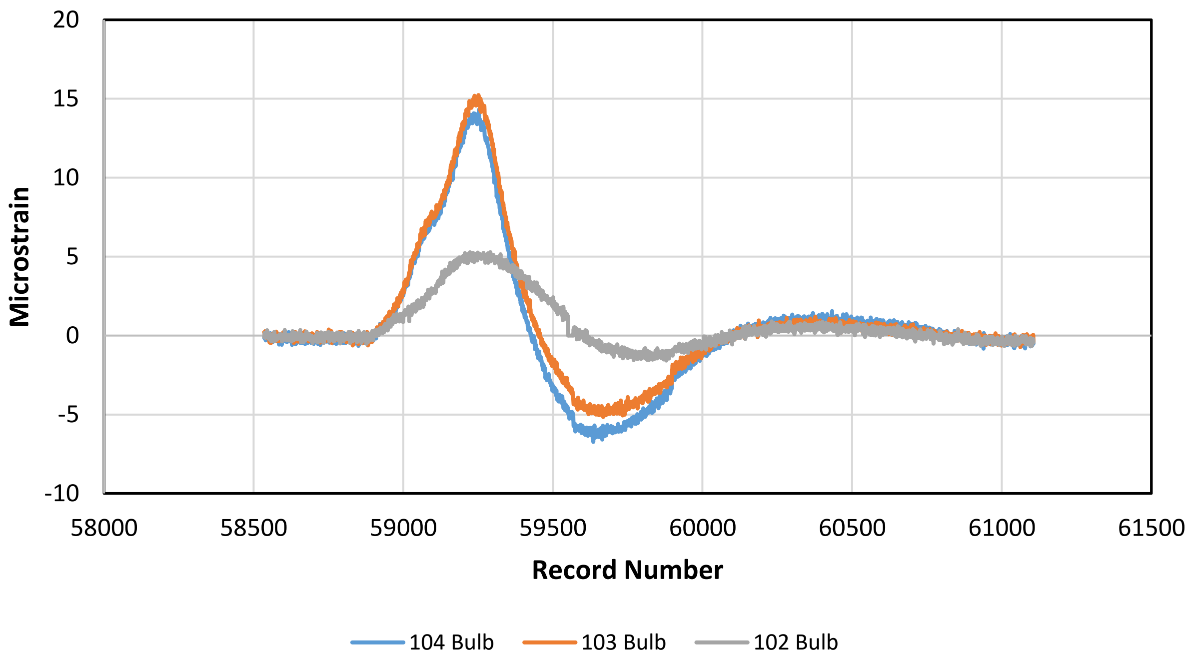


Figure D.49 Large UBIT Test 3.1 (Bulb Gages)

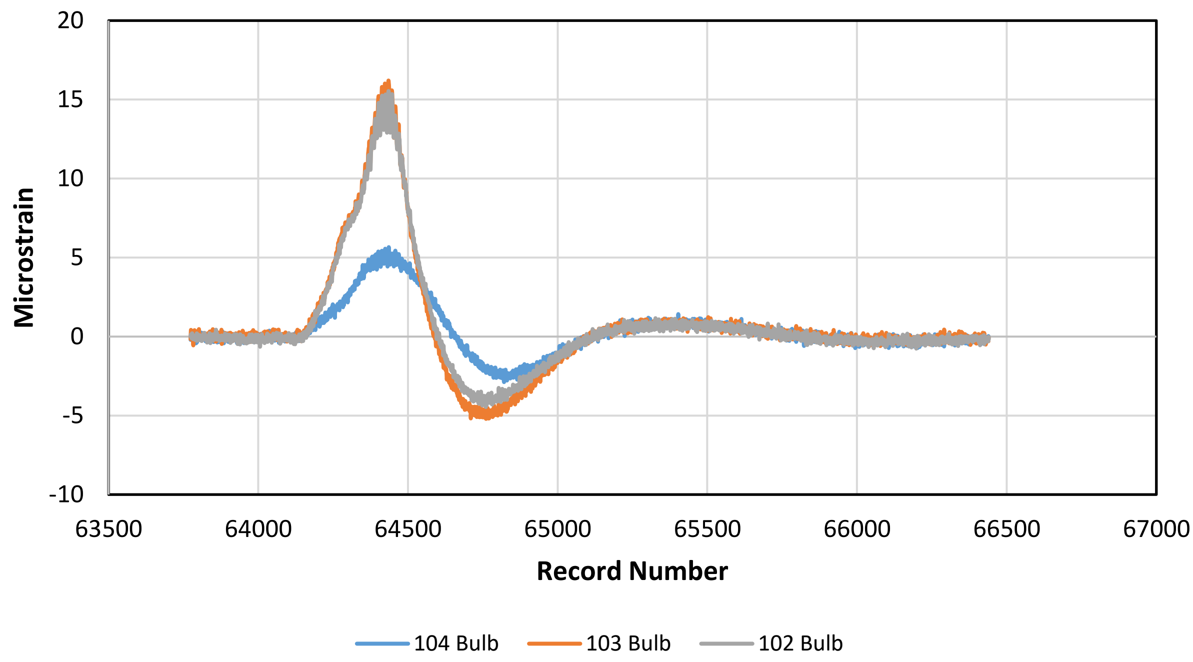


Figure D.50 Large UBIT Test 3.2 (Bulb Gages)

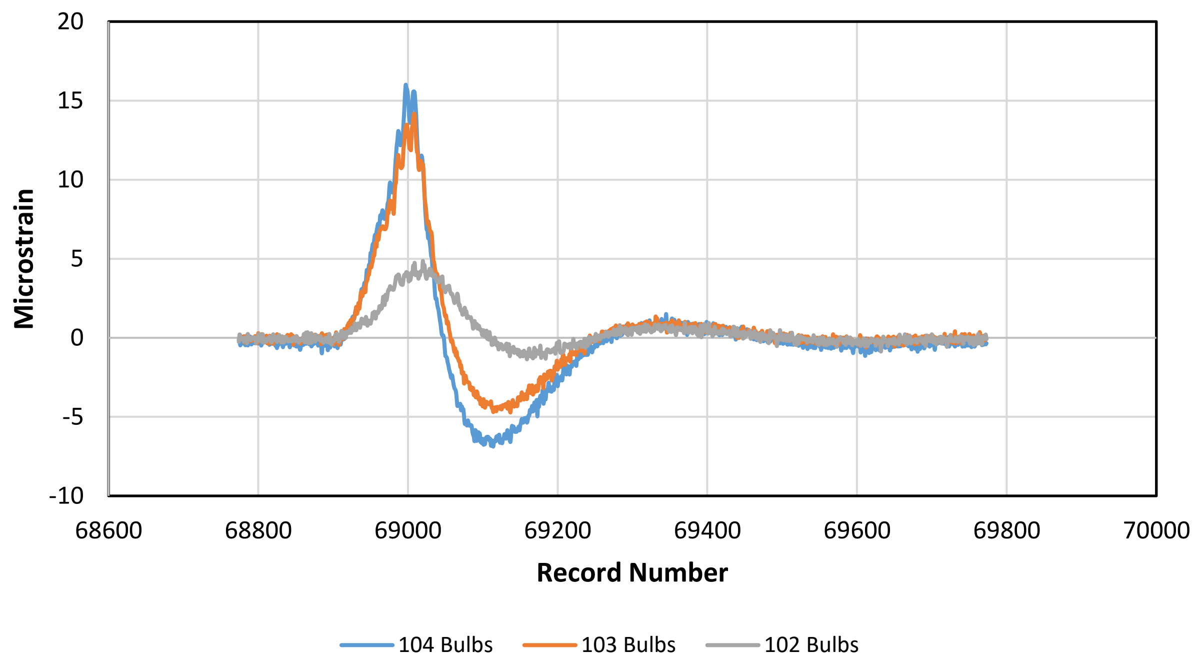


Figure D.51 Large UBIT Test 3.3 (Bulb Gages)

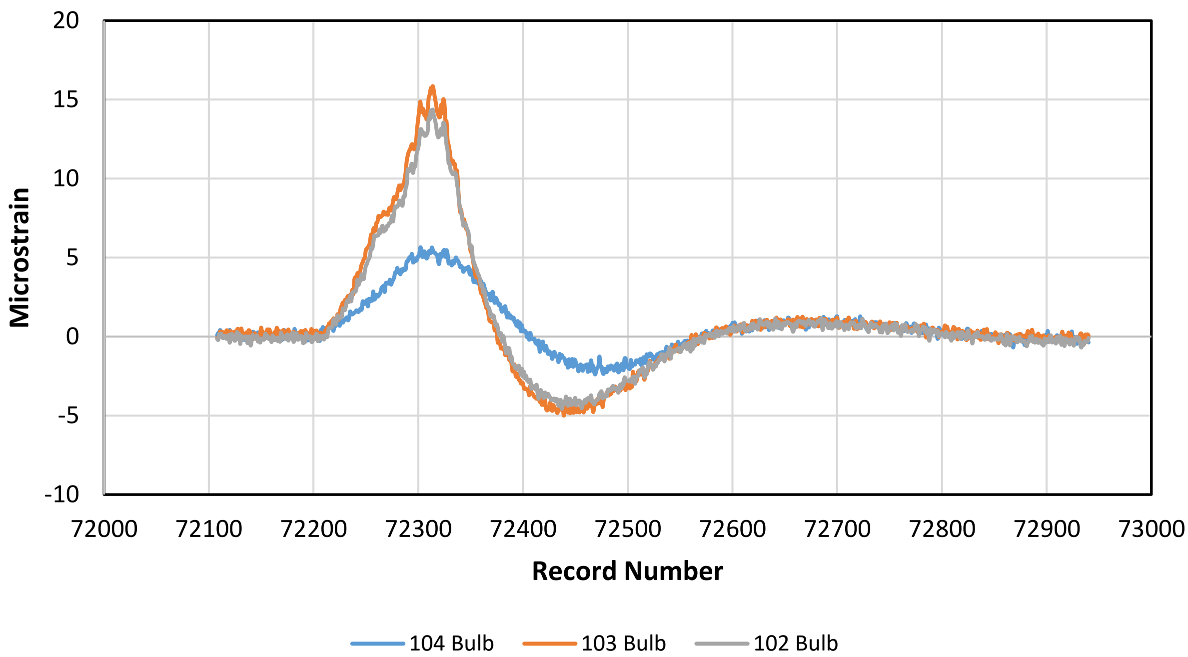


Figure D.52 Large UBIT Test 3.4 (Bulb Gages)

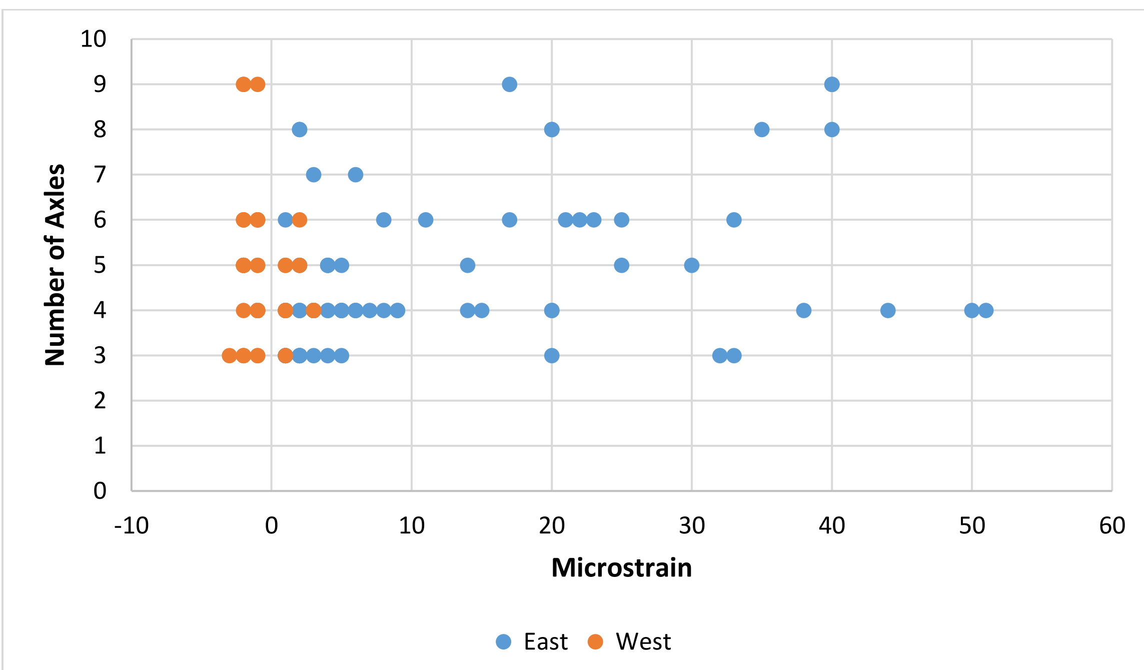


Figure D.53 Rebar Strain in Closure Pour 1 Versus Number of Axles for Commercial Traffic

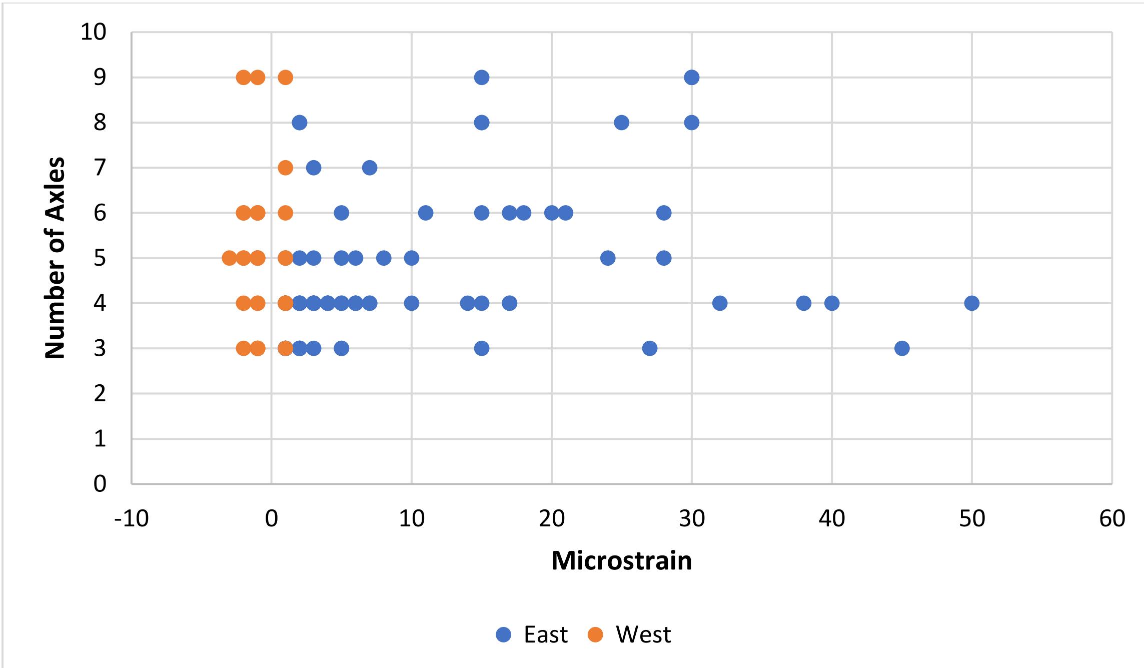


Figure D.54 Concrete Strain in Closure Pour 1 Versus Number of Axles for Commercial Traffic

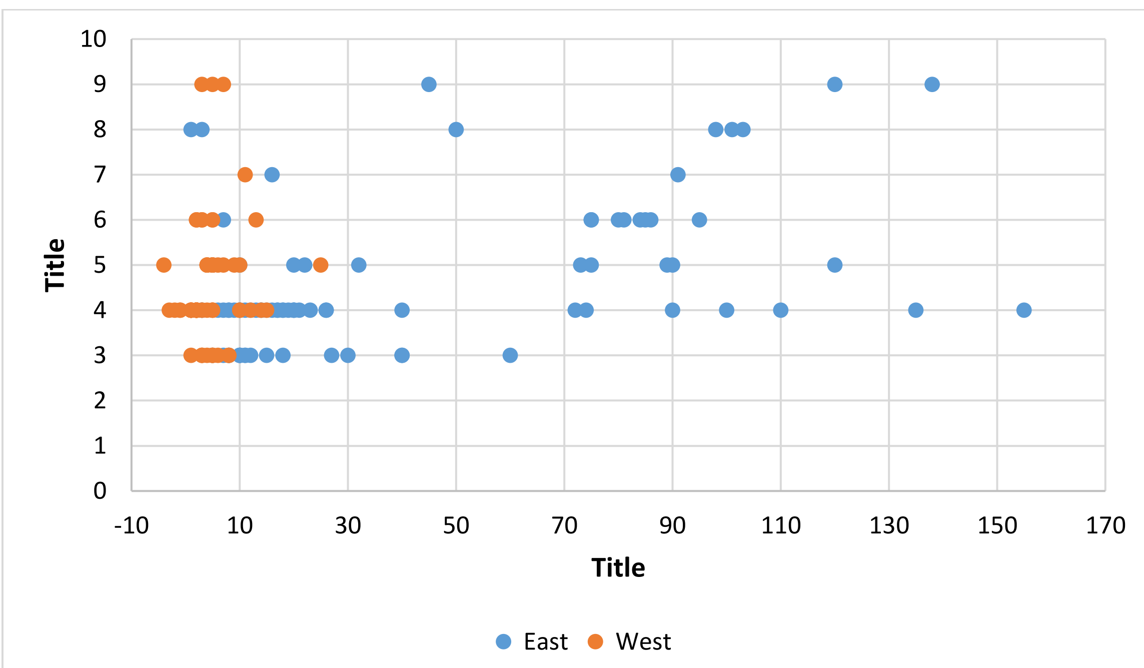


Figure D.55 Rebar Strain in Closure Pour 2 Versus Number of Axles for Commercial Traffic

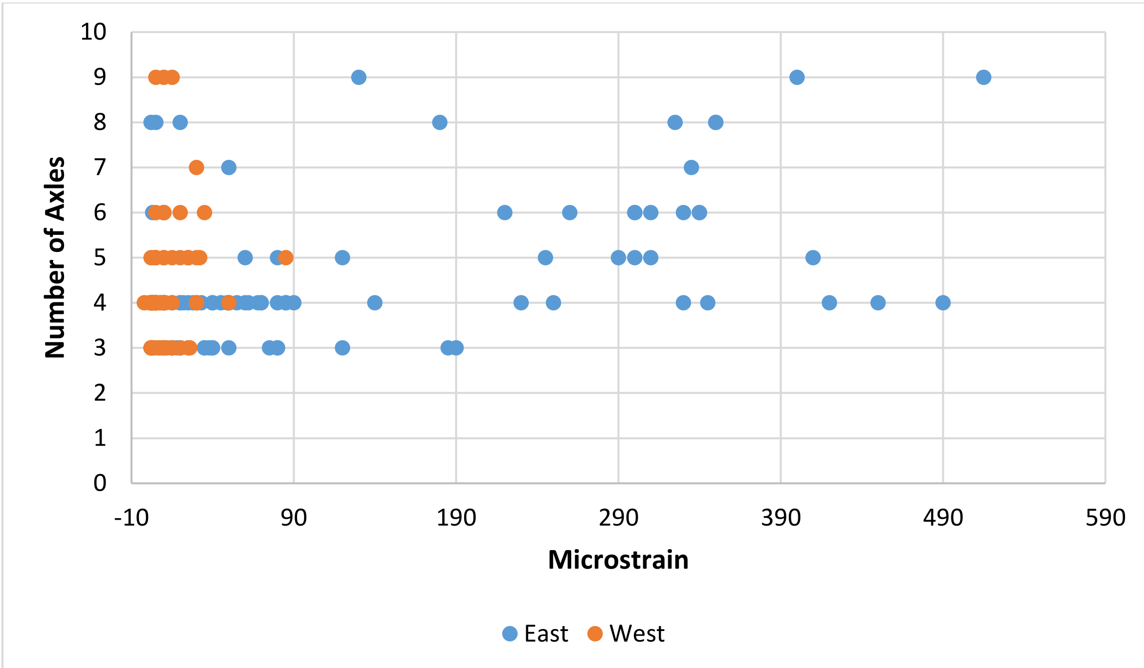


Figure D.56 Concrete Strain in Closure Pour 2 Versus Number of Axles for Commercial Traffic

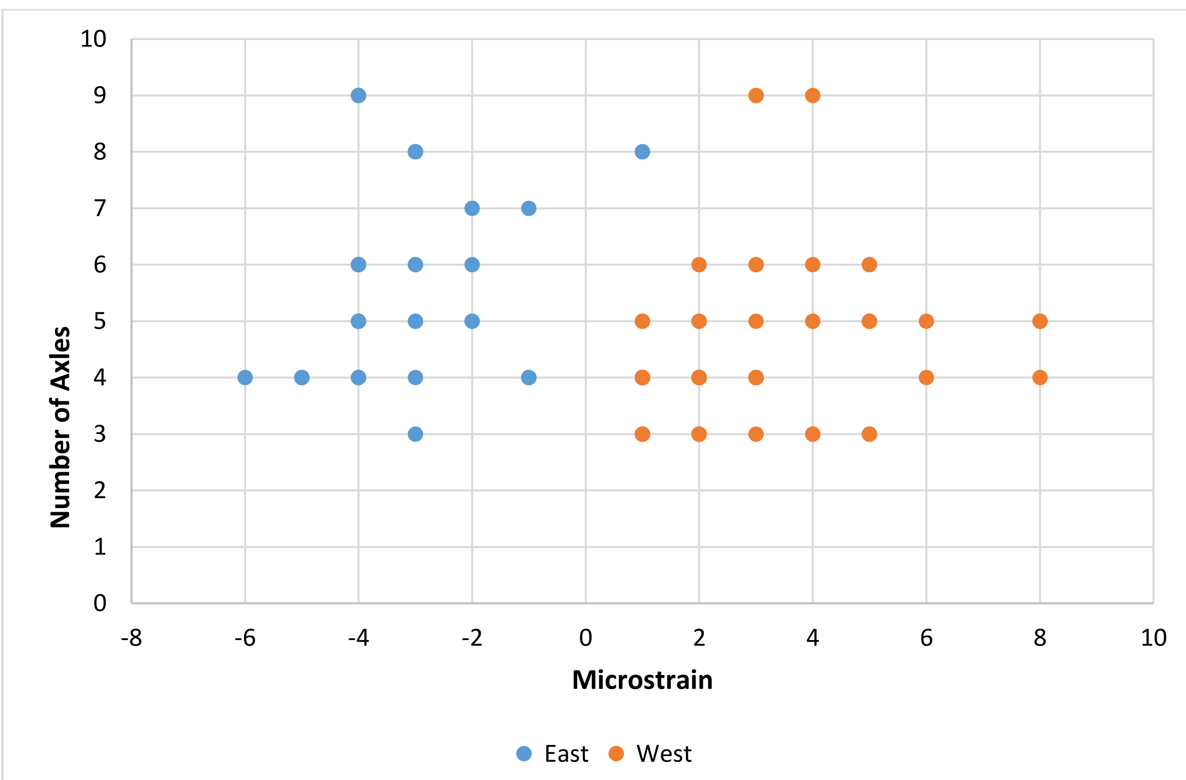


Figure D.57 Rebar Strain in Closure Pour 4 Versus Number of Axles for Commercial Traffic

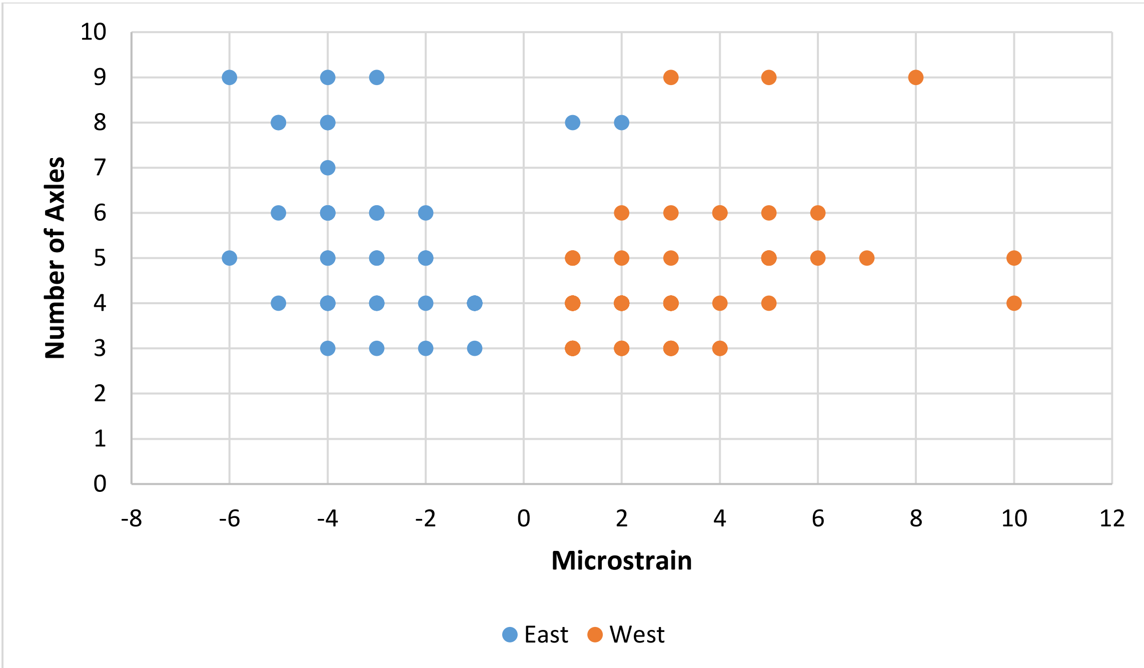


Figure D.58 Concrete Strain in Closure Pour 4 Versus Number of Axles for Commercial Traffic

Table D.1 Maximum Rebar Strain Values Under UBIT Loading

Rebar strain values in all closure pours under UBITs																	
Load Case		CP 1				CP 2				CP 3				CP 4			
		Int. E	Head E	Int. W	Head W	Int. E	Head E	Int. W	Head W	Int. E	Head E	Int. W	Head W	Int. E	Head E	Int. W	Head W
Small UBIT	1.1	9.5	8	12.5	6.5	18	4	5	2	-1	-1	-1	-1	-	-	-	-
	1.2	9	8	14.5	7.5	22	4	5	2	-1	-1	-1	-1	-	-	-	-
	1.3	-0.5	-0.5	-1.5	-0.5	34	9	18	7	5	2.5	1.5	3	-1	-0.5	-0.5	-0.5
	1.4	-0.5	-0.5	-1	-0.5	5	7.5	17	8	10	9	9	10	-0.5	-0.5	-0.5	-0.5
	1.5	-	-	-	-	-4	-1	-3.5	-1	9	8	7.5	10	9	4	4	3.5
	1.6	-	-	-	-	-3.5	-1	-3	-0.5	3.5	3	5	4	15	8	8	8
Large UBIT Trial 1	1.1	16	12	17	10	37	7	7.5	2	-3	-1.5	-1.5	-1.5	-	-	-	-
	1.2	4	5	13	4	42	18	52	18	-3	-2	-2.5	-2	-	-	-	-
	1.3	-1	-1	-2	-1	45	11	37	9.5	15	6	5	5	-2	-1	-1.5	-1
	1.4	-2	-1	-2	-1	23	8	60	12	27.5	12	8	13	-1.5	-1	-1	-1
	1.5	-	-	-	-	-5	-1	-5	-1	20	7	6	7	8.5	3	3	3
	1.6	-	-	-	-	-4.5	-1	-4.5	-1	7	4	7	5	20	14	19	14
Large UBIT Trial 2	1.1	17	11	17	9	35	8	10	3	-4	-1.5	-1.5	-1.5	-	-	-	-
	1.2	5	5	15	5	42	12	50	15	-3	-2	-2	-2	-	-	-	-
	1.3	-1	-1	-3	-1	52	13	45	13	18	8	4	7	-1.5	-1	-1	-1
	1.4	-1.5	-1.5	-2	-1	67	15	26	10	11	4	2.5	4	-2	-1	-1.5	-1
	1.5	-	-	-	-	-6	-1	-6	-1	17	7	5	8	6	3	3	3
	1.6	-	-	-	-	-5.5	-1	-5.5	-1	7	5	8	6	25	18	18	15

Table D.2 Maximum Concrete Strain Values Under UBIT Loading

Concrete strain values in all closure pours under UBITs																									
Load Case		CP 1						CP 2						CP 3						CP 4					
		CP	Girder	Trans.	Long.	Int. E	Int. W	CP	Girder	Trans.	Long.	Int. E	Int. W	CP	Girder	Trans.	Long.	Int. E	Int. W	CP	Girder	Trans.	Long.	Int. E	Int. W
Small UBIT	1.1	9	7	10	5	13	9	52	2	2	20	62	19	-1	-1	-1	-	-1	-1	-	-	-	-	-	-
	1.2	9.5	6.5	9	2	11	9.5	61	2	2	14	70	20	-1	-1.5	-1	-	-1.5	-1	-	-	-	-	-	-
	1.3	-	-	-	-	-1	-1	94	-	8	18	105	64	4	7	3	2.5	6	2	-1.5	-1	-	-	-0.5	-1
	1.4	-	-0.5	-	-	-0.5	-1.5	16	-	2	8	19	60	10	10	14	5	12	11	-1	-1	-	-	-1	-1
	1.5	-	-	-	-	-	-	12	-	-	-4	-14	-12	12	12	13	4	14	8	10.5	6	2	2	6	3
	1.6	-	-	-	-	-	-	-10	-	-0.5	-3	-12	-11	3	3	4.5	-	4	7	18	7	9	-	8	9
Large UBIT Trial 1	1.1	13	15	15	4	27	12	120	3	3	32	138	32	-5	-2	-1.5	-	-4	-2	-	-	-	-	-	-
	1.2	5	4	4	-	5	9	125	-	5	10	140	200	-5	-3	-2	-	-5	-2	-	-	-	-	-	-
	1.3	-	-	-	-	-	-	150	-	8	55	180	150	24	12	7	-	22	7	-2	-1.5	-0.5	-	-1.5	-1.5
	1.4	-	-	-	-	-	-	75	-	5	35	80	225	60	20	12	8	48	10	-2	-2	-0.5	-	-1.5	-1.5
	1.5	-	-	-	-	-	-	-17	-	-	-8	-20	-23	35	17	8	2	31	7	9	5	2	-	6	5
	1.6	-	-	-	-	-	-	-13	-	-	-6	-14	-17	9	4	4	2	7	8	23	6	12	-2	7	26
Large UBIT Trial 2	1.1	12	17	16	7	28	6	110	5	5	40	125	40	-7	-2.5	-1.5	-	-6	-2	-	-	-	-	-	-
	1.2	5	2	3	4	5	-	140	-	10	100	150	200	-6	-2.5	-2	-	-5	-2	-	-	-	-	-	-
	1.3	-	-	-	-	-	-	165	-	15	85	180	175	35	15	8	3	30	4	-2	-1.5	-0.5	-	-1.5	-1.5
	1.4	-	-	-	-	-	-	185	-	-	-	200	100	19	9	4	3	17	3	-2	-1.5	-0.5	-	-2	-1.5
	1.5	-	-	-	-	-	-	-20	1	-	-8	-24	-24	32	15	5	4	28	4	7	4	2	1	4	3
	1.6	-	-	-	-	-	-	-15	-	-	-6	-17	-20	12	4	5	3	9	10	29	4	10	7	8	35

Table D.3 Maximum Strain Values Under Small UBIT Loading

Small UBIT (1-29-2019)								
Load Test	Max. Concrete Strain, με				Location of the largest maximum concrete strain	Max. rebar strain, με	Max. rebar stress, psi	Location of bar with largest stress
	CP1	CP2	CP3	CP4				
1.1	13	62	-	-	Interface East	18	522	Interface, CP2
1.2	11	70	-2	-	Interface East	23	667	Interface, CP2
1.3	-1	105	7	-	Interface East	37	1073	Interface, CP2
1.4	-	60	14	-1	Interface West	18	522	Interface, CP2
1.5	-	-14	14	10	Interface East	12	348	Head, CP3
1.6	-	-	7	18	Closure Pour	16	464	Interface, CP4
2.1	-	79	2	-	Interface East	24	696	Interface, CP2
2.2	-	50	3	-	Interface East	16	464	Interface, CP2
2.3	-	18	1	-	Interface East	5	145	Interface, CP2
2.4	-	7	10	-	Interface East	8	232	Interface, CP3
2.5	-	15	6	-	Interface West	5	145	Interface, CP3
2.6	-	6	3	-	Interface West	2	58	Interface, CP3
3.1	-	15	13	-	Interface West	9	261	Interface, CP3
3.2	-	115	3	-	Interface East	38	1102	Interface, CP2
3.3	-	119	3	-	Interface East	38	1102	Interface, CP2
3.4	-	23	13	-	Interface West	10	290	Interface, CP3

Table D.4 Maximum Strain Values Under Large UBIT Loading

Large UBIT (3-12-2019)								
Load Test	**Max. Concrete Strain, με**				**Location of the largest maximum concrete strain**	**Max. rebar strain, με**	**Max. rebar stress, psi**	**Location of bar with largest stress**
	CP1	**CP2**	**CP3**	**CP4**				
1.1	27	138	-	-	Interface East	38	1102	Interface, CP2
1.2	10	200	-5	-	Interface West	60	1740	Interface, CP2
1.3	-2	180	24	-	Interface East	50	1450	Interface, CP2
1.4	-	225	60	-2	Interface West	68	1972	Interface, CP2
1.5	-	-23	35	9	Closure Pour	20	580	Interface, CP3
1.6	-	-	9	26	Interface West	22	638	Interface, CP4
2.1	-	195	2	-	Interface East	55	1595	Interface, CP2
2.2	-	23	35	-	Closure Pour	20	580	Interface, CP3
2.3	-	150	8	-	Interface East	42	1218	Interface, CP2
2.4	-	55	30	-	Interface West	17	493	Interface, CP2
2.5	-	70	5	-	Interface East	20	580	Interface, CP2
2.6	-	34	12	-	Interface West	10	290	Interface, CP2
3.1	-	240	7	-	Interface East	70	2030	Interface, CP2
3.2	-	58	55	-	Interface West	30	870	Interface, CP3
3.3	-	290	6	-	Interface West	80	2320	Interface, CP2
3.4	-	60	53	-	Interface West	28	812	Interface, CP3
1.1b	28	125	-	-	Interface East	35	1015	Interface, CP2
1.2b	5	200	-6	-	Interface West	52	1508	Interface, CP2
1.3b	-3	180	36	-	Interface East	52	1508	Interface, CP2
1.4b	-	200	20	-2	Interface East	72	2088	Interface, CP2
1.5b	-	-24	32	7	Closure Pour	17	493	Interface, CP3
1.6b	-	-	12	35	Interface West	26	754	Interface, CP4

Table D.5 Maximum Strain Values Under Commercial Loading

Date	Time	Number of Axles	Max. Concrete Strain, με				Location of the largest maximum concrete strain	Max. rebar strain , με	Max. rebar stress , psi	Location of bar with largest stress
			CP 1	CP 2	CP 3	CP 4				
1/26	11:04 AM	4	-	45	-	-	Interface West	13	377	Interface, CP2
1/26	11:15 AM	4	4	20	7	2	Interface East	10	290	Interface, CP2
1/26	11:17 AM	4	3	22	2	-	Interface East	10	290	Interface, CP2
1/26	11:26 AM	4	2	66	3	-	Interface West	18	522	Interface, CP2
1/26	12:03 PM	3	6	82	2	1	Interface East	27	783	Interface, CP2
1/26	12:11 PM	4	11	67	4	-	Interface East	20	580	Interface, CP2
1/26	12:34 PM	4	-	10	5	-	Interface West	4	116	Interface, CP2
1/26	12:35 PM	4	2	55	5	-	Interface West	19	551	Interface, CP2
1/26	12:39 PM	4	-	25	5	-	Interface East	9	261	Interface, CP2
1/26	12:47 PM	4	3	15	4	-	Interface East	5	145	Interface, CP2
1/26	12:49 PM	3	-	26	2	-	Interface West	10	290	Interface, CP2
1/26	12:57 PM	4	3	44	4	-	Interface East	14	406	Interface, CP2
1/26	2:23 PM	4	-	12	6	-	Interface West	4	116	Head, CP3
1/26	2:41 PM	4	4	30	-	-	Interface West	9	261	Interface, CP2
1/26	3:15 PM	3	-	5	4	-	Interface West	2	58	Interface, CP2
3/5	10:58 AM	5	8	305	20	4	Interface East	89	2581	Interface, CP2
3/5	11:04 AM	6	2	35	25	6	Interface East	14	406	Interface, CP3
3/5	11:06 AM	3	-	30	-	-	Interface West	10	290	Interface, CP2
3/5	11:13 AM	4	2	11	6	-	Interface East	4	116	Interface, CP3

3/5	11:21 AM	6	-	9	21	4	Closure Pour	12	348	Interface, CP3
3/5	11:27 AM	5	3	43	22	5	Interface East	13	377	Interface, CP3
3/5	11:28 AM	5	27	293	10	4	Interface East	90	2610	Interface, CP2
3/5	11:29 AM	4	-	5	10	2	Closure Pour	7	203	Interface, CP3
3/5	11:34 AM	4	-	16	-	-	Interface East	3	87	Interface, CP2
3/5	11:41 AM	4	51	124	10	2	Interface East	44	1276	Interface, CP2
3/5	11:47 AM	3	2	49	3	-	Interface East	16	464	Interface, CP2
3/5	11:50 AM	5	-	5	32	12	Closure Pour	22	638	Interface, CP3
3/5	11:58 AM	6	20	350	10	5	Interface West	105	3045	Interface, CP2
3/5	11:59 AM	3	27	135	20	-	Interface East	40	1160	Interface, CP2
3/5	12:11 PM	5	-	25	2	-	Interface East	13	377	Interface, CP2
3/5	12:19 PM	5	3	21	3	-	Interface East	4	116	Interface, CP2
3/5	12:22 PM	3	-	-	2	-	Closure Pour	3	87	Interface, CP3
3/5	12:30 PM	5	3	85	-	-	Interface East	22	638	Interface, CP2
3/5	12:34 PM	4	-	25	-	-	Interface West	26	754	Interface, CP2
3/5	12:40 PM	5	-	80	28	5	Interface West	18	522	Interface, CP2
3/5	12:41 PM	5	5	148	-	-	Interface West	32	928	Interface, CP2
3/5	12:48 PM	3	-	10	20	-	Closure Pour	9	261	Interface, CP3
3/5	12:57 PM	9	32	162	15	3	Interface East	44	1276	Interface, CP2
3/5	12:58 PM	4	-	50	8	-	Interface East	14	406	Interface, CP2
3/5	1:01 PM	9	-	5	20	-	Closure Pour	9	261	Interface, CP3
3/5	1:04 PM	3	-	50	7	-	Interface West	14	406	Interface, CP2
3/5	1:08 PM	9	-	10	21	5	Closure Pour	12	348	Interface, CP3

3/5	1:09 PM	5	-	60	-	-	Interface East	17	493	Interface, CP2
3/5	1:13 PM	6	10	220	8	5	Interface West	76	2204	Interface, CP2
3/5	1:19 PM	4	40	307	20	-	Interface East	90	2610	Interface, CP3
3/5	1:19 PM	6	2	10	20	5	Closure Pour	11	319	Interface, CP3
3/5	1:20 PM	5	-	10	20	4	Closure Pour	12	348	Interface, CP3
3/5	1:25 PM	9	30	400	15	5	Interface East	128	3712	Interface, CP2
3/5	1:29 PM	3	10	292	7	2	Interface West	97	2813	Interface, CP2
3/5	1:29 PM	5	5	284	8	2	Interface West	96	2784	Interface, CP2
3/5	1:30 PM	5	-	20	30	5	Closure Pour	18	522	Interface, CP3
3/5	1:49 PM	3	-	10	12	-	Closure Pour	7	203	Head, CP3
3/5	1:51 PM	4	32	480	26	5	Interface East	152	4408	Interface, CP2
3/5	1:54 PM	6	15	350	12	4	Interface West	85	2465	Interface, CP2
3/5	1:54 PM	3	15	325	12	3	Interface West	90	2610	Interface, CP2
3/5	1:55 PM	4	-	10	2	-	Interface West	3	87	Interface, CP2
3/5	1:59 PM	5	28	410	20	4	Interface East	128	3712	Interface, CP2
3/5	1:59 PM	6	26	440	22	4	Interface East	128	3712	Interface, CP2
3/5	2:02 PM	3	42	190	10	-	Interface East	58	1682	Interface, CP2
3/5	2:06 PM	6	-	23	15	2	Interface West	7	203	Interface, CP2
3/5	2:12 PM	4	-	24	18	3	Interface West	10	290	Interface, CP2
3/5	2:21 PM	5	2	21	16	4	Interface West	9	261	Interface, CP2
3/5	2:22 PM	5	10	250	10	2	Interface West	21	609	Interface, CP2
3/5	2:23 PM	5	3	25	5	-	Interface West	6	174	Interface, CP2
3/5	2:25 PM	3	1	28	12	3	Interface West	8	232	Interface, CP2

3/5	2:28 PM	4	17	410	22	3	Interface West	112	3248	Interface, CP2
3/5	2:35 PM	5	1	131	47	7	Interface West	18	522	Interface, CP2
3/5	2:52 PM	4	47	330	20	3	Interface East	112	3248	Interface, CP2
3/5	2:54 PM	4	5	44	5	-	Interface West	14	406	Interface, CP2
3/7	10:26 AM	3	-	9	4	-	Interface West	3	87	Interface, CP2
3/7	10:31 AM	7	7	325	7	5	Interface East	91	2639	Interface, CP2
3/7	10:31 AM	4	6	67	-	-	Interface West	20	580	Interface, CP2
3/7	10:32 AM	5	-	25	22	5	Interface West	12	348	Interface, CP3
3/7	10:34 AM	6	-	36	19	-	Interface West	13	377	Interface, CP2
3/7	10:35 AM	3	2	44	4	-	Interface East	10	290	Interface, CP2
3/7	10:39 AM	7	-	30	-	-	Interface West	11	319	Interface, CP2
3/7	10:45 AM	3	-	29	-	-	Interface West	9	261	Interface, CP2
3/7	10:48 AM	5	-	33	-	-	Interface East	9	261	Interface, CP2
3/7	10:52 AM	4	17	455	15	5	Interface East	135	3915	Interface, CP2
3/7	10:56 AM	3	-	6	4	-	Interface East	3	87	Interface, CP3
3/7	11:01 AM	6	18	266	-	-	Interface West	75	2175	Interface, CP2
3/7	11:03 AM	6	2	7	2	-	Interface East	4	116	Interface, CP2
3/7	11:21 AM	4	-	1	3	-	Closure Pour	2	58	Interface, CP3
3/7	11:26 AM	3	2	26	17	4	Interface East	10	290	Interface, CP3
3/7	11:28 AM	5	-	5	6	-	Closure Pour	4	116	Interface, CP2
3/7	11:36 AM	9	16	535	5	6	Interface East	138	4002	Interface, CP2
3/7	11:45 AM	9	-	5	23	3	Interface East	15	435	Interface, CP2
3/7	11:48 AM	4	-	14	13	-	Interface East	12	348	Interface, CP2

3/7	11:52 AM	4	6	259	7	5	Interface East	74	2146	Interface, CP2
3/7	11:57 AM	6	17	309	8	2	Interface East	84	2436	Interface, CP2
3/7	12:05 PM	6	22	341	11	4	Interface East	86	2494	Interface, CP2
3/7	12:15 PM	4	10	91	5	-	Interface East	26	754	Interface, CP2
3/7	12:28 PM	6	2	5	1	-	Interface East	3	87	Interface, CP3
3/7	12:29 PM	4	3	54	23	2	Interface West	12	348	Interface, CP3
3/7	12:38 PM	4	-	30	10	-	Interface West	12	348	Interface, CP2
3/7	12:48 PM	8	3	15	7	-	Interface West	3	87	Interface, CP2
3/7	12:48 PM	8	3	13	7	-	Interface West	4	116	Interface, CP3
3/7	12:58 PM	3	-	49	7	-	Interface West	12	348	Interface, CP2
3/7	1:05 PM	4	-	7	5	-	Interface East	3	87	Interface, CP2
3/7	1:13 PM	3	-	28	18	4	Interface West	12	348	Interface, CP3
3/7	1:18 PM	5	-	85	28	-	Interface West	25	725	Interface, CP2
3/7	1:20 PM	4	3	45	4	-	Interface East	16	464	Interface, CP2
3/7	1:20 PM	7	2	52	5	-	Interface East	16	464	Interface, CP2
3/7	1:41 PM	4	7	234	6	5	Interface East	72	2088	Interface, CP2
3/7	1:50 PM	6	17	316	10	-	Interface West	81	2349	Interface, CP2
3/7	1:52 PM	6	-	16	10	2	Interface East	5	145	Interface, CP3
3/7	1:57 PM	4	-	10	-	-	Interface East	3	87	Interface, CP2
3/9	10:08 AM	4	-	10	7	-	Interface West	7	203	Interface, CP2
3/9	10:16 AM	4	5	64	16	3	Interface West	21	609	Interface, CP2
3/9	10:16 AM	4	5	58	16	3	Interface West	20	580	Interface, CP2
3/9	10:23 AM	4	-	24	8	3	Interface East	6	174	Interface, CP2

3/9	10:46 AM	4	-	10	17	4	Closure Pour	9	261	Interface, CP3
3/9	10:54 AM	4	7	58	9	-	Interface West	21	609	Interface, CP2
3/9	10:54 AM	4	7	58	7	-	Interface West	21	609	Interface, CP2
3/9	10:59 AM	4	-	30	8	-	Interface East	5	145	Interface, CP3
3/9	11:07 AM	4	4	65	5	-	Interface East	18	522	Interface, CP2
3/9	11:08 AM	3	-	42	8	-	Interface West	14	406	Interface, CP2
3/9	11:08 AM	3	-	41	8	-	Interface West	15	435	Interface, CP2
3/9	11:23 AM	4	4	61	10	-	Interface East	20	580	Interface, CP2
3/9	11:24 AM	4	-	44	17	7	Interface East	18	522	Interface, CP2
3/9	11:25 AM	4	3	77	10	2	Interface East	24	696	Interface, CP2
3/9	11:25 AM	4	3	85	11	2	Interface East	26	754	Interface, CP2
3/9	11:31 AM	4	3	52	4	-	Interface East	13	377	Interface, CP2
3/9	11:34 AM	4	-	6	3	-	Interface East	2	58	Interface, CP3
3/9	11:43 AM	4	2	44	8	-	Interface West	11	319	Interface, CP2
3/9	11:45 AM	4	3	22	6	-	Interface West	7	203	Interface, CP2
3/9	11:45 AM	3	3	23	7	-	Interface West	5	145	Interface, CP2
3/9	11:52 AM	4	3	11	10	-	Interface West	5	145	Interface, CP3
3/9	11:52 AM	4	3	11	10	-	Interface West	6	174	Interface, CP3
3/9	11:57 PM	4	6	60	5	-	Interface East	16	464	Interface, CP2
3/9	12:02 PM	3	-	12	7	-	Interface West	5	145	Interface, CP3
3/9	12:02 PM	4	-	12	7	-	Interface West	5	145	Interface, CP3
3/9	12:06 PM	4	-	45	10	2	Interface East	14	406	Interface, CP2
3/9	12:15 PM	8	28	338	20	2	Interface East	99	2871	Interface, CP2

3/9	12:15 PM	8	30	338	20	3	Interface East	98	2842	Interface, CP2
3/9	12:17 PM	4	17	72	10	-	Interface East	23	667	Interface, CP2
3/9	12:26 PM	4	-	7	5	-	Interface West	4	116	Interface, CP2
3/9	12:39 PM	4	2	40	10	2	Interface East	11	319	Interface, CP2
3/9	12:58 PM	4	3	58	-	-	Interface West	17	493	Interface, CP2
3/9	1:13 PM	4	-	32	1	-	Interface West	5	145	Interface, CP2
3/9	1:15 PM	4	6	51	4	-	Interface West	14	406	Interface, CP2
3/9	1:19 PM	3	-	21	-	-	Interface West	7	203	Interface, CP2
3/9	1:22 PM	4	-	22	2	-	Interface East	8	232	Interface, CP2
3/9	1:42 PM	4	-	29	8	2	Closure Pour	16	464	Interface, CP2
3/9	1:56 PM	8	33	339	14	6	Interface East	101	2929	Interface, CP2
3/9	1:56 PM	8	34	342	14	6	Interface East	103	2987	Interface, CP2
3/14	9:59 AM	4	-	36	-	-	Interface West	4	116	Interface, CP2
3/14	10:06 AM	3	-	1	3	-	Closure Pour	3	87	Interface, CP3
3/14	10:16 AM	3	-	10	9	-	Interface West	3	87	Interface, CP3
3/14	11:01 AM	4	-	19	9	-	Interface East	12	348	Interface, CP2
3/14	11:16 AM	4	-	35	-	-	Interface East	10	290	Interface, CP2
3/14	11:21 AM	3	-	16	22	2	Closure Pour	12	348	Interface, CP2
3/14	11:25 AM	4	3	16	5	-	Interface East	4	116	Interface, CP3
3/14	11:29 AM	4	-	6	9	-	Closure Pour	4	116	Interface, CP3
3/14	11:33 AM	4	-	8	9	-	Closure Pour	11	319	Interface, CP2
3/14	11:39 AM	3	-	22	-	-	Interface East	8	232	Interface, CP2
3/14	11:41 AM	3	-	23	-	-	Interface East	9	261	Interface, CP2

3/14	11:54 AM	4	-	43	18	9	Interface East	14	406	Interface, CP2
3/14	11:57 AM	4	-	5	8	-	Closure Pour	4	116	Interface, CP3
3/14	11:59 AM	3	-	44	-	-	Interface West	11	319	Interface, CP2
3/14	12:08 PM	8	1	-	2	-	Closure Pour	1	29	Interface, CP3
3/14	12:18 PM	4	-	64	3	-	Interface West	17	493	Interface, CP2
3/14	12:44 PM	4	-	-	1	-	Closure Pour	2	58	Interface, CP3
3/14	12:52 PM	3	-	10	14	-	Closure Pour	6	174	Interface, CP3
3/14	12:56 PM	4	-	-	1	-	Closure Pour	1	29	Interface, CP3
3/14	12:59 PM	4	-	4	2	-	Interface East	2	58	Interface, CP2
3/14	1:01 PM	3	-	4	-	-	Interface East	2	58	Interface, CP2
3/14	1:19 PM	3	-	10	-	-	Interface East	1	29	Interface, CP2
3/14	1:32 PM	3	-	-	2	-	Closure Pour	3	87	Interface, CP3
3/14	1:35 PM	4	-	-	8	-	Closure Pour	6	174	Interface, CP3
3/14	1:43 PM	3	12	114	12	-	Interface East	40	1160	Interface, CP2