DESIGN, CONSTRUCTION AND DEPLOYMENT OF A COMPACT, ROBUST FIELD DATA ACQUISITION SYSTEM FOR STRUCTURAL FIELD MONITORING

by

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The portable field data acquisition system consists of four components: datalogger, Wheatstone bridges, multiplexers, and portable computer. The data acquisition system fulfills the role of a portable, self-powered measurement device necessary for structural field monitoring and will also serve as a measurement platform for future field tests conducted by the University of Pittsburgh.

To better illustrate the capabilities of the field data acquisition system, an application is illustrated using the Boyer Bridge research project in Butler County.

The Boyer Bridge over the Slippery Rock Creek in PennDOT Engineering District 10-0 has recently received a new fiber-reinforced polymer deck as part of an overall bridge replacement project. In order to quantify the composite action of the deck, effective width factor and live load distribution factors, the Boyer Bridge is instrumented with thirty strain gages and monitored with the portable field data acquisition system.

Field-testing of the Boyer Bridge over the Slippery Rock Creek in PennDOT Engineering District 10-0 consists of static loads applied by a test vehicle to the deck and measuring strain responses. To date, two field tests have been performed on the Boyer

Bridge. An examination of each stringer's strain profile from the *CR23x* datalogger reveals a very close agreement to expected behavior. From multiple tests performed at the same load position, it is evident that the *CR23x*'s strain measurements exhibit excellent repeatability, while verification tests performed in the laboratory show good linearity.

ACKNOWLEDGEMENTS

I would like to express my gratitude to my graduate advisor, Dr. Christopher Earls, for his priceless guidance and assistance throughout my undergraduate and graduate level education at the University of Pittsburgh.

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NOMENCLATURE

A1, A2, A3, B1, B2, B3, C1, C2, C3	Test Designation for Boyer Bridge Project; A is the northernmost load position over Beam 1
H1, L1, H2, L2, GND	Wiring terminals on the CR23x datalogger, 4WFB120 bridge module and AM416 multiplexer
DIFF 1, DIFF 2, etc.	Differential Analog Channels on the CR23x datalogger
COM H1, COM L1, etc.	Common line wiring terminals on the AM416 multiplexer
CLK, RES, GND, 12V	Wiring terminals on the AM416 multiplexer for datalogger control
Bridge 1, Datalogger 1, Multiplexer 1, etc.	Individual components in the Boyer Bridge Project field data acquisition system
Thermistor 1, DCDT 1, etc.	Individual components described in Section 3.0
E	Young's Modulus of Elasticity
R	Resistance
A	Area

1.0 INTRODUCTION

1.1 Experimental Stress Analysis

With the development and refinement of the finite element analysis approach, experimental stress analysis has receded in popularity. However, experimental methods remain a very relevant tool for engineering design and research since simplified analysis techniques can often lead to misleading results. Experimental investigations can lead to a "more precise accounting of redundancy and all the various other statistical variables" that cannot be determined by other techniques (ASCE 1980, p. 2).

Experimental stress analysis has been used frequently on bridges for several different purposes. Testing can be beneficial by improving bridge analysis and design procedures, and by reducing statistical uncertainties (ASCE 1980, p. 50). In *A Guide For the Field Testing of Bridges*, ASCE offers some wisdom

> "When faced with the alternative of spending 10 or 20% or more of the replacement cost of a structure to load test it with a fairly good likely-hood of saving the structure, load testing seems very reasonable."

Bridge instrumentation is necessary to better understand bridge responses to the actual loading and environment. Currently, there are major gaps in understanding of the actual service and limit state loading effects and how these loading effects change with time as a bridge ages and deteriorates.

Today, the most widely used method in experimental stress analysis employs the electrical-resistance strain gage. Experimental stress analysis, while using the metal foil gage, can easily be applied to bridge structure testing and provide very useful information.

The objective of the research is to deploy a compact, robust field data acquisition system to collect data from bridge instrumentation. To begin, a thorough understanding of the instrumentation necessary for the required measurements is gathered. Secondly, specifications are developed for components necessary to record measurements.

To fulfill the role of the field data acquisition system, the *CR23x Micrologger* and components from Campbell Scientific have been chosen based on familiarity with the Campbell Scientific products. Originally, a Campbell Scientific *21x* datalogger and two *AM416* multiplexers were available to the researchers but had not been implemented in any research projects for several years. The newer version of the *21x*, the *CR23x*, is specified based on its increased storage memory while offering a precise measurement system with processing and control capability, in a portable, self-powered operating system.

1.2 Application of the Field Data Acquisition System

To better illustrate the capabilities of the Campbell Scientific *CR23x* datalogger, an application of the field data acquisition system is illustrated using the Boyer Bridge research project in Butler County.

The Boyer Bridge over Slippery Rock Creek in PennDOT Engineering District 10-0 received a new fiber reinforced polymer (FRP) deck system as part of an overall bridge replacement project in November 2001. The FRP deck panels have been designed to act compositely with the five galvanized rolled steel shapes that are employed as stringers. The stringers are placed on the abutments, the FRP panels installed and positioned, and then the headed shear studs are inserted through openings in the FRP deck panels (spaced 2 feet o.c.) and welded to the stringer top flanges. Non-shrink grout is then injected into the stud pockets so as to create a composite system.

Such a strategy for installing FRP decking has been employed quite successfully in the past and does not represent a radical change in FRP deck installation practice. What is new, however, is the program of field monitoring that is being carried out on the bridge over the next year. Strain gages have been installed along stringer lines for the purpose of supporting field monitoring and load testing that is carried out by the University of Pittsburgh researchers. The objectives of the field-testing will be to monitor the location of the neutral axis of the instrumented composite cross-sections so as to verify the level of compositeness predicted by design equations. Measurements will be collected using the Campbell Scientific *CR23 Micrologger.*

1.3 Organization of Thesis

Instrumentation, including strain gage principles and characteristics and displacement and thermal measurements, is developed in Chapter 2, while the datalogger, components, programming and wiring are introduced in Chapter 3. A description of the Campbell Scientific *CR23x* datalogger application to the Boyer Bridge load test and results are detailed in Chapter 4. Finally, a conclusion regarding the field data acquisition system and data is presented in Chapter 5.

2.0 DESCRIPTION OF INSTRUMENTATION

2.1 Overview of Experimental Stress Analysis

2.1.1 Stress and Strain Relationships

Since stresses in solids cannot be measured directly, they must be gathered from both strain measurements and stress-strain relationships (Budynas 1999, p. 601). With this in mind, it is possible to relate the displacements of a solid to establish the stress and strain fields. When considering a transversely loaded beam, for an example, the deflections "can be accurately determined with relatively simple experimental techniques" (Dally 1991, p. 130). The strains in the beam can now be written in terms of its deflection

$$e_x = z\frac{d^2 w}{dx^2} \qquad \text{(Dally 1991, Eq. 5.1)}$$

where z is the distance to the point in question from the neutral and axis $w(x)$ is the elastic deflection function of the beam. The measurements for the scenario of a beam are relatively simple, but can become much more complex when considering a more general body. The strain-displacement relationship for a more complex object requires "a determination (or differentiation) of the gradients of experimentally determined displacements at many points on the surface of the specimen" (Dally 1991, p. 130). The differentiation method is vulnerable to large errors and the displacement field is often difficult to acquire, which necessitates measuring surface strains directly (Dally 1991, p. 130).

Measuring strains directly in a solid, rather than displacement fields can be a much more attainable task. While assuming that cross shears are equal, six independent strains must be found in order to determine the complete state of stress for a point (Budynas 1999, p. 601). For most cases, strain-gage applications, or strain measurements, are limited to the free surfaces of a solid (Dally 1991, p. 129). Since these measurements are taken at an outer face, the strain perpendicular to the surface and associated shears are assumed to be equal to zero; for cases where the "body thickness is small relative to its lateral dimensions," the assumption that these strains are zero is also valid (Dally 1991, p. 61). This eliminates three of the six stress states, which now requires three different measurements for a full understanding of the state of stress at a location. These problems are referred to as plane stress investigations. According to Budynas, plane stress states are also common for most problems, since "maximum stresses tend to develop at free surfaces (Budynas 1999, p. 601). The plane stress situation is ideally suited for thin structural shapes, such as the popular wide flange section. The relationship between stress and strain for the three remaining unknowns is given by three equations

$$
\begin{aligned}
s_x &= \frac{E}{1-n^2}(e_x + ne_y) \\
s_y &= \frac{E}{1-n^2}(e_y + ne_x) \qquad \text{(Budynas 1999, p. 22-24)} \\
t_{xy} &= \frac{2(1+n)}{E} t_{xy}
\end{aligned}
$$

where n is Poisson's ratio. Furthermore, another independent stress may be eliminated if enough information is available. If the principal axes at a point are known, then only the values for two normal stresses remain unknown. By definition, the principal axes define "mutually orthogonal surfaces that contain no shear stress" (Budynas 1999, p. 66). The principal axes may not always be easy to find but may be established along lines of symmetry and "when a surface perpendicular to the free surface exists without shear stress" (Budynas 1999, p. 601).

2.1.2 Electrical-Resistance Strain Gage Principles

Probably the most common method of measuring free surface strains is the use of electrical-resistance strain gages (Budynas 1999, p. 604). Electrical-resistance strain gage measurement is based on the principle that the resistance of a conductor changes as a function of normal strain (Budynas 1999, p. 604). Simply put, researchers can measure the change in resistance of a gage bonded to a specimen undergoing deformation and relate it to the strain component parallel to the gage's longitudinal axis. The measurement is made with a Wheatstone bridge, "a circuit sensitive to small resistance changes" (Budynas 1999, p. 611).

As stated, electrical-resistance strain gages undergo a change in resistance as a function of normal strain. The resistance change can be allotted to the change in cross section of the area and the change in specific resistance of the conductor. A conductor, with length L, cross-sectional area A and a specific resistance r, has a resistance that can be expressed as

$$R = r\,\frac{L}{A}$$ (Dally 1991, Eq. 6.1)

Considering small increments, the above equation and dividing by R, can be expressed as

$$\frac{\Delta R}{R} = \frac{\Delta r}{r} + \frac{\Delta L}{L} - \frac{\Delta A}{A}$$ (Budynas 1999, Eq. 8.3-2)

Since *DL/L* is equivalent to strain, *e*, and "it can be shown that *DA* is equal to $n^2e^2A\text{-}2en$", the previous equation can be arranged (Budynas 1999, p. 604). Also, the term, e^2, is neglected since the strain can be assumed to be a small value. The equation now becomes

$$\frac{\Delta R}{R} = (1+2n)e + \frac{\Delta r}{r}$$ (Budynas 1999, Eq. 8.3-3)

Or more simply,

$$\frac{\Delta R}{R} = S_A e$$ (Budynas 1999, Eq. 8.3-4)

where,

$$S_A = 1 + 2n + \frac{\Delta r / r}{e}$$ (Budynas 1999, Eq. 8.3-5)

The term S_A is now known as the "sensitivity of the conductor to strain" (Budynas 1999, p. 604). The first portion, $1+2n$, of this term accounts for the changes in dimension of the conductor, which varies from 1.4 to 1.7 (Budynas, 1999 p. 605). The remaining term, the change in specific resistance, can "account for much of the sensitivity to strain" (Budynas, 1999 p. 605). This is specific to the material used in the strain gage. Using Budynas' Equation 8.3-4, it is now possible to measure strain from the relation between the change in resistance and applied strain.

2.1.3 The Wheatstone Bridge

The Wheatstone bridge circuit is employed to detect the small changes in resistance of strain gages. It consists of four resistors, or bridge arms, connected to an excitation voltage, see Figure 1 (Measurements Group, Inc.). The resistors are initially set so that the top two resistance values are equal to the bottom two values. If an excitation voltage, *V*, is applied, the measured voltage at *A* will be zero, creating a "balanced" bridge circuit. If the value of one of the resistors changes, the measured voltage at *A* will not be equal to zero, but proportional to the change in resistance, since the circuit is now out of balance. Researchers are able to employ this circuit for measurements by replacing one of the resistors with a strain gage, applying a known voltage, *V*, and measuring the output voltage, *A*. (Measurements Group, Inc.)

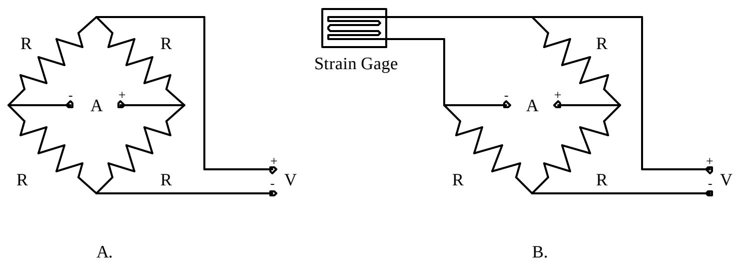

Figure 1 – A. Wheatstone Bridge, B. Wheatstone Bridge with Strain Gage
(Adapted from Measurements Group, Inc., *The Three-Wire Quarter-Bridge Circuit*, 2-3)

2.1.4 Metal Foil Strain Gage, Composition

Today, most strain gages are made from Constantan, a copper-nickel alloy. This alloy offers several advantages over other materials. The strain sensitivity, mentioned previously, exhibits linear behavior over a wide range of strain and "does not change significantly as the material goes plastic" (Budynas, 1999 p. 605). Constantan also has good thermal stability, where temperature changes do not greatly influence its performance (Dally 1991, p. 167). In addition, the small temperature-induced changes in resistance of the material can be restricted with "trace impurities or by heat treatment" (Dally 1991, p. 167). Other alloys offer higher sensitivity, which is useful in dynamic applications and high fatigue strength (Budynas, 1999 p. 605). Semiconductor materials are also available, but exhibit poor thermal stability (Budynas 1999, p. 605).

The electrical-resistance strain gage comes in two varieties, bonded wire and bonded foil. The bonded wire gages were used, almost exclusively, from the 1930's to the 1950's (Dally 1991, p. 169). The most prevalent today, are the bonded foil gages, which offer shorter gage lengths (Figure 2). These consist of a thin layer of Constantan, mounted on or between thin sheets of polyimide (Budynas 1999, p. 606). The polyimide is bonded to the specimen with an adhesive, such as epoxy or pressure-curing methyl-2-cyanoacrylate cement (Figure 3)(Budynas 1999, p. 606). Manufacturers generally supply technical data and instructions for proper installation.

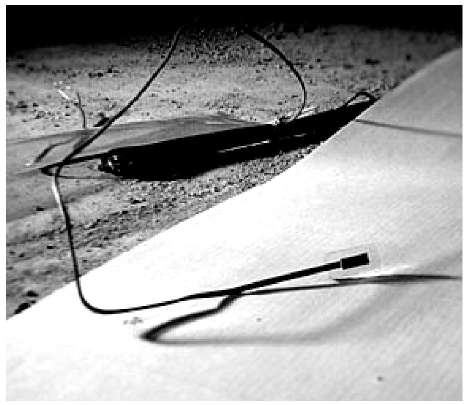

Figure 2 - Metal Foil Strain Gage (Keelor)

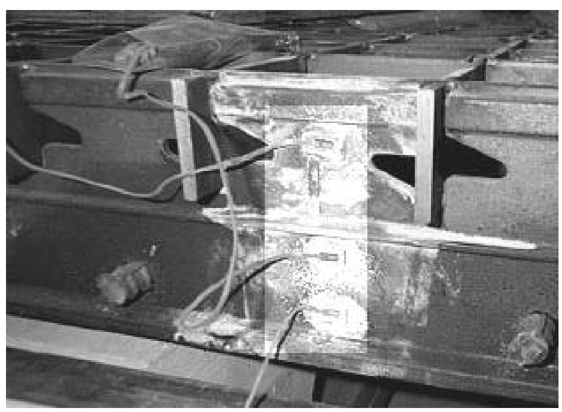

Figure 3 - Foil Gage Installed On Deck Specimen (Keelor)

The foil gage also comes in several configurations, which are tailored to the problem at hand. The uniaxial strain gage, Figure 1, provides strain readings along one axis, while the strain gage rosette, Figure 4, offers normal strain measurements in three directions. These are spaced at 45°, lending to e_A, e_B, and e_C readings (Figure 4). If $\varepsilon_x = \varepsilon_A$ and $\varepsilon_y = \varepsilon_C$ then

$$e_B = \frac{1}{2}(e_x + e_y + g_{xy}) \qquad \text{(Budynas 1999, p. 609)}$$

The equation can now be solved for the remaining unknown, γ_{xy}. This data allows the calculation of the stresses and shear stress, using Hooke's law,

$$\begin{aligned} s_x &= \frac{E}{1-n^2}(e_x + ne_y) \\ s_y &= \frac{E}{1-n^2}(e_y + ne_x) \qquad \text{(Budynas 1999, p. 22-24)} \\ t_{xy} &= \frac{2(1+n)}{E} t_{xy} \end{aligned}$$

Furthermore, this data can be converted to the principal stresses, as stated previously.

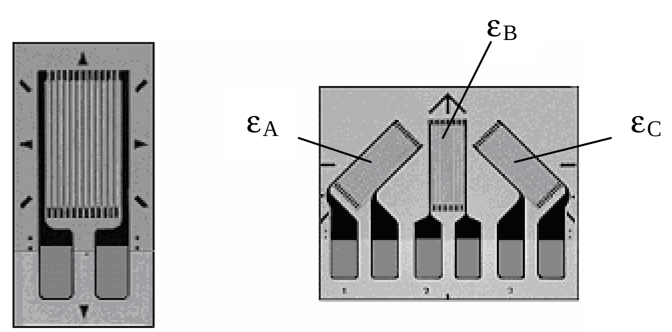

Figure 4 - Uniaxial Strain Gage (left), 3 Element Rosette Strain Gage (right), (Adapted from Measurements Group, Inc., *Micro-Measurements Strain Gages*)

2.1.5 Foil Gage Characteristics

The metal foil strain gage offers very precise measurements. The results are actually a "function of the installation procedures, the state of strain being measured and environmental conditions during the test" (Dally 1991, p. 184). This indicates that there are several factors, which may influence the data collected from these small devices.

The material that composes the foil gage is subject to three types of deviations during loading (Figure 5). As loading takes place, the measured strain may vary slightly from a true linear response (Dally 1991, p. 184). During unloading, a hysteresis loop is formed. Hysteresis is the phenomenon exhibited by an imperfectly elastic material, in which its properties are influenced by its past reactions to change ("Hysteresis"). Third, a zero shift is often observed, where the gage outputs a negative strain after the applied strain is reduced to zero (Dally 1991, p. 184). All three are dependent upon the bond adequacy, degree of cold work of the foil material and the viscoelastic properties of the carrier material (Dally 1991, p. 184).

The length of the testing will also impact the error induced by shifting. Certain applications for strain gages require measuring strains over an extended period of time "without having the opportunity to unload the specimen and recheck the zero resistance." Measurements are subjected to drift in these situations. "Drift in the zero reading from an electrical resistance strain gage installation is due to the effects of moisture or humidity variations on the carrier and the adhesive, the effects of long term stress relaxation of the adhesive, the carrier, and the strain gage alloy, and instabilities in the resistors in the inactive arms of the Wheatstone bridge" (Dally 1991, p. 194). Results from Freynik's test show a general-purpose strain gage, using an Advance alloy and a polyimide carrier, can exhibit zero shifts of 270 $\mu\varepsilon$ over a 30-day testing period (Dally 1991, p. 196).

Dally recommends that deviations from linearity be approximated as 0.05 for polyimide carriers. Also, since the zero shift per cycle is much greater during the first few cycles, Dally suggests cycling gages to “125 percent of the maxim test strain for at least 5 cycles prior to measurement (Dally 1991, p. 184).

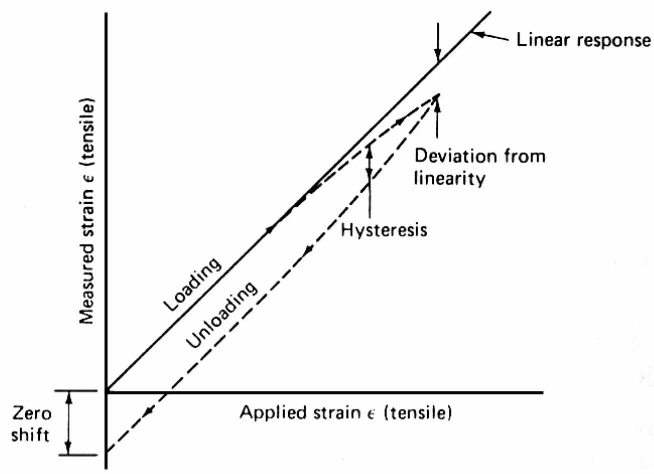

Figure 5 – Strain Cycle (Dally 1991, p. 184)

A uniaxial strain gage is intended to measure strain in one direction. However, the gage will experience strains perpendicular to the longitudinal axis of the gage. This perpendicular strain will alter the resistance of the measurement, by distorting the conductor in the transverse direction, leading to an undesirable effect. (Budynas 1999, p. 617)

The manufacturer provides a sensitivity measurement based on a uniaxial stress field and the measurement is taken from a tensile test specimen, giving axial strain, $\varepsilon_{a,}$ and transverse strain, $\varepsilon_{t.}$ The gage manufacturer provides the sensitivity or gage factor, S_g. If the gage is used where the transverse strain is $e_t = -n_0\, e_{a,}$ then Equation 6.5 would give exact results.

$$\frac{\Delta R}{R} = S_g e_a \qquad \text{(Dally 1991, Eq. 6.5)}$$

However, this can be altered by the sensitivity of the gage to transverse strain and from the "deviation of the ratio of e_t/e_a from Poisson's ratio." Thus, an alteration must be made to Equation 6.5 to account for a gage mounted in a biaxial stress field

$$\frac{\Delta R}{R} = S_g (1 - n_0 K_t) e_a \qquad \text{(Dally 1991, Eq. 6.6)}$$

The new value, K_t, is known as the transverse sensitivity factor for gage. With the transverse sensitivity factor and gage factor, the effect of biaxial strain fields on a gage can be more accurately accounted for. (Budynas 1999, p. 617)

Since strain gages are well suited for field installations, the gages can be subject to temperature changes. This can effect the change in resistance of the foil material and should be accounted for. For Constantan, the strain sensitivity varies with temperature, where $\Delta S_A/\Delta T = 0.735$. This change should be noted for fluctuations in temperature of more than ±10°C and is usually not necessary for room temperature testing. (Dally 1991, p. 185)

The gage grid and base material can also contract or expand, which requires modification to the change in resistance formula, *DR/R.* If the two materials elongate differently, an added strain will result that does not occur in the specimen. Using the thermal coefficient of expansion for the gage material, a, and the base material, b, as well as the temperature coefficient of resistivity of the gage material, γ, the difference can be accounted for in Dally's equation

$$\frac{\Delta R}{R}_{\Delta T} = (\beta - \alpha) S_g \Delta T + \gamma \Delta T \qquad \text{(Dally 1991, Eq. 6.11)}$$

Researchers have developed methods to combat contamination of strain gage response to thermal effects on the electrical-resistance strain gage. By matching the coefficients of expansion, in both the base and gage material, as well as holding the temperature coefficient of resistivity to zero, the resulting value of Dally's equation, Equation 6.11, will now vanish. In order to do this, manufacturers determine thermal response characteristics for each lot of gages produced. The foil gages manufactured with this technique are known as temperature-compensated or selected-metal gages. Matching alloy properties to the base material can still lead to errors since the expansion coefficients do not act linearly over a wide range of temperature. Therefore, it is necessary to use a calibration curve assigned to each batch of gages produced, whenever a large range of temperatures is encountered during testing. (Dally 1991, p. 187)

A second thermal effect is introduced through the lead wires in a two-wire strain gage. In Figure 6, a two-wire gage is connected to a Wheatstone bridge. Each wire has a resistance value, R_L. This will lead to added resistance in that arm of the bridge, producing an imbalance. This can easily be adjusted by balancing the bridge manually, which is an option provided with most measuring devices. However, if the temperature of the lead-wires varies during the measurement process, their resistance will also change. For a change in 10°F, a typical 120-ohm gage will give a reading of 156με (microstrain). Under a uniaxial strain field, for steel, the stress value will be

$$e \cdot E = s$$
$$156me \cdot 29000ksi = 4.52ksi$$

The measurement will be in error by approximately 4500 pounds per square inch, possibly a significant value. This problem is not so easily remedied through manual tuning. Instead, a third wire is added in parallel with one of the lead wires (Figure 7). Since all three wires are exposed to the same environment and have the same length, they will be, theoretically, the same resistance. With equal resistances, the bridge is now symmetrical and hence, balanced. (Measurements Group, Inc.)

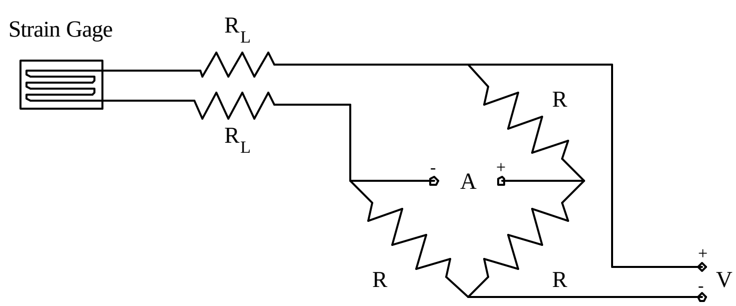

Figure 6 - Two-wire strain gage with Wheatstone Bridge

(Adapted from Measurements Group, Inc., *The Three-Wire Quarter-Bridge Circuit*, 3)

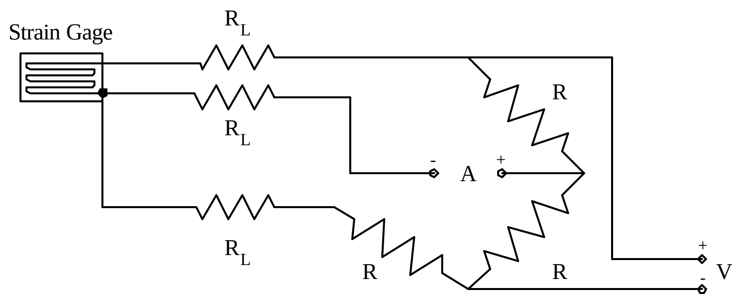

Figure 7 - Three-wire strain gage with Wheatstone Bridge
(Adapted from Measurements Group, Inc., *The Three-Wire Quarter-Bridge Circuit*, 4)

Finally, environmental conditions can negatively affect strain gage measurements. Moisture, more specifically, can be very detrimental because both the carrier and adhesive have a tendency to absorb it. The water can weaken the strength of the bond, reducing the transmission of the strain from the specimen to the gage. The adhesive will also expand and contract with varying moisture absorption and the gage material can suffer from electrolysis and corrosion. These problems will induce strains, which are inseparable from mechanically induced strains. Therefore, it is crucial that exposed strain gages be isolated from moisture contact. Generally, a coating of soft wax over the entire gage is advisable. (Dally 1991, p. 197)

During fatigue testing, the strain gage is also subject to the same cyclic strains (Dally 1991, p. 207). Under repetitious, cyclic strain, the gage grid undergoes work-hardening, changing its specific resistance, causing a zero shift (Dally 1991, p. 207). However, "the changes in gage factor are quite small due to strain cycling and in general can be neglected if the zero shift is less than 200$\mu\varepsilon$" (Dally 1991, p. 208).

Other factors, which are not quite so common to civil engineering problems, are the effects of nuclear radiation, high temperature, and cryogenic temperatures (Dally 1991, p. 199-205). With these detrimental effects in mind, the metal foil gage is still considered a powerful tool in experimental stress analysis.

2.2 Description of Field Instrumentation

2.2.1 Metal Foil Gages

Three-wire foil strain gages produced by the Tokyo Sokki Kenkyujo Company were deployed for field-testing of the Boyer County Bridge. Each gage consists of the same gage factor of 2.13 with a ±1% error, a gage resistance of 120 Ohms, and a transverse sensitivity of 0.1%. Lead wires are already attached by the manufacturer and measure five meters while the gage length measures three millimeters. Gages are selected so as to match the thermal coefficient of expansion of the steel, as indicated by the strain gage product code.

Gages are adhered to the steel wide flange sections with M-Bond 200 adhesive according to the Vishay Measurements Group procedure detailed in Section 2.3. In order to quantify the strain profile of the five steel stringers, gages are placed at three positions over the wide flange cross section, (Figure 8). One gage is placed on the top face of the bottom flange, 5.125 inches from the outside flange edge. The second gage is positioned on the web, at the one half of the depth of the cross section. The third gage is located on the bottom face of the top flange, 5.125 inches from the outside flange edge. This is repeated for all five stringers twelve inches from the centerline of the span of the bridge, midway between bearing pad centerlines. Gages are not mounted at the centerline of the span so as to not interfere with the diaphragm stiffener plate, see Figure D-13.

Since the possibility exists that not all strain gages will function properly during field monitoring, strain gages are placed at identical positions on both sides of the cross section for duplication of instrumentation (Figure 8). Gage locations are detailed in the

Boyer Bridge Project – Strain Gage Locations drawing located in Appendix B. A total of thirty strain gages are placed on the Boyer Bridge field specimen.

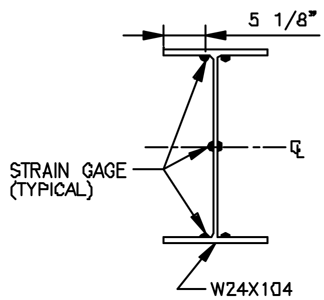

Figure 8 - Strain Gage Application Points

Strain gages are not applied to the fiber reinforced polymer deck. The manufacturer claims that successful measurements are not possible due to the lack of homogeneity of the polymer material. Results from the manufacturer's strain gage tests on fiber reinforced polymer deck have shown that "hotspots" arise, leading to deceptive strain readings.

In order to connect strain gages to the field data acquisition system, the lead wires are strung along the bottom flange of the stringer to the forward (East) abutment. Each group of three lead wire pairs is held in place on the flange with a drop of silicon deposited from a caulking gun. From the abutment, the lead wires are strung underneath the flanges and above the concrete abutment in the space provided by the sole plate, and out to the left (North) side of the bridge, see Appendix D. Strain gage channels are labeled at the ends of each pair of lead wires with masking tape. A grouping of three strain gages is wrapped in a small cellophane bag and then sealed shut with electrical tape for storage between monitoring sessions. All ten groupings of three strain gages are bundled in a plastic bag, sealed with black electrical tape and stored underneath the bridge deck, between Beam 1 and Beam 2.

2.3 Field Installation Procedure

2.3.1 Surface Preparation

In order to properly attach a metal foil strain gage to a steel specimen, specific and thorough procedures must be adhered to. Specifically, the Vishay Micro-Measurements system of surface preparation has been implemented.

The Vishay Measurements Group provides detailed instructions for metal foil gage mounting in the Student Manual for Strain Gage Technology. This exact procedure is used for Boyer Bridge field specimen. Strain gages are mounted to the stringers onsite prior to erection.

To begin, the surface is prepared to clear any visible blemishes with sanding. This is accomplished with either an angle grinder and grinding disc or a Dremel tool and sanding attachment. Care is taken during sanding to make a smooth surface, free of divots from machine sanding.

Greases, oils, organic contaminants and soluble chemical residues common to laboratory and field-testing environments are removed using the CSM-1A aerosol from Vishay Measurements Group. First, the specimen is wiped clear with a clean piece of gauze followed by a spray of the CSM-1A degreasing agent. This process is repeated three times. (Measurements Group, Inc.)

The surface is then abraded using 200-grit wet/dry sand paper. The procedure begins with wetting the gaging area using M-Prep Conditioner A, a weak, water-based acid utilized for surface cleaning, from Vishay Measurements Group. Following the Conditioner A application, the surface is sanded by hand with the 200-grit wet/dry sandpaper, meanwhile adding Conditioner A to keep the surface wet during the entire process. (Measurements Group, Inc.)

After a bright surface appears in the gaging area, the specimen is wiped clean and dry with a clean gauze sponge, making sure that only clean surfaces of the gauze is used. The gauze is applied at the middle of the gaging area and then swiped to the edge, to "ensure that contaminants will not be dragged back into the gaging area during the steps to follow" (Measurements Group, Inc.) The entire process involving Conditioner A wetting and abrasion is repeated using 400-grit paper.

After a clean, polished surface is achieved, the gaging area must be neutralized of the acidic Conditioner A. M-Prep Neutralizer 5A, a water-based alkaline surface cleaner is applied to the clean surface followed by removal with gauze sponges. The clean side of a gauze sponge is applied at the middle of the gaging area and then swiped to the edge with a single stroke. The area is wiped until dry where it is then subjected to the Neutralizer 5A application and gauze drying procedure three more times.

2.3.2 Metal Foil Gage Application

The metal foil gages, mounted in polyimide carriers by the manufacturer, are applied to the clean gaging area using an adhesive. The adhesive requires a catalyst, Catalyst-C from Vishay Measurements Group, to ensure proper adhesion. First, the catalyst brush is wiped twenty times across the lip of the catalyst bottle to remove excess catalyst. Catalyst-C is then applied carefully with the catalyst brush in a sliding motion to the underside of the metal foil gage polyimide carrier and allowed to dry for one minute. Two drops of the adhesive, M-Bond 200 from Vishay Measurements Group, are applied at the junction of the underside of the metal foil gage polyimide carrier and the specimen gaging area. This is performed while gently rolling the gage across the specimen to ensure that the adhesive is spread across the length of the gage, making sure that air bubbles are not trapped in the adhesive, between the gage and specimen. Firm pressure with the fingertips is applied for one minute.

2.3.3 Testing of Metal Foil Gage Installation

To verify successful metal foil gage installation, the gage is checked with a digital strain indicator. Specifically, the *P-3500*, a portable, battery-powered strain indicator from Vishay Measurements Group is employed, see Figure D-4. Individual gages are connected to the instrument and tested by observing the strain reading from the *P-3500* digital panel meter while moving the lead wires. A steady strain reading from the *P-3500* signals a successful installation.

2.3.4 Application of Wax Covering

A coating of micro-silica wax is applied to protect the metal foil gages and adhesive from the environmental effects. After each gage is properly mounted, the wax, supplied by Vishay Measurements Group, is warmed using a heated-air gun. The liquefied wax was painted over top of each installed strain gage and allowed to dry, providing a moisture barrier.

2.4 Thermal Measurements

2.4.1 Thermocouples and Thermistors

The Meadowcroft Bridge project requires a history of thermally induced strains to be recorded. In order to perform this task, strain readings must be recorded simultaneously with the thermal characteristics of the specimen bridge's surrounding environment. Two types of sensors are generally available for structural field monitoring: the thermocouple and the thermistor.

A simple thermocouple circuit consists of a pair of wires of different metals. These wires are joined together at the sensing junction and terminate at the reference junction that must be maintained at a constant temperature, known as the reference temperature. A voltage is produced when a temperature difference exists between the sensing and reference junctions, causing a current to flow through the circuit. The current is fed to sensing circuitry providing a temperature reading. (Hordeski 1987, p. 36)

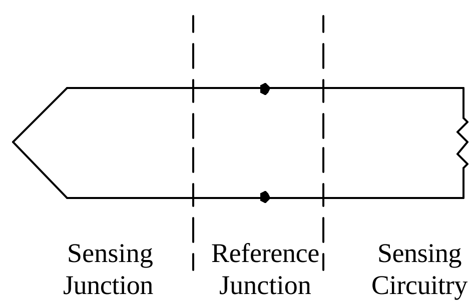

Figure 9 - Thermocouple Circuit (Hordeski 1987, p. 36)

A second type of thermal sensor, the thermistor, however, does not require a reference temperature. Instead, the thermistor relies on a semiconductor material whose resistance varies with the temperature. In this manner, a change in resistance of the sensing material provides a larger output voltage for signal conditioning equipment. (Hordeski 1987, p. 39)

With the higher output voltage, signal-conditioning equipment can be simplified, made more accurate and less expensive. The thermistor holds several other advantages over the thermocouple in that it has a better sensitivity to small temperature changes and is more resistant to electrical noise. With better resistance to electrical noise, longer lead wires can be used. (Hordeski 1987, p. 40)

Two thermistors are included within the instrumentation package for the Meadowcroft Bridge project. Specifically, a *107 Temperature Probe* from Campbell Scientific is used for temperature measurements (Figure 10). The *107 Temperature Probe* is designed for air, water and soil measurements and is recommended for use in the -35º to +50º Celsius range (Campbell Scientific 2000, *107 Temperature Probe*, p. 1). Thermal measurements from the two *107 Temperature Probes* are intended to measure a history of temperature data above and below the surface of the specimen.

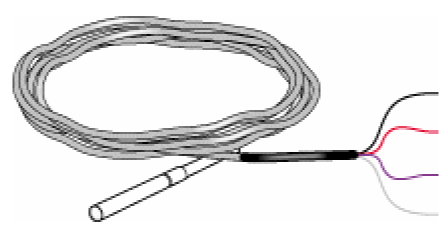

Figure 10 - 107 Temperature Probe

(Campbell Scientific, *Air Temperature Sensors*)

2.4.2 Temperature Probe Accuracy

Accuracy for the Campbell Scientific temperature probes is a combination of the "thermistor's interchangeability specification, the precision of the bridge resistors, and the polynomial error" (Campbell Scientific 2000, *107 Temperature Probe*, p. 1). The maximum error encountered in a "worst case" scenario is ±0.4° C in a normal structural field-monitoring environment of -38° C to 53° C. The largest part of the error comes from interchangeability specification and can be compensated by offsetting the resulting measurement according to

Table 1, assuming bridge resistors are 0.1% tolerant and have a 10-ppm temperature coefficient. The polynomial error for the *107 Temperature Probe*, as reported by Campbell Scientific, is given in Figure 11 and is tabulated in Table 2.

Table 1 - Thermistor Interchangeability Specification
(Campbell Scientific 2000, *107 Temperature Probe*, p. 2)

Temperature (°C)	Temperature Tolerance (±°C)
-40	0.40
-30	0.40
-20	0.32
-10	0.25
0 to +50	0.20

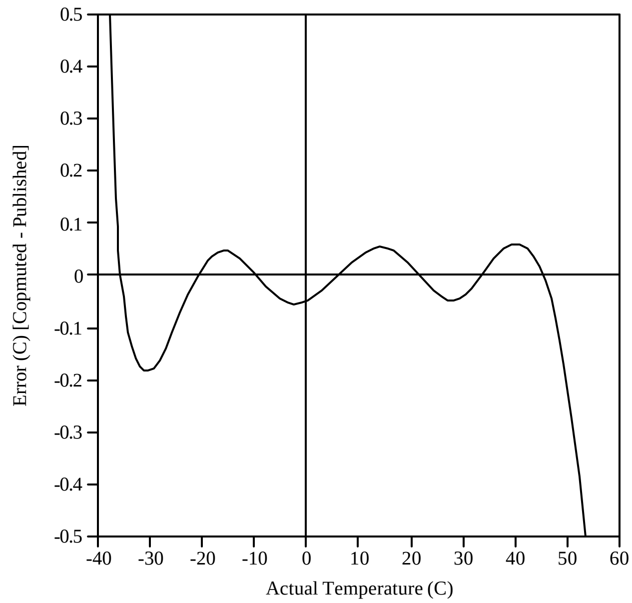

Figure 11 - Error Produced by Polynomial Fit to Published Values
(Campbell Scientific 2000, *107 Temperature Probe*, p. 2)

Table 2 - Polynomial Error (Campbell Scientific 2000, *107 Temperature Probe*, p. 2)

Temperature Range	Error
-40°C to +56°C	<±1.0°C
-38°C to +53°C	<±0.5°C
-24°C to +48°C	<±0.1°C

2.4.3 Installation of Temperature Probes

A naturally aspirated radiation shield is required for proper use of the Campbell Scientific temperature probes. A *41301 6-Plate Gill Radiation Shield* (Figure 12), from Campbell Scientific, is designed for the *107 Temperature Probe* and fulfills the necessary requirements. The shield consists of a cylindrical housing, employing six gills to reduce solar radiation loading, which is necessary for air temperature readings. The temperature probe is inserted in an opening on the underside of the gill and gently clamped into place with a U-bolt fitting. (Campbell Scientific 2000, *107 Temperature Probe*, p. 2)

Hordeski recommends a number of precautions when installing thermocouples. First, locate the temperature probes in an average-temperature zone, completely immersed in the medium so a true temperature can be measured. Secondly, since any induced currents can cause errors, "cable runs parallel to or closer than one foot to AC supply lines" should be avoided. Finally, all connections should be "clean and tight in order to avoid errors due to contact resistance." (Hordeski 1987, p. 39-40)

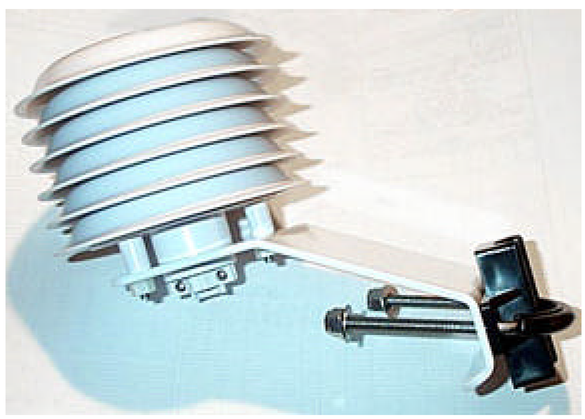

Figure 12 - Campbell Scientific 4130 Radiation Shield (Keelor)

2.5 Displacement Transducers

A common instrument for measuring the displacement response of structures in the field or laboratory is the linear variable differential transformer (LVDT). An LVDT consists of a ferretic core and a coil former onto which three coils are wound (Figure 13). (RDP Electronics)

The primary coil is excited with AC current. The remaining two secondary coils are wound such that when a ferritic core is in the central linear position, an equal voltage is induced into each coil. However, the secondary coils are connected in opposition. By opposing each other, the outputs of the two secondary coils cancel each other out when the ferritic core is in the central position. (RDP Electronics)

The armature assists the induction of current into the secondary coils. As the armature moves towards a secondary coil, the output waveform changes. By measuring the AC signal from the secondary coils, the displacement of the armature can be deduced. (RDP Electronics)

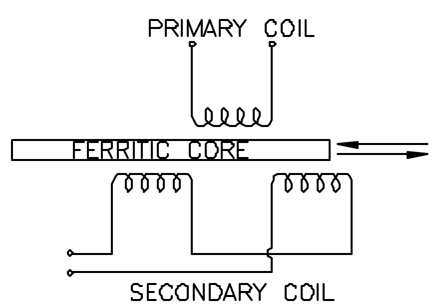

Figure 13 - LVDT Coils and Armature

The main advantage of the LVDT transducer over other types of displacement transducer is their extreme robustness because no physical contact occurs across the sensing element. Given that measurement is based on magnetic transfer, "the resolution of LVDT transducers is infinite" since the smallest fraction of movement can be detected by suitable signal conditioning electronics (i.e. this is an analog device). (RDP Electronics)

In order to quantify displacements in field and laboratory testing, direct current displacement transducers (DCDT) can also be employed (Figure 14). The direct current displacement transducer operation is based on the linear variable differential transformer (LVDT) with the addition of built-in DC-to-DC signal conditioning. (RDP Electronics)

Specifically, RDP Electronics' *LDC3000C* DCDT is used for displacement measurements. The *LDC3000C* DCDT is approximately 18 inches long, with a stroke of ±3 inches. With DC-to-DC signal conditioning, the *LDC3000C* is better suited for field data acquisition systems since only a 100mA, 6 to 18V unregulated power supply is required. An internal bearing guides the armature and is fitted with a male thread while the body is fitted with a female thread in order to ease mounting. (RDP Electronics)

Figure 14 - RDP Electronics' LDC3000C Direct Current Displacement Transducer (Keelor 2001)

3.0 DESCRIPTION OF DATA ACQUISITION SYSTEM

3.1 Overview

The Boyer Bridge over the Slippery Rock Creek in PennDOT Engineering District 10-0 has recently received a new deck as part of an overall bridge replacement project. The new deck consists of a fiber-reinforced polymer deck system acting compositely with five galvanized rolled steel shape stringers. In order to quantify the composite action of the deck, effective width factor and live load distribution factors, the Boyer bridge is instrumented with thirty strain gages, as described in Section 2, and monitored with a portable field data acquisition system.

The portable field data acquisition system consists of four components: datalogger, Wheatstone bridges, multiplexers and portable computer.

3.2 Component Overview

3.2.1 Datalogger Physical Description

Campbell Scientific's *CR23x Micrologger* (*CR23x*) is employed as a portable datalogger to perform strain and thermal measurements for structural field monitoring. The *CR23X* is a compact, battery operated programmable datalogger, measuring approximately 9.5 inches by 7 inches by 3.8 inches and weighing 10.7 pounds with rechargeable battery base, capable of being operated between -25°C and 50°C, see Figure D-1. A self-contained, rechargeable 12V battery or an external 12V power input provided by a wall transformer can power the datalogger.

Wiring terminals are provided on the faceplate of the *CR23x* to allow for connections of external sensors and other peripherals. The device allows for twelve differential analog channels, four pulse inputs, four excitation outputs, two continuous analog output channels, and eight digital input/output channels, see Figure C-1. The faceplate also features a two-line alphanumeric liquid crystal display and a sixteen-digit keypad for manual programming. The *CR23x* is equipped with a switched twelve-volt output to power sensors and peripherals with an unregulated voltage. Computer interfacing for programming and data retrieval is performed through an optically isolated computer RS232 input/output port located on the cover of the datalogger. A separate 9-pin port enables the *CR23X* to communicate with external telecommunication devices. A built-in thermistor for panel temperature readings and a clock with second/minute/hour/day/year resolution are also provided with the device.

3.2.2 Datalogger Programming and Data Storage

The *CR23x* is equipped with processing and control capability for enhanced data collection. Five hundred and twelve kilobytes of Flash Electronically Erasable Programmable Read Only Memory (EEPROM) allows the datalogger to be programmed to perform various sensor measurements and data manipulation tasks, either through an external computer or the panel-mounted sixteen-digit keypad. Four megabytes of Flash Random Access Memory (RAM) is available for final storage of data points.

3.2.3 Programming the CR23x Micrologger

Manual programming of the *CR23x* datalogger is performed through the sixteen-digit keypad and the LCD display on the front cover. The process involves entering two-digit processing instructions with a number of parameters in sequence. Each instruction is defined in the *CR23x's* instruction manual. Since programs can typically use over 100 keypad entries, programming the *CR23x* manually through the keypad can become frustrating and time consuming.

Programming the *CR23x* is greatly simplified with *SCWin - Shortcut For Windows* (*SCWin*), a free program provided by Campbell Scientific, available from the company's ftp site. *SCWin* creates simple programs for most of Campbell Scientific's dataloggers, including the *CR23x.* A graphical user interface guides the user through five simple steps to select sensors and appropriate data output. Screen captures are provided in Appendix E.

Programming begins with selecting a file name for the datalogger program by clicking on the 'Program' icon. The software also prompts for a scan interval, or more simply, the time interval in which the datalogger executes a program.

In Step 2, sensors are selected from a list of pre-selected input devices. For two and three -wire strain gages, the user selects the 'Full Bridge' sensor from the 'Available Sensors' list on the left and places it in the 'Selected Sensors' list on the right. A similar procedure is followed for a *107 Temperature Probe* by choosing the '107 Temperature Probe' from the 'Available Sensors' list and placing it in the 'Selected Sensors' list. By default, *SCWin* includes the battery voltage and program signature measurement. The panel temperature, however, is not included automatically and can be selected from the 'Available Sensors' list.

"The program signature measurement is a unique number that is calculated based on the size of the program, order of instructions, and other factors." If a program downloaded to a datalogger is modified in any way, the program signature will also change. By examining the program signature, tampering and datalogger program corruption can be closely monitored. (Campbell Scientific, *Short Cut for Windows*).

SCWin also provides a step for performing calculations on data before being stored in Final Storage. Step 3 allows the user to enter math expressions using mathematical operators and functions, as well as measurements, as variables. With this capability, sensor data can be manipulated. For example, multiple sensors can be averaged and stored as a separate data points or temperature readings in degrees Celsius can be converted to the Fahrenheit scale (Campbell Scientific, *Short Cut for Windows*).

Performing calculations, however, are optional; the raw data could also be manipulated using a simple spreadsheet program.

The fourth step in creating an *SCWin* program is to define the output processing for all sensor measurements (Campbell Scientific, *Short Cut for Windows*). The 'Output' section allows data to be stored at a specified interval in the datalogger's Final Storage Area. More specifically, data from multiple sensors can be stored at multiple, separate time intervals. For example, thermal measurements can be stored every minute, while strain reading can be stowed every 15 minutes. The 'Output' section also provides an option for finding the average, minimum or maximum values of data from scans between output intervals.

To complete the process, the program must be compiled in the fifth step. By clicking on 'Finish,' the program is automatically checked for errors, compiled and converted into an *SCWin* download file (.DLD extension), capable of being downloaded to a datalogger through the computer's RS232 serial port.

3.2.4 Transferring Data Between Datalogger and Computer

In order to download *SCWin* DLD files to the *CR23x* and retrieve data from the *CR23x*, a second program provided by Campbell Scientific is utilized. The Campbell Scientific *PC200W Basic Datalogger Support Software* version 1.2.1.0 offers an easy-to-use graphic interface to download programs, set the datalogger clock, monitor sensors and collect data.

To begin, the computer must be powered up and connected to the datalogger through a nine-pin serial cable to the optically isolated CS input/output port on the CR23x's front cover before starting the PC200W software.

PC200W must be setup for proper communication between the computer and datalogger. By clicking on the 'Add Logger' icon, the appropriate datalogger can be selected from a list of Campbell Scientific instruments. Following the datalogger selection, the appropriate communications port must be chosen for a serial connection. The software is now ready to begin a communications session between the datalogger and computer.

After the user connects to the datalogger with the 'Connect' icon, the first step is to set the datalogger clock to the correct setting. *PC200W* allows the datalogger internal clock to be calibrated with the communicating computer's internal clock using the 'Set Now' icon located on the right side of the first screen.

Monitoring data can be performed through the 'Monitor Locations' icon located on the top of the screen. With this feature, sensor measurements from each scan interval, in real time, can be visually inspected for troubleshooting purposes.

Data collection is performed through the 'Data Collection' icon located on the top of the screen. *PC200W* requires two options to be set for storing data retrieved directly from the datalogger. First, the name of the data file to be stored is entered in the 'Collect To' text box where it will be stored as an ASCII text file. Second, the data to be collected is specified in the 'What To Collect' area. Selecting 'New Data From Logger,' in this area, collects only the data recorded since the previous data collection and appends this new data to the end of the existing file. Choosing 'All Data From Logger' retrieves all of the data in the datalogger and overwrites the existing file. By clicking on the 'Click Now' icon, the data collection event is initiated and performed. Data collection, using the *PC200W* software, can only be initiated manually in this manner.

PC200W also offers a session status screen, where all status and warning messages of datalogger operation and communication are displayed.

3.2.5 Wheatstone Bridges

The *CR23x* does not contain internal Wheatstone bridges; therefore, it requires external modules for proper full bridge measurements. Two *4WFB120 4 Wire Full Bridge Terminal Input Modules* from Campbell Scientific, are included with the field data acquisition system to act as external Wheatstone bridge circuits. One 120-Ohm resistor, required to match the nominal resistance of the 120-Ohm strain gages used in the Boyer Bridge project, is included within the circuit (Figure 15). A photograph is provided in Appendix D, Figure D-2.

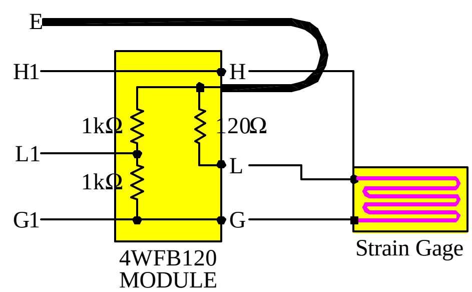

Figure 15 - Schematic of the 4WFB120 4 Wire Full Bridge Terminal Input Module with Three Wire Strain Gage (Adapted from Campbell Scientific, Inc 1996, *4WFB120, 4WFB350, 4WFB1K 4 Wire Full Bridge Terminal Input Modules Instruction Manual*, p. 1)

The *4WFB120* contains three input screw terminals, three output posts and one excitation lead wire. The excitation lead wire (E) protruding from the module is connected a datalogger excitation channel after the module's three terminal posts have been inserted in a single differential analog measurement channel.

Both three and two-wire strain gages can be connected to the full bridge module. However, only one gage can be connected to the module at one time. The two common leads of a three-wire strain gage are connected to the *4WFB120* 's 'H' and 'L" terminals. The third wire, with a red stripe on the insulating jacket, is connected to the *4WFB120's* ground terminal. It is crucial for proper measurements that the lead wires connected to the 'L' and 'G' terminals are of the same length to keep the Wheatstone bridge balanced, as mentioned in Section 2.

Two-strain gages are connected in a similar manner as the three-wire strain gage, with one modification. Both leads are connected to the *4WFB120*'s 'L' and 'G' terminals, while a short jumper wire is connected between the *4WFB120*'s 'L' and 'H' terminals.

3.2.6 Full Bridge Measurements

To perform strain gage measurements using the *4WFG120* Wheatstone bridge module, the full bridge measurement instruction is used in the datalogger measurement program. The instruction can easily be configured through the *SCWin* software, allowing a large range of features to be modified.

The *CR23x's* full bridge measurement performs a voltage measurement at the Wheatstone bridge circuit output after applying an excitation voltage. Following the first measurement, a second excitation voltage with reverse polarity is applied and a second voltage measurement is recorded. By reversing the excitation voltage, thermoelectric offsets in the bridge module are cancelled. (Campbell Scientific, *CR23x Micrologger Instruction Manual*, 2000, p. 13.20)

The result from the full bridge voltage measurement is the measured bridge output in millivolts divided by the excitation in volts. Using ohm's law, the ratio can be expressed in terms of the resistance values of the resistors in the Wheatstone bridge module:

$$\frac{V_{out}}{V_{in}} = \frac{R_g}{R_3 + R_g} - \frac{R_2}{R_1 + R_2}$$

Equation 1 - (Campbell Scientific, Inc.)

Where R_g is the strain gage resistance value, see Figure 16. In terms of a change in resistance resulting from applied strained, the equation for bridge output becomes:

$$\left.\frac{V_{out}}{V_{in}}\right|_{strained} = \frac{R_g + \Delta R_g}{R_3 + R_g + \Delta R_g} - \frac{R_2}{R_1 + R_2}$$

Equation 2 - (Campbell Scientific, Inc.)

Subtracting the strained state from the unstrained state results in:

$$V_r = \left.\frac{V_{out}}{V_{in}}\right|_{strained} - \left.\frac{V_{out}}{V_{in}}\right|_{unstrained} = \frac{R_g \cdot \Delta R_g}{(R_3 + R_g + \Delta R_g) \cdot (R_3 + R_g)}$$

Equation 3 - (Campbell Scientific, Inc.)

Solving for strain, dividing by the gage factor, GF, and multiplying by 10^6 yields the final conversion equation necessary for bridge output measurement to strain reported in microstrains:

$$me = \frac{4 \cdot 10^6 \cdot V_r}{GF \cdot (1 - 2V_r)}$$

Equation 4 - (Campbell Scientific, Inc.)

Since the full bridge measurement instruction result is reported in millivolts per volts, Equation 4 must be modified by multiplying V_r by 0.001.

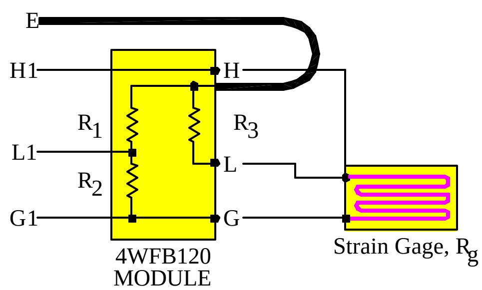

Figure 16 - 4WFB120 4 Wire Full Bridge Terminal Input Module (Adapted from Campbell Scientific, Inc. 1996, *4WFB120, 4WFB350, 4WFB1K 4 Wire Full Bridge Terminal Input Modules Instruction Manual, p*. 13)

Unfortunately, programs generated with SCWin are only set for low-resolution measurements, providing three decimal point precision for the ratiometric bridge output value. Therefore, using 0.001 mV/V as the minimum difference in strained state and unstrained state, the smallest strain value attainable is:

$$V := 0.002 - 0.001$$

$$\mu\varepsilon := \frac{4 \cdot 10^{6} \cdot V \cdot 0.001}{GF \cdot (1 - 2V \cdot 0.001)} \qquad \mu\varepsilon = 1.869$$

$$\sigma := 29000\,ksi \cdot \frac{\mu\varepsilon}{10^{6}} \qquad \sigma = 0.054\,ksi$$

Equation 5

In order to attain five decimal point precision, a special instruction must be manually inserted in the program. Campbell Scientific's *Edlog* program generator contained in the Campbell Scientific *PC208W Datalogger Support Software* provides an easy method for writing datalogger programs. Screen captures are provided in Appendix E.

To begin, *PC208W* is opened and the 'Program' icon is selected. From the File menu, the appropriate document from the 'Document DLD File' option is selected, in order to import the targeted *SCWin* DLD file. The resolution instruction, Instruction 78, from the Edit menu, is inserted just before the sample instruction, Instruction 70, while changing the parameter to 1, high resolution. Following the instruction insertion procedure, the program is compiled by choosing the Compile Program option from the Compile menu and downloaded to the datalogger using the *PC200W* software.

An internal calibration function is provided with the *CR23x* datalogger. Positive and negative voltages are fed through circuitry and new calibration coefficients are calculated, providing accurate voltage measurements over the temperature operating range of the datalogger. The calibration procedure is executed when the CR23x is powered up, and when the calibration instruction, Instruction 24, is performed. When Instruction 24 is not contained in a program table, the calibration procedure is performed automatically. Resetting the watchdog timer on the processor will also execute the calibration procedure. The calibration process combats changes due to aging along with environmental temperature fluctuations. (Campbell Scientific 2000, *CR23x Micrologger Instruction Manual*, p. 13.25)

3.2.7 Multiplexers

Since the *CR23x* datalogger only supports twelve analog measurement channels necessary for full bridge measurements and one channel is need for each of the thirty strain gages, a deficit exists. In order to solve the deficiency, two multiplexers are employed to expand the measurement capability of the *CR23x*. A multiplexer allows multiple channels, each assigned to an individual strain gage, to be connected to a single differential analog measurement channel. Two Campbell Scientific *AM416* four-line, sixteen-channel multiplexers, designed specifically for the Campbell Scientific dataloggers, are included with the field data acquisition system. A photograph is provided in Appendix D, Figure D-2.

The *AM416* is placed between the datalogger and sensors, schematically; using mechanical relays to switch the desired sensor signals through the system, see Figure C-5. Four lines, labeled H1, L1, H2 and L2, connected to an individual sensor, are switched simultaneously through mechanical relay action to a set of four common terminals, labeled COM H1, L1, H2, and L2. The common terminals are wired to one differential analog measurement channel located on the *CR23x* datalogger. A maximum of sixteen sets of four lines may be scanned per *AM416* multiplexer. (Campbell Scientific, *AM416 Relay Multiplexer Instruction Manual*)

In order for multiple measurements to be assigned to a single differential analog channel, the datalogger must able to control which multiplexer channel is available for measurement. For control, the *AM416* contains two wiring terminals: the clock and reset inputs, see Figure C-2. These two inputs are connected to two separate control port terminals on the *CR23x* datalogger. Digital logic is utilized to control the multiplexer's state, as well as channel switching. (Campbell Scientific, *AM416 Relay Multiplexer Instruction Manual*)

The *AM416*'s reset terminal controls the state of the multiplexer. By setting the reset input low, less than 0.9 VDC, the *AM416* is kept in a low current drain state. The multiplexer is activated when the reset input is set high, greater than 3.5 VDC. To switch between each sequential channel, the clock input is pulsed high, greater than 3.5 VDC and longer than 5 ms. After the first clock pulse is received by the multiplexer from the datalogger, the four common lines, COM H1, L1, H2, and L2, are switched into contact with multiplexer channel 1 (H1, L1, H2, L2). When a second clock pulse is received, the common lines are connected to multiplexer channel 2 (H1, L1, H2, L2). After the last sensor is switched, the relays are reset to multiplexer channel 1 and the process repeats itself for each scan. (Campbell Scientific, *AM416 Relay Multiplexer Instruction Manual*)

Two lead terminals are also provided for powering the *AM416* multiplexer's mechanical relays. A 12 volt supply is fed from the datalogger to the multiplexer's 12V and GND terminals.

3.2.8 Programming In SCWin with AM416 Multiplexers

SCWin – Shortcut For Windows provides an easy method of programming with multiple *AM416* multiplexers. From the “Choose Sensors to Monitor” screen in Step 2, the software enables the user to add peripherals, including the *AM416*, by clicking on the ‘Add Device’ icon. After choosing the AM416 and placing it in the ‘Available Sensors’ list, appropriate sensors to be wired to the multiplexer are added, e.g. sixteen full bridge sensors for sixteen strain gages. *SCWin* subsequently provides a wiring diagram based on the user’s input of peripherals and sensors.

3.3 Boyer Bridge Project Field Data Acquisition System Setup

3.3.1 Wiring Nomenclature

To simplify wiring connections, a unique nomenclature is used. The component name and number is given, followed by the terminal number. For example, the Common ‘H1’ terminal on the first of two multiplexers is designated Multiplexer 1 COM H1.

3.3.2 Datalogger Measurement Program

In order to begin with the description of the Boyer Bridge project field data acquisition system setup, it is first necessary to describe the datalogger measurement program employed for measurements.

The program is developed in *SCWin* from Campbell Scientific, as described in Section 3.2.3, and is transferred to the Campbell Scientific *CR23x Micrologger*, as described in Section 3.2.4.

To begin, ‘boyer.scw’ is chosen as the filename for the SCWin program followed by the selection of the CR23x datalogger model from the dialogue box prompt. Since two multiplexers are involved, thirty seconds is selected as the scan interval, as recommended by Campbell Scientific.

Since thirty strain gages are required for the Boyer Bridge project, two *AM416* multiplexers are added. Sixteen three-wire strain gages are selected for the first AM416 multiplexer, while fourteen three-wire strain gages are selected for the second datalogger. Each strain gage is configured with a ±10V sensor range, slow measurement integration, and 2000 mV excitation as recommended by Campbell Scientific. A 1.0 multiplier and 0.0 offset is also specified.

No calculations are performed on the data in the Step 3 of the *SCWin*. Instead, calculations on the raw data obtained from the datalogger are performed in a separate spreadsheet program.

One output table is utilized for strain measurements at an output interval of sixty seconds. Sample measurements are added to the ‘Selected Outputs’ panel, taken from each strain gage sensor, as well as the battery voltage, panel temperature and program signature. Battery voltage and program signature is also recorded in a second output table.

3.3.3 Field Data Acquisition System Wiring

Two *AM416* multiplexers are utilized for connection of the thirty three-wire strain gages to the *CR23x* datalogger. Sixteen gages are connected to Multiplexer 1, while fourteen gages are connected to Multiplexer 2, see Figure C-3. The two common leads from each strain gage are connected to H1 and L1 on the appropriate channel printed on the cover of the multiplexer. The third lead, marked with a red stripe, is connected to H2 on the same channel of the multiplexer.

The common terminals, found on the center of Multiplexer 1's front cover, are connected to a single *4WFB120 Four Wire Full Bridge Terminal Input Module,* Bridge 1, which is attached to differential analog measurement channel Datalogger DIFF 1 on the *CR23x* datalogger. Specifically, Multiplexer 1 COM H1 is connected to Bridge 1 H, Multiplexer 1 COM L1 to Bridge 1 L and Multiplexer 1 COM H2 to Bridge 1 Ground. A second *4WFB120* module, Bridge 2, is connected to Datalogger DIFF 2. The identical procedure is followed for Multiplexer 2 COM channels connecting to Bridge 2 terminals: Multiplexer 2 COM H1 is connected to Bridge 2 H, Multiplexer 2 COM L1 to Bridge 2 L and Multiplexer 2 COM H2 to Bridge 2 Ground

For datalogger control of the multiplexers, as described in Section 3.3, Multiplexer 1 RES is connected to Datalogger C1, Multiplexer 1 CLK to Datalogger C2, Multiplexer 1 GND to Datalogger G, and Multiplexer 1 12V to Datalogger 12V. Similarly, Multiplexer 2 RES is connected to Datalogger C3, Multiplexer 2 CLK to Datalogger C4, Multiplexer 2 GND to Datalogger G, and Multiplexer 2 12V to Datalogger 12V.

Short lengths of four-conductor telephone cable are utilized for connections between *4WFB120* modules, multiplexer terminals and the *CR23x* datalogger.

Although thermocouples were eventually ruled out from the Boyer Bridge project instrumentation package, it is important to detail *107 Temperature Probe* thermistor wiring for use in future projects. Two *107 Temperature Prob*es are used, Thermistor 1 and 2. A wiring diagram is provided in Appendix C, Figure C-4.

To begin, the clear shield lead from both Thermistor 1 and 2 is connected to a ground connection, Datalogger Ground, on the *CR23x's* front panel. The black excitation lead from both temperature probes is connected to an unused excitation channel on the *CR23x,* Datalogger E3. Finally, Thermistor 1's red temperature signal lead is connected to a differential analog measurement channel, Datalogger 4L, while Thermistor 2's red temperature signal lead is connected to Datalogger 4H.

Both thermistors are mounted in separate *41301 Radiation Shields* as detailed in Section 2 and positioned appropriately near the specimen.

3.3.4 DCDT Wiring

Although Direct Current Displacement Transducers are not contained in the Boyer Bridge project instrumentation package, it is important to detail the RDP Electronic's *LDC3000C* direct current displacement transducer (DCDT) wiring for use in future projects. Wiring for one DCDT to the *CR23x* datalogger is illustrated in Appendix C, Figure C-7.

Protruding from the LDC3000C DCDT's stainless steel housing are six stranded wire leads for power and measurement purposes and one copper shield for reducing electromagnetic interference. In order to use the DCDT with a separate +6 to +18 Volt power supply, the DCDT's red and blue leads are connected to the positive and ground connections, respectively. The yellow and brown lead wires are shorted together while the copper shield is connected to a grounding terminal on the *CR23x* front cover. For the required differential analog voltage measurements, the green lead wire is connected to a 'high' terminal and the black lead wire is connected to a 'low' terminal on the CR23x's grouping of differential analog channel terminals. (RDP Electronics)

3.3.5 Datalogger – Computer Interface

A laptop PC is connected to the *CR23x* datalogger for data transfer. The laptop transmits the SCWin datalogger measurement program to the *CR23x* and receives raw data back for storage and processing in a separate spreadsheet software package. The connection is made from the laptop PC's 9 pin serial port to the 'CS I/O' port on the cover of the *CR23x* datalogger with a simple three foot 9 to 9 pin serial cable.

The internal, rechargeable 12V battery provides power to the datalogger while an internal, rechargeable battery also powers the laptop PC.

3.3.6 P-3500 and Switch and Balance Unit Setup

Before field-testing commenced on February 15, 2002 it was discovered that lead wires from strain gages 1, 2 and 3 located on Beam 5 had been severed. Since the remaining lead wire lengths were too short to reach to the field data acquisition setup, but long enough to reach the top of the bridge deck, a portable Measurement Group's *P-3500 Strain Indicator* and *SB-10 Switch and Balance Unit* (Figure D-5), were employed to retrieve data from these gages. The *P-3500* provides a digital strain readout while the *SB-10* permits up to 10 strain gages to be connected to the *P-3500*.

Short lengths of jacketing are stripped from strain gages 1, 2 and 3 applied to Beam 5 and connected directly to the *SB-10 Switch and Balance Unit*. Each gage is connected to a separate measurement channel; the red striped lead from the strain gage is inserted in the red P+ terminal, and the remaining two leads are inserted in the white S- and yellow D terminals, separately.

From the *SB-10 Switch and Balance Unit*, short lengths of connection wire are connected to the *P-3500 Strain Indicator*. These wires connect the red P+ terminals on both units and the white S- terminals on both units. A connection is also made between the yellow D_{EXT} terminal on the *SB-10* and the yellow D_{120} terminal on the *P-3500*, corresponding to 120-Ohm strain gage measurements.

3.4 Verification of CR23x Datalogger and P3500 Strain Indicator

In order to verify the strain results provided by the *CR23x* datalogger and *P3500* strain indicator, strain measurements are performed on a uniaxial tension specimen. The specimen consists of a 36 inch long piece of ASTM 36 flat bar stock measuring 3/16 inches thick by 1.5 inches wide.

A single uniaxial, two-wire strain gage is affixed to the width dimension, at the center of the specimen with M-Bond 200 adhesive using the same procedure described in Section 2.3.

The specimen, with strain gage attached, is inserted into a Baldwin Universal Testing Machine, capable of providing 200 kilopounds of tension using hydraulic action. Calibrated load values are displayed on a digital panel at a resolution of ten pounds. The specimen is clamped into place at the top and bottom with the testing machine's cross-heads.

The first test examines the Campbell Scientific *CR23x* datalogger accuracy; two tests are performed on the device. The first test measures strain in the specimen under load with an *AM416* multiplexer connected to an *FWB120* Wheatstone bridge module inserted in the datalogger. The strain gage from the specimen is wired directly to the multiplexer. A schematic is provided in Appendix C. The *CR23x* datalogger is connected to a laptop computer via the optically isolated computer RS232 input/output port for program transfer and raw data collection.

A second test is performed with the Vishay Measurements' *P3500 Strain Indicator*. The strain gage is wired to the instrument by connecting one lead to the red P+ terminal and the other to the white S- terminal. A jumper cable connects the yellow D_{120} terminal and the white S- terminal. Strain is recorded manually from the digital panel.

Before load is applied in each of the tests, a measurement of the unstrained state is recorded. Rather than recording separate data files for each measurement while using the *CR23x* datalogger, as in Section 3.3.2, the ratiometric voltage measurement is read directly from the real-time *PC200W* 'Monitor Locations' screen and recorded manually with each load increment. Load is applied steadily at increments of five hundred pounds in uniaxial tension. Strain gage measurements are recorded at each five hundred pound increments.

A comparison of results is provided in Appendix H. The graphical comparison of results presents strain values on the abscissa while stress values are displayed on the ordinate, in accordance with stress-strain curve conventions. However, the abscissa displays the independent variable, stress, rather than the dependent variable. Linear regression lines and correlation values are displayed for each instruments response.

From the graphical stress-strain representation, it is clear that *CR23x* strain measurements display linear behavior with a very high correlation coefficient. The stress-strain measurement relationship is also linear for the *P3500* strain indicator and correlates very well with the theoretical behavior.

The results reveal that the *CR23x* strain measurements are offset from the theoretical linear elastic response. The offset occurs possibly because the zero measurement was performed prior to clamping the specimen in the testing machine and before the hydraulic actuator was engaged. By adding the 31 microstrain-offset value at the origin to the *CR23x* datalogger's strain results, the stress-strain curve closely matches the theoretical behavior.

4.0 FIELD TESTING OF SYSTEM

4.1 Description of Field Test

4.1.1 Overview of Testing Procedure

Field testing of the Boyer Bridge over the Slippery Rock Creek in PennDOT Engineering District 10-0 consists of a static loads applied by a test vehicle to the deck and measuring responses of the five galvanized rolled steel I-shaped stringers.

The static loads are provided by one tandem axle truck loaded with sand, furnished by the Pennsylvania Department of Transportation's Butler County Maintenance Garage, see Appendix D for photographs. The truck is moved into one of three different positions on the bridge deck, where strain gage measurements, using the portable data acquisition system, are performed.

To date, two field tests have been performed on the Boyer Bridge. The first occurred on November 13, 2001 and the second on February 15, 2002.

4.1.2 Test Site Preparation

The testing procedure requires the test vehicle's wheelbase centerline to be situated directly over the centerline of the three stringers involved in Position A, B and C. Load position drawings can be found in Appendix B.

To begin, the asphalt surface overlay covering the fiber reinforced deck is marked for proper alignment of the test vehicle. A chalk line is applied to the asphalt between the two center guide rail posts bolted to the exterior stringers, Beams 1 and 5, dividing the span into two equal sections. A second chalk line is set between the forward (eastern) abutments' outer face, clear from the stringer bearing points. The bridge is divided down the centerline by marking the chalk lines at their midpoint with crayon. From the centerline on each chalk line, four crayon markings are laid out on the asphalt at a 5'-9" spacing, situating them over the five stringers. A layout drawing is provided in Figure B-4.

Measurements of the test vehicle's front wheelbase are recorded. From the four crayon markings and one centerline marking, the wheelbase dimension is centered and marked at Positions A, B and C on both the midspan and abutment chalk lines. By marking these positions, the vehicle can be properly aligned when driving into position, making sure that it is parallel to all five stringers. Measurements of the vehicle's dimensions are provided in Appendix B.

4.1.3 Wheel Load Measurement

In order to quantify the force applied over the contact surface of the tire to the asphalt, a weigh team from PennDOT District 10 is dispatched to the Boyer Bridge. The mobile weigh team performs wheel load measurements by positioning the test vehicle over six portable scales outfitted with dial gages and recording each load in pounds, see Figure D-23 and Figure D-24. A tabulated record of gross weight for each axle is provided in Appendix B as submitted by the mobile weigh team on the day of testing.

4.1.4 Instrumentation Check

Strain gages are checked using methods in Section 2.3.3 following installation at the field site in October of 2001. Unfortunately, not every strain gage survived the period between installation and testing. Strain gages 2, 5, 6, 9, 13, 14 and 22 gave overflow values during the measurement process, rendering the data unusable for these channels during the November 17, 2002 field test, see Figure B-3. Strain gages 1, 2, 3, 4, 5, 6, 7, 8, 13, 15, 19, 21, 22, and 27 also gave overflow values during the February 15 field test, see Figure B-3.

Since strain gage locations were duplicated on both sides of each stringer, data is still recoverable from Beams 1, 2, 3, 4 and 5 from the November 17, 2001 field test and from Beams 2, 3 and 4 and 5 from the February 15, 2002 field test. During the setup for the February 15, 2002 field test, it was discovered that the lead wires from strain gages 1, 2 and 3 had been severed sometime prior to the February 15, 2002 test date. The break in wiring occurred approximately ten feet from the application point of the gages on exterior Beam 1.

To recover the strain gages, the remaining lengths of lead wires are removed from the silicon caulking adhered to the Beam 1 and strung upwards, over the guardrail and onto the bridge deck, see Figure D-31. From the bridge deck, the three strain gage lead wires are connected to the *SB-10 Switch and Balance Unit* connected to the *P-3500 Strain Indicator*. In this manner, strain is measured with the *P-3500* and recorded.

4.1.5 Field Testing Procedure

Before the test vehicle is placed into Position A, strain measurements are taken from each of the thirty strain gages in order to establish a reference or zero strain state measurement. This is performed with both the *CR23x* datalogger and the *P-3500 Strain Indicator*. The measurements are initiated by sending the datalogger measurement program, as described in Section 3.3.2, to the datalogger from the PC200W software on the laptop computer. After two scan intervals have been executed, the data is written to an ASCII text file on the laptop computer under the name A1zero.dat, where 'A' denotes the load position, '1' denotes the first of three cycles at this position, and 'zero' indicates that the measurement is of the unloaded state. Strain from the *P-3500* is recorded manually.

Following the zero measurement, the test vehicle is driven forward into position from the forward (eastern) abutment and aligned with the position markings. The vehicle is placed so that the entire contact area of the front axle is just off the deck and on the road surface, not bearing on the deck supported by the five stringers of the bridge. In this configuration, only the two rear axles provide static loading to the bridge deck and structure. Once the truck is in position, the distance between the rear axle and forward (eastern) abutment chalk line is recorded.

While in position A, data is collected from the strain gages to the laptop under the filename A1.dat after at least two scan intervals have been executed. Data is also gathered from the *P-3500* strain indicator. To reduce electromagnetic interference, the truck engine is shut off during the strain measuring process.

Following strain measurements, the test vehicle is backed off the bridge, beyond the rear (western) abutment. With the engine shutoff, another set of zero measurements is performed and stored under the filename B1zero.dat on the laptop computer. Zero measurements are also performed with the *P-3500*.

Again, the test vehicle is moved into position and data is gathered from both the *P-3500* and *CR23x*. The vehicle is backed off the bridge in reverse, followed by performing a third set of zero measurements. Finally, the test vehicle is aligned and driven into position C.

After the test vehicle is backed out of Position C, the process of testing all three positions is repeated two more times, each time performing a zero measurement between loadings. Each of the three tests at common load positions will be referred to as Cycle 1, 2 and 3. Performing the load test three times at each load position helps reduce erroneous readings. To clarify the procedure, a schematic of measurements performed for each load test is provided in Appendix I, Figures I-5 and I-6.

4.2 Results

4.2.1 Presentation of Results

Results from field tests conducted on November 13, 2001 are tabulated in Appendix F while results from field tests conducted on February 15, 2002 are tabulated in Appendix G. Strain data from the *P-3500* taken from the February 15, 2002 tests are tabulated in Appendix H.

In Appendix F and G, zero measurements, V_0, and strained state measurements, V_1, are included. In addition, V_r, as explained in Section 3.2.6, and strain is tabulated in both appendices.

Data is presented in a hierarchal form in each appendix; the first grouping consists of load positions (i.e. Position A, B, and C). Within each load position, data is reported as grouped by strain gages attached to common stringers (i.e. Beam 1, 2, 3, 4, 5). Within each beam report, strain gage channel data is presented for the three cycles of load tests performed at the corresponding position.

Results from individual positions and cycles will be referred to by a 2-character descriptor: the first character indicates position while the second character indicates cycle number. For example, results from Position A and Cycle 2 are referred to as A2.

Values returned from the datalogger that are considered unusable are reported as "-99999" and will be referred to as "unusable." Unusable data is a result of overflow errors occurring during ratiometric measurements, where either the measured bridge output in millivolts is much greater than the excitation voltage in volts or the excitation in volts is much smaller than the measured bridge output in millivolts. Unusable data in this form is reported as a hyphen, "-," in each appendix. Otherwise, data points are reported in each table regardless of validity. Values that do not equal the overflow error result will be referred to as "usable."

4.2.2 Complete Data Set Description

Assuming that the strain varies linearly with depth, a complete data set requires two usable data points necessary to interpolate the strain profile across the beams' cross-sectional depth. It is preferable to have at least two points from the top and bottom flanges. Each stringer contains gages mounted on the top face of the bottom flange, bottom face of the top flange and on the web, at one half of the depth of the cross section, as described in 2.2.1.

An examination of the November 13, 2001 V_r values, based solely on data returned from the *CR23x* datalogger, indicate that Beams 1, 2, 3, 4, and 5 contain complete data sets for strain profile analysis. *CR23x* Datalogger V_r results from the February 15, 2002 tests indicate that Beams 2, 3, 4 and 5 contain complete data sets. Strain measurements, however, were collected from strain gages 1, 2 and 3 using the *P-3500* strain indicator, forming a complete data set for Beam 1.

4.2.3 Zero Measurement Record

Load test protocol performed on November 13, 2001 required measuring the unstrained state prior to Test A1 and following test C3. Test A1 was initiated at 11:15 AM while Test C3 concluded slightly after 12:00 PM. Performing zero measurements before and after load testing was assumed to be adequate to account for drift as described in Section 2.1.5. While most V_0 values for individual gages varied only slightly between cycles, it was apparent that some strain gage V_0 values differed significantly between the first zero measurement before Test A1 and the second zero measurement after Test C3.

To reduce the effects of drift in the February 15, 2002 field test, zero measurements are performed and recorded prior to each load position and cycle, providing 9 separate unstrained state measurement sets.

V_0 values from November 13, 2001 field tests for Cycle 1 and 3, as reported in Appendix E for each load position, are strictly values obtained before the A1 test and after the C3 test. Unlike the November 13, 2002 results, February 15, 2001 field test V_0 values for Cycle 1, 2 and 3, in Appendix F, are zero measurement values obtained before loading the bridge for each load position.

4.2.4 Maximum Range of Strain Values

To examine the repeatability of the strain gage data, the maximum range of measured strain is compared for each strain gage channel over the three cycles. The maximum range of measured strain is obtained by subtracting the minimum strain measurement from the maximum strain measurement from Cycle 1, 2 and 3 effectively and is reported in Appendix E for each strain gage channel and load position. The maximum strain measurement range per beam is also tabulated within the same table.

Typical ranges for Position A for the November 13, 2001 tests fall between 1 and 20 microstrain. Assuming a modulus of elasticity for steel equal to 29,000 ksi, 20 microstrain corresponds to 0.57 ksi flexural stress. Typical Position B ranges fall between 1 and 30 microstrain while typical Position C ranges lie between 1 and 33 microstrain.

Position A strain measurement ranges on November 13, 2001, for channels 17 through 28, are significantly higher than the remaining channels. By examining the V_1 values for these gages, it is apparent that there is a significant difference between Cycle 1 and between Cycles 2 and 3. There is very little difference between V_0 values during the November 13, 2001 testing with the exception of Strain Gage 17 where the ratiometric value differs by approximately 0.4.

The strain measurement ranges for Strain Gage 17 for each load position are significantly higher than the remaining strain gages. This trend does not occur in the February 15, 2002 test measurements.

Typical ranges for Position A for the February 15, 2002 tests fall between 1 and 30 microstrain. Typical Position B ranges fall between 1 and 23 microstrain while typical Position C ranges lie between 0 and 19 microstrain.

4.2.5 Strain Profile

The maximum compressive strain is expected to be located in the bottom flange of each simply supported stringer, loaded in flexure. A positive strain value found in Appendix E and F indicates compression. Secondly, each beam should exhibit a linearly decreasing strain profile.

An examination of each stringer's strain profile from the *CR23x* datalogger reveals a very close agreement to expected behavior, with the exception of Strain Gage

17 mounted on Beam 3, for tests conducted on November 13, 2001. Field tests conducted on February 15, 2002 display the appropriate linear behavior for each stringer.

Stringers located furthest from the load application point in Position A and C do not appear to display the expected linear behavior, but since strain values are so small, this can be attributed to "noise."

As expected, maximum compressive strain values are largest for stringers located directly beneath load application points for field tests conducted on both November 13, 2001 and February 15, 2002.

4.2.6 Validity of Results

Based on expected behavior for simply supported beams acting compositely, as described in Section 4.2.5, and measurements that deviate appreciably between cycles, it appears that results from several strain gages readings from the November 13, 2001 tests are unacceptable. By visual inspection, Strain Gage 17 seems to exhibit invalid behavior for all load positions and cycles with strains much larger than expected. In addition, Strain Gages 19, 21, 23, 24, 25, 26, 27, and 28 exhibit the same invalid behavior during Cycle 1 at load Position A.

Beam 1 strain results from the *P-3500 Strain Indicator* for the February 15, 2002 field tests do not agree with *CR23x* datalogger results from Beam 1 for field tests conducted on November 13, 2001 field tests. Strain profiles only exhibit a linear distribution for Position C during Cycles 2 and 3. These results are very similar to strain data from symmetrical case, Beam 5, Position A.

5.0 CONCLUSION

The Boyer Bridge over the Slippery Rock Creek in PennDOT Engineering District 10-0 has recently received a new deck as part of an overall bridge replacement project. The new deck consists of a fiber-reinforced polymer deck system acting compositely with five galvanized rolled steel shape stringers. In order to quantify the composite action of the deck, effective width factor and live load distribution factors, the Boyer Bridge is instrumented with thirty strain gages and monitored with a portable field data acquisition system.

Field testing of the Boyer Bridge over the Slippery Rock Creek in PennDOT Engineering District 10-0 consists of a static loads applied by a test vehicle to the deck and measuring responses of the five galvanized rolled steel I-shaped stringers. To date, two field tests have been performed on the Boyer Bridge. The first occurred on November 13, 2001 and the second on February 15, 2002.

Thirty, three-wire, foil strain gages were deployed for field-testing of the Boyer County Bridge. In order to quantify the strain profile of the five steel stringers, gages are placed at three positions through the depth of the wide flange cross section. One gage is placed on the top face of the bottom flange. The second gage is positioned on the web, at one half of the depth of the cross section and the third gage is located on the bottom face of the top flange.

The portable field data acquisition system consists of four components: datalogger, Wheatstone bridges, multiplexers, and portable computer. Campbell Scientific's *CR23x Micrologger* (*CR23x*) is employed as a portable datalogger to perform strain and thermal measurements for structural field monitoring. Manual programming of the *CR23x* datalogger is performed through the sixteen-digit keypad and the LCD display on the front cover. Programming the *CR23x* is greatly simplified with *SCWin - Shortcut For Windows* (*SCWin*), a free program provided by Campbell Scientific.

Strain results provided by the *CR23x* datalogger have been verified by performing strain measurements on a uniaxial tension specimen. From the graphical stress-strain representation in Appendix I, it is clear that *CR23x* strain measurements display linear behavior with a very high correlation coefficient.

An examination of each stringer's strain profile from the *CR23x* datalogger reveals a very close agreement to expected behavior. From multiple tests performed at the same load position, it is evident that the *CR23x*'s strain measurements exhibit excellent repeatability. Strain gage measurements vary insignificantly between cycles and typically less than six microstrain, with the exception of strain gage 17.

The *CR23x* provides a portable, self-powered datalogger necessary for field-testing and is capable of being setup in a short amount of time. The entire system, consisting of datalogger, multiplexers, Wheatstone bridges, and laptop computer can be setup and connected to installed instrumentation in under a half hour. Setup and load testing conducted on the Boyer Bridge was executed in less than three hours. Campbell Scientific's *CR23x Micrologger* fulfills the requirement for a compact and robust field data acquisition system suitable for structural field monitoring.

APPENDIX A

Boyer Bridge Drawings

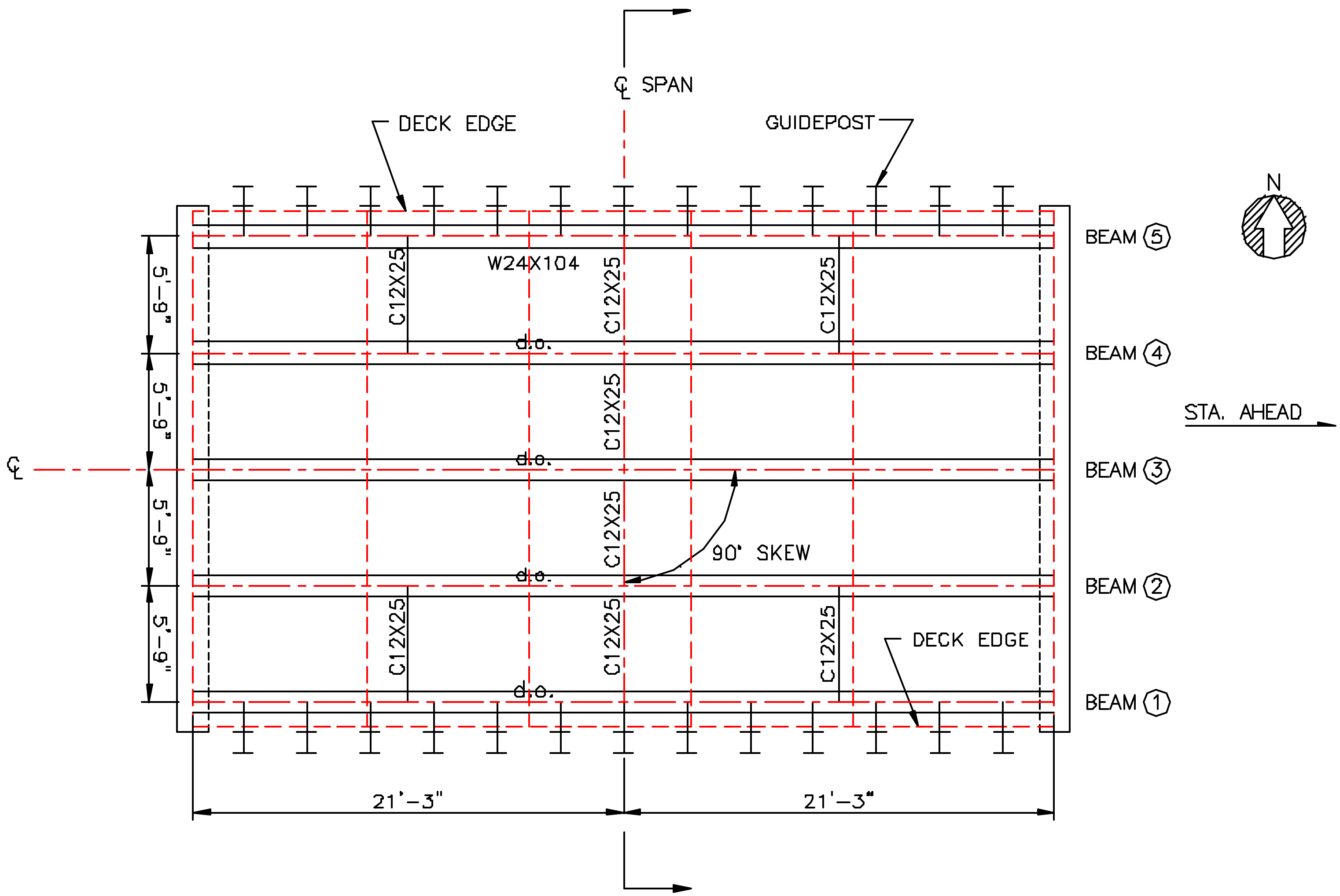

Figure A-1 – Boyer Bridge Plan

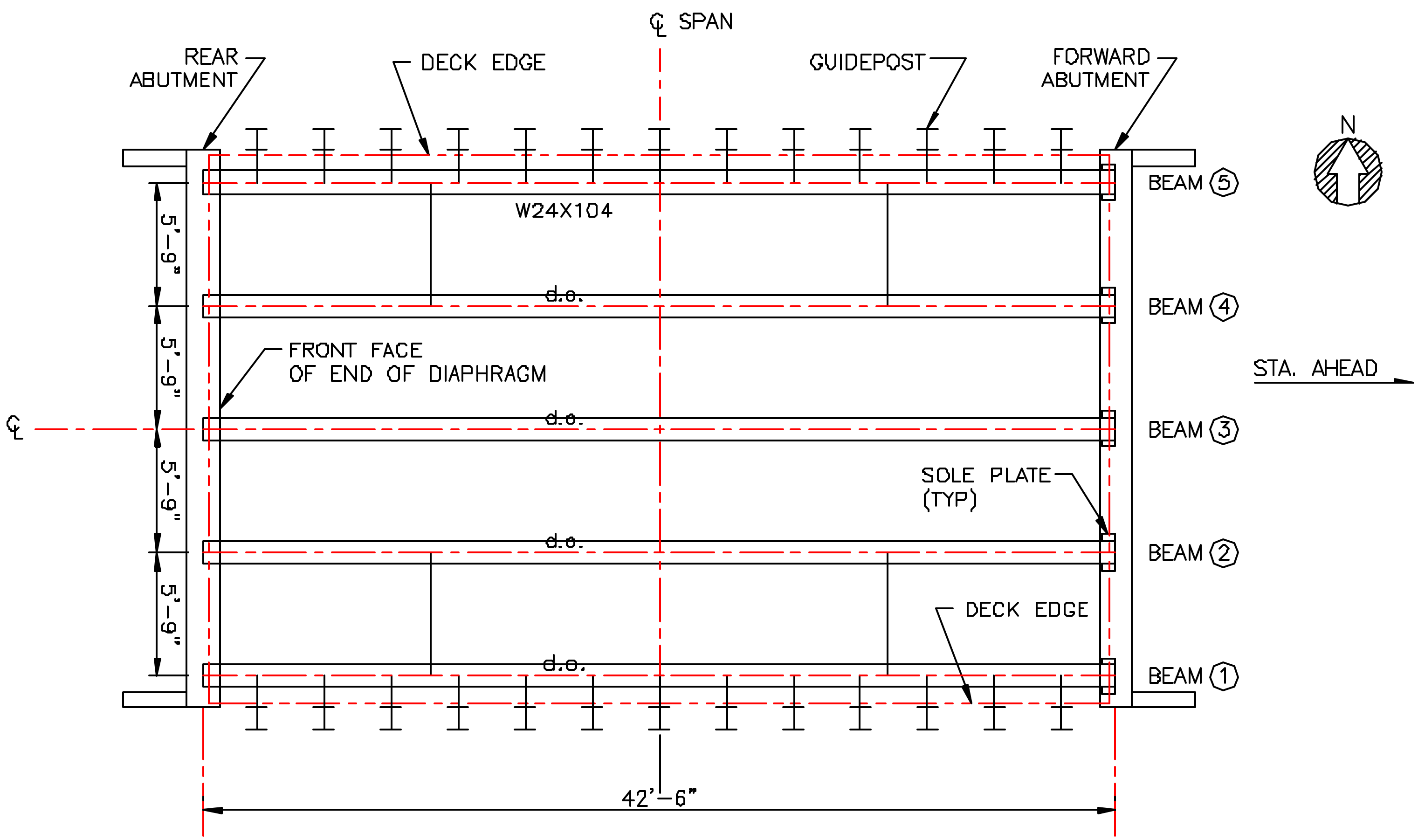

Figure A-2 – Boyer Bridge Abutment Plan

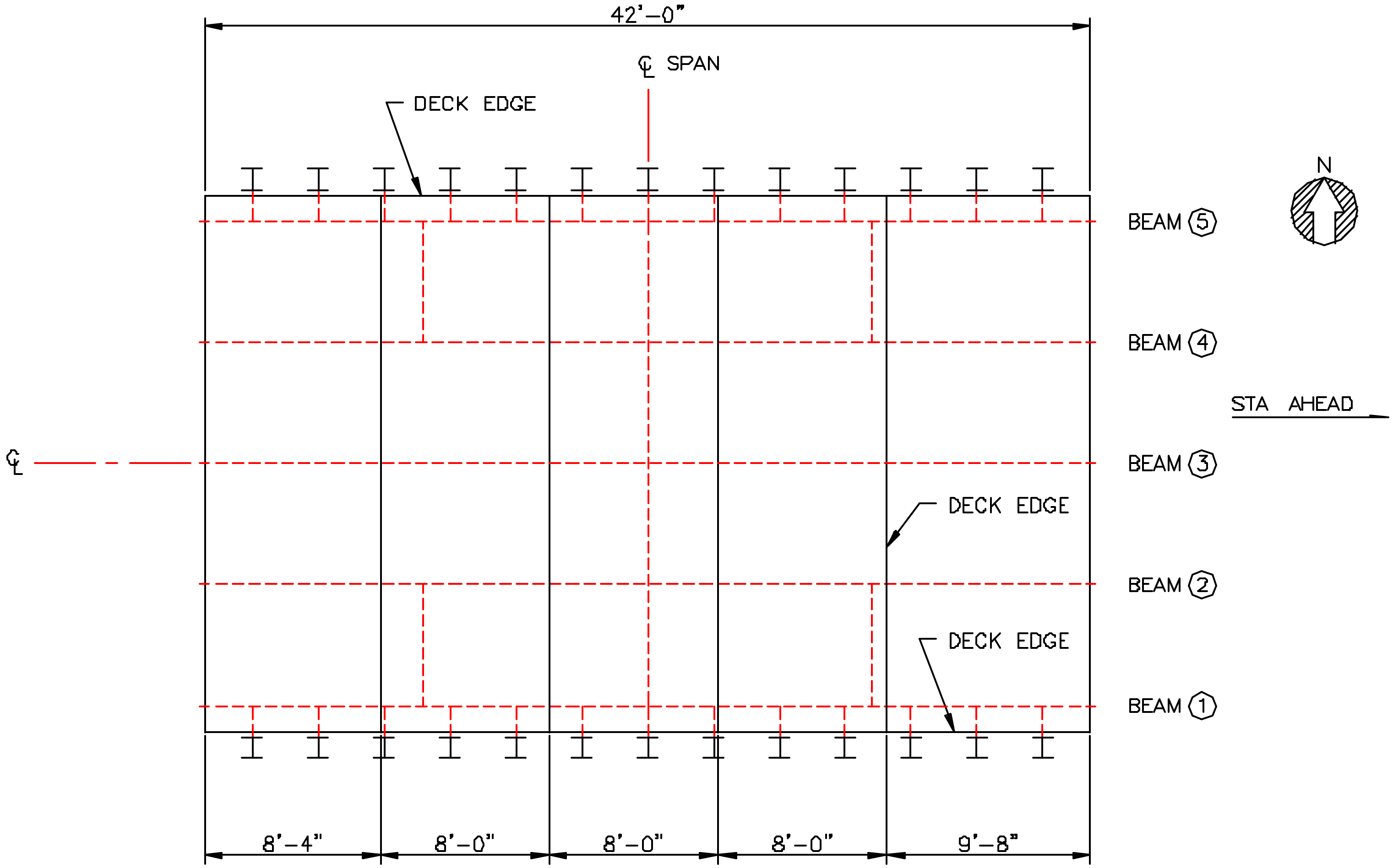

Figure A-3 – Boyer Bridge Deck Plan

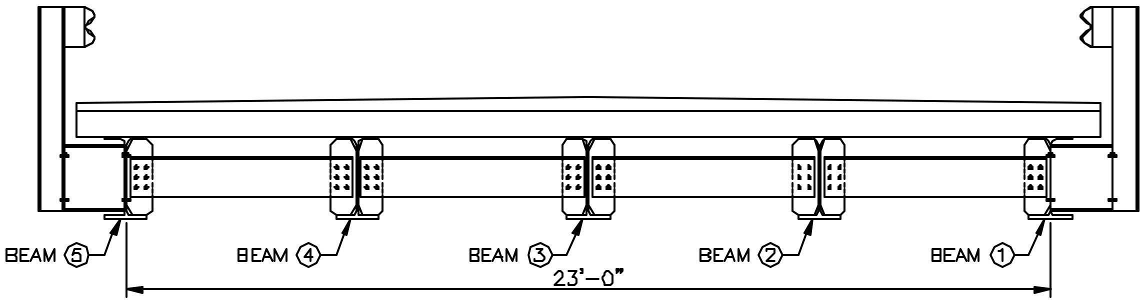

Figure A-4 – Boyer Bridge, Cross Section

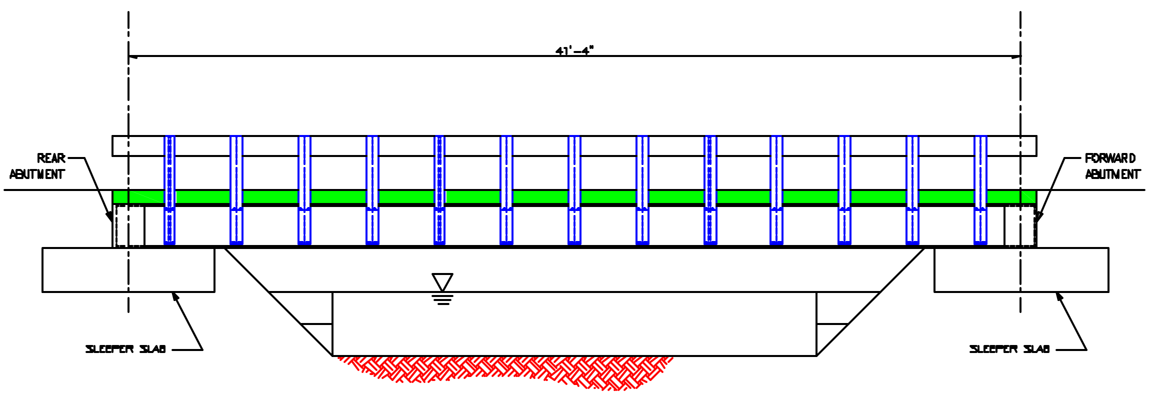

Figure A-5 – Boyer Bridge, Elevation

APPENDIX B

Boyer Bridge Project Test Setup

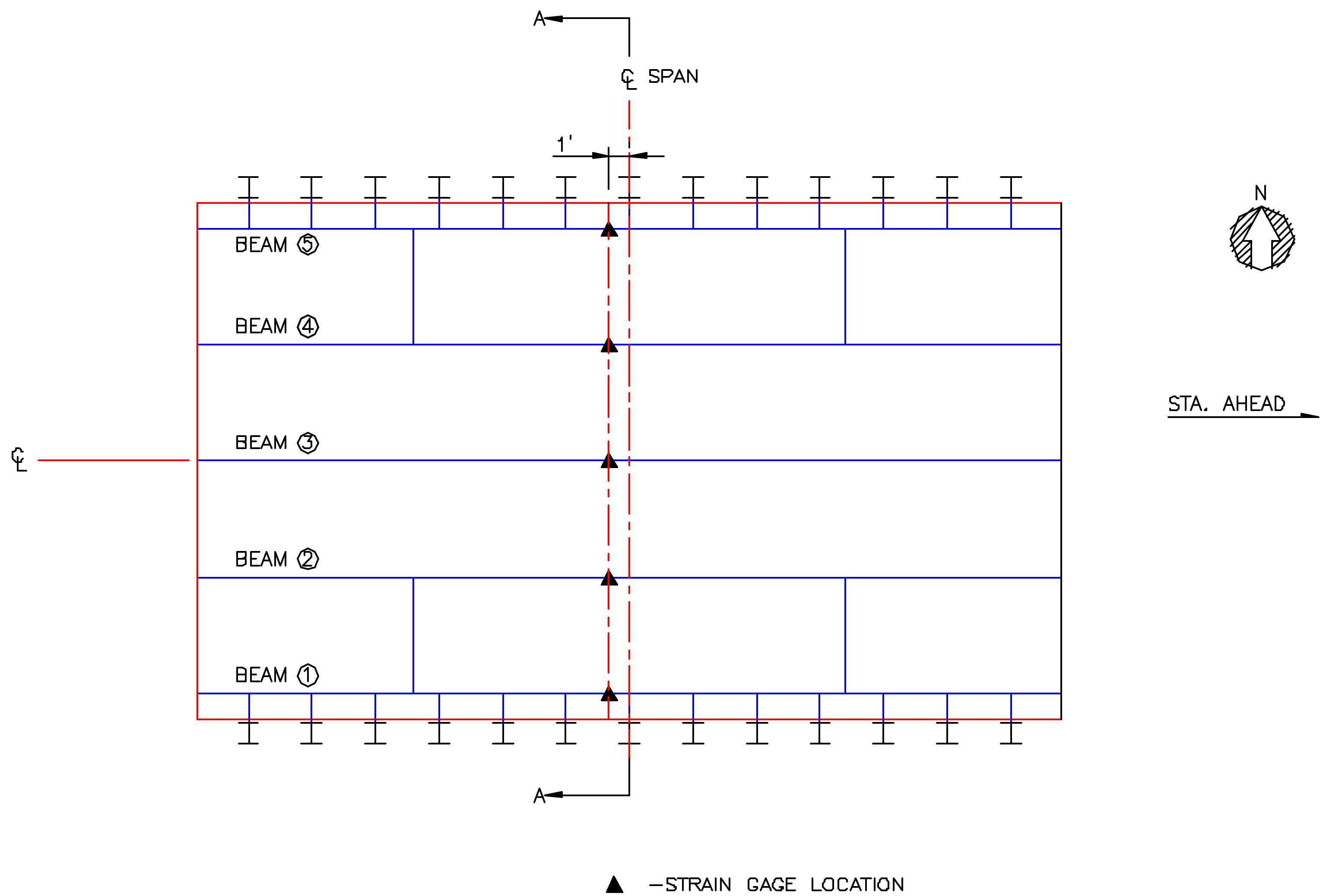

Figure B-1 – Strain Gage Layout Plan

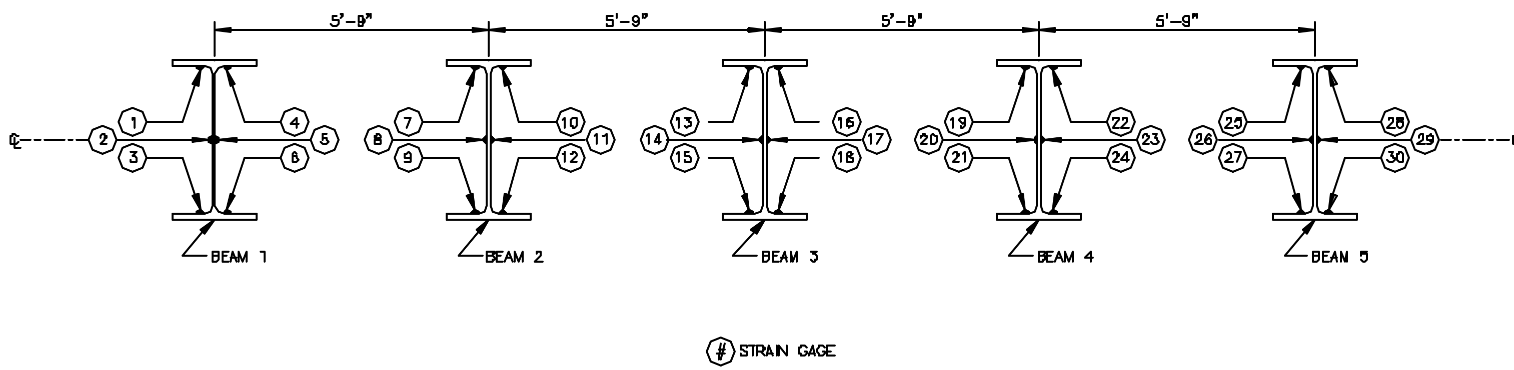

Figure B-2 – Section A-A, Strain Gage Layout

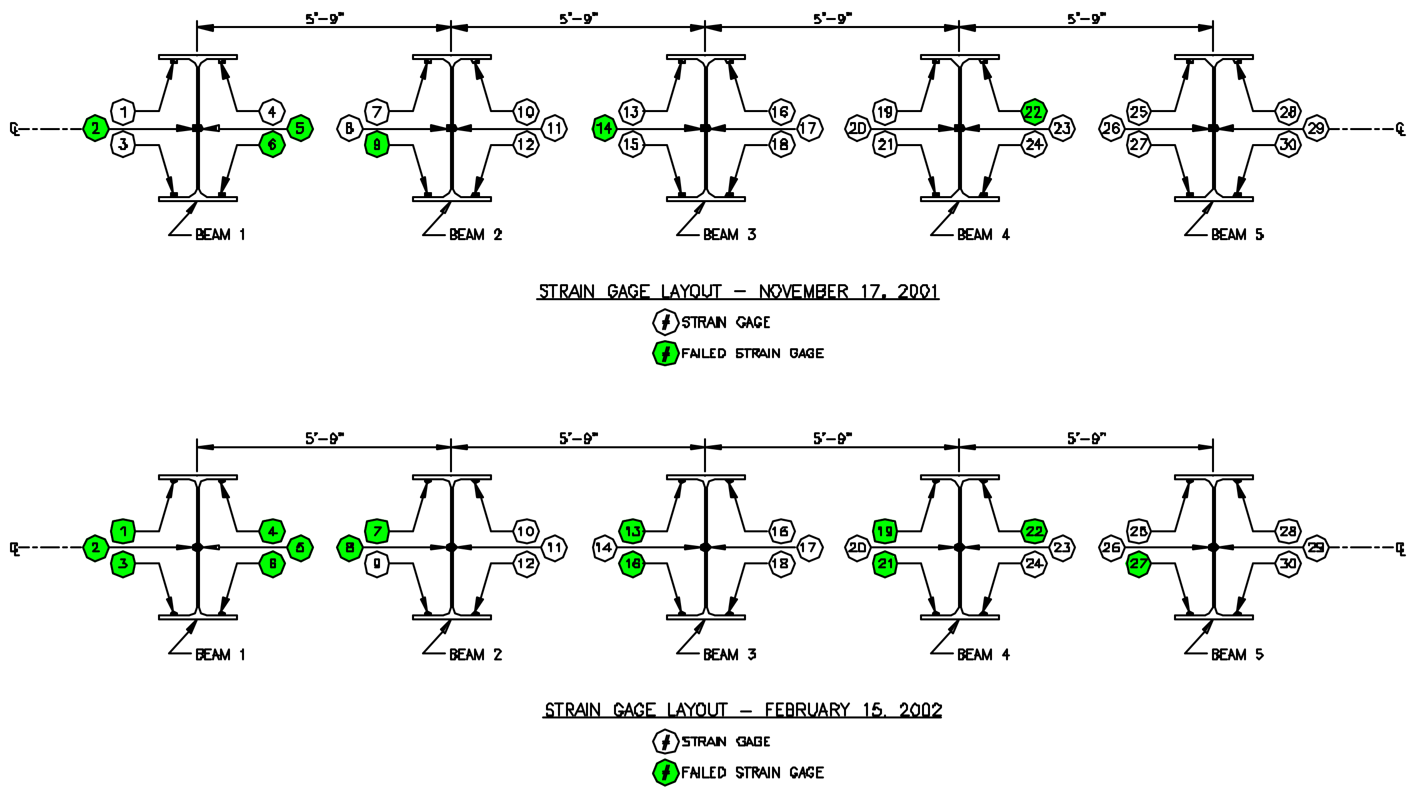

Figure B-3 – Strain Gage Failures, Unusable Data

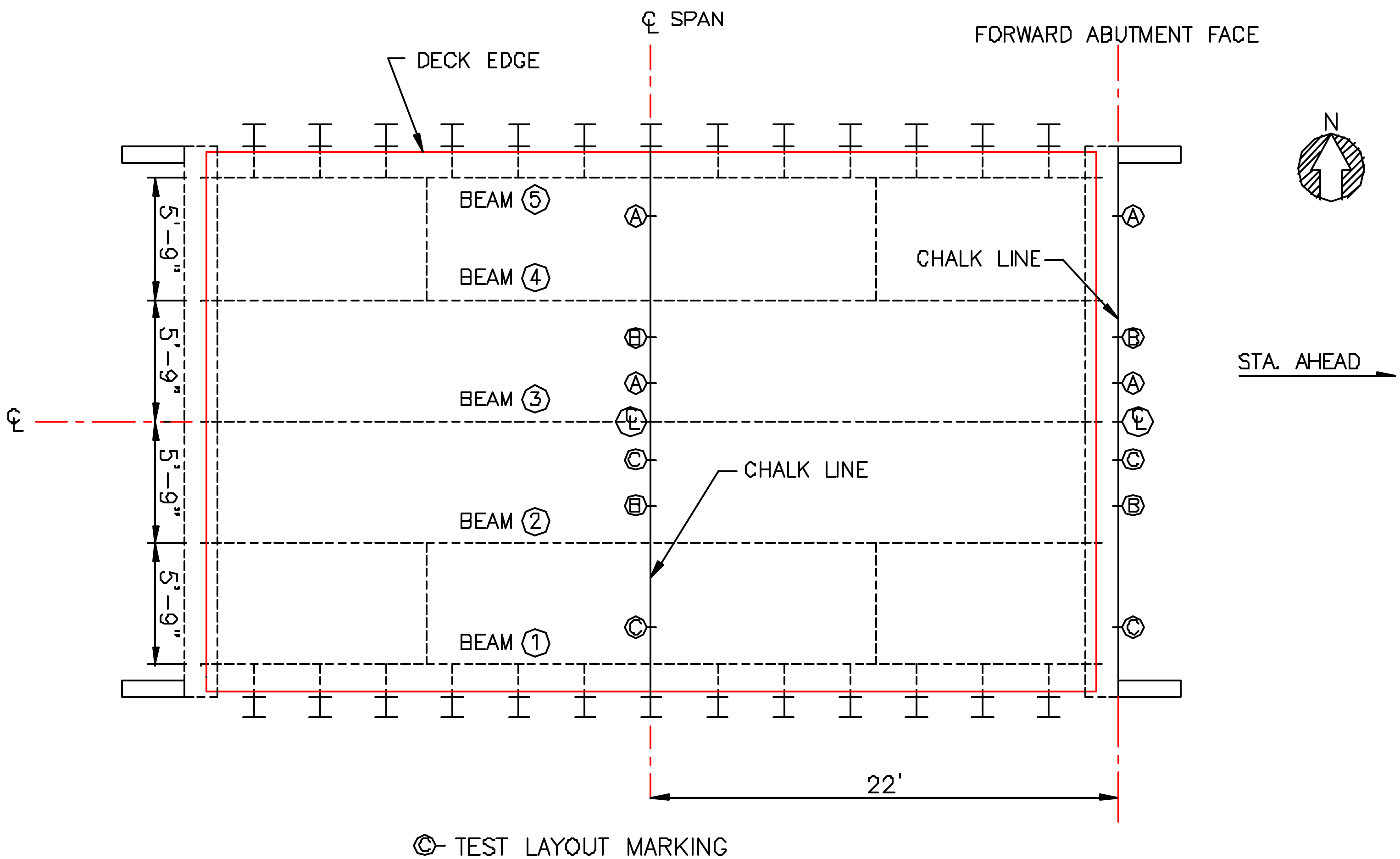

Figure B-4 – Test Layout

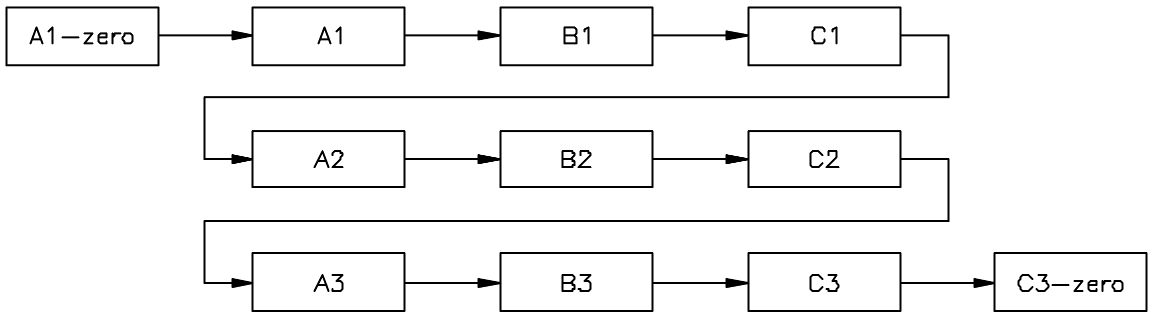

Figure B-5 - Schematic of measurements performed during November 13, 2001 field test

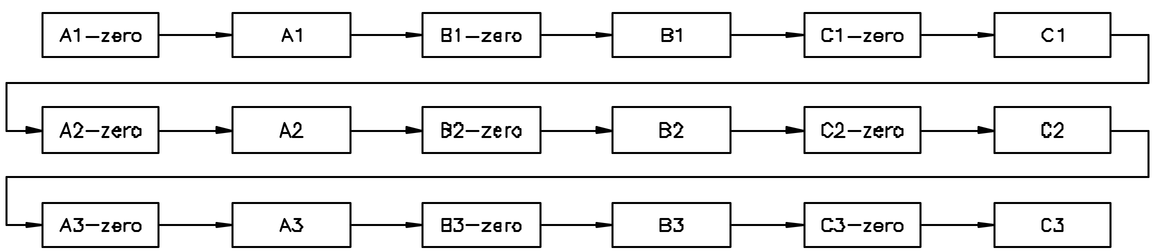

Figure B-6 - Schematic of measurements performed during February 15, 2002 field test

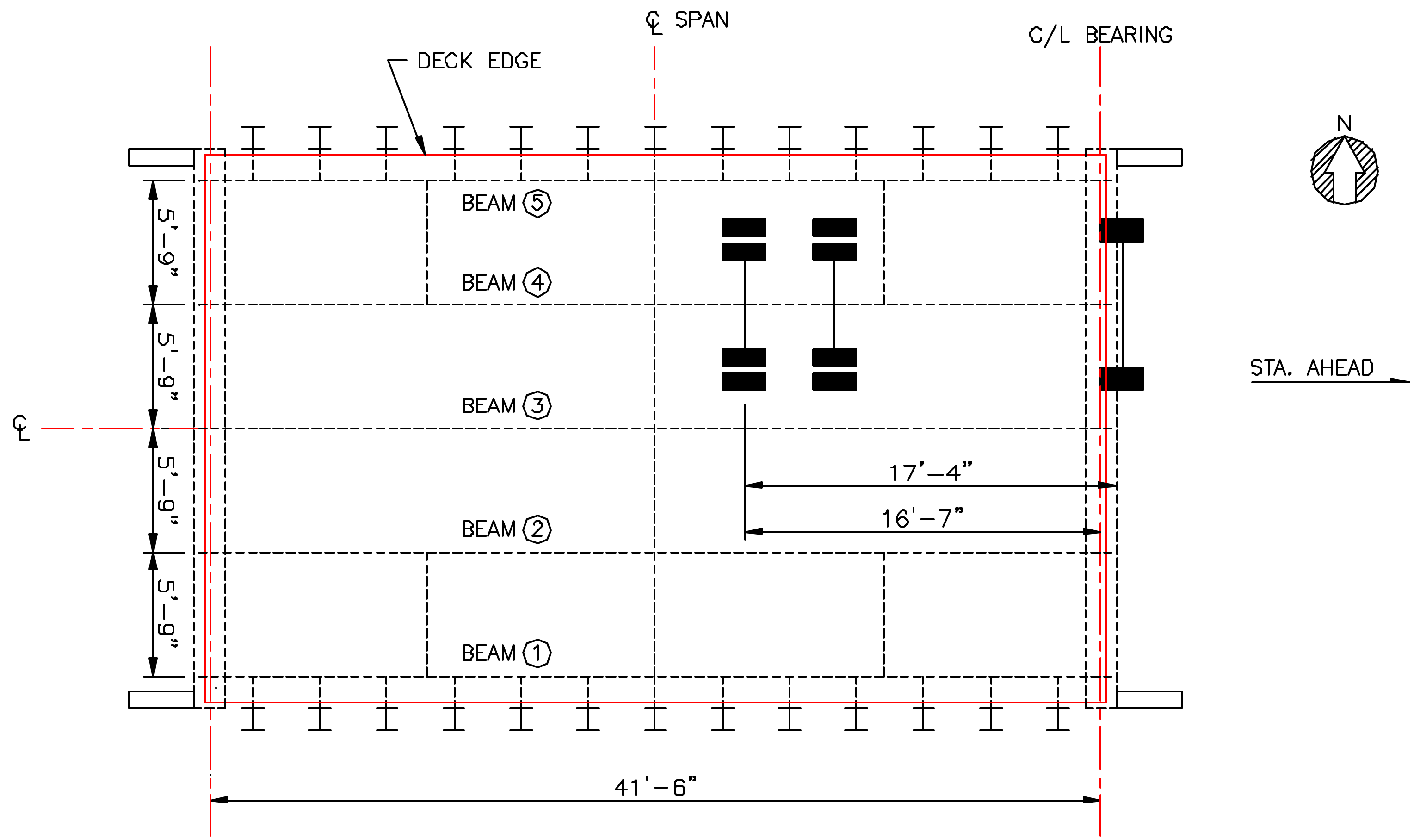

Figure B-7 – Load Position A Plan

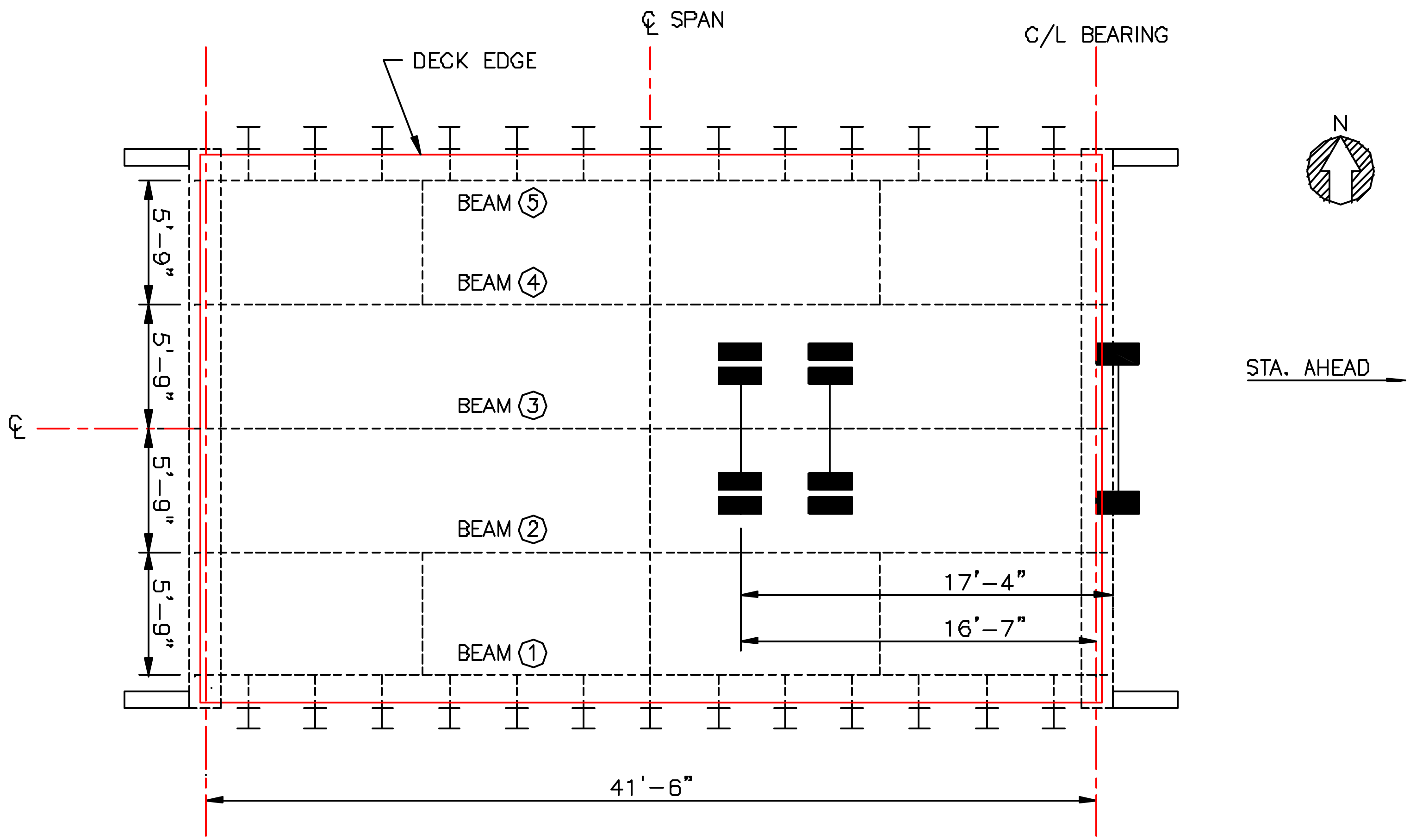

Figure B-8– Load Position B Plan

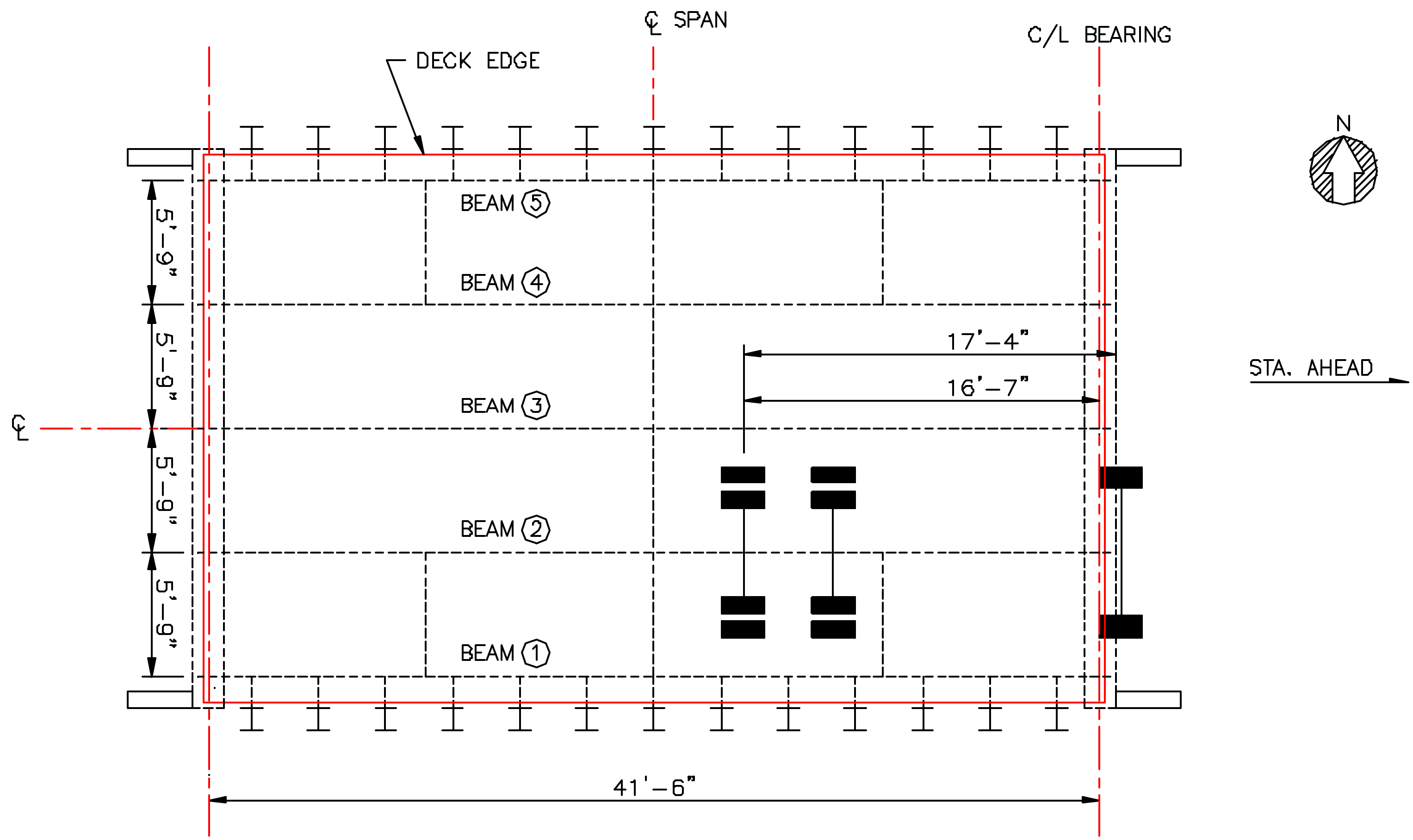

Figure B-9– Load Position C Plan

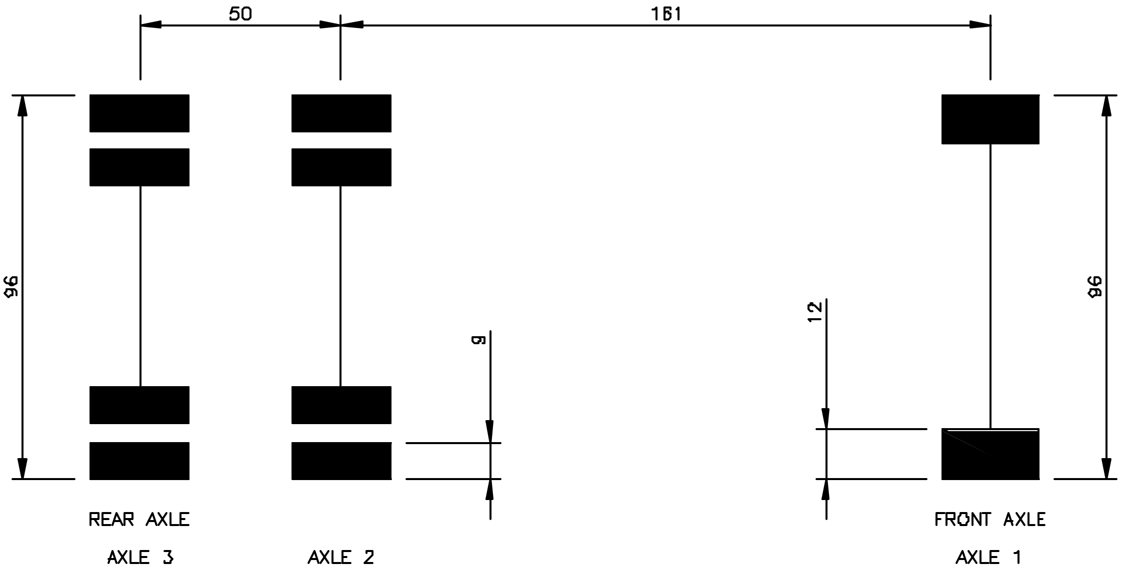

Figure B-10 – Test Vehicle (Top), Test Vehicle Dimensions (Bottom)

(All dimensions given in inches)

Table B-1 – Test Vehicle Axle Loads - November 13, 2001 Field Test

	November 13, 2001 Tests		
	Axle 1 (lbs)	Axle 2 (lbs)	Axle 3 (lbs)
Left Side	7500	9400	9100
Right Side	9400	10400	10450
Total	16900	19800	19550

Table B-2 – Test Vehicle Axle Loads – February 15, 2002 Field Test

	February 15, 2002 Tests		
	Axle 1 (lbs)	Axle 2 (lbs)	Axle 3 (lbs)
Left Side	7500	12800	12650
Right Side	8300	11850	12000
Total	15800	24650	24650

APPENDIX C

Wiring Diagrams and Schematics

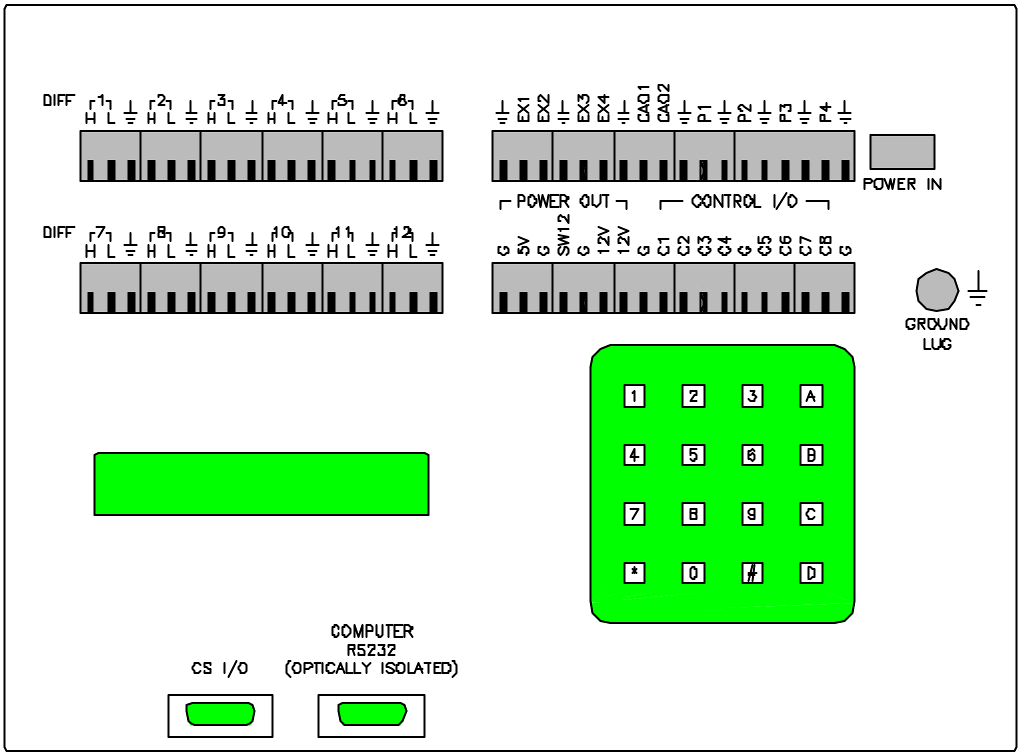

Figure C-1 - Campbell Scientific CR23x Micrologger, Wiring Terminals

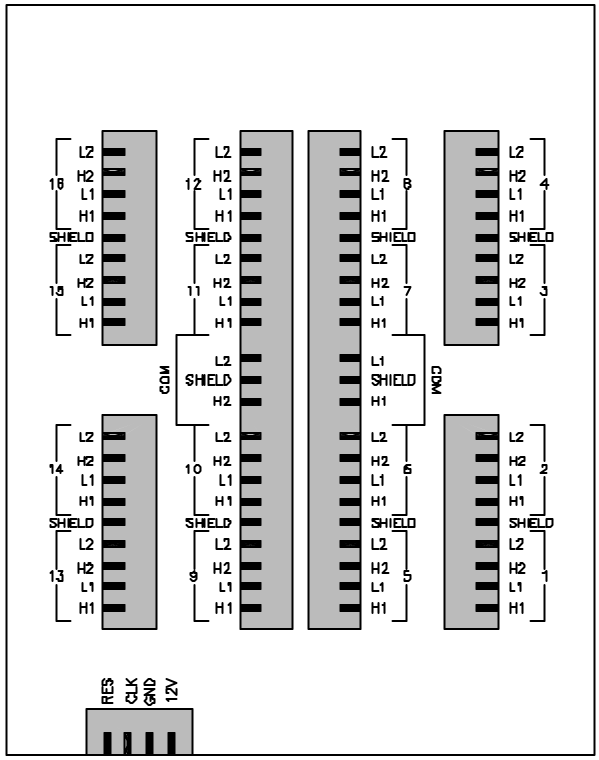

Figure C-2 - Campbell Scientific AM416 Multiplexer, Wiring Terminals

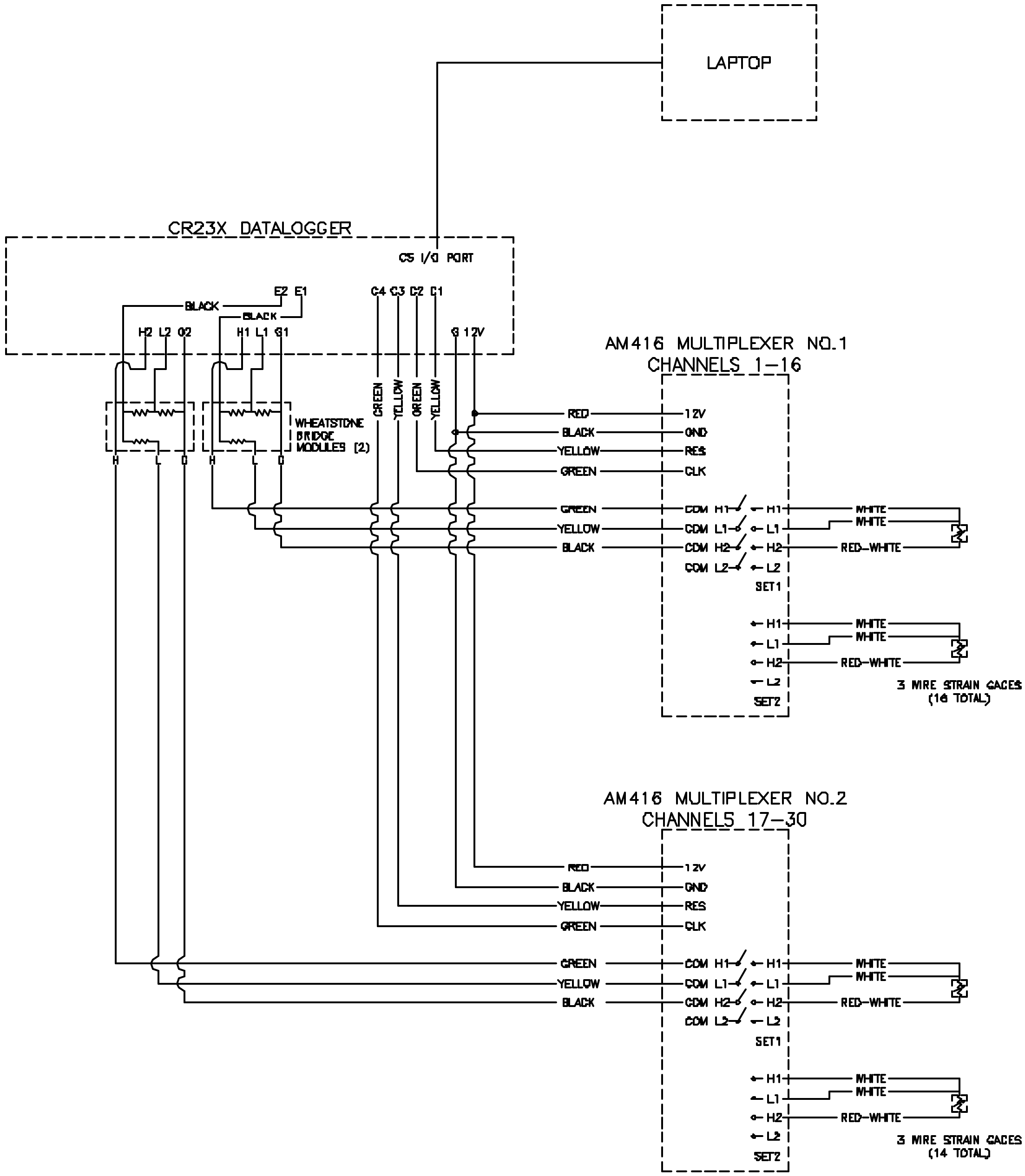

Figure C-3 - Wiring Diagram, Boyer Bridge Project

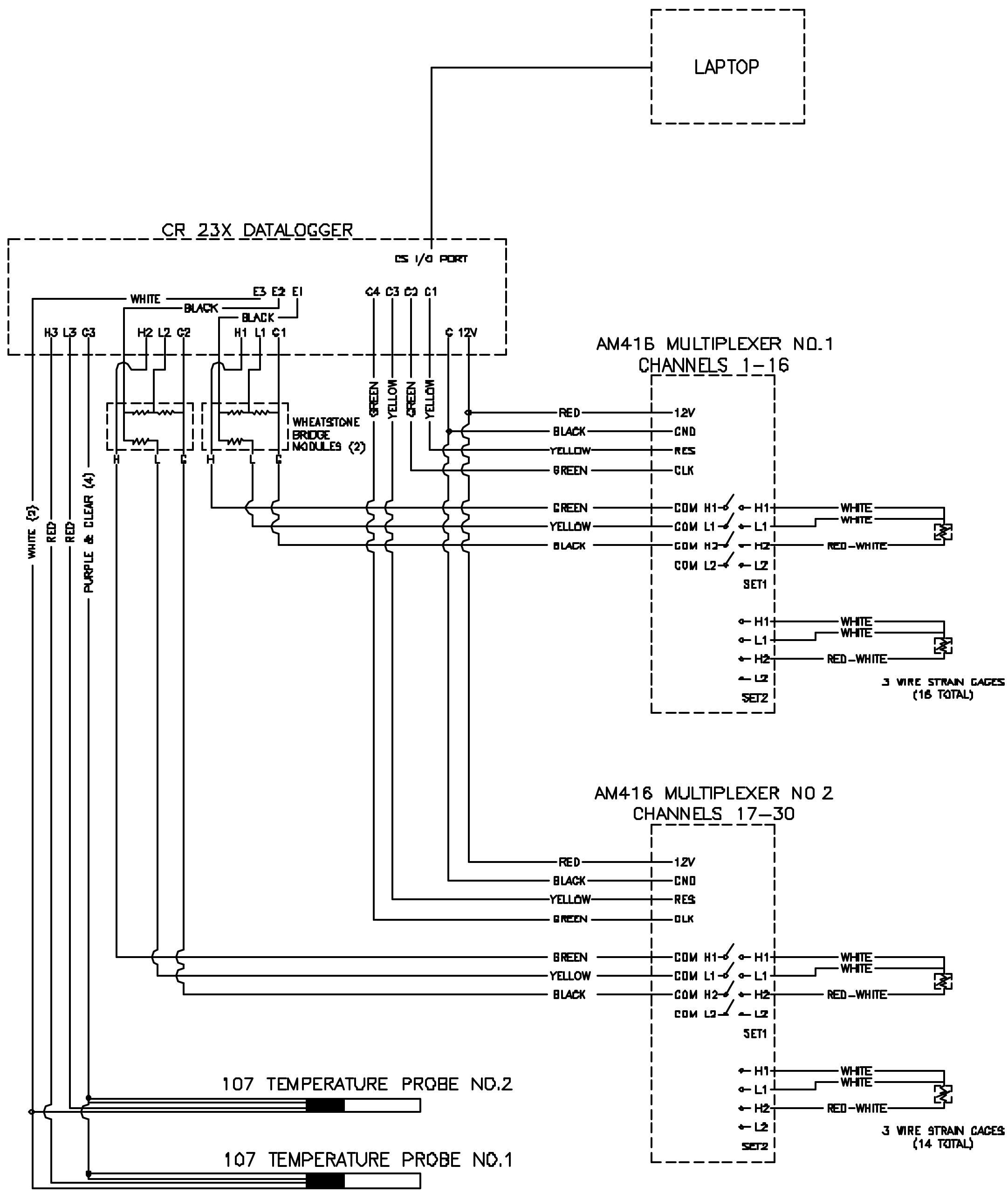

Figure C-4 - Wiring Diagram, Meadowcroft Bridge Project

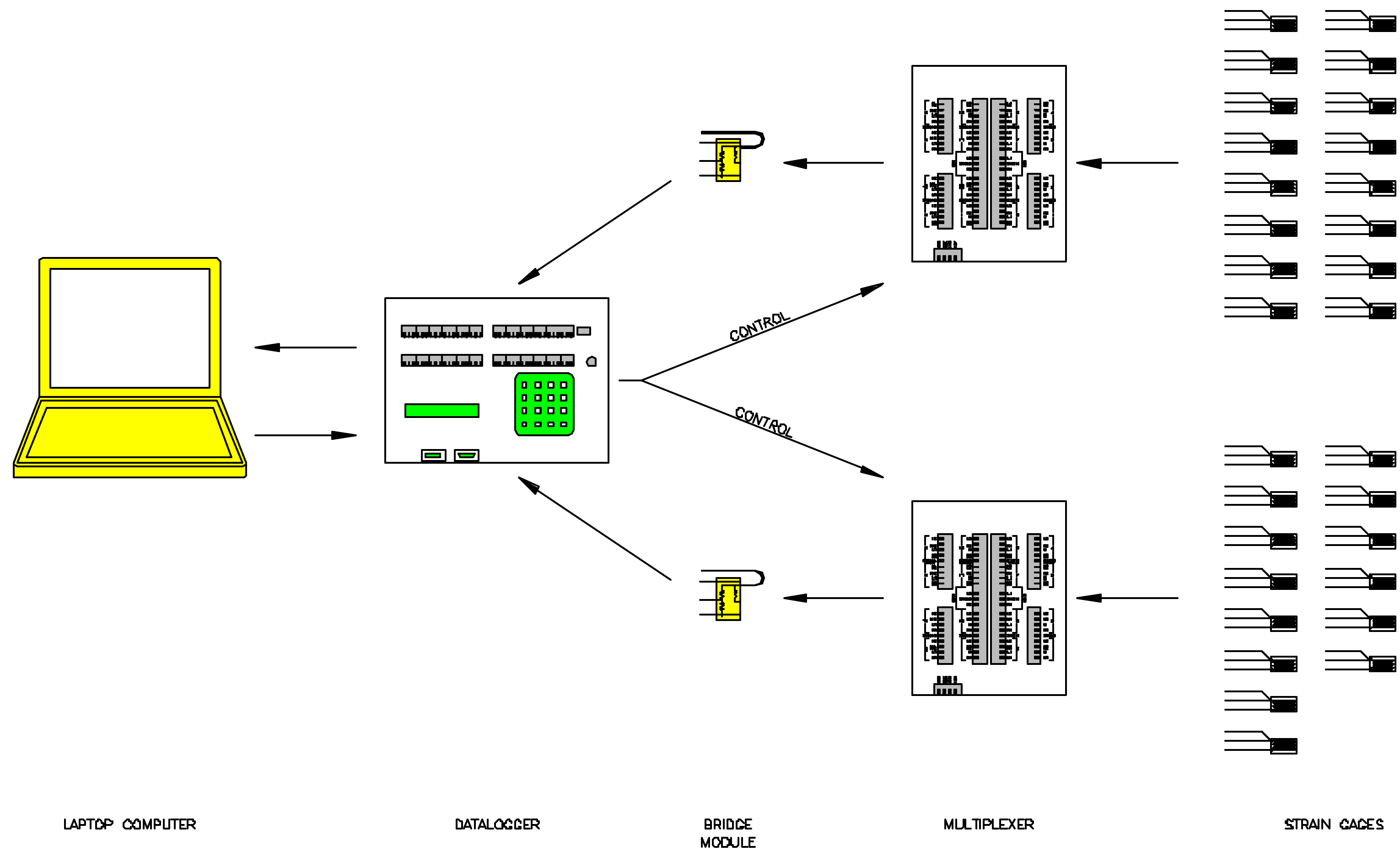

Figure C-5 - Boyer Bridge Project Setup Schematic

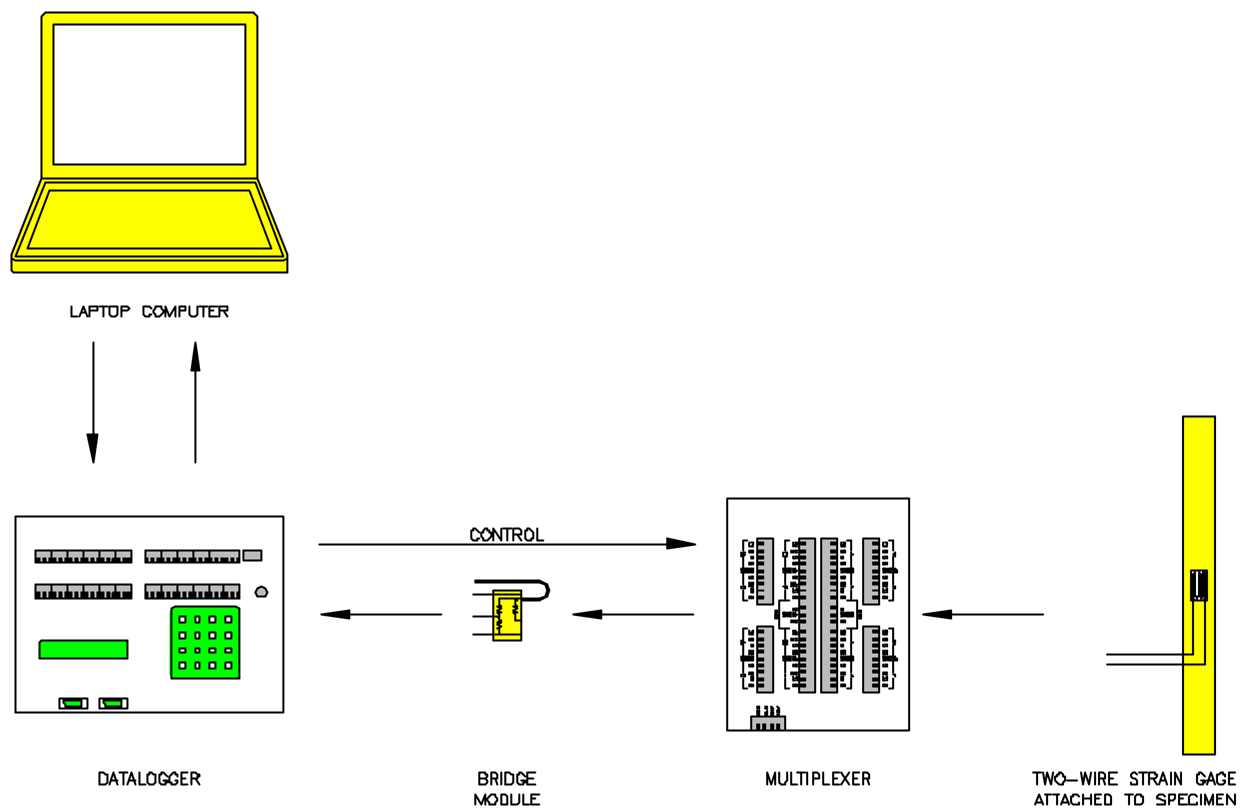

Figure C-6 - Verification Test Setup Schematic

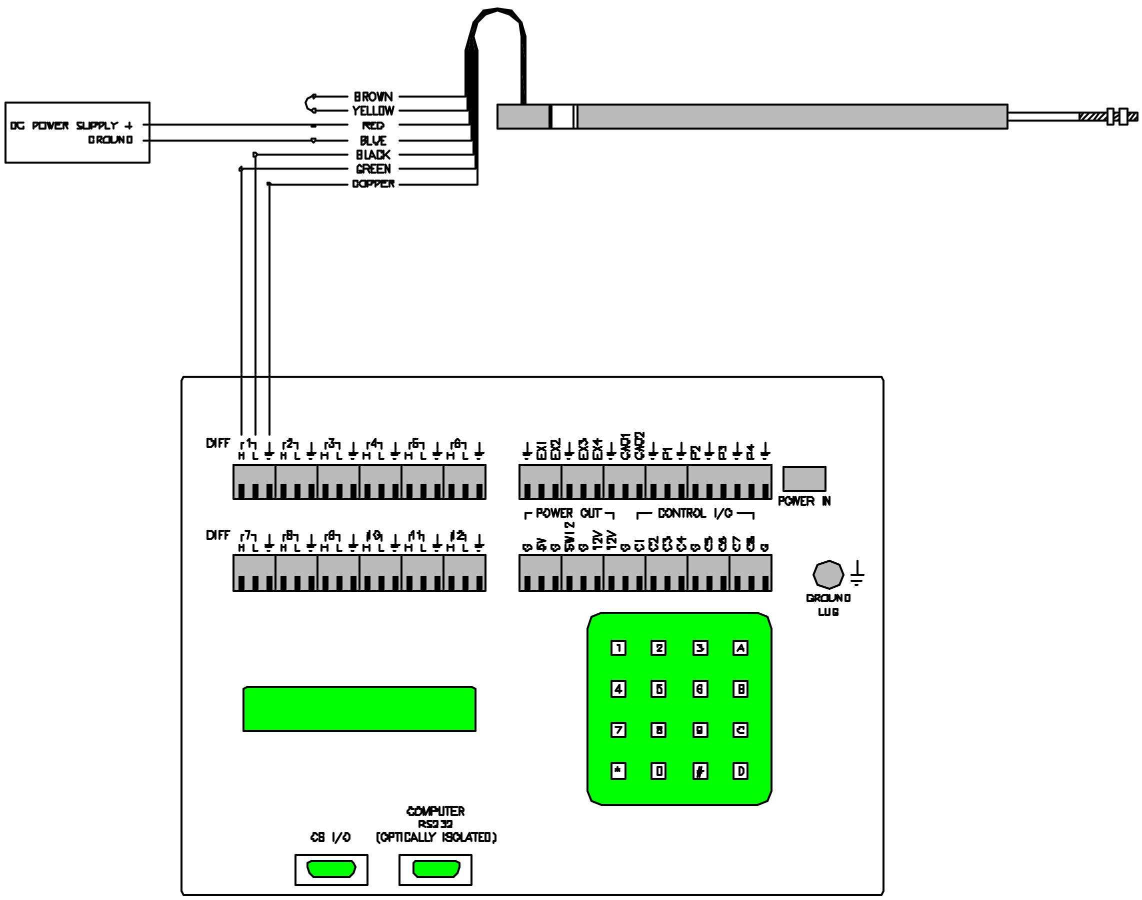

Figure C-7 - LDC3000C DCDT to CR23x Datalogger Wiring Diagram

APPENDIX D

Photographs

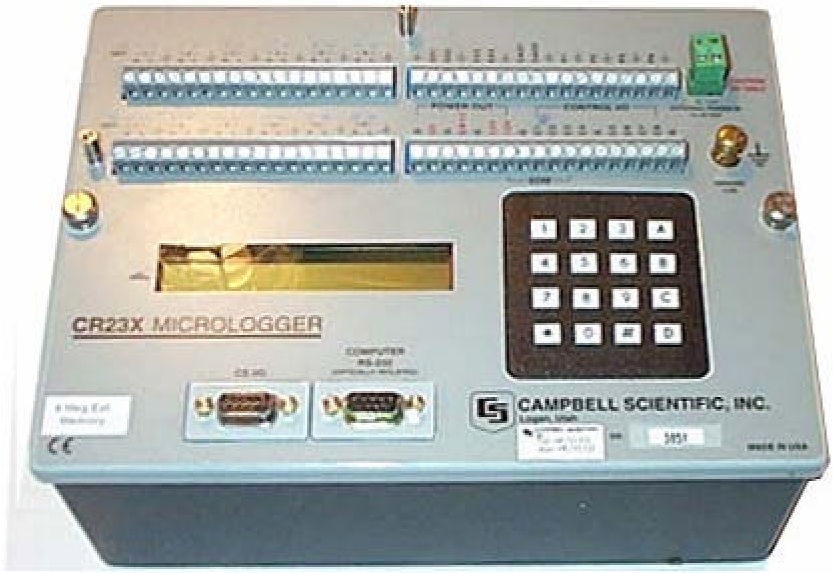

Figure D-1 - Campbell Scientific CR23x Micrologger

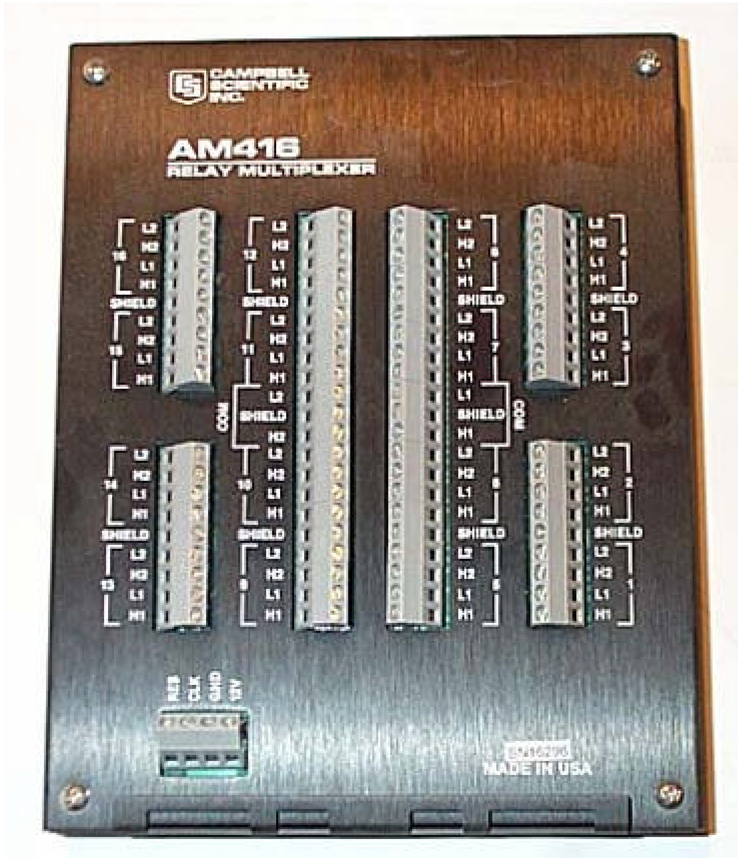

Figure D-2 - Campbell Scientific AM416 Multiplexer

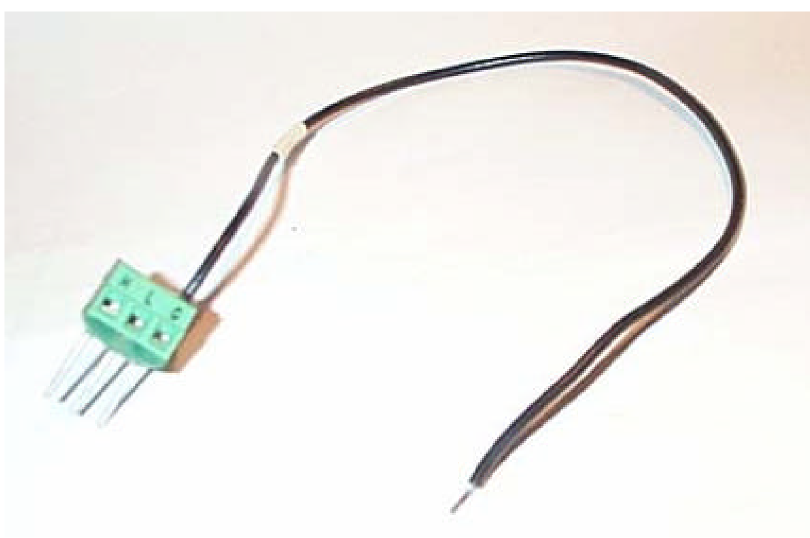

Figure D-3 - Campbell Scientific 4WFB120 4 Wire Full Bridge Terminal Input Module

Figure D-4 - Measurements Group P3500 Strain Indicator

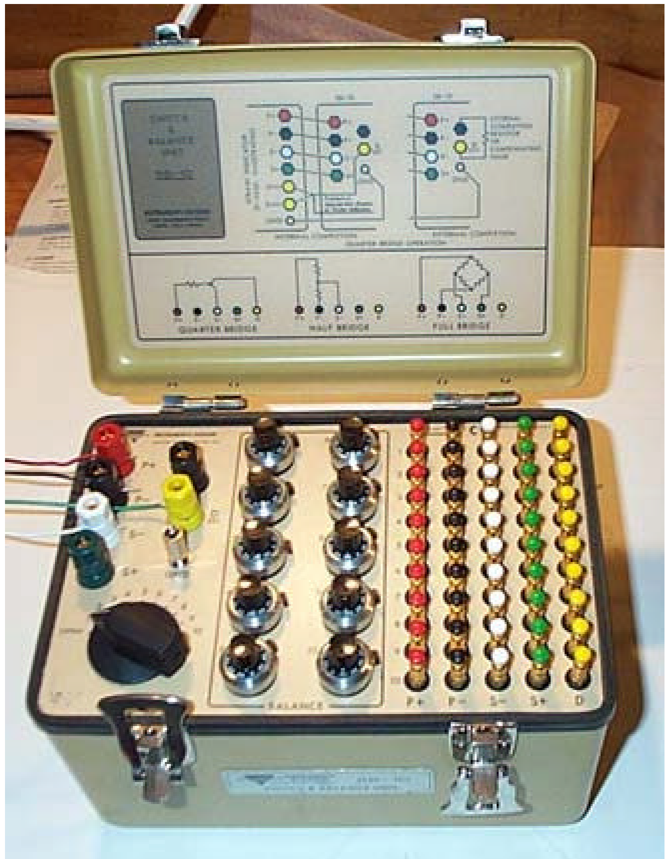

Figure D-5 - Measurements Group SB10 Switch and Balance Unit

Figure D-6 - Verification test setup

Figure D-7 - Boyer Bridge, Facing East

Figure D-8 - Boyer Bridge, Diaphragm

Figure D-9 - Boyer Bridge, Facing West

Figure D-10 - Boyer Bridge, Forward Abutment

Figure D-11 - Paving over the FRP deck, Boyer Bridge

Figure D-12 - Graduate students applying strain gages on site

Figure D-13 - Strain gages applied to stringer before erection

Figure D-14 - Strain gage wires strung along bottom flanges of stringers

Figure D-15 - Strain gage lead wires strung through stiffener plates

Figure D-16- Strain gage lead wires bundled at forward abutment

Figure D-17 - Strain gage lead wires gathered at forward abutment

Figure D-18 – Midspan test layout points

Figure D-19 - Endspan test layout points

Figure D-20 - Test layout

Figure D-21 - Boyer Bridge, showing field data acquisition setup point

Figure D-22 - Wiring the AM416 multiplexers

Figure D-23 - Wheel load measurement apparatus

Figure D-24- Measurement of test vehicle wheel loads

Figure D-25 - Test vehicle positioned off structure during "zero" measurements

Figure D-26 - Lining up test vehicle with layout markings for Position A

Figure D-27 - Position A

Figure D-28 - Measurements are recorded while in Position A

Figure D-29 - Aligning test vehicle for Position B

Figure D-30 - Field Data Acquisition Setup

Figure D-31- P3500 Strain Indicator with SB10 Switch and Balance Unit

Figure D-32 - Positioning test vehicle into Position C

Figure D-33 - Positioning test vehicle into Position B

APPENDIX E

Campbell Scientific Software

APPENDIX E Campbell Scientific Software

Appendix E.1 Campbell Scientific Software Screen Captures

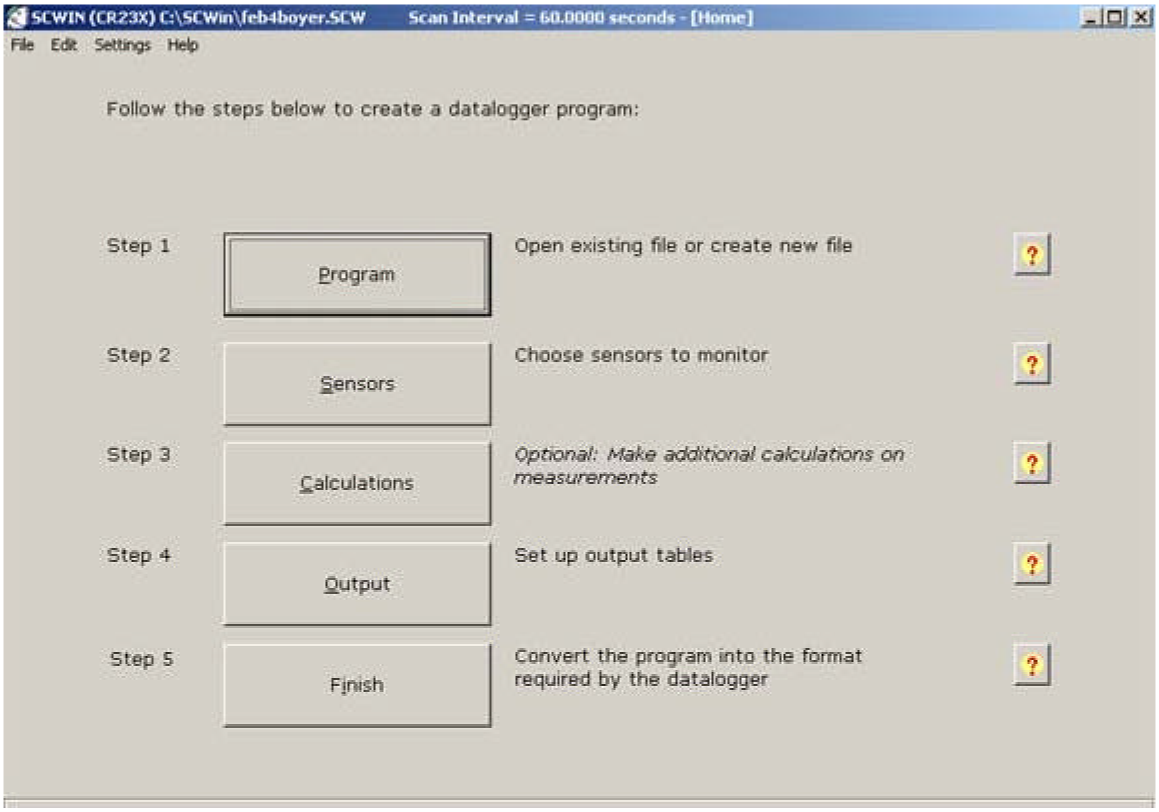

Figure E-1 - SCWin main screen

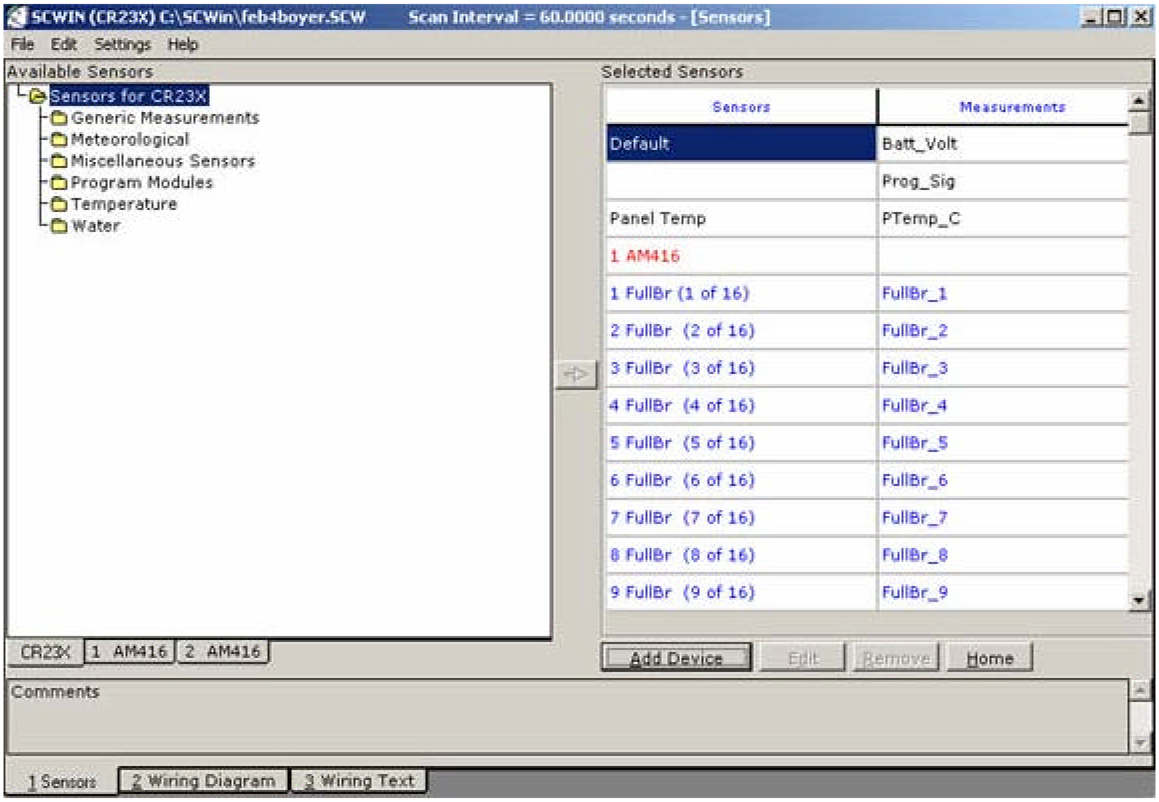

Figure E-2 - SCWin Step 2 Sensors screen

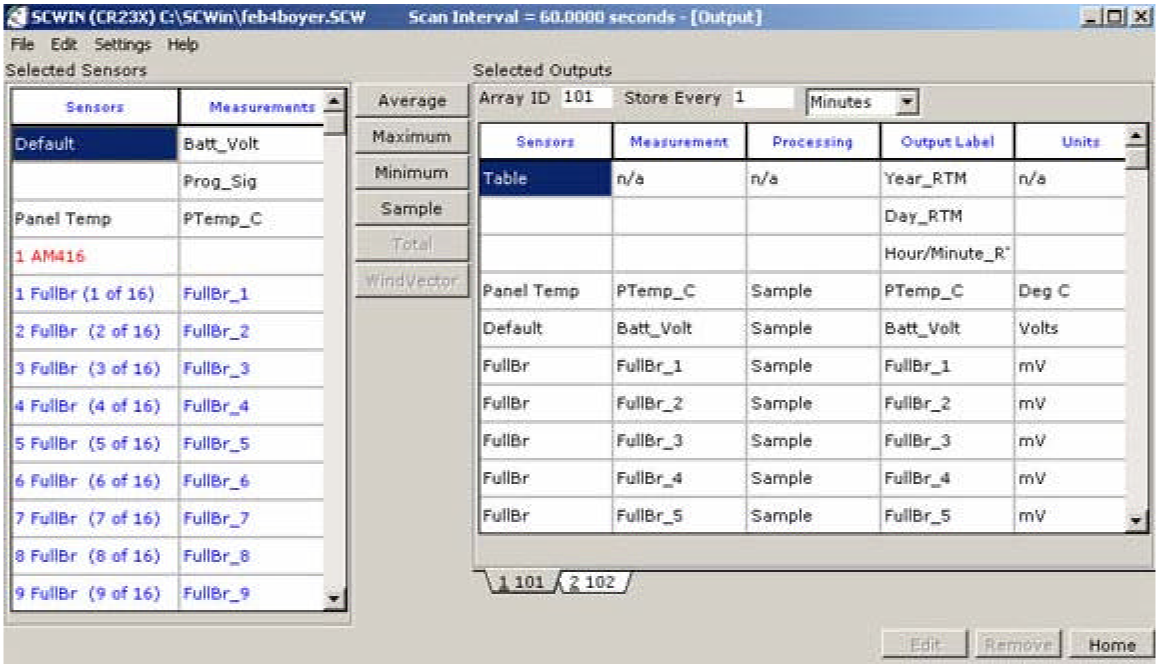

Figure E-3 - SCWin Output Screen

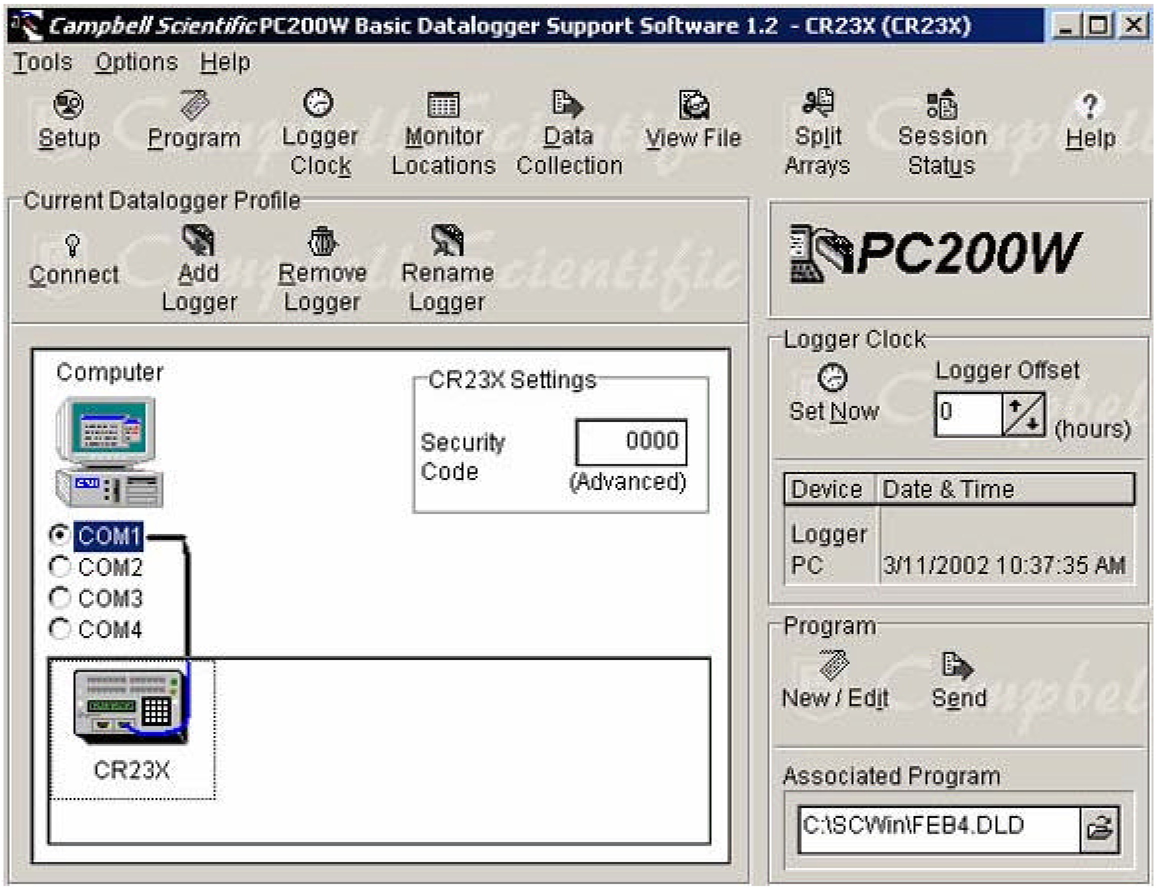

Figure E-4 - PC200W Startup screen

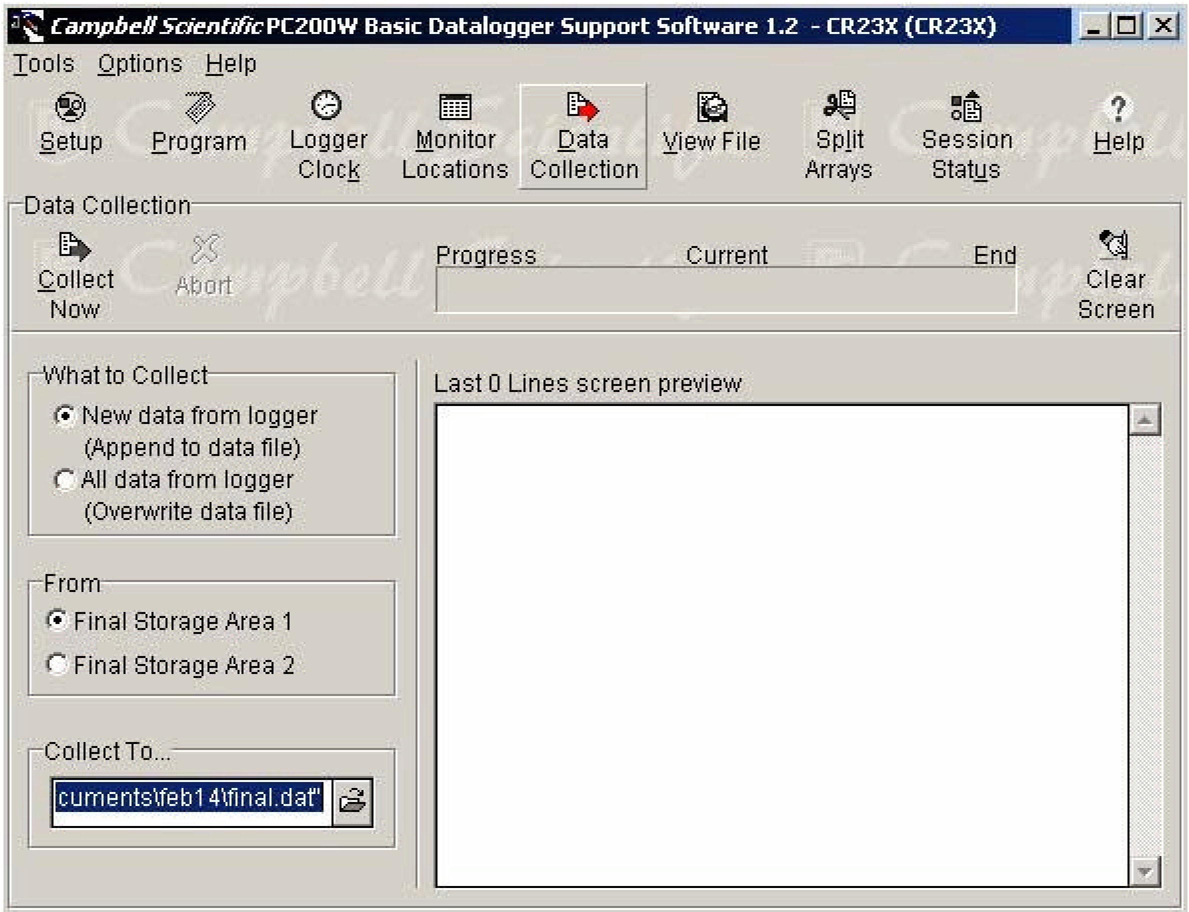

Figure E-5 - PC200W Data Collection screen

Appendix E.2 CR23x Program for February 15, 2002 field testing

```
;{CR23X}
*Table 1 Program
  01: 30.0000   Execution Interval (seconds)

1:  Batt Voltage (P10)
 1: 1        Loc [ Batt_Volt ]

2:  If time is (P92)
 1: 0        Minutes (Seconds --) into a
 2: 1440     Interval (same units as above)
 3: 30       Then Do

3:  Signature (P19)
 1: 2        Loc [ Prog_Sig  ]

4:  End (P95)

5:  Do (P86)
 1: 41       Set Port 1 High

6:  Beginning of Loop (P87)
 1: 0        Delay
 2: 16       Loop Count

7:  Do (P86)
 1: 72       Pulse Port 2

8:  Delay w/Opt Excitation (P22)
 1: 1        Ex Channel
 2: 0        Delay W/Ex (units = 0.01 sec)
 3: 1        Delay After Ex (units = 0.01 sec)
 4: 0        mV Excitation

9:  Delay w/Opt Excitation (P22)
 1: 1        Ex Channel
 2: 0        Delay W/Ex (units = 0.01 sec)
 3: 1        Delay After Ex (units = 0.01 sec)
 4: 0        mV Excitation

10:  Full Bridge (P6)
 1: 1        Reps
 2: 21       10 mV, 60 Hz Reject, Slow Range
 3: 1        DIFF Channel
 4: 1        Excite all reps w/Exchan 1
 5: 2000     mV Excitation
 6: 3     -- Loc [ FullBr_1  ]
 7: 1.0      Mult
 8: 0.0      Offset

11:  End (P95)

12:  Do (P86)
```

```
 1: 51       Set Port 1 Low

13:  Do (P86)
 1: 43       Set Port 3 High

14:  Beginning of Loop (P87)
 1: 0        Delay
 2: 14       Loop Count

15:  Do (P86)
 1: 74       Pulse Port 4

16:  Delay w/Opt Excitation (P22)
 1: 1        Ex Channel
 2: 0        Delay W/Ex (units = 0.01 sec)
 3: 1        Delay After Ex (units = 0.01 sec)
 4: 0        mV Excitation

17:  Delay w/Opt Excitation (P22)
 1: 1        Ex Channel
 2: 0        Delay W/Ex (units = 0.01 sec)
 3: 1        Delay After Ex (units = 0.01 sec)
 4: 0        mV Excitation

18:  Full Bridge (P6)
 1: 1        Reps
 2: 21       10 mV, 60 Hz Reject, Slow Range
 3: 2        DIFF Channel
 4: 2        Excite all reps w/Exchan 2
 5: 2000     mV Excitation
 6: 19    -- Loc [ FullBr_17 ]
 7: 1.0      Mult
 8: 0.0      Offset

19:  End (P95)

20:  Do (P86)
 1: 53       Set Port 3 Low

21:  If time is (P92)
 1: 0        Minutes (Seconds --) into a
 2: 1        Interval (same units as above)
 3: 10       Set Output Flag High (Flag 0)

22:  Set Active Storage Area (P80)
 1: 1        Final Storage Area 1
 2: 101      Array ID

23:  Real Time (P77)
 1: 1220     Year,Day,Hour/Minute (midnight = 2400)

24:  Resolution (P78)
 1: 1        High Resolution

25:  Sample (P70)
 1: 1        Reps
 2: 3        Loc [ FullBr_1  ]
```

```
26:  Sample (P70)
 1: 1        Reps
 2: 4        Loc [ FullBr_2  ]

27:  Sample (P70)
 1: 1        Reps
 2: 5        Loc [ FullBr_3  ]

28:  Sample (P70)
 1: 1        Reps
 2: 6        Loc [ FullBr_4  ]

29:  Sample (P70)
 1: 1        Reps
 2: 7        Loc [ FullBr_5  ]

30:  Sample (P70)
 1: 1        Reps
 2: 8        Loc [ FullBr_6  ]

31:  Sample (P70)
 1: 1        Reps
 2: 9        Loc [ FullBr_7  ]

32:  Sample (P70)
 1: 1        Reps
 2: 10       Loc [ FullBr_8  ]

33:  Sample (P70)
 1: 1        Reps
 2: 11       Loc [ FullBr_9  ]

34:  Sample (P70)
 1: 1        Reps
 2: 12       Loc [ FullBr_10 ]

35:  Sample (P70)
 1: 1        Reps
 2: 13       Loc [ FullBr_11 ]

36:  Sample (P70)
 1: 1        Reps
 2: 14       Loc [ FullBr_12 ]

37:  Sample (P70)
 1: 1        Reps
 2: 15       Loc [ FullBr_13 ]

38:  Sample (P70)
 1: 1        Reps
 2: 16       Loc [ FullBr_14 ]

39:  Sample (P70)
 1: 1        Reps
 2: 17       Loc [ FullBr_15 ]
```

```
40:  Sample (P70)
 1: 1        Reps
 2: 18       Loc [ FullBr_16 ]

41:  Sample (P70)
 1: 1        Reps
 2: 19       Loc [ FullBr_17 ]

42:  Sample (P70)
 1: 1        Reps
 2: 20       Loc [ FullBr_18 ]

43:  Sample (P70)
 1: 1        Reps
 2: 21       Loc [ FullBr_19 ]

44:  Sample (P70)
 1: 1        Reps
 2: 22       Loc [ FullBr_20 ]

45:  Sample (P70)
 1: 1        Reps
 2: 23       Loc [ FullBr_21 ]

46:  Sample (P70)
 1: 1        Reps
 2: 24       Loc [ FullBr_22 ]

47:  Sample (P70)
 1: 1        Reps
 2: 25       Loc [ FullBr_23 ]

48:  Sample (P70)
 1: 1        Reps
 2: 26       Loc [ FullBr_24 ]

49:  Sample (P70)
 1: 1        Reps
 2: 27       Loc [ FullBr_25 ]

50:  Sample (P70)
 1: 1        Reps
 2: 28       Loc [ FullBr_26 ]

51:  Sample (P70)
 1: 1        Reps
 2: 29       Loc [ FullBr_27 ]

52:  Sample (P70)
 1: 1        Reps
 2: 30       Loc [ FullBr_28 ]

53:  Sample (P70)
 1: 1        Reps
 2: 31       Loc [ FullBr_29 ]

54:  Sample (P70)
```

```
 1: 1        Reps
 2: 32       Loc [ FullBr_30 ]


55:  If time is (P92)
 1: 0        Minutes (Seconds --) into a
 2: 1440     Interval (same units as above)
 3: 10       Set Output Flag High (Flag 0)

56:  Set Active Storage Area (P80)
 1: 1        Final Storage Area 1
 2: 102      Array ID

57:  Real Time (P77)
 1: 1220     Year,Day,Hour/Minute (midnight = 2400)

58:  Minimum (P74)
 1: 1        Reps
 2: 0        Value Only
 3: 1        Loc [ Batt_Volt ]

59:  Sample (P70)
 1: 1        Reps
 2: 2        Loc [ Prog_Sig  ]

*Table 2 Program
  01: 10.0000   Execution Interval (seconds)

1:  Serial Out (P96)
 1: 71       Destination Output

*Table 3 Subroutines

End Program

-Input Locations-
1 Batt_Volt 1 1 1
2 Prog_Sig  1 1 1
3 FullBr_1  1 1 1
4 FullBr_2  1 1 0
5 FullBr_3  1 1 0
6 FullBr_4  1 1 0
7 FullBr_5  1 1 0
8 FullBr_6  1 1 0
9 FullBr_7  1 1 0
10 FullBr_8  1 1 0
11 FullBr_9  1 1 0
12 FullBr_10 1 1 0
13 FullBr_11 1 1 0
14 FullBr_12 1 1 0
15 FullBr_13 1 1 0
16 FullBr_14 1 1 0
17 FullBr_15 1 1 0
18 FullBr_16 1 1 0
19 FullBr_17 1 1 1
20 FullBr_18 1 1 0
21 FullBr_19 1 1 0
```

```
22 FullBr_20 1 1 0
23 FullBr_21 1 1 0
24 FullBr_22 1 1 0
25 FullBr_23 1 1 0
26 FullBr_24 1 1 0
27 FullBr_25 1 1 0
28 FullBr_26 1 1 0
29 FullBr_27 1 1 0
30 FullBr_28 1 1 0
31 FullBr_29 1 1 0
32 FullBr_30 1 1 0
-Program Security-
0
0
0
-Mode 4-
-Final Storage Area 2-
0
-CR10X ID-
0
-CR10X Power Up-
3
-CR10X Compile Setting-
3
-CR10X RS-232 Setting-
-1
```

APPENDIX F

Boyer Bridge Project - November 13, 2001 Field Test, CR23x Datalogger Data

Table F-1– V_0 Measurement, Position A, Beam 1

	Beam 1 – Strain Gage Channel Measurement, V_0					
	1	2	3	4	5	6
A1	-0.710	-	-0.614	-0.464	-	-
	-0.710	-	-0.614	-0.463	-	-
C3	-0.700	-	-0.611	-0.457	-	-
	-0.699	-	-0.612	-0.456	-	-
Average	-0.705	-	-0.613	-0.460	-	-
Minimum	-0.710	-	-0.614	-0.464	-	-
Maximum	-0.699	-	-0.611	-0.456	-	-
Standard Deviation	0.006	-	0.001	0.004	-	-

Table F-2– V_1 Measurement, Position A, Beam 1

Position A	Beam 1 – Strain Gage Channel Measurement, V_1					
	1	2	3	4	5	6
1	-0.708	-	-0.614	-0.462	-	-
	-0.707	-	-0.613	-0.462	-	-
2	-0.703	-	-0.613	-0.460	-	-
3	-0.699	-	-0.612	-0.457	-	-
	-0.699	-	-0.612	-0.457	-	-
Average	-0.703	-	-0.613	-0.460	-	-
Minimum	-0.708	-	-0.614	-0.462	-	-
Maximum	-0.699	-	-0.612	-0.457	-	-
Standard Deviation	0.004	-	0.001	0.003	-	-

Table F-3– V_r Measurement, Position A, Beam 1

Position A	Beam 1 – Strain Gage Channel Measurement, V_r					
	1	2	3	4	5	6
1	0.002	-	0.001	0.002	-	-
2	-0.003	-	-0.002	-0.004	-	-
3	0.001	-	-0.001	-0.001	-	-
Average	0.000	-	-0.001	-0.001	-	-
Minimum	-0.003	-	-0.002	-0.004	-	-
Maximum	0.002	-	0.001	0.002	-	-
Standard Deviation	0.003	-	0.001	0.003	-	-

Table F-4– Strain Measurement, Position A, Beam 1

Test A	Beam 1 - Strain Measurement, Microstrain					
	1	2	3	4	5	6
1	5	-	1	3	-	-
2	-7	-	-3	-7	-	-
3	1	-	-1	-1	-	-
Average	0	-	-1	-2	-	-
Minimum	-7	-	-3	-7	-	-
Maximum	5	-	1	3	-	-
Standard Deviation	6	-	2	5	-	-

Table F-5– Maximum Ranges, Position A, Beam 1

Position A	Beam 1						Beam
	1	2	3	4	5	6	Max
Max Range, V_r	0.006	-	0.002	0.005	-	-	0.006
Microstrain	11	-	4	9	-	-	11
Stress, ksi	0.32524	-	0.10841	0.27103	-	-	0.3

Table F-6– V_0 Measurement, Position A, Beam 2

	Beam 2 - Strain Gage Channel Measurement, V_0					
	7	8	9	10	11	12
A1	0.489	-1.033	-	0.108	0.347	-0.741
	0.490	-1.032	-	0.108	0.347	-0.740
C3	0.497	-1.025	-	0.117	0.356	-0.717
	0.498	-1.025	-	0.118	0.356	-0.717
Average	0.494	-1.029	-	0.113	0.352	-0.729
Minimum	0.489	-1.033	-	0.108	0.347	-0.741
Maximum	0.498	-1.025	-	0.118	0.356	-0.717
Standard Deviation	0.005	0.004	-	0.006	0.005	0.014

Table F-7- V_1 Measurement, Position A, Beam 2

Position A	Beam 2 - Strain Gage Channel Measurement, V_1					
	7	8	9	10	11	12
1	0.484	-1.028	-	0.102	0.353	-0.723
	0.485	-1.027	-	0.103	0.353	-0.723
2	0.488	-1.021	-	0.106	0.357	-0.710
3	0.489	-1.021	-	0.108	0.358	-0.707
	0.489	-1.021	-	0.108	0.358	-0.706
Average	0.487	-1.024	-	0.105	0.356	-0.714
Minimum	0.484	-1.028	-	0.102	0.353	-0.723
Maximum	0.489	-1.021	-	0.108	0.358	-0.706
Standard Deviation	0.002	0.004	-	0.003	0.003	0.009

Table F-8– V_r Measurement, Position A, Beam 2

Position A	Beam 2 - Strain Gage Channel Measurement, V_r					
	7	8	9	10	11	12
1	-0.005	0.005	-	-0.006	0.006	0.018
2	-0.010	0.004	-	-0.012	0.001	0.007
3	-0.009	0.004	-	-0.009	0.002	0.011
Average	-0.008	0.004	-	-0.009	0.003	0.012
Minimum	-0.010	0.004	-	-0.012	0.001	0.007
Maximum	-0.005	0.005	-	-0.006	0.006	0.018
Standard Deviation	0.002	0.001	-	0.003	0.003	0.005

Table F-9– Strain Measurement, Position A, Beam 2

Test A	Beam 2 – Strain Measurement, Microstrain					
	7	8	9	10	11	12
1	-9	9	-	-10	11	33
2	-18	8	-	-22	2	13
3	-16	8	-	-18	4	20
Average	-14	8	-	-17	6	22
Minimum	-18	8	-	-22	2	13
Maximum	-9	9	-	-10	11	33
Standard Deviation	4	1	-	6	5	10

Table F-10 Maximum Ranges, Position A, Beam 2

Position A	Beam 2						Beam
	7	8	9	10	11	12	Max
Max Range, V_r	0.005	0.001	-	0.006	0.005	0.011	0.011
Microstrain	8	2	-	11	9	20	20
Stress, ksi	0.24	0.05	-	0.33	0.27	0.57	0.57

Table F-11 V_0 Measurement, Position A, Beam 3

	Beam 3 - Strain Gage Channel Measurement, V_0					
	13	14	15	16	17	18
A1	-	-	-	-	0.242	-0.393
	-	-	-	-	0.212	-0.393
C3	-	-	-0.221	-0.048	0.623	-0.390
	-	-	-0.222	-0.048	0.620	-0.391
Average	-	-	-0.222	-0.048	0.424	-0.392
Minimum	-	-	-0.222	-0.048	0.212	-0.393
Maximum	-	-	-0.221	-0.048	0.623	-0.390
Standard Deviation	-	-	0.001	0.000	0.228	0.001

Table F-12 V_1 Measurement, Position A, Beam 2

Position A	Beam 3 - Strain Gage Channel Measurement, V_1					
	13	14	15	16	17	18
1	-	-	0.212	-0.363	-0.489	-1.150
	-	-	0.212	-0.363	-0.489	-1.149
2	-	-	-0.191	-0.075	0.456	-0.360
3	-	-	-0.191	-0.074	0.492	-0.359
	-	-	-0.190	-0.074	0.492	-0.359
Average	-	-	-0.030	-0.190	0.092	-0.675
Minimum	-	-	-0.191	-0.363	-0.489	-1.150
Maximum	-	-	0.212	-0.074	0.492	-0.359
Standard Deviation	-	-	0.221	0.158	0.531	0.433

Table F-13 V_r Measurement, Position A, Beam 3

Position A	Beam 3 - Strain Gage Channel Measurement, V_r					
	13	14	15	16	17	18
1	-	-	-	-	-0.716	-0.757
2	-	-	0.031	-0.027	-0.166	0.031
3	-	-	0.031	-0.026	-0.130	0.032
Average	-	-	0.031	-0.027	-0.337	-0.232
Minimum	-	-	0.031	-0.027	-0.716	-0.757
Maximum	-	-	0.031	-0.026	-0.130	0.032
Standard Deviation	-	-	0.000	0.001	0.329	0.455

Table F-14 Strain Measurement, Position A, Beam 3

Test A	Beam 3 – Strain Measurement, Microstrain					
	13	14	15	16	17	18
1	-	-	-	-	-1343	-1419
2	-	-	57	-51	-311	57
3	-	-	58	-49	-243	59
Average	-	-	58	-50	-632	-434
Minimum	-	-	57	-51	-1343	-1419
Maximum	-	-	58	-49	-243	59
Standard Deviation	-	-	1	1	616	853

Table F-15 Maximum Ranges, Position A, Beam 3

Position A	Beam 3						Beam Max
	13	14	15	16	17	18	
Max Range, V_r	-	-	0.001	0.001	0.587	0.788	0.788
Microstrain	-	-	1	2	1098	1475	1475
Stress, ksi	-	-	0.03	0.05	31.83	42.78	42.78

Table F-16 V_0 Measurement, Position A, Beam 4

	Beam 4 - Strain Gage Channel Measurement, V_0					
	19	20	21	22	23	24
A1	-0.460	-1.159	-0.926	-	-0.084	-0.471
	-0.459	-1.158	-0.926	-	-0.084	-0.471
C3	-0.460	-1.154	-0.926	-	-0.080	-0.470
	-0.458	-1.154	-0.927	-	-0.081	-0.470
Average	-0.459	-1.156	-0.926	-	-0.082	-0.471
Minimum	-0.460	-1.159	-0.927	-	-0.084	-0.471
Maximum	-0.458	-1.154	-0.926	-	-0.080	-0.470
Standard Deviation	0.001	0.003	0.001	-	0.002	0.001

Table F-17 V_1 Measurement, Position A, Beam 4

Position A	Beam 4 - Strain Gage Channel Measurement, V_1					
	19	20	21	22	23	24
1	-0.883	-	-0.077	-0.426	-1.364	-0.241
	-0.883	-	-0.077	-0.426	-1.364	-0.240
2	-0.494	-1.147	-0.881	-	-0.076	-0.423
3	-0.497	-1.147	-0.881	-	-0.075	-0.423
	-0.498	-1.147	-0.881	-	-0.076	-0.423
Average	-0.651	-1.147	-0.559	-0.426	-0.591	-0.350
Minimum	-0.883	-1.147	-0.881	-0.426	-1.364	-0.423
Maximum	-0.494	-1.147	-0.077	-0.426	-0.075	-0.240
Standard Deviation	0.212	0.000	0.440	0.000	0.706	0.100

Table F-18 V_r Measurement, Position A, Beam 4

Position A	Beam 4 - Strain Gage Channel Measurement, V_r					
	19	20	21	22	23	24
1	-0.424	-	0.849	-	-1.280	0.231
2	-0.035	0.007	0.046	-	0.005	0.047
3	-0.039	0.007	0.046	-	0.005	0.047
Average	-0.166	0.007	0.313	-	-0.424	0.108
Minimum	-0.424	0.007	0.046	-	-1.280	0.047
Maximum	-0.035	0.007	0.849	-	0.005	0.231
Standard Deviation	0.223	0.000	0.464	-	0.742	0.106

Table F-19 Strain Measurement, Position A, Beam 4

Test A	Beam 4 – Strain Measurement, Microstrain					
	19	20	21	22	23	24
1	-795	-	1597	-	-2398	433
2	-66	13	85	-	8	88
3	-72	13	85	-	9	88
Average	-311	13	589	-	-793	203
Minimum	-795	13	85	-	-2398	88
Maximum	-66	13	1597	-	9	433
Standard Deviation	419	0	873	-	1389	199

Table F-20 Maximum Ranges, Position A, Beam 4

Position A	Beam 4						Beam
	19	20	21	22	23	24	Max
Max Range, V_r	0.389	-	0.804	-	1.285	0.184	1.285
Microstrain	727	-	1504	-	2408	343	2408
Stress, ksi	21.08	-	43.62	-	69.83	9.95	69.83

Table F-21 V_0 Measurement, Position A, Beam 5

	Beam 5 - Strain Gage Channel Measurement, V_0					
	25	26	27	28	29	30
A1	-1.337	-0.247	-0.339	-0.812	-0.192	-0.531
	-1.337	-0.247	-0.339	-0.812	-0.191	-0.531
C3	-1.332	-0.242	-0.333	-0.807	-0.187	-0.525
	-1.332	-0.242	-0.334	-0.808	-0.188	-0.526
Average	-1.335	-0.245	-0.336	-0.810	-0.190	-0.528
Minimum	-1.337	-0.247	-0.339	-0.812	-0.192	-0.531
Maximum	-1.332	-0.242	-0.333	-0.807	-0.187	-0.525
Standard Deviation	0.003	0.003	0.003	0.003	0.002	0.003

Table F-22 V_1 Measurement, Position A, Beam 5

Position A	Beam 5 - Strain Gage Channel Measurement, V_1					
	25	26	27	28	29	30
1	-0.298	-0.836	-0.184	-0.491	-	-
	-0.297	-0.836	-0.183	-0.491	-	-
2	-1.363	-0.239	-0.295	-0.835	-0.181	-0.490
3	-1.362	-0.238	-0.294	-0.834	-0.181	-0.488
	-1.362	-0.238	-0.294	-0.834	-0.180	-0.487
Average	-0.936	-0.477	-0.250	-0.697	-0.181	-0.488
Minimum	-1.363	-0.836	-0.295	-0.835	-0.181	-0.490
Maximum	-0.297	-0.238	-0.183	-0.491	-0.180	-0.487
Standard Deviation	0.583	0.327	0.061	0.188	0.001	0.002

Table F-23 V_r Measurement, Position A, Beam 5

Position A	Beam 5 - Strain Gage Channel Measurement, V_r					
	25	26	27	28	29	30
1	1.040	-0.589	0.156	0.321	-	-
2	-0.031	0.003	0.039	-0.027	0.007	0.036
3	-0.030	0.004	0.040	-0.026	0.007	0.038
Average	0.326	-0.194	0.078	0.089	0.007	0.037
Minimum	-0.031	-0.589	0.039	-0.027	0.007	0.036
Maximum	1.040	0.004	0.156	0.321	0.007	0.038
Standard Deviation	0.618	0.342	0.067	0.201	0.000	0.002

Table F-24 Strain Measurement, Position A, Beam 5

Test A	Beam 5 – Strain Measurement, Microstrain					
	25	26	27	28	29	30
1	1956	-1105	292	603	-	-
2	-58	6	72	-52	12	67
3	-56	8	74	-50	13	71
Average	614	-364	146	167	13	69
Minimum	-58	-1105	72	-52	12	67
Maximum	1956	8	292	603	13	71
Standard Deviation	1162	642	126	378	1	3

Table F-25 Maximum Ranges, Position A, Beam 5

Position A	Beam 5						Beam Max
	25	26	27	28	29	30	
Max Range, V_r	1.071	0.593	0.117	0.349	0.001	0.003	1.071
Microstrain	2005	1110	219	652	1	5	2005
Stress, ksi	58.15	32.18	6.34	18.90	0.03	0.14	58.15

Table F-26 Maximum Ranges, Position A, All Beams

Position A	Beam Max
Max Range, V_r	1
Microstrain	2408
Stress, ksi	70

Table F-27 V_0 Measurement, Position B, Beam 1

	Beam 1 - Strain Gage Channel Measurement, V_0					
	1	2	3	4	5	6
A1	-0.710	-	-0.614	-0.464	-	-
	-0.710	-	-0.614	-0.463	-	-
C3	-0.700	-	-0.611	-0.457	-	-
	-0.699	-	-0.612	-0.456	-	-
Average	-0.705	-	-0.613	-0.460	-	-
Minimum	-0.710	-	-0.614	-0.464	-	-
Maximum	-0.699	-	-0.611	-0.456	-	-
Standard Deviation	0.006	-	0.001	0.004	-	-

Table F-28 V_1 Measurement, Position B, Beam 1

Position B	Beam 1 - Strain Gage Channel Measurement, V_1					
	1	2	3	4	5	6
1	-0.712	-	-0.604	-0.467	-	-
2	-0.709	-	-0.603	-0.467	-	-
	-0.709	-	-0.603	-0.467	-	-
3	-0.705	-	-0.602	-0.463	-	-
	-0.705	-	-0.601	-0.463	-	-
Average	-0.708	-	-0.603	-0.465	-	-
Minimum	-0.712	-	-0.604	-0.467	-	-
Maximum	-0.705	-	-0.601	-0.463	-	-
Standard Deviation	0.003	-	0.001	0.002	-	-

Table F-29 V_r Measurement, Position B, Beam 1

Position B	Beam 1 - Strain Gage Channel Measurement, V_r					
	1	2	3	4	5	6
1	-0.002	-	0.010	-0.004	-	-
2	-0.009	-	0.0085	-0.0105	-	-
3	-0.0055	-	0.01	-0.0065	-	-
Average	-0.005667	-	0.0095	-0.006833	-	-
Minimum	-0.0095	-	0.0085	-0.0105	-	-
Maximum	-0.002	-	0.01	-0.0035	-	-
Standard Deviation	0.0037528	-	0.000866	0.0035119	-	-

Table F-30 Strain Measurement, Position B, Beam 1

Test B	Beam 1 – Strain Measurement, Microstrain					
	1	2	3	4	5	6
1	-4	-	19	-7	-	-
2	-18	-	16	-20	-	-
3	-10	-	19	-12	-	-
Average	-11	-	18	-13	-	-
Minimum	-18	-	16	-20	-	-
Maximum	-4	-	19	-7	-	-
Standard Deviation	7	-	2	7	-	-

Table F-31 Maximum Ranges, Position B, Beam 1

Position B	Beam 1						Beam
	1	2	3	4	5	6	Max
Max Range, V_r	0.007	-	0.002	0.007	-	-	0.007
Microstrain	14	-	3	13	-	-	14
Stress, ksi	0.41	-	0.08	0.38	-	-	0.41

Table F-32 V_0 Measurement, Position B, Beam 2

	Beam 2 - Strain Gage Channel Measurement, V_0					
	7	8	9	10	11	12
A1	0.489	-1.033	-	0.108	0.347	-0.741
	0.490	-1.032	-	0.108	0.347	-0.740
C3	0.497	-1.025	-	0.117	0.356	-0.717
	0.498	-1.025	-	0.118	0.356	-0.717
Average	0.494	-1.029	-	0.113	0.352	-0.729
Minimum	0.489	-1.033	-	0.108	0.347	-0.741
Maximum	0.498	-1.025	-	0.118	0.356	-0.717
Standard Deviation	0.005	0.004	-	0.006	0.005	0.014

Table F-33 V_1 Measurement, Position B, Beam 1

Position B	Beam 2 - Strain Gage Channel Measurement, V_1					
	7	8	9	10	11	12
1	0.479	-1.017	-	0.099	0.361	-0.697
2	0.479	-1.016	-	0.099	0.362	-0.691
	0.48	-1.015	-	0.099	0.362	-0.688
3	0.482	-1.016	-	0.102	0.364	-0.686
	0.481	-1.016	-	0.102	0.364	-0.687
Average	0.480	-1.016	-	0.100	0.363	-0.690
Minimum	0.479	-1.017	-	0.099	0.361	-0.697
Maximum	0.482	-1.015	-	0.102	0.364	-0.686
Standard Deviation	0.001	0.001	-	0.002	0.001	0.004

Table F-34 V_r Measurement, Position B, Beam 2

Position B	Beam 2 - Strain Gage Channel Measurement, V_r					
	7	8	9	10	11	12
1	-0.0105	0.0155	-	-0.009	0.014	0.0435
2	-0.018	0.0095	-	-0.0185	0.006	0.0275
3	-0.016	0.009	-	-0.0155	0.008	0.0305
Average	-0.014833	0.0113333	-	-0.01433	0.00933	0.03383
Minimum	-0.018	0.009	-	-0.01850	0.00600	0.02750
Maximum	-0.0105	0.0155	-	-0.00900	0.01400	0.04350
Standard Deviation	0.0038837	0.0036171	-	0.00486	0.00416	0.00850

Table F-35 Strain Measurement, Position B, Beam 2

Test B	Beam 2 - Strain Measurement, Microstrain					
	7	8	9	10	11	12
1	-20	29	-	-17	26	82
2	-34	18	-	-35	11	52
3	-30	17	-	-29	15	57
Average	-28	21	-	-27	18	64
Minimum	-34	17	-	-35	11	52
Maximum	-20	29	-	-17	26	82
Standard Deviation	7	7	-	9	8	16

Table F-36 Maximum Ranges, Position B, Beam 2

Position B	Beam 2						Beam
	7	8	9	10	11	12	Max
Max Range, V_r	0.008	0.007	-	0.009	0.008	0.016	0.016
Microstrain	14	12	-	18	15	30	30
Stress, ksi	0.41	0.35	-	0.51	0.43	0.87	0.87

Table F-37 V_0 Measurement, Position B, Beam 3

	Beam 3 - Strain Gage Channel Measurement, V_0					
	13	14	15	16	17	18
A1	-	-	-	-	0.242	-0.393
	-	-	-	-	0.212	-0.393
C3	-	-	-0.221	-0.048	0.623	-0.39
	-	-	-0.222	-0.048	0.62	-0.391
Average	-	-	-0.2215	-0.04800	0.42425	-0.39175
Minimum	-	-	-0.222	-0.04800	0.21200	-0.39300
Maximum	-	-	-0.221	-0.04800	0.62300	-0.39000
Standard Deviation	-	-	0.0007071	0.00000	0.22810	0.00150

Table F-38 V_1 Measurement, Position B, Beam 3

Position B	Beam 3 - Strain Gage Channel Measurement, V_1					
	13	14	15	16	17	18
1	-	-	-0.18	-0.085	0.237	-0.349
2	-	-	-0.18	-0.086	0.457	-0.349
	-	-	-0.18	-0.085	0.457	-0.348
3	-	-	-0.18	-0.08	0.493	-0.348
	-	-	-0.179	-0.079	0.492	-0.348
Average	-	-	-0.180	-0.083	0.427	-0.348
Minimum	-	-	-0.180	-0.086	0.237	-0.349
Maximum	-	-	-0.179	-0.079	0.493	-0.348
Standard Deviation	-	-	0.000	0.003	0.108	0.001

Table F-39 V_r Measurement, Position B, Beam 3

Position B	Beam 3 - Strain Gage Channel Measurement, V_r					
	13	14	15	16	17	18
1	-	-	-	-	0.01	0.044
2	-	-	0.0415	-0.0375	-0.1645	0.042
3	-	-	0.042	-0.0315	-0.129	0.0425
Average	-	-	0.04175	-0.03450	-0.09450	0.04283
Minimum	-	-	0.0415	-0.03750	-0.16450	0.04200
Maximum	-	-	0.042	-0.03150	0.01000	0.04400
Standard Deviation	-	-	0.0003536	0.00424	0.09222	0.00104

Table F-40 Strain Measurement, Position B, Beam 3

Test B	Beam 3 - Strain Measurement, Microstrain					
	13	14	15	16	17	18
1	-	-	-	-	19	83
2	-	-	78	-70	-309	79
3	-	-	79	-59	-242	80
Average	-	-	78	-65	-177	80
Minimum	-	-	78	-70	-309	79
Maximum	-	-	79	-59	19	83
Standard Deviation	-	-	1	8	173	2

Table F-41 Maximum Ranges, Position B, Beam 3

Position B	Beam 3						Beam Max
	13	14	15	16	17	18	
Max Range, V_r	-	-	0.001	0.006	0.175	0.002	0.175
Microstrain	-	-	1	11	326	4	326
Stress, ksi	-	-	0.03	0.33	9.46	0.11	9.46

Table F-42 V_0 Measurement, Position B, Beam 3

	Beam 4 - Strain Gage Channel Measurement, V_0					
	19	20	21	22	23	24
A1	-0.46	-1.159	-0.926	-	-0.084	-0.471
	-0.459	-1.158	-0.926	-	-0.084	-0.471
C3	-0.46	-1.154	-0.926	-	-0.08	-0.47
	-0.458	-1.154	-0.927	-	-0.081	-0.47
Average	-0.45925	-1.15625	-0.92625	-	-0.08225	-0.47050
Minimum	-0.46	-1.15900	-0.927	-	-0.08400	-0.47100
Maximum	-0.458	-1.15400	-0.926	-	-0.08000	-0.47000
Standard Deviation	0.0009574	0.00263	0.0005	-	0.00206	0.00058

Table F-43 V_1 Measurement, Position B, Beam 3

Position B	Beam 4 - Strain Gage Channel Measurement, V_1					
	19	20	21	22	23	24
1	-0.481	-1.15	-0.894	-	-0.077	-0.435
2	-0.485	-1.15	-0.895	-	-0.077	-0.436
	-0.485	-1.15	-0.895	-	-0.077	-0.435
3	-0.483	-1.148	-0.894	-	-0.077	-0.435
	-0.483	-1.149	-0.894	-	-0.076	-0.434
Average	-0.483	-1.149	-0.894	-	-0.077	-0.435
Minimum	-0.485	-1.150	-0.895	-	-0.077	-0.436
Maximum	-0.481	-1.148	-0.894	-	-0.076	-0.434
Standard Deviation	0.002	0.001	0.001	-	0.000	0.001

Table F-44 V_r Measurement, Position B, Beam 4

Position B	Beam 4 - Strain Gage Channel Measurement, V_r					
	19	20	21	22	23	24
1	-0.0215	0.0085	0.032	-	0.007	0.036
2	-0.026	0.004	0.0315	-	0.0035	0.0345
3	-0.024	0.0055	0.0325	-	0.004	0.0355
Average	-0.023833	0.00600	0.032	-	0.00483	0.03533
Minimum	-0.026	0.00400	0.0315	-	0.00350	0.03450
Maximum	-0.0215	0.00850	0.0325	-	0.00700	0.03600
Standard Deviation	0.0022546	0.00229	0.0005	-	0.00189	0.00076

Table F-45 Strain Measurement, Position B, Beam 4

Test B	Beam 4 - Strain Measurement, Microstrain					
	19	20	21	22	23	24
1	-40	16	60	-	13	68
2	-49	8	59	-	7	65
3	-45	10	61	-	8	67
Average	-45	11	60	-	9	66
Minimum	-49	8	59	-	7	65
Maximum	-40	16	61	-	13	68
Standard Deviation	4	4	1	-	4	1

Table F-46 Maximum Ranges, Position B, Beam 4

Position B	Beam 4						Beam
	19	20	21	22	23	24	Max
Max Range, V_r	0.005	0.005	0.001	-	0.004	0.002	0.005
Microstrain	8	8	2	-	7	3	8
Stress, ksi	0.24	0.24	0.05	-	0.19	0.08	0.24

Table F-47 – V_0 Measurement, Position B, Beam 5

	Beam 5 - Strain Gage Channel Measurement, V_0					
	25	26	27	28	29	30
A1	-1.337	-0.247	-0.339	-0.812	-0.192	-0.531
	-1.337	-0.247	-0.339	-0.812	-0.191	-0.531
C3	-1.332	-0.242	-0.333	-0.807	-0.187	-0.525
	-1.332	-0.242	-0.334	-0.808	-0.188	-0.526
Average	-1.335	-0.245	-0.336	-0.810	-0.190	-0.528
Minimum	-1.337	-0.247	-0.339	-0.812	-0.192	-0.531
Maximum	-1.332	-0.242	-0.333	-0.807	-0.187	-0.525
Standard Deviation	0.003	0.003	0.003	0.003	0.002	0.003

Table F-48 - V_1 Measurement, Position B, Beam 5

Position B	Beam 5 - Strain Gage Channel Measurement, V_1					
	25	26	27	28	29	30
1	-1.342	-0.242	-0.326	-0.815	-0.185	-0.516
2	-1.342	-0.243	-0.325	-0.815	-0.186	-0.516
	-1.342	-0.242	-0.325	-0.815	-0.185	-0.516
3	-1.341	-0.241	-0.324	-0.814	-0.185	-0.514
	-1.341	-0.241	-0.323	-0.814	-0.184	-0.514
Average	-1.342	-0.242	-0.325	-0.815	-0.185	-0.515
Minimum	-1.342	-0.243	-0.326	-0.815	-0.186	-0.516
Maximum	-1.341	-0.241	-0.323	-0.814	-0.184	-0.514
Standard Deviation	0.001	0.001	0.001	0.001	0.001	0.001

Table F-49 – V_r Measurement, Position B, Beam 5

Position B	Beam 5 - Strain Gage Channel Measurement, V_r					
	25	26	27	28	29	30
1	-0.005	0.005	0.013	-0.003	0.0065	0.015
2	-0.01	-0.0005	0.0085	-0.0075	0.002	0.0095
3	-0.009	0.001	0.01	-0.0065	0.003	0.0115
Average	-0.00800	0.00183	0.0105	-0.00567	0.00383	0.01200
Minimum	-0.01000	-0.00050	0.0085	-0.00750	0.00200	0.00950
Maximum	-0.00500	0.00500	0.013	-0.00300	0.00650	0.01500
Standard Deviation	0.00265	0.00284	0.0022913	0.00236	0.00236	0.00278

Table F-50– Strain Measurement, Position B, Beam 5

Test B	Beam 5 – Strain Measurement, Microstrain					
	25	26	27	28	29	30
1	-9	9	24	-6	12	28
2	-19	-1	16	-14	4	18
3	-17	2	19	-12	6	22
Average	-15	3	20	-11	7	23
Minimum	-19	-1	16	-14	4	18
Maximum	-9	9	24	-6	12	28
Standard Deviation	5	5	4	4	4	5

Table F-51 – Maximum Ranges, Position B, Beam 5

Position B	Beam 5						Beam
	25	26	27	28	29	30	Max
Max Range, V_r	0.005	0.006	0.005	0.004	0.005	0.005	0.006
Microstrain	9	10	8	8	8	10	10
Stress, ksi	0.27	0.30	0.24	0.24	0.24	0.30	0.30

Table F-52 – Maximum Ranges, Position B, All Beams

Position B	Beam Max
Max Range, V_r	0.175
Microstrain	326
Stress, ksi	9.46

Table F-53 – V_0 Measurement, Position C, Beam 1

	Beam 1 - Strain Gage Channel Measurement, V_0					
	1	2	3	4	5	6
A1	-0.710	-	-0.614	-0.464	-	-
	-0.710	-	-0.614	-0.463	-	-
C3	-0.700	-	-0.611	-0.457	-	-
	-0.699	-	-0.612	-0.456	-	-
Average	-0.705	-	-0.613	-0.460	-	-
Minimum	-0.710	-	-0.614	-0.464	-	-
Maximum	-0.699	-	-0.611	-0.456	-	-
Standard Deviation	0.006	-	0.001	0.004	-	-

Table F-54 - V_1 Measurement, Position C, Beam 1

Position C	Beam 1 - Strain Gage Channel Measurement, V_1					
	1	2	3	4	5	6
1	-0.735	-	-0.573	-0.489	-	-
2	-0.73	-	-0.571	-0.486	-	-
	-0.73	-	-0.571	-0.485	-	-
3	-0.728	-	-0.57	-0.484	-	-
	-0.728	-	-0.57	-0.484	-	-
Average	-0.730	-	-0.571	-0.486	-	-
Minimum	-0.735	-	-0.573	-0.489	-	-
Maximum	-0.728	-	-0.570	-0.484	-	-
Standard Deviation	0.003	-	0.001	0.002	-	-

Table F-55 – V_r Measurement, Position C, Beam 1

Position C	Beam 1 - Strain Gage Channel Measurement, V_r					
	1	2	3	4	5	6
1	-0.025	-	0.041	-0.026	-	-
2	-0.031	-	0.0405	-0.029	-	-
3	-0.0285	-	0.0415	-0.0275	-	-
Average	-0.028	-	0.041	-0.027	-	-
Minimum	-0.031	-	0.041	-0.029	-	-
Maximum	-0.025	-	0.042	-0.026	-	-
Standard Deviation	0.003	-	0.000	0.002	-	-

Table F-56 – Strain Measurement, Position C, Beam 1

Test C	Beam 1 - Strain Measurement, Microstrain					
	1	2	3	4	5	6
1	-47	-	77	-48	-	-
2	-57	-	76	-54	-	-
3	-54	-	78	-52	-	-
Average	-53	-	77	-51	-	-
Minimum	-57	-	76	-54	-	-
Maximum	-47	-	78	-48	-	-
Standard Deviation	5	-	1	3	-	-

Table F-57 – Maximum Ranges, Position C, Beam 1

Position C	Beam 1						Beam Max
	1	2	3	4	5	6	
Max Range, V_r	0.005	-	0.001	0.004	-	-	0.005
Microstrain	10	-	2	7	-	-	10
Stress, ksi	0.30	-	0.05	0.19	-	-	0.30

Table F-58 – V_0 Measurement, Position C, Beam 2

	Beam 2 - Strain Gage Channel Measurement, V_0					
	7	8	9	10	11	12
A1	0.489	-1.033	-	0.108	0.347	-0.741
	0.490	-1.032	-	0.108	0.347	-0.740
C3	0.497	-1.025	-	0.117	0.356	-0.717
	0.498	-1.025	-	0.118	0.356	-0.717
Average	0.494	-1.029	-	0.113	0.352	-0.729
Minimum	0.489	-1.033	-	0.108	0.347	-0.741
Maximum	0.498	-1.025	-	0.118	0.356	-0.717
Standard Deviation	0.005	0.004	-	0.006	0.005	0.014

Table F-59 - V_1 Measurement, Position C, Beam 2

Position C	Beam 2 - Strain Gage Channel Measurement, V_1					
	7	8	9	10	11	12
1	0.471	-1.015	-	0.092	0.365	-0.681
2	0.474	-1.012	-	0.095	0.366	-0.675
	0.474	-1.012	-	0.094	0.366	-0.675
3	0.475	-1.014	-	0.096	0.367	-0.673
	0.475	-1.014	-	0.097	0.367	-0.672
Average	0.474	-1.013	-	0.095	0.366	-0.675
Minimum	0.471	-1.015	-	0.092	0.365	-0.681
Maximum	0.475	-1.012	-	0.097	0.367	-0.672
Standard Deviation	0.002	0.001	-	0.002	0.001	0.003

Table F-60 – V_r Measurement, Position C, Beam 2

Position C	Beam 2 - Strain Gage Channel Measurement, V_r					
	7	8	9	10	11	12
1	-0.0185	0.0175	-	-0.016	0.018	0.0595
2	-0.0235	0.013	-	-0.023	0.01	0.042
3	-0.0225	0.011	-	-0.021	0.011	0.0445
Average	-0.022	0.014	-	-0.020	0.013	0.049
Minimum	-0.024	0.011	-	-0.023	0.010	0.042
Maximum	-0.019	0.018	-	-0.016	0.018	0.059
Standard Deviation	0.003	0.003	-	0.004	0.004	0.009

Table F-61 – Strain Measurement, Position C, Beam 2

Test C	Beam 2 - Strain Measurement, Microstrain					
	7	8	9	10	11	12
1	-35	33	-	-30	34	112
2	-44	24	-	-43	19	79
3	-42	21	-	-39	21	84
Average	-40	26	-	-38	24	91
Minimum	-44	21	-	-43	19	79
Maximum	-35	33	-	-30	34	112
Standard Deviation	5	6	-	7	8	18

Table F-62 – Maximum Ranges, Position C, Beam 2

Position C	Beam 2						Beam
	7	8	9	10	11	12	Max
Max Range, V_r	0.005	0.007	-	0.007	0.008	0.018	0.018
Microstrain	9	12	-	13	15	33	33
Stress, ksi	0.27	0.35	-	0.38	0.43	0.95	0.95

Table F-63 – V_0 Measurement, Position C, Beam 3

	Beam 3 - Strain Gage Channel Measurement, V_0					
	13	14	15	16	17	18
A1	-	-	-	-	0.242	-0.393
	-	-	-	-	0.212	-0.393
C3	-	-	-0.221	-0.048	0.623	-0.39
	-	-	-0.222	-0.048	0.62	-0.391
Average	-	-	-0.2215	-0.04800	0.42425	-0.39175
Minimum	-	-	-0.222	-0.04800	0.21200	-0.39300
Maximum	-	-	-0.221	-0.04800	0.62300	-0.39000
Standard Deviation	-	-	0.0007071	0.00000	0.22810	0.00150

Table F-64 - V_1 Measurement, Position C, Beam 3

Position C	Beam 3 - Strain Gage Channel Measurement, V_1					
	1	14	15	16	17	18
1	-	-	-0.197	-0.076	0.291	-0.362
2	-	-	-0.196	-0.074	0.494	-0.36
	-	-	-0.196	-0.074	0.494	-0.36
3	-	-	-0.195	-0.069	0.489	-0.36
	-	-	-0.195	-0.068	0.49	-0.36
Average	-	-	-0.196	-0.072	0.452	-0.360
Minimum	-	-	-0.197	-0.076	0.291	-0.362
Maximum	-	-	-0.195	-0.068	0.494	-0.360
Standard Deviation	-	-	0.001	0.003	0.090	0.001

Table F-65 – V_r Measurement, Position C, Beam 3

Position C	Beam 3 - Strain Gage Channel Measurement, V_r					
	13	14	15	16	17	18
1	-	-	-	-	0.064	0.031
2	-	-	0.0255	-0.026	-0.128	0.0305
3	-	-	0.0265	-0.0205	-0.132	0.0305
Average	-	-	0.026	-0.023	-0.065	0.031
Minimum	-	-	0.026	-0.026	-0.132	0.031
Maximum	-	-	0.027	-0.021	0.064	0.031
Standard Deviation	-	-	0.001	0.004	0.112	0.000

Table F-66– Strain Measurement, Position C, Beam 3

Test C	Beam 3 - Strain Measurement, Microstrain					
	13	14	15	16	17	18
1	-	-	-	-	120	58
2	-	-	48	-49	-239	57
3	-	-	50	-38	-248	57
Average	-	-	49	-44	-122	58
Minimum	-	-	48	-49	-248	57
Maximum	-	-	50	-38	120	58
Standard Deviation	-	-	1	7	210	1

Table F-67 – Maximum Ranges, Position C, Beam 3

Position C	Beam 3						Beam Max
	13	14	15	16	17	18	
Max Range, V_r	-	-	0.001	0.005	0.196	0.001	0.196
Microstrain	-	-	2	10	366	1	366
Stress, ksi	-	-	0.05	0.30	10.63	0.03	10.63

Table F-68 – V_0 Measurement, Position C, Beam 4

	Beam 4 - Strain Gage Channel Measurement, V_0					
	19	20	21	22	23	24
A1	-0.46 -0.459	-1.159 -1.158	-0.926 -0.926	- -	-0.084 -0.084	-0.471 -0.471
C3	-0.46 -0.458	-1.154 -1.154	-0.926 -0.927	- -	-0.08 -0.081	-0.47 -0.47
Average	-0.45925	-1.15625	-0.92625	-	-0.08225	-0.47050
Minimum	-0.46	-1.15900	-0.927	-	-0.08400	-0.47100
Maximum	-0.458	-1.15400	-0.926	-	-0.08000	-0.47000
Standard Deviation	0.0009574	0.00263	0.0005	-	0.00206	0.00058

Table F-69 - V_1 Measurement, Position C, Beam 4

Position C	Beam 4 - Strain Gage Channel Measurement, V_1					
	19	20	21	22	23	24
1	-0.469	-1.154	-0.915	-	-0.079	-0.457
2	-0.471 -0.471	-1.152 -1.152	-0.914 -0.914	- -	-0.078 -0.078	-0.455 -0.455
3	-0.466 -0.467	-1.152 -1.152	-0.914 -0.914	- -	-0.077 -0.077	-0.455 -0.455
Average	-0.469	-1.152	-0.914	-	-0.078	-0.455
Minimum	-0.471	-1.154	-0.915	-	-0.079	-0.457
Maximum	-0.466	-1.152	-0.914	-	-0.077	-0.455
Standard Deviation	0.002	0.001	0.000	-	0.001	0.001

Table F-70 – V_r Measurement, Position C, Beam 4

Position C	Beam 4 - Strain Gage Channel Measurement, V_r					
	19	20	21	22	23	24
1	-0.009	0.005	0.011	-	0.005	0.014
2	-0.012	0.002	0.013	-	0.003	0.015
3	-0.008	0.002	0.013	-	0.004	0.015
Average	-0.010	0.003	0.012	-	0.004	0.015
Minimum	-0.012	0.002	0.011	-	0.003	0.014
Maximum	-0.008	0.005	0.013	-	0.005	0.015
Standard Deviation	0.002	0.001	0.001	-	0.001	0.001

Table F-71– Strain Measurement, Position C, Beam 4

Test C	Beam 4 – Strain Measurement, Microstrain					
	19	20	21	22	23	24
1	-18	8	21	-	9	26
2	-23	4	23	-	5	28
3	-14	4	23	-	7	28
Average	-18	5	23	-	7	28
Minimum	-23	4	21	-	5	26
Maximum	-14	8	23	-	9	28
Standard Deviation	4	3	2	-	2	1

Table F-72 – Maximum Ranges, Position C, Beam 4

Position C	Beam 4						Beam Max
	19	20	21	22	23	24	
Max Range, V_r	0.004	0.003	0.002	-	0.003	0.001	0.004
Microstrain	8	5	3	-	5	2	8
Stress, ksi	0.24393	0.14	0.08	-	0.14	0.05	0.24

Table F-73 – V_0 Measurement, Beam 5

	Beam 5 - Strain Gage Channel Measurement, V_0					
	25	26	27	28	29	30
A1	-1.337	-0.247	-0.339	-0.812	-0.192	-0.531
	-1.337	-0.247	-0.339	-0.812	-0.191	-0.531
C3	-1.332	-0.242	-0.333	-0.807	-0.187	-0.525
	-1.332	-0.242	-0.334	-0.808	-0.188	-0.526
Average	-1.335	-0.245	-0.336	-0.810	-0.190	-0.528
Minimum	-1.337	-0.247	-0.339	-0.812	-0.192	-0.531
Maximum	-1.332	-0.242	-0.333	-0.807	-0.187	-0.525
Standard Deviation	0.003	0.003	0.003	0.003	0.002	0.003

Table F-74 - V_1 Measurement, Position C, Beam 5

Position C	Beam 5 - Strain Gage Channel Measurement, V_1					
	25	26	27	28	29	30
1	-1.335	-0.244	-0.337	-0.81	-0.188	-0.527
2	-1.333	-0.242	-0.334	-0.808	-0.186	-0.525
	-1.333	-0.242	-0.334	-0.808	-0.186	-0.525
3	-1.331	-0.241	-0.333	-0.807	-0.186	-0.524
	-1.331	-0.241	-0.333	-0.806	-0.185	-0.524
Average	-1.333	-0.242	-0.334	-0.808	-0.186	-0.525
Minimum	-1.335	-0.244	-0.337	-0.810	-0.188	-0.527
Maximum	-1.331	-0.241	-0.333	-0.806	-0.185	-0.524
Standard Deviation	0.002	0.001	0.002	0.001	0.001	0.001

Table F-75 – V_r Measurement, Position C, Beam 5

Position C	Beam 5 - Strain Gage Channel Measurement, V_r					
	25	26	27	28	29	30
1	0.002	0.003	0.002	0.002	0.004	0.004
2	-0.001	0.000	-0.001	0.000	0.002	0.001
3	0.001	0.001	0.001	0.001	0.002	0.002
Average	0.001	0.001	0.001	0.001	0.002	0.002
Minimum	-0.001	0.000	-0.001	0.000	0.002	0.001
Maximum	0.002	0.003	0.002	0.002	0.004	0.004
Standard Deviation	0.002	0.002	0.001	0.001	0.001	0.002

Table F-76 – Strain Measurement, Position C, Beam 5

Test C	Beam 5 - Strain Measurement, Microstrain					
	25	26	27	28	29	30
1	4	6	4	4	7	8
2	-2	0	-1	-1	3	1
3	2	2	1	2	4	3
Average	1	3	1	2	4	4
Minimum	-2	0	-1	-1	3	1
Maximum	4	6	4	4	7	8
Standard Deviation	3	3	2	2	2	3

Table F-77 – Maximum Ranges, Position C, Beam 5

Position C	Beam 5						Beam
	25	26	27	28	29	30	Max
Max Range, V_r	0.003	0.003	0.003	0.002	0.002	0.003	0.003
Microstrain	6	6	5	5	4	7	7
Stress, ksi	0.16	0.16	0.14	0.14	0.11	0.19	0.19

Table F-78 – Maximum Ranges, Position C, All Beams

Position C	Beam Max
Max Range, V_r	0.196
Microstrain	366
Stress, ksi	10.63

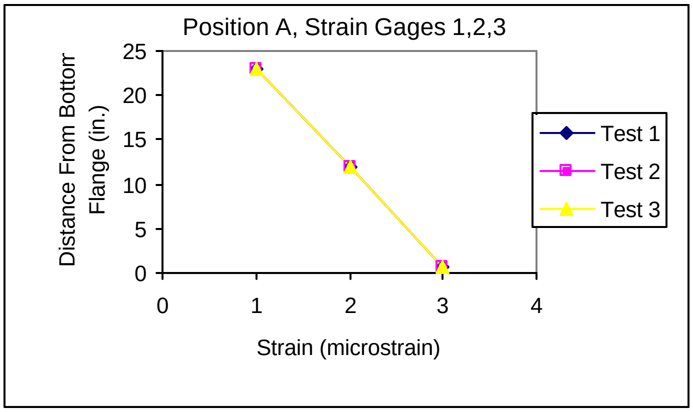

Figure F-1 – Strain Profile, Position A, Strain Gages 1,2,3

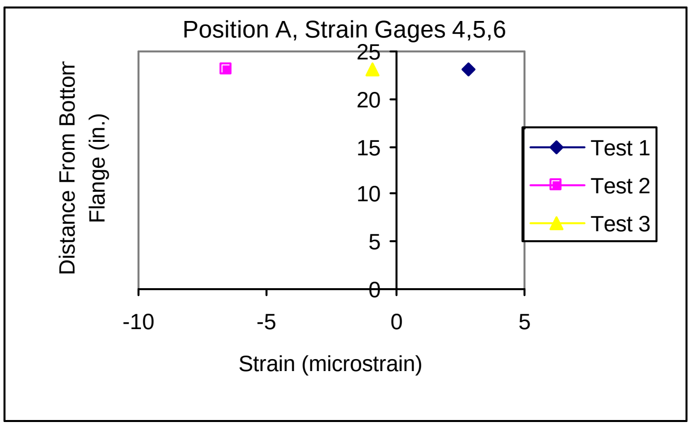

Figure F-2– Strain Profile, Position A, Strain Gages 3,4,5

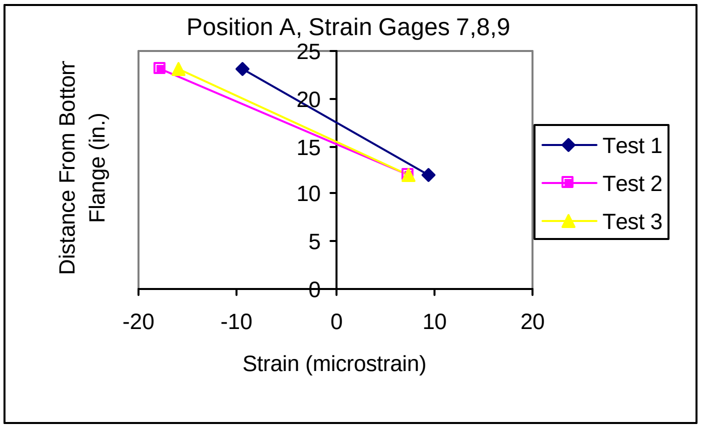

Figure F-3 – Strain Profile, Position A, Strain Gages 7,8,9

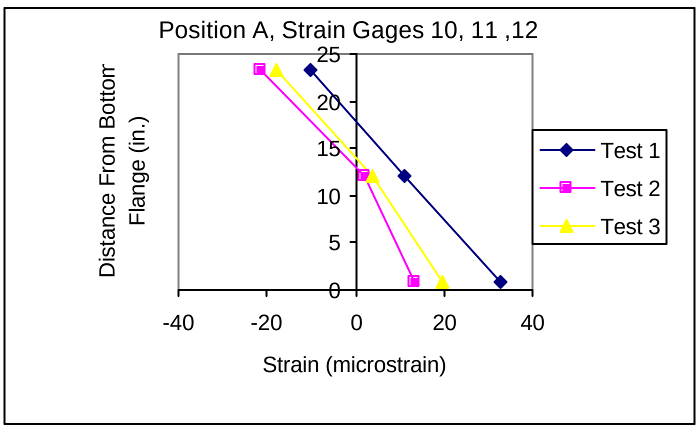

Figure F-4 – Strain Profile, Position A, Strain Gages 10,11,12

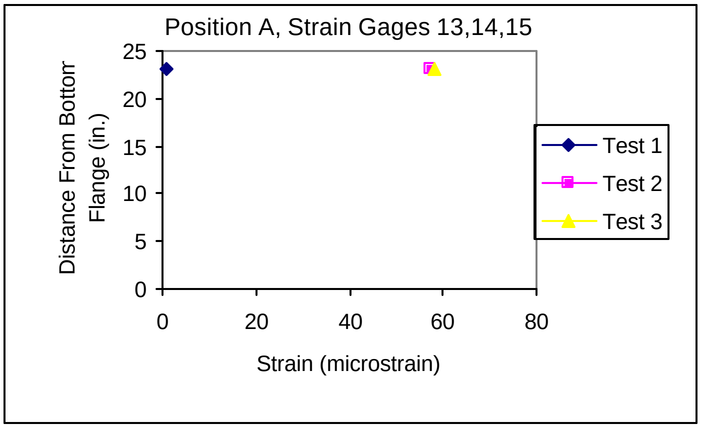

Figure F-5 – Strain Profile, Position A, Strain Gages 13,14,15

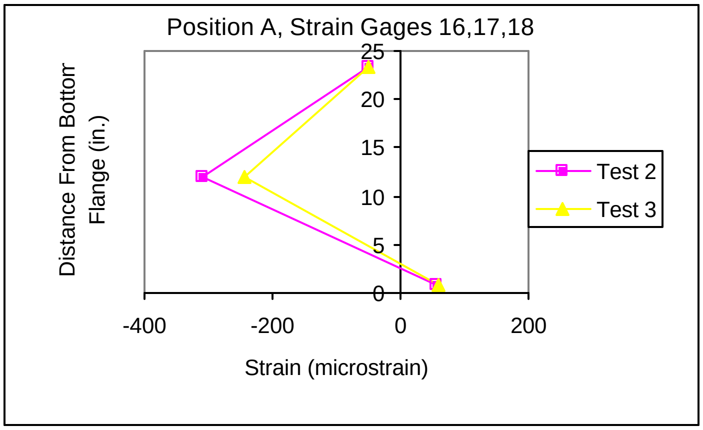

Figure F-6 – Strain Profile, Position A, Strain Gages, 16,17,18

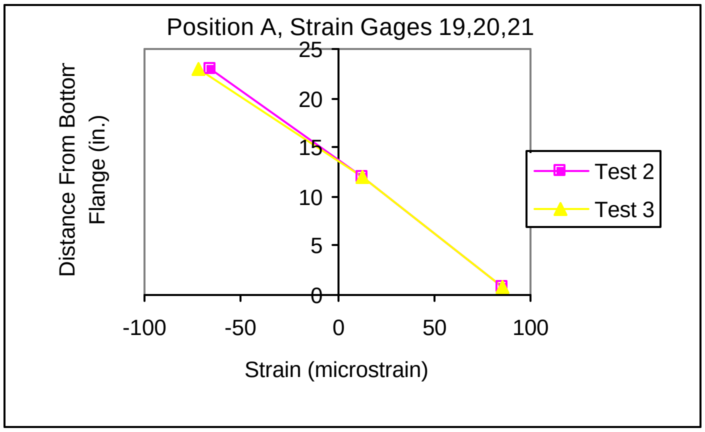

Figure F-7 – Strain Profile, Position A, Strain Gages 19,20,21

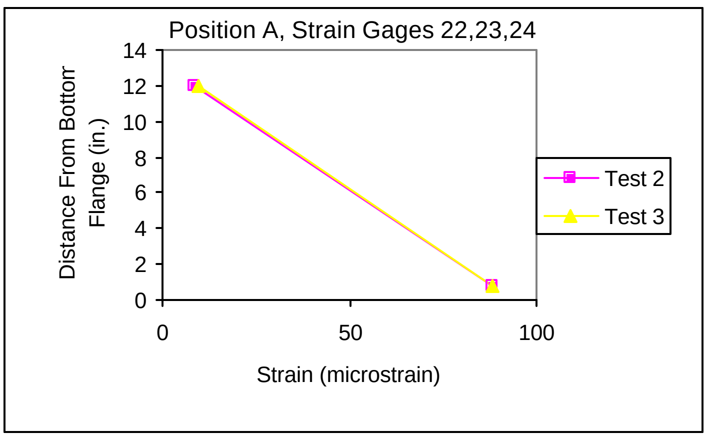

Figure F-8 – Strain Profile, Position A, Strain Gages 22,23,24

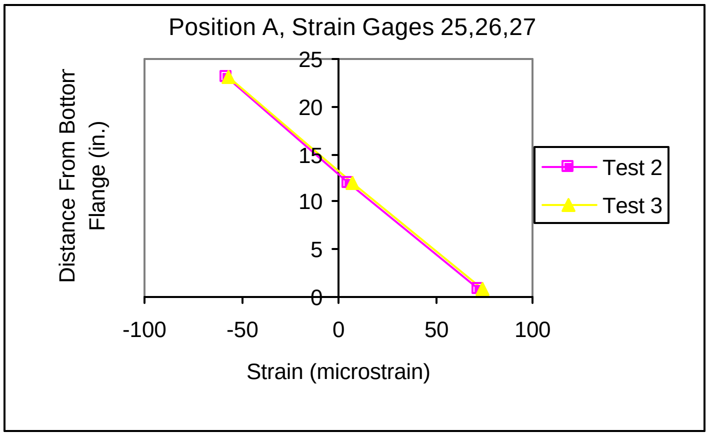

Figure F-9 – Strain Profile, Position A, Strain Gages 25,26,27

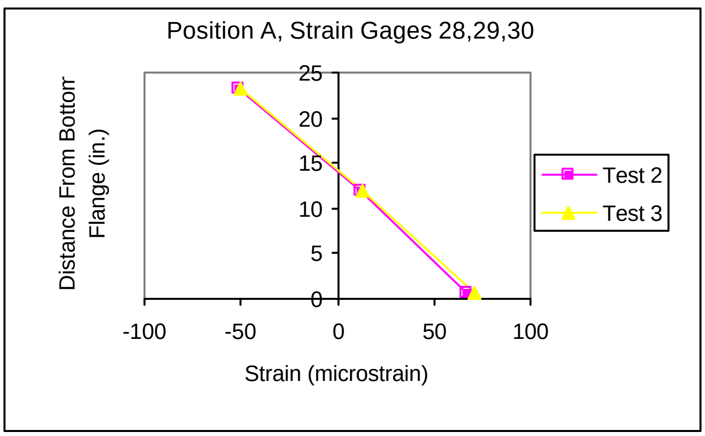

Figure F-10 – Strain Profile, Position A, Strain Gages 28,29,30

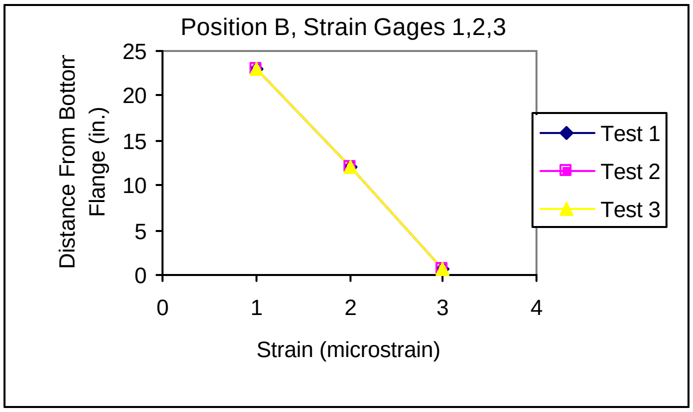

Figure F-11 – Strain Profile, Position B, Strain Gages 1,2,3

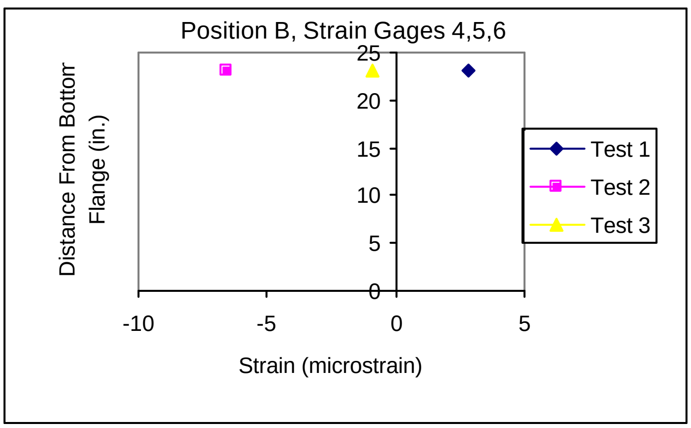

Figure F-12 – Strain Profile, Position B, Strain Gages 4,5,6

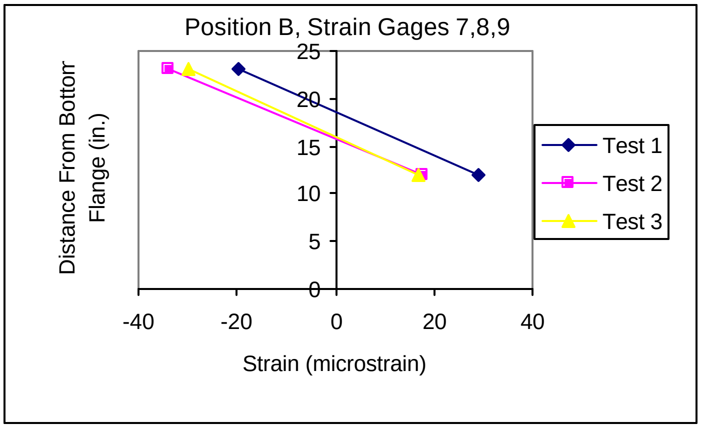

Figure F-13 – Strain Profile, Position B, Strain Gages 7,8,9

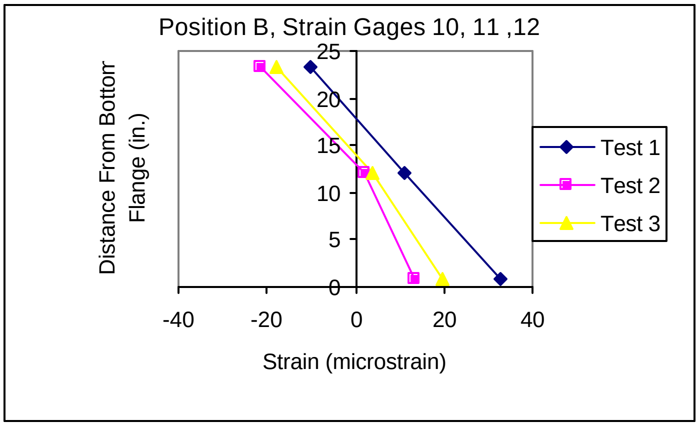

Figure F-14 – Strain Profile, Position B, Strain Gages 10,11,12

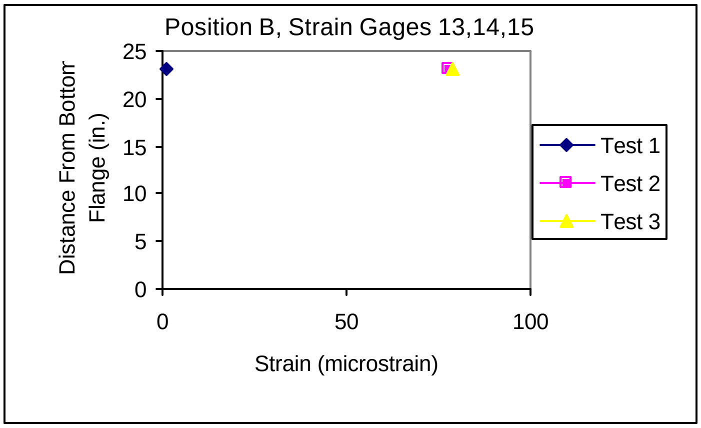

Figure F-15 – Strain Profile, Position B, Strain Gages 13,14,15

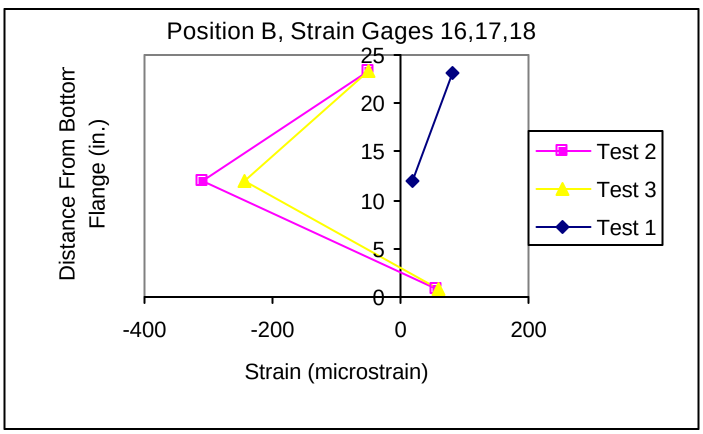

Figure F-16 – Strain Profile, Position B, Strain Gages 16,17,18

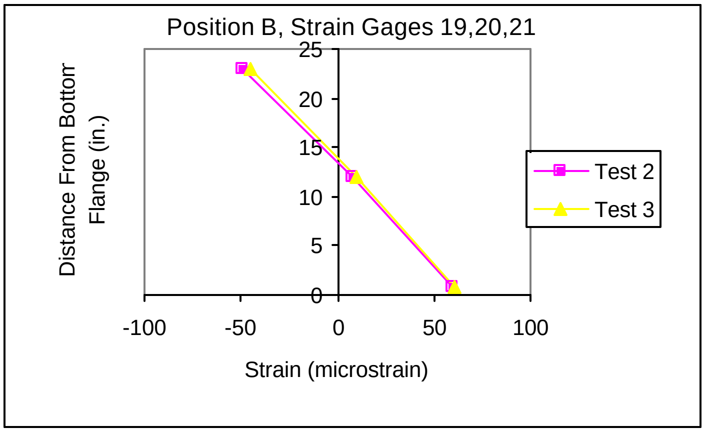

Figure F-17 – Strain Profile, Position B, Strain Gages 19,20,21

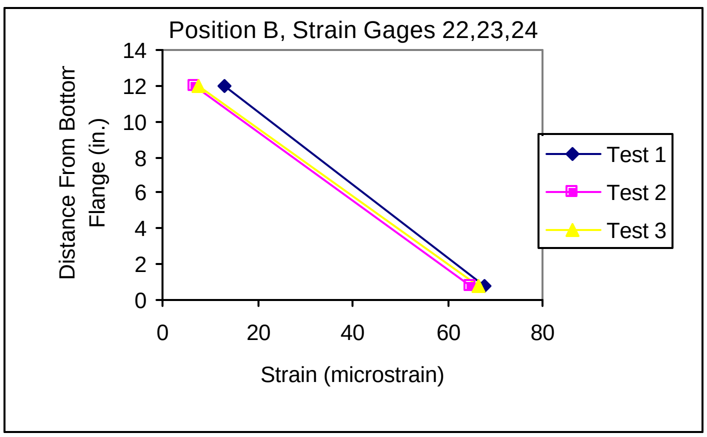

Figure F-18 – Strain Profile, Position B, Strain Gages 22,23,24

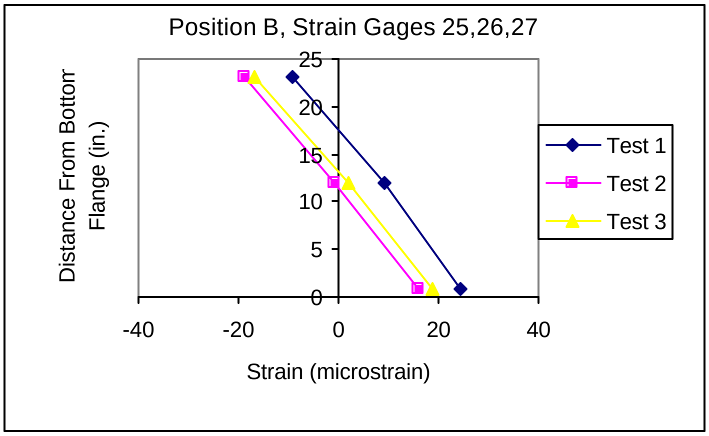

Figure F-19 – Strain Profile, Position B, Strain Gages 25,26,27

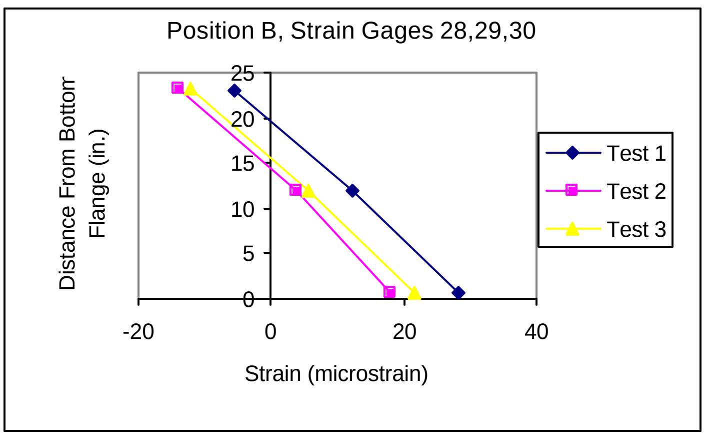

Figure F-20 – Strain Profile, Position B, Strain Gages 28,29,30

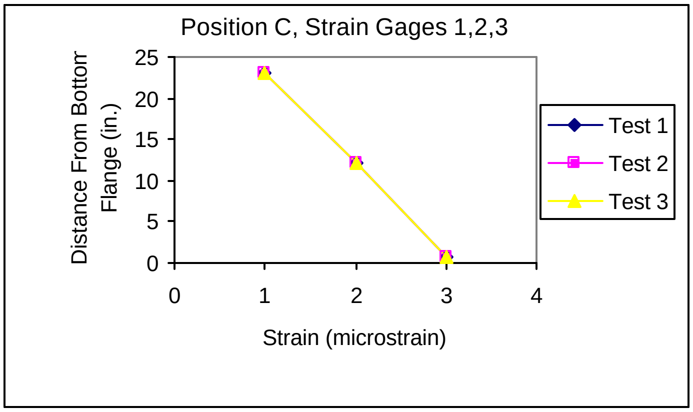

Figure F-21 – Strain Profile, Position C, Strain Gages 1,2,3

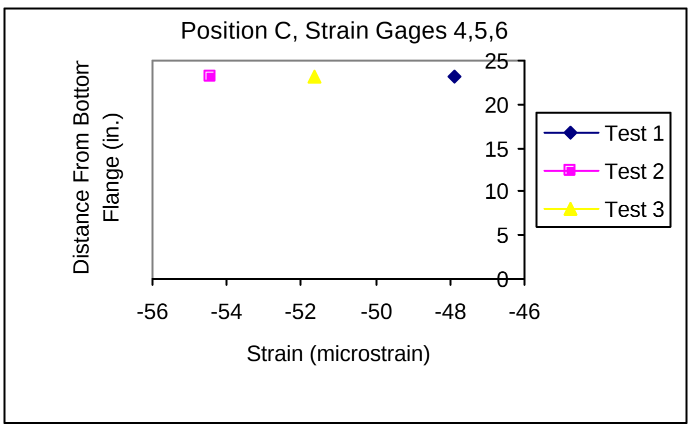

Figure F-22 – Strain Profile, Position C, Strain Gages 4,5,6

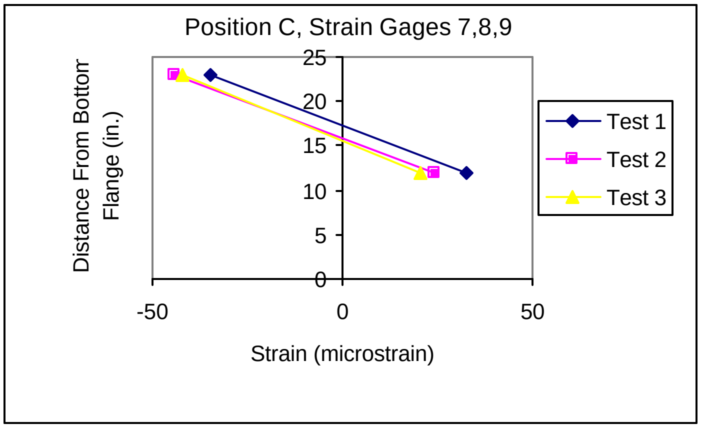

Figure F-23 – Strain Profile, Position C, Strain Gages 7,8,9

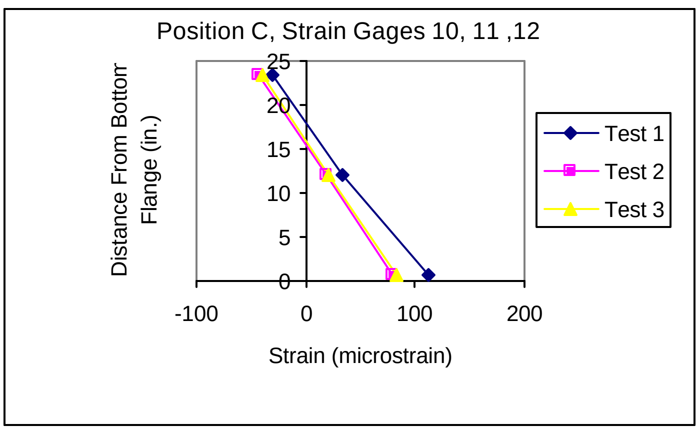

Figure F-24 – Strain Profile, Position C, Strain Gages 10,11,12

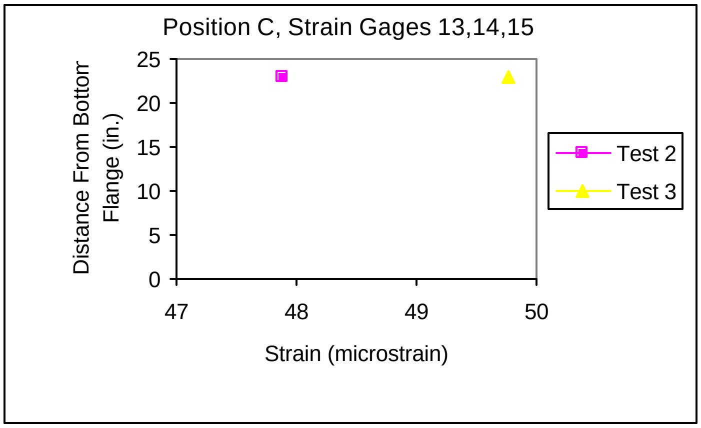

Figure F-25 – Strain Profile, Position C, Strain Gages 13,14,15

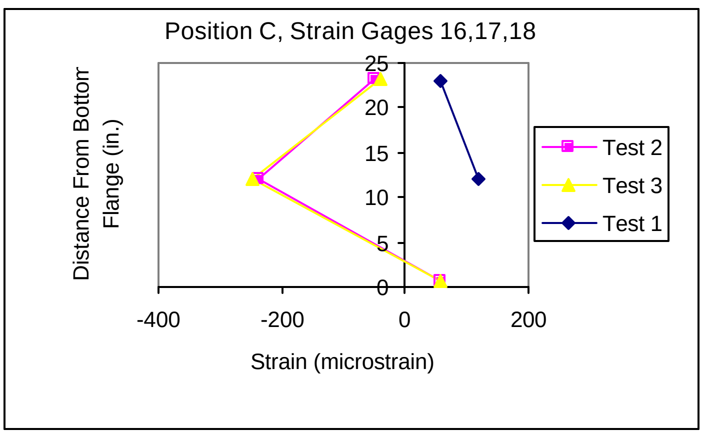

Figure F-26 – Strain Profile, Position C, Strain Gages 16,17,18

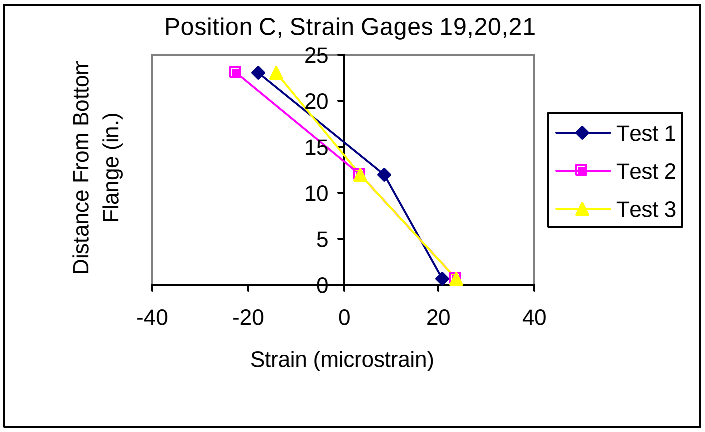

Figure F-27 – Strain Profile, Position C, Strain Gages 19,20,21

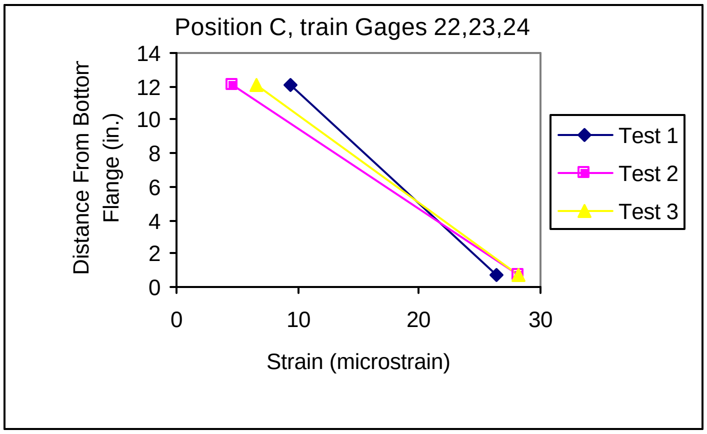

Figure F-28 – Strain Profile, Position C, Strain Gages 22,23,24

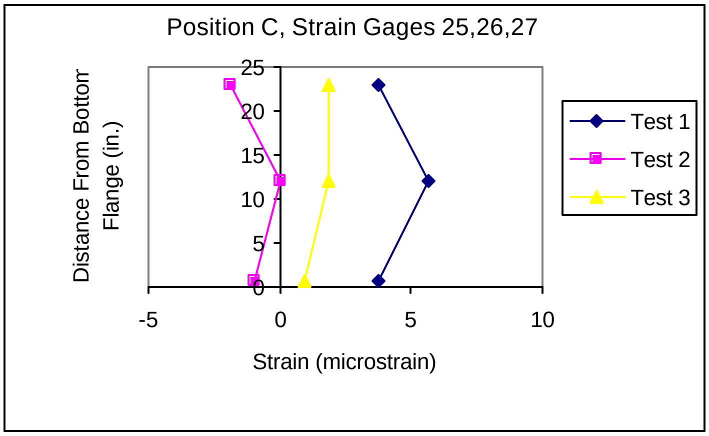

Figure F-29 – Strain Profile, Position C, Strain Gages 25,26,27

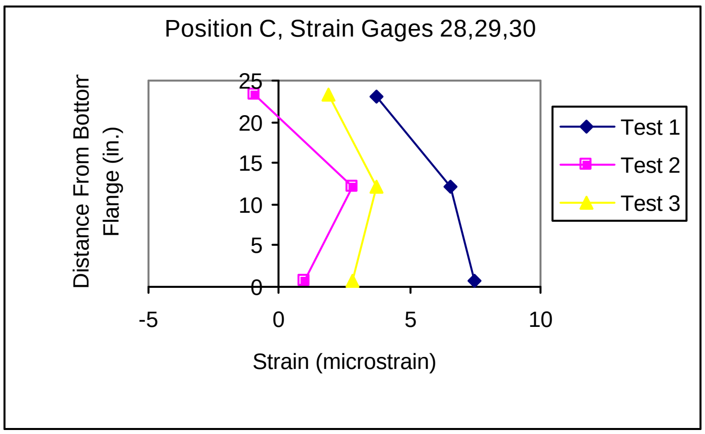

Figure F-30 – Strain Profile, Position C, Strain Gages 28,29,30

APPENDIX G

Boyer Bridge Project – February 15, 2002 Field Test, CR23x Datalogger Data

Table G-1 – V_0 Measurement, Position A, Beam 1

Position A	Beam 1 - Strain Gage Channel Measurement, V_0					
	1	2	3	4	5	6
1	-	-	-	-	-	-
	-	-	-	-	-	-
2	-	-	-	-	-	-
	-	-	-	-	-	-
3	-	-	-	-	-	-
	-	-	-	-	-	-
Average	-	-	-	-	-	-
Minimum	-	-	-	-	-	-
Maximum	-	-	-	-	-	-
Standard Deviation	-	-	-	-	-	-

Table G-2 - V_1 Measurement, Position A, Beam 1

Position A	Beam 1 - Strain Gage Channel Measurement, V_1					
	1	2	3	4	5	6
1	-	-	-	-	-	-
	-	-	-	-	-	-
2	-	-	-	-	-	-
	-	-	-	-	-	-
3	-	-	-	-	-	-
	-	-	-	-	-	-
Average	-	-	-	-	-	-
Minimum	-	-	-	-	-	-
Maximum	-	-	-	-	-	-
Standard Deviation	-	-	-	-	-	-

Table G-3 – V_r Measurement, Position A, Beam 1

Position A	Beam 1 - Strain Gage Channel Measurement, V_r					
	1	2	3	4	5	6
1	- -	- -	- -	- -	- -	- -
2	- -	- -	- -	- -	- -	- -
3	- -	- -	- -	- -	- -	- -
Average	-	-	-	-	-	-
Minimum	-	-	-	-	-	-
Maximum	-	-	-	-	-	-
Standard Deviation	-	-	-	-	-	-

Table G-4 – Strain Measurement, Position A, Beam 1

Test A	Beam 1 – Strain Measurement, Microstrain					
	1	2	3	4	5	6
1	- -	- -	- -	- -	- -	- -
2	- -	- -	- -	- -	- -	- -
3	- -	- -	- -	- -	- -	- -
Average	-	-	-	-	-	-
Minimum	-	-	-	-	-	-
Maximum	-	-	-	-	-	-
Standard Deviation	-	-	-	-	-	-

Table G-5 – Maximum Ranges, Position A, Beam 1

Position A	Beam 1						Beam
	1	2	3	4	5	6	Max
Max Range, V_r	-	-	-	-	-	-	-
Microstrain	-	-	-	-	-	-	-
Stress, ksi	-	-	-	-	-	-	-

Table G-6– V_0 Measurement, Position A, Beam 2

Position A	Beam 2 - Strain Gage Channel Measurement, V_0					
	7	8	9	10	11	12
1	-	-	-0.69701	0.04561	0.30429	-0.79748
	-	-	-0.69668	0.04561	0.30446	-0.7969
2	-	-	-0.69914	0.04471	0.30412	-0.79788
	-	-				
3	-	-	-0.69561	0.04199	0.30545	-0.79401
	-	-	-0.69792	0.04438	0.30438	-0.79839
Average	-	-	-0.69727	0.04446	0.30454	-0.79693
Minimum	-	-	-0.69914	0.04199	0.30412	-0.79839
Maximum	-	-	-0.69561	0.04561	0.30545	-0.79401
Standard Deviation	-	-	0.00133	0.00148	0.00052	0.00172

Table G-7 - V_1 Measurement, Position A, Beam 2

Position A	Beam 2 - Strain Gage Channel Measurement, V_1					
	7	8	9	10	11	12
1	-	-	-0.68884	0.0358	0.30759	-0.78328
	-	-	-0.68908	0.03605	0.30734	-0.78361
2	-	-	-0.68908	0.03555	0.3075	-0.78377
	-	-	-0.68867	0.03555	0.30742	-0.78385
3	-	-	-0.68886	0.03506	0.30776	-0.78454
	-	-	-0.68969	0.03489	0.30752	-0.78372
Average	-	-	-0.68904	0.03548	0.30752	-0.78380
Minimum	-	-	-0.68969	0.03489	0.30734	-0.78454
Maximum	-	-	-0.68867	0.03605	0.30776	-0.78328
Standard Deviation	-	-	0.00036	0.00044	0.00015	0.00042

Table G-8 – V_r Measurement, Position A, Beam 2

Position A	Beam 2 - Strain Gage Channel Measurement, V_r					
	7	8	9	10	11	12
1	-	-	0.007885	-0.009685	0.00309	0.013745
2	- -	- -	0.010265	-0.00916	0.00334	0.01407
3	- -	- -	0.00749	-0.00821	0.002725	0.01207
Average	-	-	0.00855	-0.00902	0.00305	0.01330
Minimum	-	-	0.00749	-0.00969	0.00273	0.01207
Maximum	-	-	0.01027	-0.00821	0.00334	0.01407
Standard Deviation	-	-	0.00150	0.00075	0.00031	0.00107

Table G-9 – Strain Measurement, Position A, Beam 2

Test A	Beam 2 – Strain Measurement, Microstrain					
	7	8	9	10	11	12
1	-	-	15	-18	6	26
2	-	-	19	-17	6	26
3	-	-	14	-15	5	23
Average	-	-	16	-17	6	25
Minimum	-	-	14	-18	5	23
Maximum	-	-	19	-15	6	26
Standard Deviation	-	-	3	1	1	2

Table G-10 – Maximum Ranges, Position

Position A	Beam 2						Beam Max
	7	8	9	10	11	12	
Max Range, V_r	-	-	0.00278	0.00148	0.00061	0.00200	0.00278
Microstrain	-	-	5	3	1	4	5
Stress, ksi	-	-	0.15	0.08	0.03	0.11	0.15

Table G-11 – V_0 Measurement, Position A, Beam 3

Position A	Beam 3 - Strain Gage Channel Measurement, V_0					
	13	14	15	16	17	18
1	-	-0.91832	-	-0.17149	0.69231	-0.36723
	-	-0.91799	-	-0.17157	0.69148	-0.36682
2	-	-0.91814	-	-0.17652	0.65708	-0.36632
3	-	-0.91576	-	-0.17768	0.64348	-0.36096
	-	-0.91701	-	-0.17528	0.64183	-0.36583
Average	-	-0.91744	-	-0.17451	0.66524	-0.36543
Minimum	-	-0.91832	-	-0.17768	0.64183	-0.36723
Maximum	-	-0.91576	-	-0.17149	0.69231	-0.36096
Standard Deviation	-	0.00107	-	0.00285	0.02505	0.00255

Table G-12 - V_1 Measurement, Position A, Beam 3

Position A	Beam 3 - Strain Gage Channel Measurement, V_1					
	13	14	15	16	17	18
1	-	-0.91072	-	-0.19186	0.68537	-0.33357
	-	-0.91064	-	-0.19186	0.68256	-0.33407
2	-	-0.91063	-	-0.19607	0.6546	-0.33316
	-	-0.91055	-	-0.19598	0.65419	-0.33283
3	-	-0.90943	-	-0.19467	0.64481	-0.33317
	-	-0.90952	-	-0.19492	0.64407	-0.33309
Average	-	-0.91025	-	-0.19423	0.66093	-0.33332
Minimum	-	-0.91072	-	-0.19607	0.64407	-0.33407
Maximum	-	-0.90943	-	-0.19186	0.68537	-0.33283
Standard Deviation	-	0.00060	-	0.00192	0.01841	0.00044

Table G-13 – V_r Measurement, Position A, Beam 3

Position A	Beam 3 - Strain Gage Channel Measurement, V_r					
	13	14	15	16	17	18
1	-	0.007475	-	-0.02033	-0.00793	0.033205
2	- -	0.00755	- -	-0.019505	-0.002685	0.033325
3	- -	0.00691	- -	-0.018315	0.001785	0.030265
Average	-	0.00731	-	-0.01938	-0.00294	0.03227
Minimum	-	0.00691	-	-0.02033	-0.00793	0.03027
Maximum	-	0.00755	-	-0.01832	0.00179	0.03332
Standard Deviation	-	0.00035	-	0.00101	0.00486	0.00173

Table G-14 – Strain Measurement, Position A, Beam 3

Test A	Beam 3 – Strain Measurement, Microstrain					
	13	14	15	16	17	18
1	-	14	-	-38	-15	62
2	-	14	-	-37	-5	63
3	-	13	-	-34	3	57
Average	-	14	-	-36	-6	61
Minimum	-	13	-	-38	-15	57
Maximum	-	14	-	-34	3	63
Standard Deviation	-	1	-	2	9	3

Table G-15 – Maximum Ranges, Position A, Beam 3

Position A	Beam 3						Beam Max
	13	14	15	16	17	18	
Max Range, V_r	-	0.00064	-	0.00201	0.00972	0.00306	0.00972
Microstrain	-	1	-	4	18	6	18
Stress, ksi	-	0.03	-	0.11	0.53	0.17	0.53

Table G-16 – V_0 Measurement, Position A, Beam 4

Position A	Beam 4 - Strain Gage Channel Measurement, V_0					
	19	20	21	22	23	24
1	-	-1.0933	-	-	-0.1055	-0.45244
	-	-1.093	-	-	-0.1055	-0.45227
2	-	-1.0933	-	-	-0.1055	-0.45095
3	-	-1.0909	-	-	-0.10418	-0.44708
	-	-1.0915	-	-	-0.10418	-0.44815
Average	-	-1.09240	-	-	-0.10497	-0.45018
Minimum	-	-1.09330	-	-	-0.10550	-0.45244
Maximum	-	-1.09090	-	-	-0.10418	-0.44708
Standard Deviation	-	0.00112	-	-	0.00072	0.00244

Table G-17 - V_1 Measurement, Position A, Beam 4

Position A	Beam 4 - Strain Gage Channel Measurement, V_1					
	19	20	21	22	23	24
1	-	-1.081	-	-	-0.09519	-0.40253
	-	-1.0811	-	-	-0.09544	-0.40236
2	-	-1.0808	-	-	-0.09543	-0.40046
	-	-1.0806	-	-	-0.0951	-0.3998
3	-	-1.0788	-	-	-0.09453	-0.398
	-	-1.0789	-	-	-0.09445	-0.39792
Average	-	-1.08020	-	-	-0.09502	-0.40018
Minimum	-	-1.08110	-	-	-0.09544	-0.40253
Maximum	-	-1.07880	-	-	-0.09445	-0.39792
Standard Deviation	-	0.00106	-	-	0.00043	0.00202

Table G-18– V_r Measurement, Position A, Beam 4

Position A	Beam 4 - Strain Gage Channel Measurement, V_r					
	19	20	21	22	23	24
1	-	0.0121	-	-	0.010185	0.04991
2	- -	0.0126	- -	- -	0.010235	0.05082
3	- -	0.01235	- -	- -	0.00969	0.049655
Average	-	0.01235	-	-	0.01004	0.05013
Minimum	-	0.01210	-	-	0.00969	0.04966
Maximum	-	0.01260	-	-	0.01024	0.05082
Standard Deviation	-	0.00025	-	-	0.00030	0.00061

Table G-19 – Strain Measurement, Position A, Beam 4

Test A	Beam 4 – Strain Measurement, Microstrain					
	19	20	21	22	23	24
1	-	23	-	-	19	94
2	-	24	-	-	19	95
3	-	23	-	-	18	93
Average	-	23	-	-	19	94
Minimum	-	23	-	-	18	93
Maximum	-	24	-	-	19	95
Standard Deviation	-	0	-	-	1	1

Table G-20 – Maximum Ranges, Position A, Beam 4

Position A	Beam 4						Beam
	19	20	21	22	23	24	Max
Max Range, V_r	-	0.00050	-	-	0.00055	0.00117	0.00117
Microstrain	-	1	-	-	1	2	2
Stress, ksi	-	0.03	-	-	0.03	0.06	0.06

Table G-21 – V_0 Measurement, Position A, Beam 5

Position A	Beam 5 - Strain Gage Channel Measurement, V_0					
	25	26	27	28	29	30
1	-1.889	-0.77818	-	-0.909	-0.2407	-0.1917
	-1.8887	-0.77809	-	-0.90784	-0.24069	-0.19178
2	-1.9043	-0.74319	-	-0.89802	-0.23904	-0.19557
3	-1.9024	-0.7385	-	-0.89151	-0.23756	-0.19929
	-1.9019	-0.73826	-	-0.8902	-0.2374	-0.19929
Average	-1.89726	-0.75524	-	-0.89931	-0.23908	-0.19553
Minimum	-1.90430	-0.77818	-	-0.90900	-0.24070	-0.19929
Maximum	-1.88870	-0.73826	-	-0.89020	-0.23740	-0.19170
Standard Deviation	0.00773	0.02099	-	0.00883	0.00161	0.00378

Table G-22 - V_1 Measurement, Position A, Beam 5

Position A	Beam 5 - Strain Gage Channel Measurement, V_1					
	25	26	27	28	29	30
1	-1.9153	-0.77124	-	-0.92656	-0.23137	-0.15177
	-1.9208	-0.73989	-	-0.92713	-0.23145	-0.15194
2	-1.9312	-0.73552	-	-0.91971	-0.23063	-0.15689
	-1.9312	-0.73461	-	-0.91971	-0.23021	-0.15763
3	-1.9297	-0.73175	-	-0.9124	-0.22866	-0.15871
	-1.9301	-0.73159	-	-0.91208	-0.22874	-0.15846
Average	-1.92638	-0.74077	-	-0.91960	-0.23018	-0.15590
Minimum	-1.93120	-0.77124	-	-0.92713	-0.23145	-0.15871
Maximum	-1.91530	-0.73159	-	-0.91208	-0.22866	-0.15177
Standard Deviation	0.00671	0.01523	-	0.00654	0.00123	0.00320

Table G-23– V_r Measurement, Position A, Beam 5

Position A	Beam 5 - Strain Gage Channel Measurement, V_r					
	25	26	27	28	29	30
1	-0.0292	0.02257	-	-0.018425	0.009285	0.039885
2	-0.0269	0.008125	- -	-0.02169	0.00862	0.03831
3	-0.02775	0.00671	- -	-0.021385	0.00878	0.040705
Average	-0.02795	0.01247	-	-0.02050	0.00889	0.03963
Minimum	-0.02920	0.00671	-	-0.02169	0.00862	0.03831
Maximum	-0.02690	0.02257	-	-0.01843	0.00928	0.04071
Standard Deviation	0.00116	0.00878	-	0.00180	0.00035	0.00122

Table G-24 – Strain Measurement, Position A, Beam 5

Test A	Beam 5 - Strain Measurement, Microstrain					
	25	26	27	28	29	30
1	-55	42	-	-35	17	75
2	-51	15	-	-41	16	72
3	-52	13	-	-40	16	76
Average	-52	23	-	-38	17	74
Minimum	-55	13	-	-41	16	72
Maximum	-51	42	-	-35	17	76
Standard Deviation	2	16	-	3	1	2

Table G-25 – Maximum Ranges, Position A, Beam 5

Position A	Beam 5						Beam Max
	25	26	27	28	29	30	
Max Range, V_r	0.00230	0.01586	-	0.00326	0.00066	0.00240	0.01586
Microstrain	4	30	-	6	1	4	30
Stress, ksi	0.12	0.86	-	0.18	0.04	0.13	0.86

Table G-26 - Position A, All Beams

Test A	Beam Max
Max Range, V_r	0.01586
Microstrain	30
Stress, ksi	0.86

Table G-27– V_0 Measurement, Position B, Beam 1

Position B	Beam 1 - Strain Gage Channel Measurement, V_0					
	1	2	3	4	5	6
1	- -	- -	- -	- -	- -	- -
2	- -	- -	- -	- -	- -	- -
3	- -	- -	- -	- -	- -	- -
Average	-	-	-	-	-	-
Minimum	-	-	-	-	-	-
Maximum	-	-	-	-	-	-
Standard Deviation	-	-	-	-	-	-

Table G-28 - V_1 Measurement, Position B, Beam 1

Position B	Beam 1 - Strain Gage Channel Measurement, V_1					
	1	2	3	4	5	6
1	- -	- -	- -	- -	- -	- -
2	- -	- -	- -	- -	- -	- -
3	- -	- -	- -	- -	- -	- -
Average	-	-	-	-	-	-
Minimum	-	-	-	-	-	-
Maximum	-	-	-	-	-	-
Standard Deviation	-	-	-	-	-	-

Table G-29– V_r Measurement, Position B, Beam 1

Position B	Beam 1 - Strain Gage Channel Measurement, V_r					
	1	2	3	4	5	6
1	- -	- -	- -	- -	- -	- -
2	- -	- -	- -	- -	- -	- -
3	- -	- -	- -	- -	- -	- -
Average	-	-	-	-	-	-
Minimum	-	-	-	-	-	-
Maximum	-	-	-	-	-	-
Standard Deviation	-	-	-	-	-	-

Table G-30 – Strain Measurement, Position B, Beam 1

Test B	Beam 1 - Strain Measurement, Microstrain					
	1	2	3	4	5	6
1	- -	- -	- -	- -	- -	- -
2	- -	- -	- -	- -	- -	- -
3	- -	- -	- -	- -	- -	- -
Average	-	-	-	-	-	-
Minimum	-	-	-	-	-	-
Maximum	-	-	-	-	-	-
Standard Deviation	-	-	-	-	-	-

Table G-31– Maximum Ranges, Position B, Beam 1

Position B	Beam 1						Beam
	1	2	3	4	5	6	Max
Max Range, V_r	-	-	-	-	-	-	-
Microstrain	-	-	-	-	-	-	-
Stress, ksi	-	-	-	-	-	-	-

Table G-32 – V_0 Measurement, Position B, Beam 2

Position B	Beam 2 - Strain Gage Channel Measurement, V_0					
	7	8	9	10	11	12
1	-	-	-0.69815	0.04537	0.30396	-0.79829
	-	-	-0.69791	0.04553	0.30388	-0.79821
2	-	-	-0.69815	0.04495	0.30387	-0.7982
	-	-	-0.69798	0.04528	0.30412	-0.79895
3	-	-	-0.69826	0.04421	0.30438	-0.79915
	-	-	-0.69819	0.04421	0.30447	-0.79833
Average	-	-	-0.69811	0.04493	0.30411	-0.79852
Minimum	-	-	-0.69826	0.04421	0.30387	-0.79915
Maximum	-	-	-0.69791	0.04553	0.30447	-0.79820
Standard Deviation	-	-	0.00013	0.00059	0.00026	0.00042

Table G-33 - V_1 Measurement, Position B, Beam 2

Position B	Beam 2 - Strain Gage Channel Measurement, V_1					
	7	8	9	10	11	12
1	-	-	-0.68125	0.02821	0.31188	-0.76588
	-	-	-0.68166	0.02846	0.31188	-0.76637
2	-	-	-0.68058	0.02788	0.3122	-0.76504
	-	-	-0.68108	0.02772	0.31221	-0.76645
3	-	-	-0.68153	0.02689	0.31272	-0.76575
	-	-	-0.68186	0.02681	0.31264	-0.76468
Average	-	-	-0.68133	0.02766	0.31226	-0.76570
Minimum	-	-	-0.68186	0.02681	0.31188	-0.76645
Maximum	-	-	-0.68058	0.02846	0.31272	-0.76468
Standard Deviation	-	-	0.00046	0.00068	0.00036	0.00071

Table G-34 – V_r Measurement, Position B, Beam 2

Position B	Beam 2 - Strain Gage Channel Measurement, V_r					
	7	8	9	10	11	12
1	-	-	0.016575	-0.017115	0.00796	0.032125
2	- -	- -	0.017235	-0.017315	0.00821	0.03283
3	- -	- -	0.01653	-0.01736	0.008255	0.033525
Average	-	-	0.01678	-0.01726	0.00814	0.03283
Minimum	-	-	0.01653	-0.01736	0.00796	0.03213
Maximum	-	-	0.01724	-0.01712	0.00825	0.03353
Standard Deviation	-	-	0.00039	0.00013	0.00016	0.00070

Table G-35 – Strain Measurement, Position B, Beam 2

Test B	Beam 2 - Strain Measurement, Microstrain					
	7	8	9	10	11	12
1	-	-	31	-32	15	60
2	-	-	32	-33	15	62
3	-	-	31	-33	16	63
Average	-	-	32	-32	15	62
Minimum	-	-	31	-33	15	60
Maximum	-	-	32	-32	16	63
Standard Deviation	-	-	1	0	0	1

Table G-36 – Maximum Ranges, Position B, Beam 2

Position B	Beam 2						Beam
	7	8	9	10	11	12	Max
Max Range, V_r	-	-	0.00070	0.00024	0.00029	0.00140	0.00140
Microstrain	-	-	1	0	1	3	3
Stress, ksi	-	-	0.04	0.01	0.02	0.08	0.08

Table G-37– V_0 Measurement, Position B, Beam 3

Position B	Beam 3 - Strain Gage Channel Measurement, V_0					
	13	14	15	16	17	18
1	-	-0.91814	-	-0.17322	0.67778	-0.36656
	-	-0.91823	-	-0.17256	0.67638	-0.36698
2	-	-0.91797	-	-0.17668	0.64874	-0.36607
	-	-0.91797	-	-0.17594	0.64849	-0.3664
3	-	-0.91686	-	-0.17562	0.63417	-0.36584
	-	-0.91703	-	-0.17537	0.63417	-0.36567
Average	-	-0.91770	-	-0.17490	0.65329	-0.36625
Minimum	-	-0.91823	-	-0.17668	0.63417	-0.36698
Maximum	-	-0.91686	-	-0.17256	0.67778	-0.36567
Standard Deviation	-	0.00060	-	0.00163	0.01953	0.00049

Table G-38 - V_1 Measurement, Position B, Beam 3

Position B	Beam 3 - Strain Gage Channel Measurement, V_1					
	13	14	15	16	17	18
	-	-0.90858	-	-0.20077	0.67688	-0.31947
	-	-0.9085	-	-0.20308	0.67349	-0.31955
2	-	-0.90774	-	-0.20382	0.6541	-0.31922
	-	-0.90775	-	-0.20407	0.65295	-0.3193
3	-	-0.90664	-	-0.204	0.64441	-0.31808
	-	-0.90664	-	-0.20416	0.64499	-0.31792
Average	-	-0.90764	-	-0.20332	0.65780	-0.31892
Minimum	-	-0.90858	-	-0.20416	0.64441	-0.31955
Maximum	-	-0.90664	-	-0.20077	0.67688	-0.31792
Standard Deviation	-	0.00085	-	0.00131	0.01408	0.00073

Table G-39 – V_r Measurement, Position B, Beam 3

Position B	Beam 3 - Strain Gage Channel Measurement, V_r					
	13	14	15	16	17	18
1	-	0.009645	-	-0.029035	-0.001895	0.04726
2	- -	0.010225	- -	-0.027635	0.00491	0.046975
3	- -	0.010305	- -	-0.028585	0.01053	0.047755
Average	-	0.01006	-	-0.02842	0.00452	0.04733
Minimum	-	0.00965	-	-0.02904	-0.00189	0.04698
Maximum	-	0.01031	-	-0.02764	0.01053	0.04776
Standard Deviation	-	0.00036	-	0.00071	0.00622	0.00039

Table G-40 – Strain Measurement, Position B, Beam 3

Test B	Beam 3 – Strain Measurement, Microstrain					
	13	14	15	16	17	18
1	-	18	-	-55	-4	89
2	-	19	-	-52	9	88
3	-	19	-	-54	20	90
Average	-	19	-	-53	8	89
Minimum	-	18	-	-55	-4	88
Maximum	-	19	-	-52	20	90
Standard Deviation	-	1	-	1	12	1

Table G-41 – Maximum Ranges, Position B, Beam 3

Position B	Beam 3						Beam
	13	14	15	16	17	18	Max
Max Range, V_r	-	0.00066	-	0.00140	0.01243	0.00078	0.01243
Microstrain	-	1	-	3	23	1	23
Stress, ksi	-	0.04	-	0.08	0.67	0.04	0.67

Table G-42 – V_0 Measurement, Position B, Beam 4

Position B	Beam 4 - Strain Gage Channel Measurement, V_0					
	19	20	21	22	23	24
1	-	-1.0933	-	-	-0.10533	-0.45053
	-	-1.093	-	-	-0.10542	-0.45103
2	-	-1.093	-	-	-0.1055	-0.44929
	-	-1.0926	-	-	-0.105	-0.44938
3	-	-1.0912	-	-	-0.10451	-0.44692
	-	-1.091	-	-	-0.10402	-0.4466
Average	-	-1.09235	-	-	-0.10496	-0.44896
Minimum	-	-1.09330	-	-	-0.10550	-0.45103
Maximum	-	-1.09100	-	-	-0.10402	-0.44660
Standard Deviation	-	0.00100	-	-	0.00059	0.00183

Table G-43 - V_1 Measurement, Position B, Beam 4

Position B	Beam 4 - Strain Gage Channel Measurement, V_1					
	19	20	21	22	23	24
1	-	-1.0832	-	-	-0.097	-0.41127
	-	-1.0838	-	-	-0.09717	-0.41144
2	-	-1.0834	-	-	-0.09675	-0.41077
	-	-1.0837	-	-	-0.09692	-0.41086
3	-	-1.0816	-	-	-0.09561	-0.40717
	-	-1.0815	-	-	-0.09569	-0.40717
Average	-	-1.08287	-	-	-0.09652	-0.40978
Minimum	-	-1.08380	-	-	-0.09717	-0.41144
Maximum	-	-1.08150	-	-	-0.09561	-0.40717
Standard Deviation	-	0.00104	-	-	0.00069	0.00204

Table G-44 – V_r Measurement, Position B, Beam 4

Position B	Beam 4 - Strain Gage Channel Measurement, V_r					
	19	20	21	22	23	24
1	-	0.00965	-	-	0.00829	0.039425
2	- -	0.00925	- -	- -	0.008415	0.03852
3	- -	0.00955	- -	- -	0.008615	0.03959
Average	-	0.00948	-	-	0.00844	0.03918
Minimum	-	0.00925	-	-	0.00829	0.03852
Maximum	-	0.00965	-	-	0.00862	0.03959
Standard Deviation	-	0.00021	-	-	0.00016	0.00058

Table G-45 – Strain Measurement, Position B, Beam 4

Test B	Beam 4 - Strain Measurement, Microstrain					
	19	20	21	22	23	24
1	-	18	-	-	16	74
2	-	17	-	-	16	72
3	-	18	-	-	16	74
Average	-	18	-	-	16	74
Minimum	-	17	-	-	16	72
Maximum	-	18	-	-	16	74
Standard Deviation	-	0	-	-	0	1

Table G-46 – Maximum Ranges, Position B, Beam 4

Position B	Beam 4						Beam Max
	19	20	21	22	23	24	
Max Range, V_r	-	0.00040	-	-	0.00033	0.00107	0.00107
Microstrain	-	1	-	-	1	2	2
Stress, ksi	-	0.02	-	-	0.02	0.06	0.06

Table G-47– V_0 Measurement, Position B, Beam 5

Position B	Beam 5 - Strain Gage Channel Measurement, V_0					
	25	26	27	28	29	30
1	-1.8944	-0.74533	-	-0.90445	-0.23978	-0.19203
	-1.894	-0.74509	-	-0.9033	-0.23979	-0.1926
2	-1.905	-0.74071	-	-0.89677	-0.23855	-0.19755
	-1.9038	-0.74022	-	-0.8957	-0.23813	-0.19788
3	-1.9028	-0.73761	-	-0.88766	-0.2374	-0.19979
	-1.9019	-0.7372	-	-0.88742	-0.23683	-0.19946
Average	-1.90032	-0.74103	-	-0.89588	-0.23841	-0.19655
Minimum	-1.90500	-0.74533	-	-0.90445	-0.23979	-0.19979
Maximum	-1.89400	-0.73720	-	-0.88742	-0.23683	-0.19203
Standard Deviation	0.00485	0.00352	-	0.00733	0.00122	0.00340

Table G-48 - V_1 Measurement, Position B, Beam 5

Position B	Beam 5 - Strain Gage Channel Measurement, V_1					
	25	26	27	28	29	30
1	-1.9026	-0.7432	-	-0.90883	-0.23715	-0.17916
	-1.917	-0.74319	-	-0.90808	-0.23748	-0.17974
2	-1.913	-0.73873	-	-0.90123	-0.2364	-0.18642
	-1.9131	-0.73865	-	-0.90049	-0.23616	-0.18658
3	-1.9119	-0.73606	-	-0.89361	-0.23526	-0.18766
	-1.9119	-0.73589	-	-0.89402	-0.2351	-0.18742
Average	-1.91158	-0.73929	-	-0.90104	-0.23626	-0.18450
Minimum	-1.91700	-0.74320	-	-0.90883	-0.23748	-0.18766
Maximum	-1.90260	-0.73589	-	-0.89361	-0.23510	-0.17916
Standard Deviation	0.00479	0.00326	-	0.00656	0.00096	0.00394

Table G-49 – V_r Measurement, Position B, Beam 5

Position B	Beam 5 - Strain Gage Channel Measurement, V_r					
	25	26	27	28	29	30
1	-0.0156	0.002015	-	-0.00458	0.00247	0.012865
2	-0.00865	0.001775	- -	-0.004625	0.00206	0.011215
3	-0.00955	0.00143	- -	-0.006275	0.001935	0.012085
Average	-0.01127	0.00174	-	-0.00516	0.00216	0.01206
Minimum	-0.01560	0.00143	-	-0.00628	0.00194	0.01122
Maximum	-0.00865	0.00201	-	-0.00458	0.00247	0.01287
Standard Deviation	0.00378	0.00029	-	0.00097	0.00028	0.00083

Table G-50 – Strain Measurement, Position B, Beam 5

Test B	Beam 5 – Strain Measurement, Microstrain					
	25	26	27	28	29	30
1	-29	4	-	-9	5	24
2	-16	3	-	-9	4	21
3	-18	3	-	-12	4	23
Average	-21	3	-	-10	4	23
Minimum	-29	3	-	-12	4	21
Maximum	-16	4	-	-9	5	24
Standard Deviation	7	1	-	2	1	2

Table G-51– Maximum Ranges, Position B, Beam 5

Position B	Beam 5						Beam
	25	26	27	28	29	30	Max
Max Range, V_r	0.00695	0.00059	-	0.00170	0.00053	0.00165	0.00695
Microstrain	13	1	-	3	1	3	13
Stress, ksi	0.38	0.03	-	0.09	0.03	0.09	0.38

Table G-52 - Position B, All Beams

Test B	Beam Max
Max Range, V_r	0.01243
Microstrain	23
Stress, ksi	0.67

Table G-53 – V_0 Measurement, Position C, Beam 1

Position C	Beam 1 - Strain Gage Channel Measurement, V_0					
	1	2	3	4	5	6
1	-	-	-	-	-	-
	-	-	-	-	-	-
2	-	-	-	-	-	-
	-	-	-	-	-	-
3	-	-	-	-	-	-
	-	-	-	-	-	-
Average	-	-	-	-	-	-
Minimum	-	-	-	-	-	-
Maximum	-	-	-	-	-	-
Standard Deviation	-	-	-	-	-	-

Table G-54- V_1 Measurement, Position C, Beam 1

Position C	Beam 1 - Strain Gage Channel Measurement, V_1					
	1	2	3	4	5	6
1	-	-	-	-	-	-
	-	-	-	-	-	-
2	-	-	-	-	-	-
	-	-	-	-	-	-
3	-	-	-	-	-	-
	-	-	-	-	-	-
Average	-	-	-	-	-	-
Minimum	-	-	-	-	-	-
Maximum	-	-	-	-	-	-
Standard Deviation	-	-	-	-	-	-

Table G-55– V_r Measurement, Position C, Beam 1

Position C	Beam 1 - Strain Gage Channel Measurement, V_r					
	1	2	3	4	5	6
1	- -	- -	- -	- -	- -	- -
2	- -	- -	- -	- -	- -	- -
3	- -	- -	- -	- -	- -	- -
Average	-	-	-	-	-	-
Minimum	-	-	-	-	-	-
Maximum	-	-	-	-	-	-
Standard Deviation	-	-	-	-	-	-

Table G-56 – Strain Measurement, Position C, Beam 1

Test C	Beam 1 - Strain Measurement, Microstrain					
	1	2	3	4	5	6
1	- -	- -	- -	- -	- -	- -
2	- -	- -	- -	- -	- -	- -
3	- -	- -	- -	- -	- -	- -
Average	-	-	-	-	-	-
Minimum	-	-	-	-	-	-
Maximum	-	-	-	-	-	-
Standard Deviation	-	-	-	-	-	-

Table G-57 – Maximum Ranges, Position C, Beam 1

Position C	Beam 1						Beam
	1	2	3	4	5	6	Max
Max Range, V_r	-	-	-	-	-	-	-
Microstrain	-	-	-	-	-	-	-
Stress, ksi	-	-	-	-	-	-	-

Table G-58 – V_0 Measurement, Position C, Beam 2

Position C	Beam 2 - Strain Gage Channel Measurement, V_0					
	7	8	9	10	11	12
1	-	-	-0.69824	0.04504	0.30388	-0.79854
2	-	-	-0.69832	0.04421	0.30387	-0.79854
	-	-	-0.69807	0.04479	0.30404	-0.79936
3	-	-	-0.6995	0.04447	0.30467	-0.79866
	-	-	-0.699	0.04471	0.30483	-0.79841
Average	-	-	-0.69863	0.04464	0.30426	-0.79870
Minimum	-	-	-0.69950	0.04421	0.30387	-0.79936
Maximum	-	-	-0.69807	0.04504	0.30483	-0.79841
Standard Deviation	-	-	0.00060	0.00032	0.00046	0.00038

Table G-59 - V_1 Measurement, Position C, Beam 2

Position C	Beam 2 - Strain Gage Channel Measurement, V_1					
	7	8	9	10	11	12
1	-	-	-0.67539	0.02145	0.31625	-0.74922
	-	-	-0.67572	0.02145	0.316	-0.7488
2	-	-	-0.67531	0.02103	0.31641	-0.74979
	-	-	-0.67531	0.02095	0.3165	-0.74971
3	-	-	-0.67656	0.02062	0.31737	-0.74957
	-	-	-0.67762	0.02046	0.31703	-0.74898
Average	-	-	-0.67599	0.02099	0.31659	-0.74935
Minimum	-	-	-0.67762	0.02046	0.31600	-0.74979
Maximum	-	-	-0.67531	0.02145	0.31737	-0.74880
Standard Deviation	-	-	0.00093	0.00041	0.00051	0.00041

Table G-60 – V_r Measurement, Position C, Beam 2

Position C	Beam 2 - Strain Gage Channel Measurement, V_r					
	7	8	9	10	11	12
1	-	-	0.022685	-0.02359	0.012245	0.04953
2	- -	- -	0.022885	-0.02351	0.0125	0.0492
3	- -	- -	0.02216	-0.02405	0.01245	0.04926
Average	-	-	0.02258	-0.02372	0.01240	0.04933
Minimum	-	-	0.02216	-0.02405	0.01225	0.04920
Maximum	-	-	0.02289	-0.02351	0.01250	0.04953
Standard Deviation	-	-	0.00037	0.00029	0.00014	0.00018

Table G-61– Strain Measurement, Position C, Beam 2

Test C	Beam 2 - Strain Measurement, Microstrain					
	7	8	9	10	11	12
1	-	-	43	-44	23	93
2	-	-	43	-44	23	92
3	-	-	42	-45	23	93
Average	-	-	42	-45	23	93
Minimum	-	-	42	-45	23	92
Maximum	-	-	43	-44	23	93
Standard Deviation	-	-	1	1	0	0

Table G-62 – Maximum Ranges, Position C, Beam 2

Position C	Beam 2						Beam Max
	7	8	9	10	11	12	
Max Range, V_r	-	-	0.00073	0.00054	0.00026	0.00033	0.00073
Microstrain	-	-	1	1	0	1	1
Stress, ksi	-	-	0.04	0.03	0.01	0.02	0.04

Table G-63 – V_0 Measurement, Position C, Beam 3

Position C	Beam 3 - Strain Gage Channel Measurement, V_0					
	13	14	15	16	17	18
1	-	-0.91839	-	-0.17569	0.66566	-0.36624
2	-	-0.91773	-	-0.17677	0.64198	-0.36582
	-	-0.91756	-	-0.17602	0.64182	-0.36607
3	-	-0.91672	-	-0.17564	0.63499	-0.36547
	-	-0.91663	-	-0.17547	0.63457	-0.36546
Average	-	-0.91741	-	-0.17592	0.64380	-0.36581
Minimum	-	-0.91839	-	-0.17677	0.63457	-0.36624
Maximum	-	-0.91663	-	-0.17547	0.66566	-0.36546
Standard Deviation	-	0.00074	-	0.00052	0.01273	0.00035

Table G-64 - V_1 Measurement, Position C, Beam 3

Position C	Beam 3 - Strain Gage Channel Measurement, V_1					
	13	14	15	16	17	18
1	-	-0.91056	-	-0.19813	0.665	-0.32928
	-	-0.91056	-	-0.19813	0.66252	-0.32912
2	-	-0.91006	-	-0.19664	0.64941	-0.32986
	-	-0.90998	-	-0.19673	0.65073	-0.32953
3	-	-0.9092	-	-0.19692	0.64282	-0.32817
	-	-0.90902	-	-0.19791	0.64281	-0.32842
Average	-	-0.90990	-	-0.19741	0.65222	-0.32906
Minimum	-	-0.91056	-	-0.19813	0.64281	-0.32986
Maximum	-	-0.90902	-	-0.19664	0.66500	-0.32817
Standard Deviation	-	0.00066	-	0.00072	0.00955	0.00065

Table G-65 – V_r Measurement, Position C, Beam 3

Position C	Beam 3 - Strain Gage Channel Measurement, V_r					
	13	14	15	16	17	18
1	-	0.00783	-	-0.02244	-0.0019	0.03704
2	- -	0.007625	- -	-0.02029	0.00817	0.03625
3	- -	0.007565	- -	-0.02186	0.008035	0.03717
Average	-	0.00767	-	-0.02153	0.00477	0.03682
Minimum	-	0.00756	-	-0.02244	-0.00190	0.03625
Maximum	-	0.00783	-	-0.02029	0.00817	0.03717
Standard Deviation	-	0.00014	-	0.00111	0.00578	0.00050

Table G-66 – Strain Measurement, Position C, Beam 3

Test C	Beam 3 – Strain Measurement, Microstrain					
	13	14	15	16	17	18
1	-	15	-	-42	-4	70
2	-	14	-	-38	15	68
3	-	14	-	-41	15	70
Average	-	14	-	-40	9	69
Minimum	-	14	-	-42	-4	68
Maximum	-	15	-	-38	15	70
Standard Deviation	-	0	-	2	11	1

Table G-67 – Maximum Ranges, Position C, Beam 3

Position C	Beam 3						Beam
	13	14	15	16	17	18	Max
Max Range, V_r	-	0.00027	-	0.00215	0.01007	0.00092	0.01007
Microstrain	-	0	-	4	19	2	19
Stress, ksi	-	0.01	-	0.12	0.55	0.05	0.55

Table G-68 – V_0 Measurement, Position C, Beam 4

Position C	Beam 4 - Strain Gage Channel Measurement, V_0					
	19	20	21	22	23	24
1	-	-1.0929	-	-	-0.10558	-0.45054
2	-	-1.0923	-	-	-0.10517	-0.4488
	-	-1.0924	-	-	-0.10476	-0.4488
3	-	-1.0908	-	-	-0.1037	-0.4464
	-	-1.0906	-	-	-0.10362	-0.44664
Average	-	-1.09180	-	-	-0.10457	-0.44824
Minimum	-	-1.09290	-	-	-0.10558	-0.45054
Maximum	-	-1.09060	-	-	-0.10362	-0.44640
Standard Deviation	-	0.00103	-	-	0.00088	0.00172

Table G-69 - V_1 Measurement, Position C, Beam 4

Position C	Beam 4 - Strain Gage Channel Measurement, V_1					
	19	20	21	22	23	24
	-	-1.0899	-	-	-0.10137	-0.43363
	-	-1.09	-	-	-0.10162	-0.4333
2	-	-1.0889	-	-	-0.1008	-0.43222
	-	-1.0886	-	-	-0.10055	-0.4319
3	-	-1.0873	-	-	-0.09949	-0.42964
	-	-1.0876	-	-	-0.09965	-0.42972
Average	-	-1.08872	-	-	-0.10058	-0.43174
Minimum	-	-1.09000	-	-	-0.10162	-0.43363
Maximum	-	-1.08730	-	-	-0.09949	-0.42964
Standard Deviation	-	0.00113	-	-	0.00087	0.00172

Table G-70 – V_r Measurement, Position C, Beam 4

Position C	Beam 4 - Strain Gage Channel Measurement, V_r					
	19	20	21	22	23	24
1	-	0.00295	-	-	0.004085	0.017075
2	- -	0.0036	- -	- -	0.00429	0.01674
3	- -	0.00325	- -	- -	0.00409	0.01684
Average	-	0.00327	-	-	0.00416	0.01689
Minimum	-	0.00295	-	-	0.00408	0.01674
Maximum	-	0.00360	-	-	0.00429	0.01708
Standard Deviation	-	0.00033	-	-	0.00012	0.00017

Table G-71 – Strain Measurement, Position C, Beam 4

Test C	Beam 4 - Strain Measurement, Microstrain					
	19	20	21	22	23	24
1	-	6	-	-	8	32
2	-	7	-	-	8	31
3	-	6	-	-	8	32
Average	-	6	-	-	8	32
Minimum	-	6	-	-	8	31
Maximum	-	7	-	-	8	32
Standard Deviation	-	1	-	-	0	0

Table G-72 – Maximum Ranges, Position C, Beam 4

Position C	Beam 4						Beam Max
	19	20	21	22	23	24	
Max Range, V_r	-	0.00065	-	-	0.00021	0.00034	0.00065
Microstrain	-	1	-	-	0	1	1
Stress, ksi	-	0.04	-	-	0.01	0.02	0.04

Table G-73 – V_0 Measurement, Position C, Beam 5

Position C	Beam 5 - Strain Gage Channel Measurement, V_0					
	25	26	27	28	29	30
1	-1.9055	-0.74402	-	-0.90074	-0.23954	-0.19326
2	-1.9035	-0.73931	-	-0.89306	-0.23789	-0.19871
	-1.9028	-0.73915	-	-0.8924	-0.23747	-0.19887
3	-1.902	-0.73671	-	-0.88504	-0.23652	-0.19981
	-1.9018	-0.7367	-	-0.88487	-0.23652	-0.20014
Average	-1.90312	-0.73918	-	-0.89122	-0.23759	-0.19816
Minimum	-1.90550	-0.74402	-	-0.90074	-0.23954	-0.20014
Maximum	-1.90180	-0.73670	-	-0.88487	-0.23652	-0.19326
Standard Deviation	0.00149	0.00299	-	0.00659	0.00124	0.00280

Table G-74 - V_1 Measurement, Position C, Beam 5

Position C	Beam 5 - Strain Gage Channel Measurement, V_1					
	25	26	27	28	29	30
1	-1.9057	-0.74278	-	-0.89942	-0.23913	-0.19186
	-1.9058	-0.74295	-	-0.89942	-0.23896	-0.19252
2	-1.9033	-0.73808	-	-0.89257	-0.23714	-0.19656
	-1.9034	-0.73783	-	-0.89266	-0.23698	-0.19623
3	-1.9025	-0.73587	-	-0.88478	-0.23561	-0.19733
	-1.9028	-0.73611	-	-0.88518	-0.23594	-0.19749
Average	-1.90392	-0.73894	-	-0.89234	-0.23729	-0.19533
Minimum	-1.90580	-0.74295	-	-0.89942	-0.23913	-0.19749
Maximum	-1.90250	-0.73587	-	-0.88478	-0.23561	-0.19186
Standard Deviation	0.00146	0.00317	-	0.00646	0.00148	0.00249

Table G-75 – V_r Measurement, Position C, Beam 5

Position C	Beam 5 - Strain Gage Channel Measurement, V_r					
	25	26	27	28	29	30
1	-0.00025	0.001155	-	0.00132	0.000495	0.00107
2	-0.0002	0.001275	- -	0.000115	0.00062	0.002395
3	-0.00075	0.000715	- -	-2.5E-05	0.000745	0.002565
Average	-0.00040	0.00105	-	0.00047	0.00062	0.00201
Minimum	-0.00075	0.00071	-	-0.00002	0.00049	0.00107
Maximum	-0.00020	0.00128	-	0.00132	0.00074	0.00257
Standard Deviation	0.00030	0.00029	-	0.00074	0.00013	0.00082

Table G-76 – Strain Measurement, Position C, Beam 5

Test C	Beam 5 – Strain Measurement, Microstrain					
	25	26	27	28	29	30
1	0	2	-	2	1	2
2	0	2	-	0	1	4
3	-1	1	-	0	1	5
Average	-1	2	-	1	1	4
Minimum	-1	1	-	0	1	2
Maximum	0	2	-	2	1	5
Standard Deviation	1	1	-	1	0	2

Table G-77 – Maximum Ranges, Position C, Beam 5

Position C	Beam 5						Beam Max
	25	26	27	28	29	30	
Max Range, V_r	0.00055	0.00056	-	0.00134	0.00025	0.00150	0.00150
Microstrain	1	1	-	3	0	3	3
Stress, ksi	0.03	0.03	-	0.07	0.01	0.08	0.08

Table G-78 – Position C, All Beams

Test C	Beam Max
Max Range, V_r	0.01007
Microstrain	19
Stress, ksi	0.55

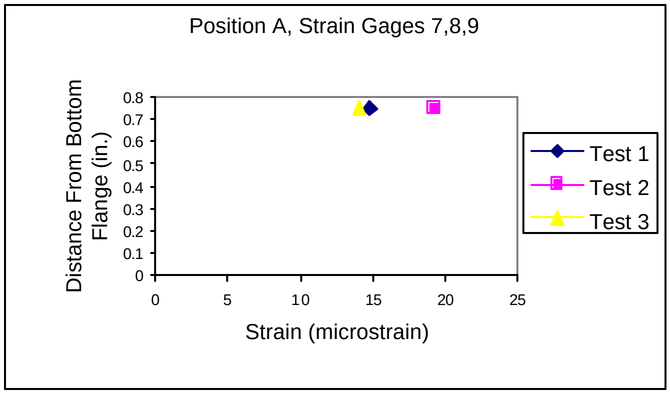

Figure G-1 – Strain Profile, Position A, Strain Gages 7,8,9

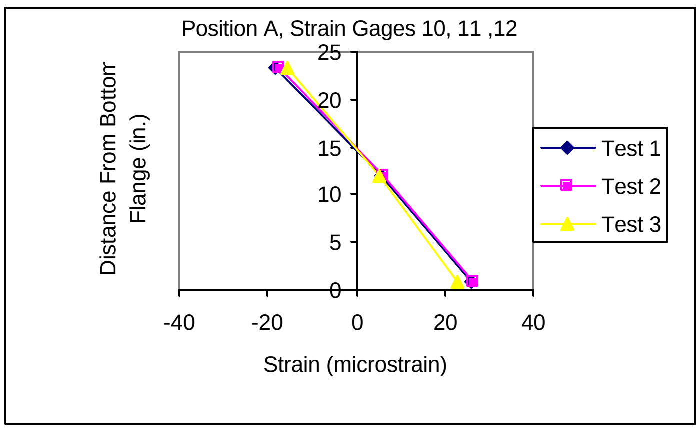

Figure G-2 – Strain Profile, Position A, Strain Gages 10,11,12

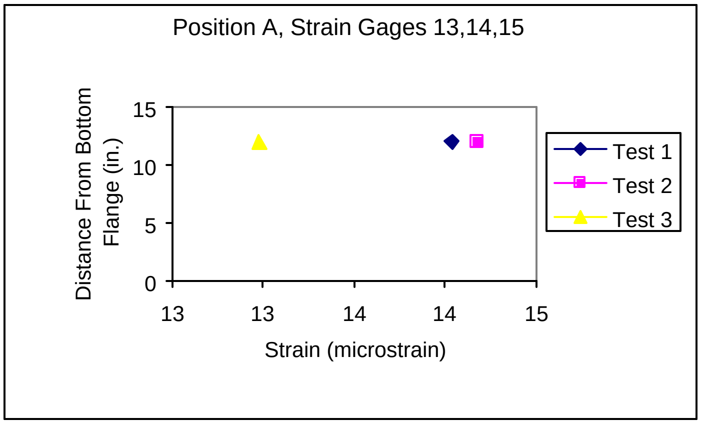

Figure G-3 – Strain Profile, Position A, Strain Gages 13,14,15

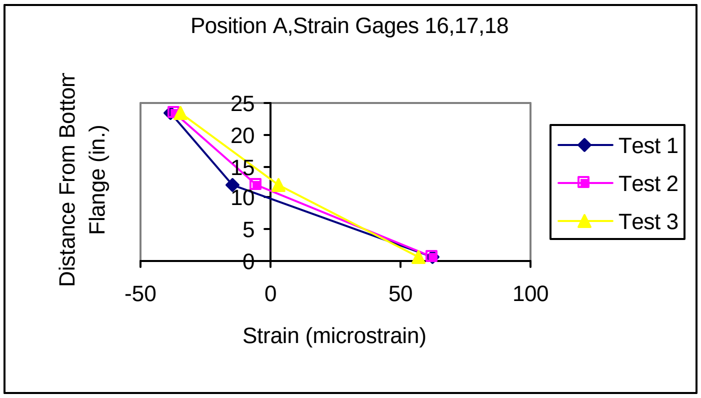

Figure G-4 – Strain Profile, Position A, Strain Gages 16,17,18

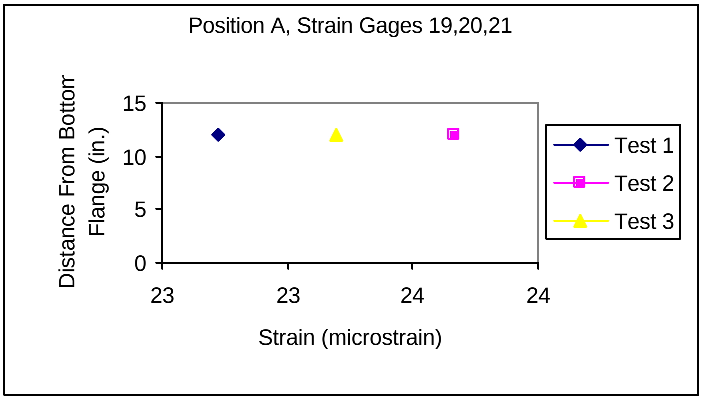

Figure G-5 – Strain Profile, Position A, Strain Gages 19,20,21

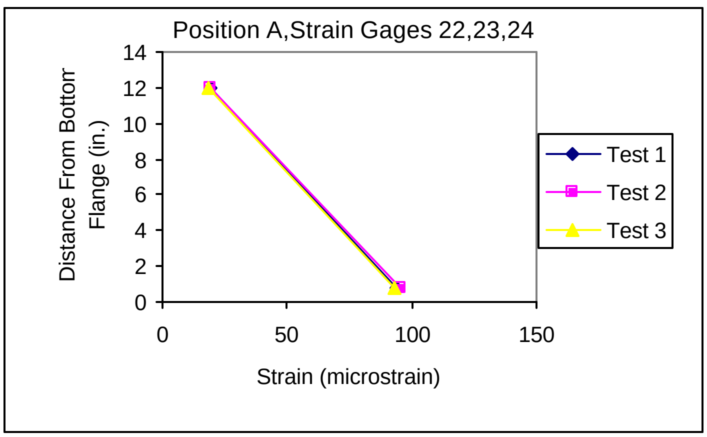

Figure G-6 – Strain Profile, Position A, Strain Gages 22,23,24

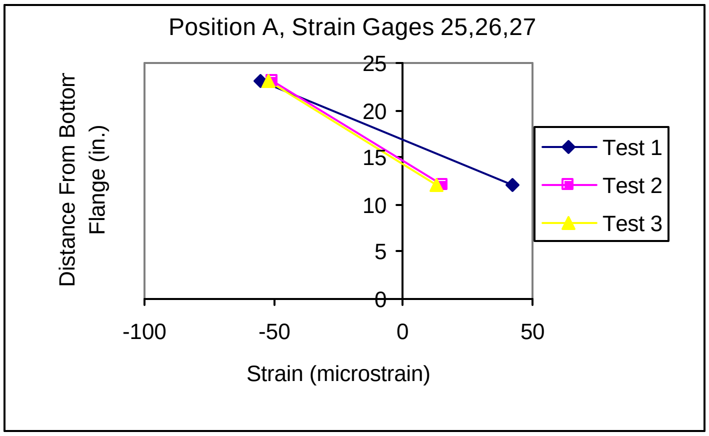

Figure G-7 – Strain Profile, Position A, Strain Gages 25,26,27

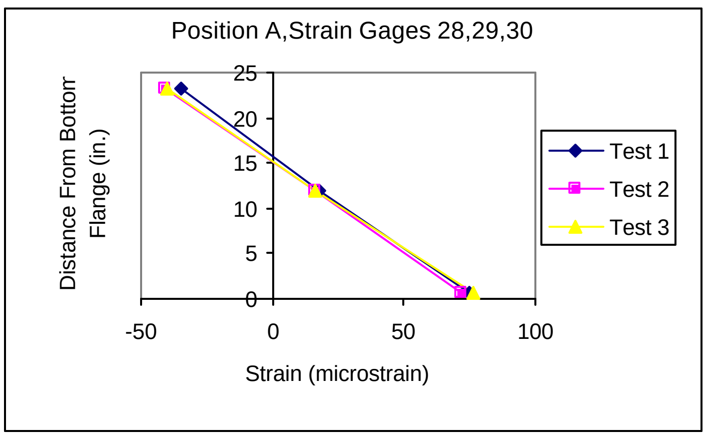

Figure G-8 – Strain Profile, Position A, Strain Gages 28,29,30

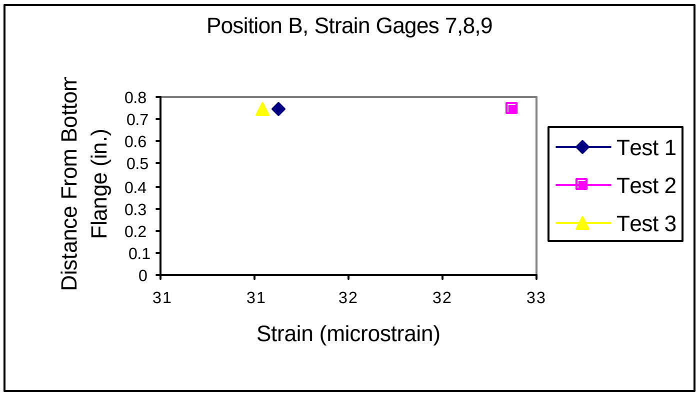

Figure G-9 – Strain Profile, Position B, Strain Gages 7,8,9

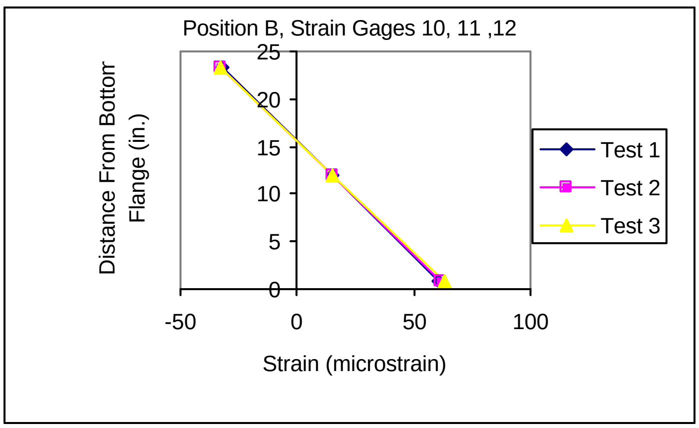

Figure G-10 – Strain Profile, Position B, Strain Gages 10,11,12

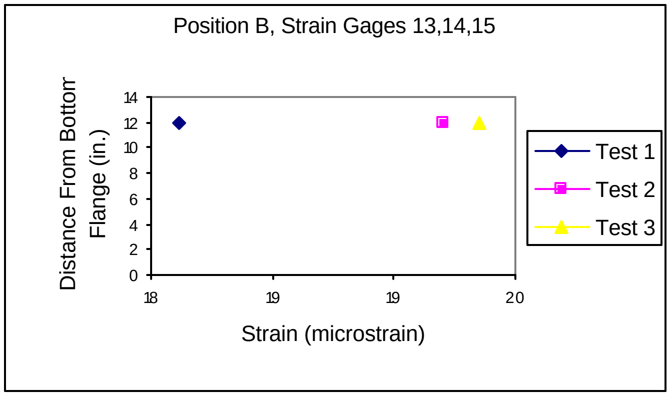

Figure G-11 – Strain Profile, Position B, Strain Gages 13,14,15

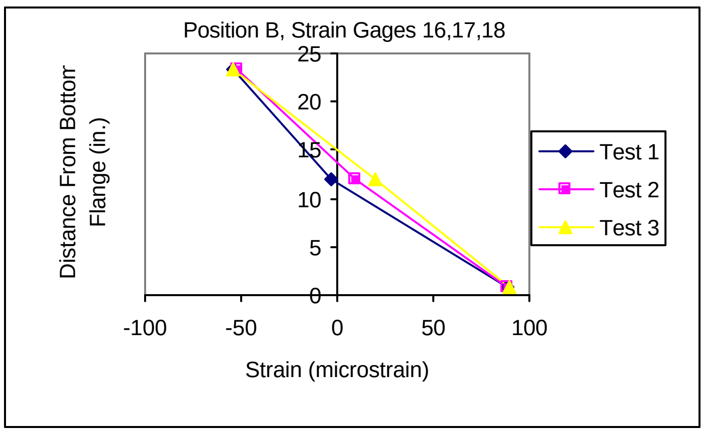

Figure G-12 – Strain Profile, Position B, Strain Gages 16,17,18

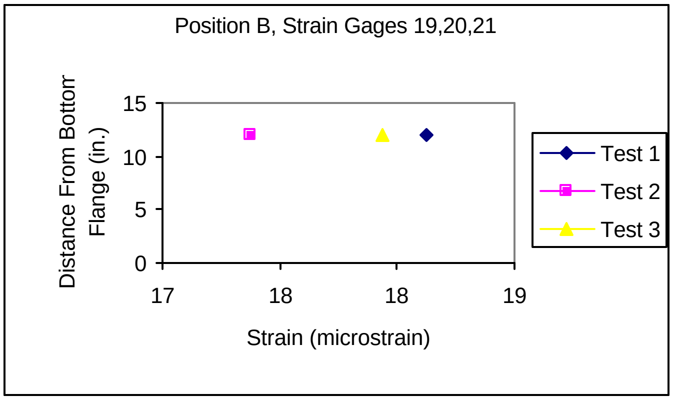

Figure G-13 – Strain Profile, Position B, Strain Gages 19,20,21

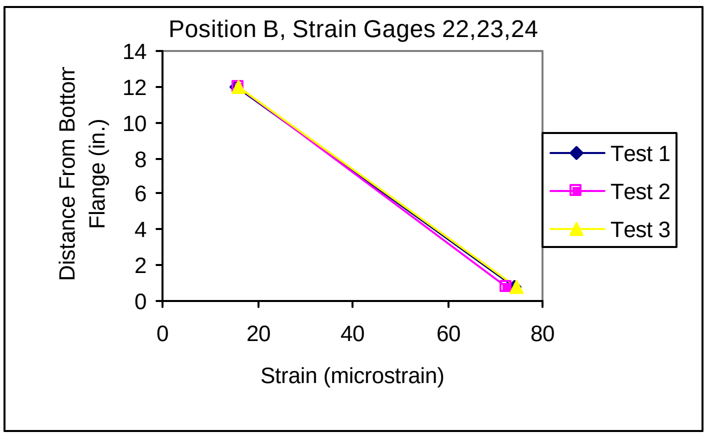

Figure G-14 – Strain Profile, Position B, Strain Gages 22,23,24

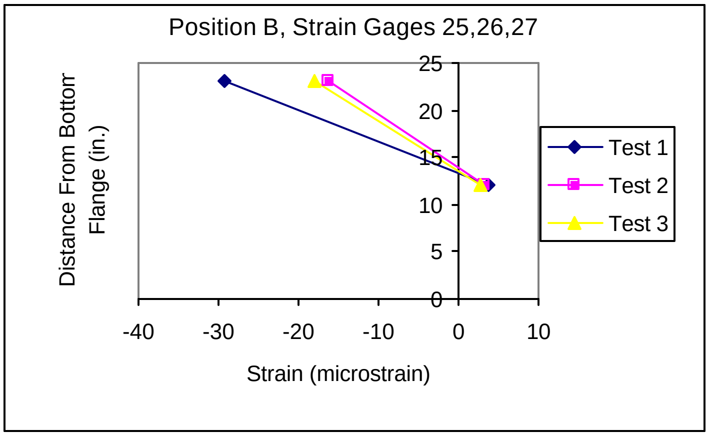

Figure G-15 – Strain Profile, Position B, Strain Gages 25,26,27

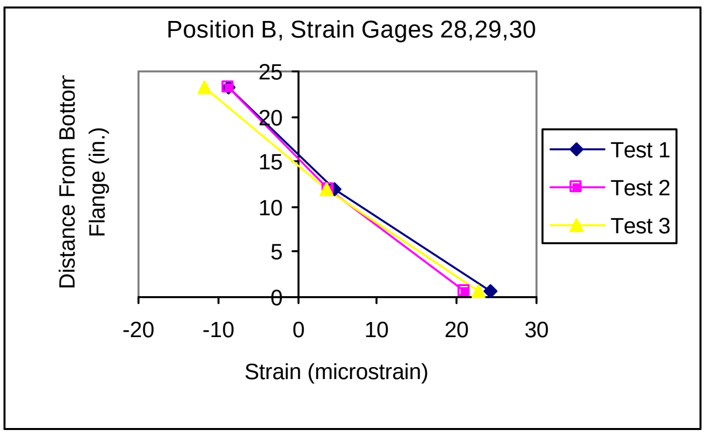

Figure G-16 – Strain Profile, Position B, Strain Gages 28,29,30

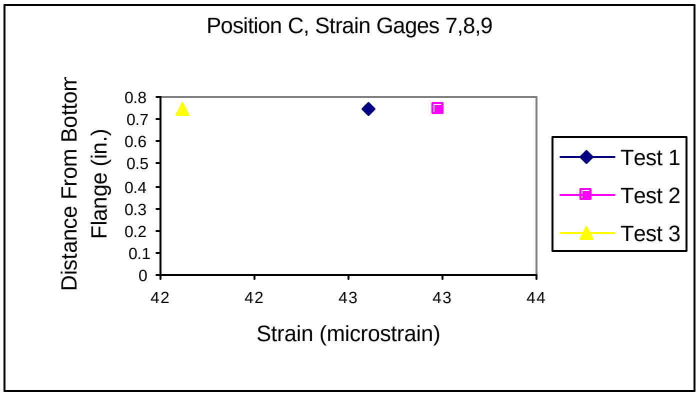

Figure G-17 – Strain Profile, Position C, Strain Gages 7,8,9

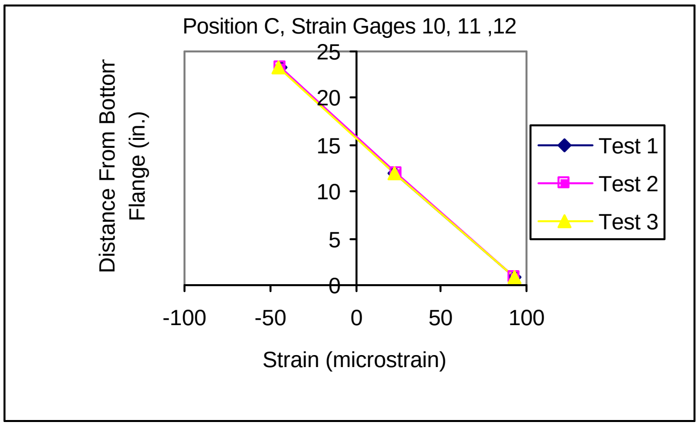

Figure G-18 – Strain Profile, Position C, Strain Gages 10,11,12

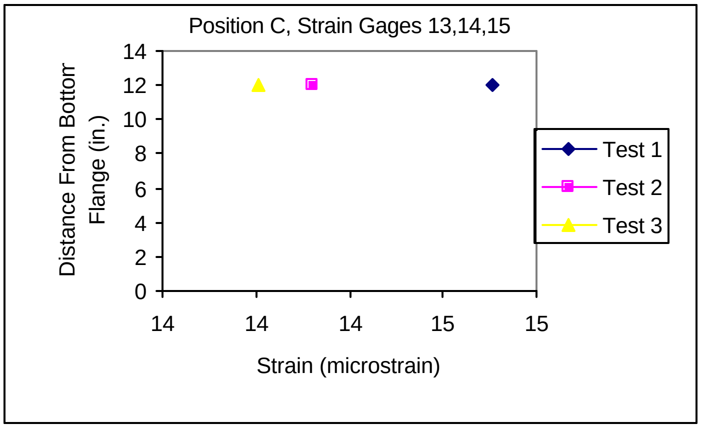

Figure G-19 – Strain Profile, Position C, Strain Gages 13,14,15

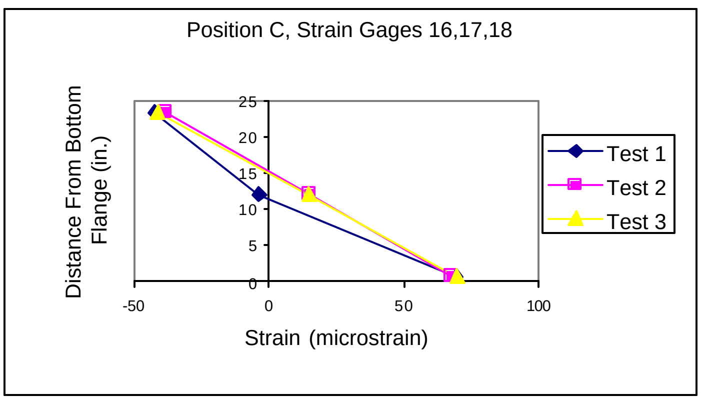

Figure G-20 – Strain Profile, Position C, Strain Gages 16,17,18

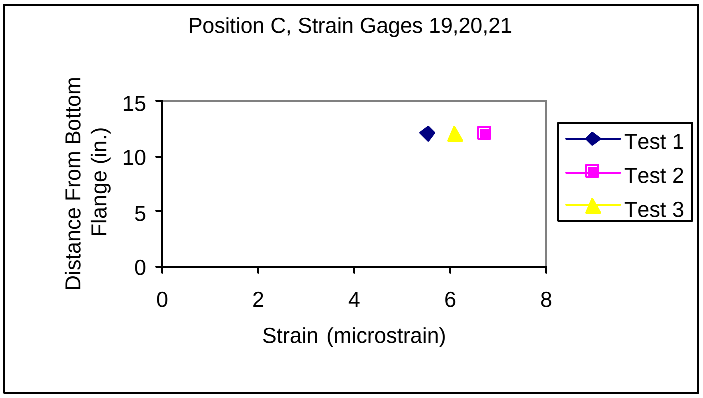

Figure G-21 – Strain Profile, Position C, Strain Gages 18,20,21

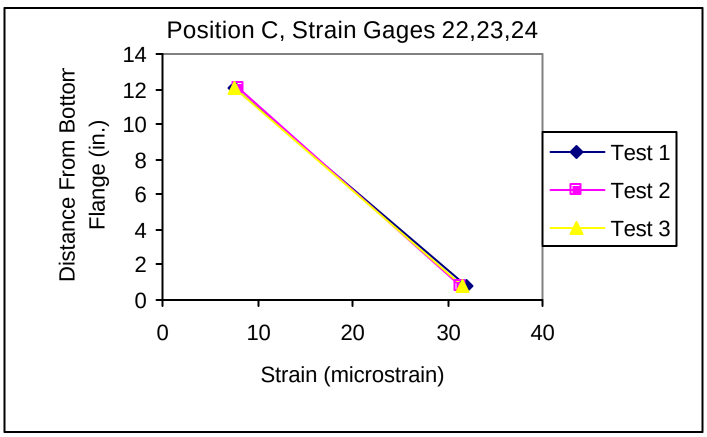

Figure G-22 – Strain Profile, Position C, Strain Gages 22,23,24

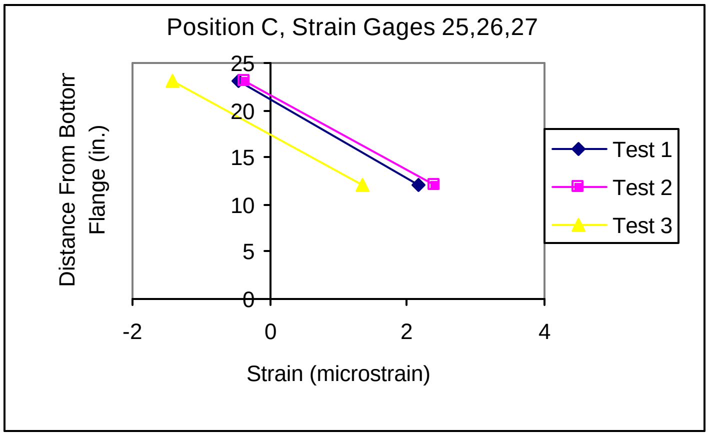

Figure G-23 – Strain Profile, Position C, Strain Gages 25,26,27

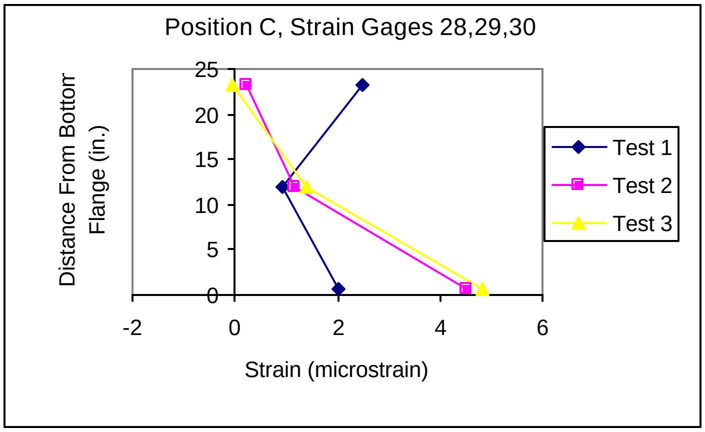

Figure G-24 – Strain Profile, Position C, Strain Gages 28,29,30

Table H-1 – Strain Measurement, Position A, Beam 1, Strain Gages 1,2,3

Position A	Beam 1 - Strain Channel Measurement, Microstrain		
	1	2	3
1	1	3	39
2	99	14	5
3	-7	-24	-1
Average	31	-2	14
Minimum	-7	-24	-1
Maximum	99	14	39
Standard Deviation	59	20	22

Table H-2 - Strain Measurement, Position B, Beam 1, Strain Gages 1,2,3

Position B	Beam 1 - Strain Channel Measurement, Microstrain		
	1	2	3
1	-15	-165	34
2	-83	62	29
3	-5	-79	19
Average	-34	-61	27
Minimum	-83	-165	19
Maximum	-5	62	34
Standard Deviation	42	115	8

Table H-3 - Strain Measurement, Position C, Beam 1, Strain Gages 1,2,3

Position C	Beam 1 - Strain Channel Measurement, Microstrain		
	1	2	3
1	-79	106	36
2	-51	25	77
3	-60	2	71
Average	-63	44	61
Minimum	-79	2	36
Maximum	-51	106	77
Standard Deviation	14	55	22

APPENDIX H

Boyer Bridge Project – February 15, 2002 Field Test, P3500 Strain Indicator Data

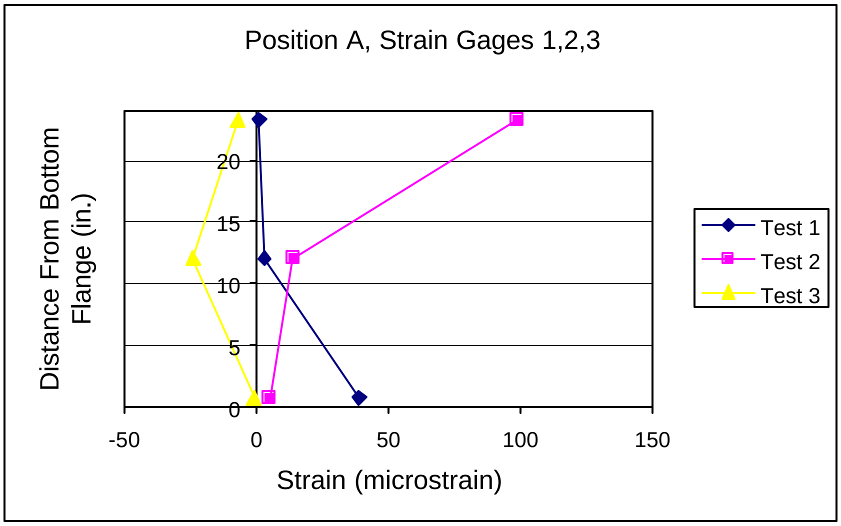

Figure H-1 – Strain Profile, Position A, Beam 1, Strain Gages 1,2,3

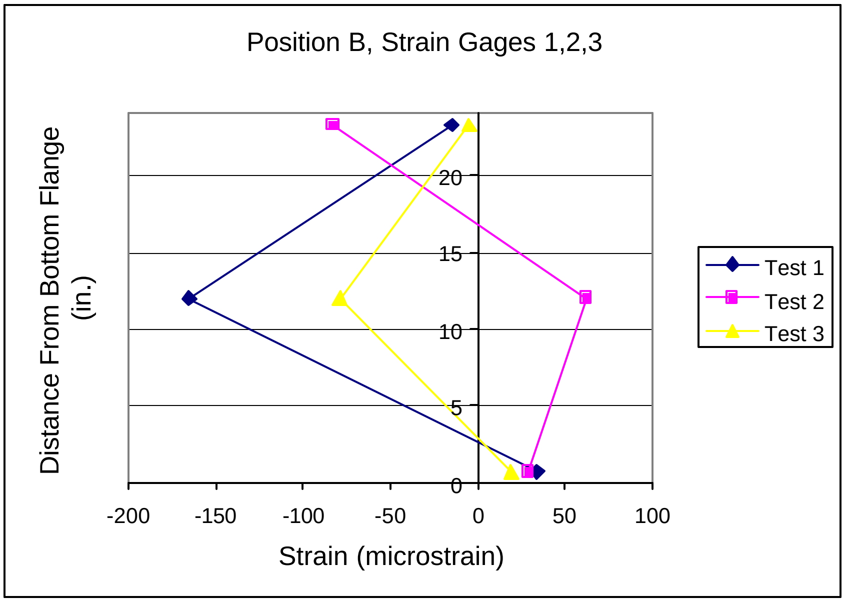

Figure H-2 – Strain Profile, Position B, Beam 1, Strain Gages 1,2,3

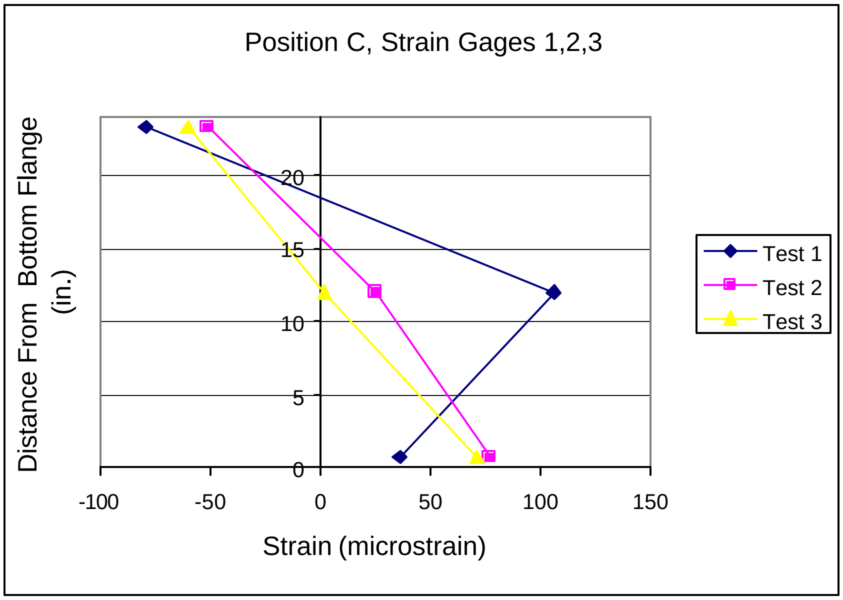

Figure H-3 – Strain Profile, Position C, Beam 1, Strain Gages 1,2,3

Table I-1 – Specimen Properties

Specimen Properties	
Depth (in)	0.1875
Width (in)	1.5
Area (in^2)	0.28125
Yield Stress (ksi)	36
Yield Strength (kip)	10.125

Table I-2 – *CR23x* Datalogger Verification Results

	Theoretical Linear-Elastic Response		CR23x Datalogger		
Load (lbs)	Stress (ksi)	Strain (Microstrain)	Ratiometric Voltage Measurement	Strain (Microstrain)	Balanced (Offset = 31) (Microstrain)
0	0	0	4.484	0	
500	1.8	61	4.501	32	63
1000	3.6	123	4.535	95	126
1500	5.3	184	4.567	155	186
2000	7.1	245	4.602	221	252
2500	8.9	307	4.636	284	315
3000	10.7	368	4.666	340	371
3500	12.4	429	4.698	400	431
4000	14.2	490	4.730	460	491
4500	16.0	552	4.761	518	549
5000	17.8	613	4.793	578	609
5500	19.6	674	4.825	638	669
6000	21.3	736	4.857	698	729
6500	23.1	797	4.891	761	792
7000	24.9	858	4.923	821	852

Table I-3 - *P3500* Strain Indicator Verifcation Results

Load (lbs)	Theoretical Linear-Elastic Response		P3500 Strain Indicator	
	Stress (ksi)	Microstrain	Reading	Microstrain
0	0	0	8244	0
500	1.8	61	8297	53
1000	3.6	123	8360	116
1500	5.3	184	8420	176
2000	7.1	245	8480	236
2500	8.9	307	8541	297
3000	10.7	368	8601	357
3500	12.4	429	8665	421
4000	14.2	490	8720	476
4500	16.0	552	8785	541
5000	17.8	613	8840	596
5500	19.6	674	8902	658
6000	21.3	736	8962	718
6500	23.1	797	9023	779
7000	24.9	858	9081	837

APPENDIX I

CR23x Datalogger and P3500 Strain Indicator Verification Test Results

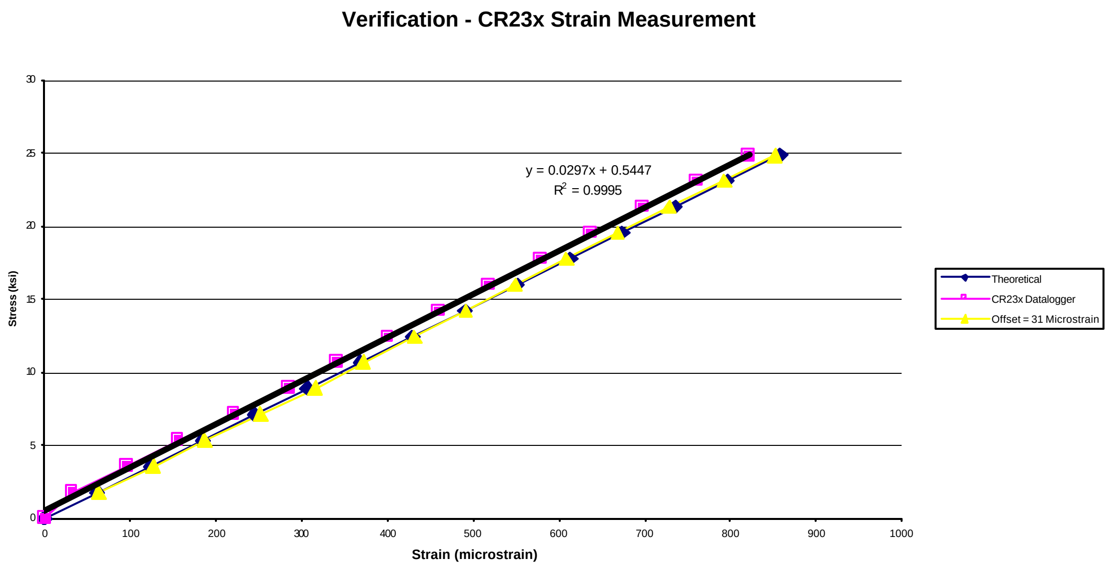

Figure I-1 – *CR23x* Datalogger Verification Stress-Strain Plot

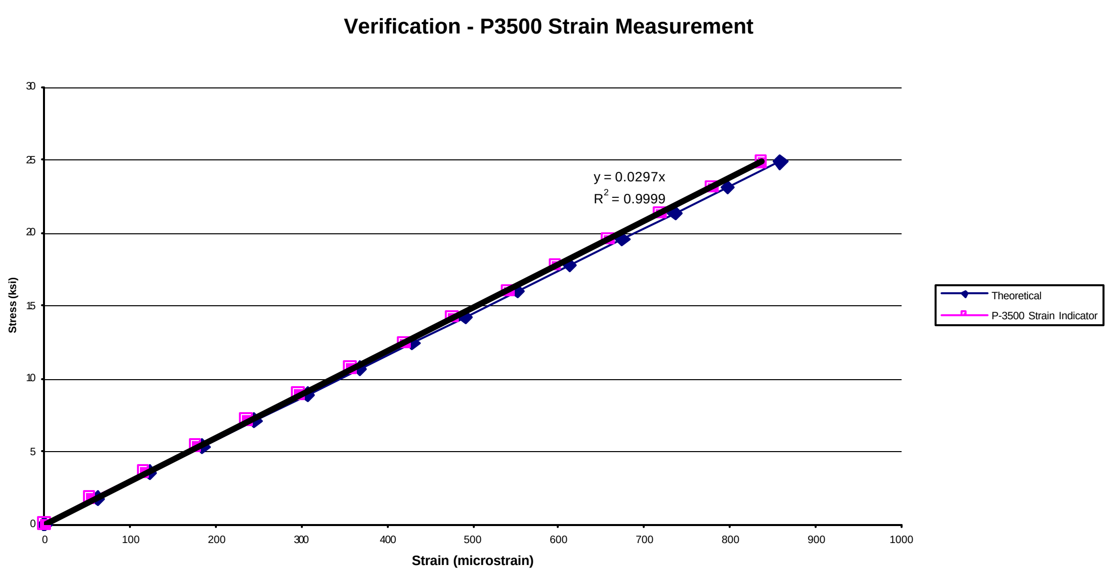

Figure I-2– *P3500* Strain Indicator Verification Stress-Strain Plot

Table I-4 – Specimen Properties

Specimen Properties	
Depth (in)	0.1875
Width (in)	1.5
Area (in^2)	0.28125
Yield Stress (ksi)	36
Yield Strength (kip)	10.125

Table I-5 – *CR23x* Datalogger Verification Results

	Theoretical Linear-Elastic Response		CR23x Datalogger		
Load (lbs)	Stress (ksi)	Strain (Microstrain)	Ratiometric Voltage Measurement	Strain (Microstrain)	Balanced (Offset = 31) (Microstrain)
0	0	0	4.484	0	
500	1.8	61	4.501	32	63
1000	3.6	123	4.535	95	126
1500	5.3	184	4.567	155	186
2000	7.1	245	4.602	221	252
2500	8.9	307	4.636	284	315
3000	10.7	368	4.666	340	371
3500	12.4	429	4.698	400	431
4000	14.2	490	4.730	460	491
4500	16.0	552	4.761	518	549
5000	17.8	613	4.793	578	609
5500	19.6	674	4.825	638	669
6000	21.3	736	4.857	698	729
6500	23.1	797	4.891	761	792
7000	24.9	858	4.923	821	852

Table I-6 - *P3500* Strain Indicator Verifcation Results

Load (lbs)	Theoretical Linear-Elastic Response		P3500 Strain Indicator	
	Stress (ksi)	Microstrain	Reading	Microstrain
0	0	0	8244	0
500	1.8	61	8297	53
1000	3.6	123	8360	116
1500	5.3	184	8420	176
2000	7.1	245	8480	236
2500	8.9	307	8541	297
3000	10.7	368	8601	357
3500	12.4	429	8665	421
4000	14.2	490	8720	476
4500	16.0	552	8785	541
5000	17.8	613	8840	596
5500	19.6	674	8902	658
6000	21.3	736	8962	718
6500	23.1	797	9023	779
7000	24.9	858	9081	837

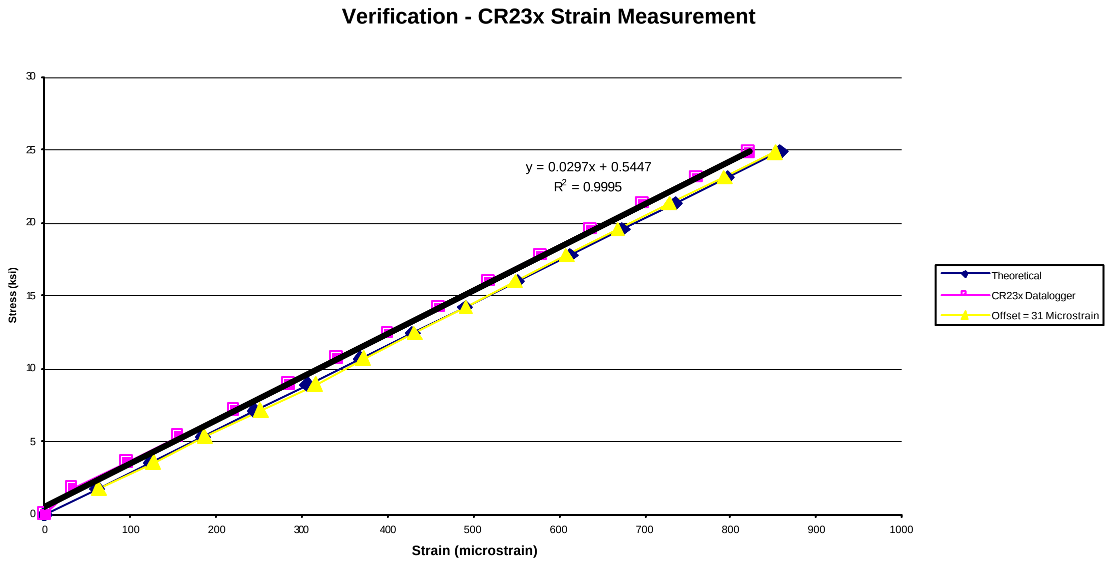

Figure I-3 – *CR23x* Datalogger Verification Stress-Strain Plot

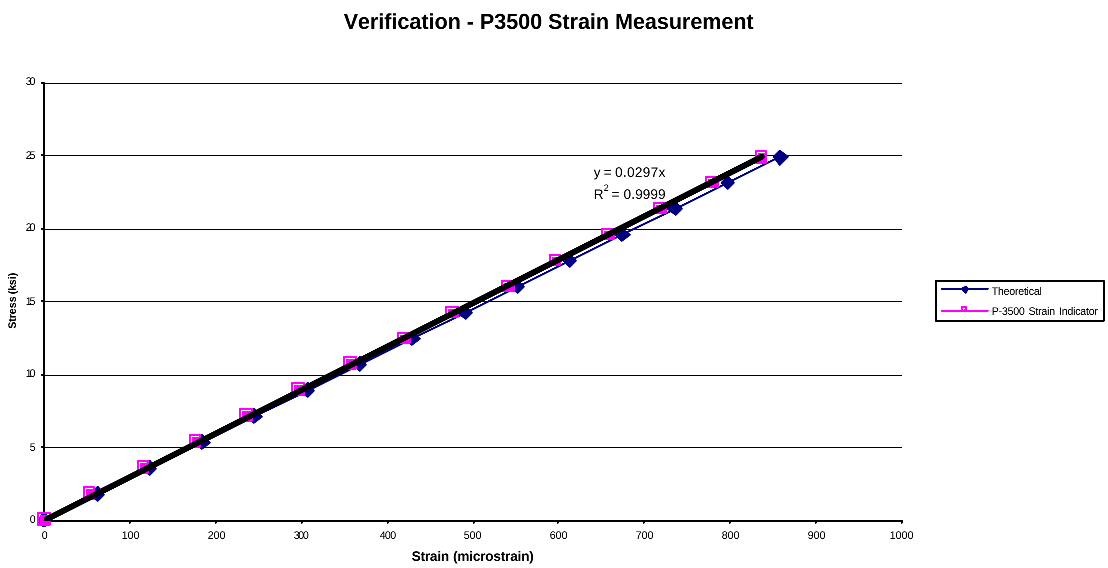

Figure I-4– *P3500* Strain Indicator Verification Stress-Strain Plot

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