

# **BEHAVIOR AND ANALYSIS OF AN INTEGRAL ABUTMENT BRIDGE**

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## EXECUTIVE SUMMARY

As part of a study to develop design guidelines for integral abutment bridges, a study was undertaken in which the bridge movement of the 400 South Street Bridge was surveyed for one year to quantify changes in bridge movement due to temperature variations. These quantitative bridge movements were compared to predicted behavior from a finite-element model. The model was subsequently used to determine likely causes of cracking stresses in the 400 South Street Bridge north abutment. The modeling scheme was further implemented to investigate the influence that various bridge parameters have on the integral abutment stresses. This final report presents the survey and finite element analyses of the investigation. These findings will be used to develop design guidelines for integral abutment bridges.

In order to quantify the influence of temperature changes on the 400 South Street Bridge, 32 Sokkia RS30N reflective targets were strategically attached to the bridge at various locations along its length. Eight targets were attached near the joints at the approach slab such that one target was positioned on each side of the joint at all four corners of the bridge. Three targets in a vertical line were used on each of the exterior girders directly adjacent to each abutment. The remaining 12 targets were implemented by attaching three targets in a vertical line at the middle of the pier diaphragm directly above each side of both bents. The targets placed in groups of three were approximately located at the top, middle, and bottom of the section. These targets were surveyed every month for 12 consecutive months during the early morning hours. The average difference between the maximum recorded length measured and the minimum recorded length measured was 17.52 mm (0.690 in.) for the east side of Span 1, 18.42 mm (0.725 in.) for the west side of Span 1, 10.51 mm (0.414 in.) for the west side of Span 3, and 10.67 mm (0.420 in.) for the east side of Span 3. These changes in length coincided with restraint conditions between purely fixed and simply supported. Movement of expansion joints was also recorded. The movements of the expansion gaps at opposite corners appear to exhibit similar movements. This behavior indicates a type of twisting motion occurring within the bridge as a result of unequal movements at the east and west sides of each abutment. This motion suggests that the bridge abutments experience forces that incite weak axis bending in the abutments, especially in the north abutment.

A detailed finite-element model of the bridge was created using SAP2000 (Computers and Structures, Inc.) software. A detailed model was developed using solid elements for all components of the bridge except piles and bents. Longitudinal surface springs were placed at the abutment elements in order to simulate the soil-abutment interaction. A typical temperature load was assigned to the bridge deck and girder elements to compare the calculated stress concentrations in the model with the observed cracking on the abutment on the 400 South Street Bridge. The model produced high stress concentrations in the abutment adjacent to the bottom girder flange, which was the same location of observed cracking. The finite-element model also showed lateral movement of the abutment. This lateral abutment explains the unequal movements of the bridge spans.

Once the comparison between the measured bridge behavior of the survey and the findings of the detailed finite element model was completed, a simplified model was used to evaluate the bending moment and stresses in the abutment of the 400 South Street Bridge. The model was also used to perform a parametric study on the influence of skew, span length, and temperature gradient. The study provided the basis for the following conclusions:

1. Bridge Movement - In general, expansion and contraction of the 400 South Street Bridge was observed as temperature increased and decreased, respectively. The observed movements were unequal when comparing the east and west sides of the bridge. Through finite-element analyses, this unequal movement is believed to be a result of lateral movement at the skewed support of the north abutment. Reduction of the lateral movement would reduce tensile stress in the abutment.

2. Skew – As little as a 5° increase in skew angle can significantly increase the weak axis bending moment of the bridge abutment.
3. Length – As the span length increases by a factor of 2, an approximate 60% increase in weak-axis bending moment in the bridge abutments was observed.
4. Temperature Gradient – Temperature gradients, in combination with uniform temperature changes, influence the stresses in the bridge abutments. A 20 °F increase in temperature difference between the girders and deck of the bridge can cause an increase in the stresses observed in the bridge abutments. The influence of temperature gradients on abutment stresses should be investigated.
5. The abutment cracking of the 400 South Street Bridge is likely a result of a combination of bridge parameters. These properties include a combination of skew, curvature, span length, and detailing. Integral abutment bridges with more than one of these conditions require additional design checks.
6. Finite element models can predict localized and global increases in demand on integral abutments.



# **1. INTRODUCTION**

## **1.1 CONTEXT**

Integral abutment bridges possess a number of unique design details that make them desirable in many applications. Integral abutment bridges can be single-span or multi-span. These bridges are constructed without expansion joints within the superstructure of the bridge. The superstructure is constructed integrally with the abutments. Normally these abutments are supported by rows of vertically driven piles.

Integral abutment bridges eliminate the use of moveable joints and the expensive maintenance or replacement costs that go with them. The overall design of integral abutment bridges is simpler than that of their non-integral counterparts. The simplicity of these bridges allows for rapid construction. These bridges have proven themselves in earthquakes and performance studies. The advantages of integral abutment bridges make them the preferred choice for many departments of transportation throughout the United States.

The Utah Department of Transportation (UDOT) has successfully used integral abutment bridges for a variety of applications throughout the state. One such bridge exists over 400 South Street in Salt Lake City. This bridge has curved and skewed geometry. The north abutment of this bridge began to show signs of cracking and spalling adjacent to the bridge girders. UDOT initiated a study of this bridge in order to better understand the source of the cracking and spalling of the north abutment. Consequently, a year-long bridge survey was conducted and a parametric study was performed using a series of finite element models. These serve to explain the observed behavior of the 400 South Street Bridge and develop guidelines for future applications of integral abutment bridges in the state of Utah.

## **1.2 400 SOUTH STREET BRIDGE**

The bridge investigated is situated over 400 South Street in Salt Lake City just east of the Interstate-15 corridor. The bridge facilitates flow of traffic from 500 South Street and from northbound I-15 onto Interstate-80 westbound toward Salt Lake City International Airport. The three-span bridge exceeds 300 feet in length and has a curved and skewed geometry. This bridge was selected for study due to the presence of cracking at the north abutment.

## **1.3 RESEARCH OBJECTIVES**

The general objectives of this report are as follows:

- Develop a comprehensive literature review concerning implementation of integral abutment bridges.
- Document the findings of a monthly-obtained year-long survey taken of the 400 South Street Bridge.
- Present the development and results of a finite element model of the 400 South Street Bridge.
- Outline the effects of skew, bridge length, and soil conditions as obtained by a parametric study finite element model.
- Provide conclusions and recommendations useful in the future application of integral abutment bridges in the state of Utah.

## **1.4 OUTLINE OF REPORT**

The organization of this report is as follows:

Section 2 presents a literature review containing information about integral abutment bridges in general, as well as research that has been done regarding integral abutment bridge behavior.

Section 3 describes the dimensions and properties of the bridge used in this study. It also presents the details and results of the thermal analysis study conducted through surveying and the finite-element model of the bridge.

Section 4 describes the finite element model developed for the bridge used in this study. A parametric study is also contained therein.

Section 5 includes a summary of the content of this report, as well as conclusions and recommendations regarding this bridge and the future application of integral abutment bridges.

## **2. LITERATURE REVIEW**

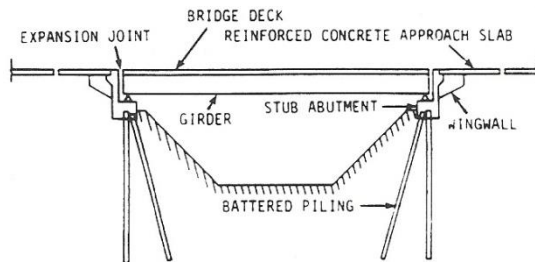
### **2.1 HISTORICAL BACKGROUND**

Integral abutment bridges have been built throughout the United States since the 1930s and have since become more common, especially for bridges with short, continuous spans. An integral abutment bridge is designed without the use of expansion joints in the bridge deck. This requires the bridge and abutment to be detailed so that the developed loads during expansion and contraction will be resisted by its members. This jointless design allows for lower installation and maintenance costs by avoiding costly bearings and the inevitable maintenance they require. This design philosophy has evolved since its introduction in the United States and has improved through the individual experience of various states in constructing these integral bridges.

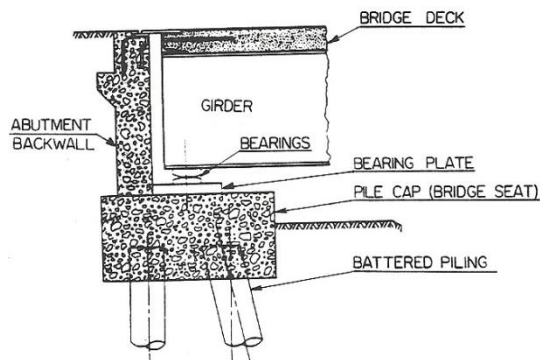
Current trends regarding integral construction originated in 1930 when Professor Hardy Cross presented a method for analysis of integral-type structures following a publication on distributing fixed end moments for continuous frames. Based on Cross's methods, bridge design began moving toward continuous construction. The Ohio Highway Department, now Ohio DOT, was one of the first agencies to embrace the use of continuous construction. Methods for achieving continuity evolved from riveted field splices to field butt welding and then to high-strength bolting, which became the method of choice for the Ohio DOT in 1963. These various methods have given the Ohio DOT more than 70 years of experience in continuous construction. In conjunction with their practice of continuous construction, the Ohio DOT was the first state to routinely eliminate deck joints at abutments. This configuration implemented the use of flexible piles as abutment supports instead of movable deck joints and was designated as an integral abutment. The Ohio DOT used a modified version of this design in several hundred bridges and applied the integral abutment concept to a steel beam bridge in the early 1960s. Since that time, most steel beam and girder bridges with skew angles less than 30° and lengths less than approximately 300 feet were designed with integral construction when conditions permitted. The Ohio DOT also pioneered the use of prestressed concrete girders for highway bridges. Subsequently, other states followed suit by implementing integral abutments for continuous construction and by 1987, 87% (26 of 30) of responding transportation departments indicated that they were using continuous construction for short- and moderate-length bridges. Gradual design changes in the Ohio DOT and other state agencies allowed for longer integral abutment bridges based upon the positive maintenance performance. The Tennessee DOT currently is regarded as the leader in continuous integral abutment bridge construction, building a continuous bridge in 1980 with a length of 2,700 feet center-to-center of the abutment bearings. Continuous integral abutment bridges with concrete substructure members ranging from 500- to 800-ft long have also been constructed in Kansas, California, Colorado, and Tennessee. Continuous integral bridges with steel substructure members in the 300-foot range have had few maintenance problems for years in such states as North Dakota, South Dakota, and Tennessee (Burke, 2009).

In conventionally designed bridges, expansion joints and bearing details are required in the bridge deck and at the abutments as shown in Figures 2.1 and 2.2 (Soltani 1992). These details have been found to have a tendency to deteriorate and freeze up, leading to large maintenance and/or replacement costs. Failure of these expansion devices can also introduce large stresses that were not considered in the design and can damage the superstructure. In many cases (Burke 2009), "significantly more damage and distress have been caused by the use of movable deck joints at piers and abutments than the secondary stresses that these joints were intended to prevent." These expansion details are the primary source of maintenance and performance issues in this type of bridge. Thus, the main goal of an integral abutment bridge is to eliminate the expansion joints and bearings completely. Eliminating bearings decreases installation costs and the long-term maintenance costs that have been found to be associated with conventional bridges. The complete removal of these components is accomplished by creating a structural connection between the

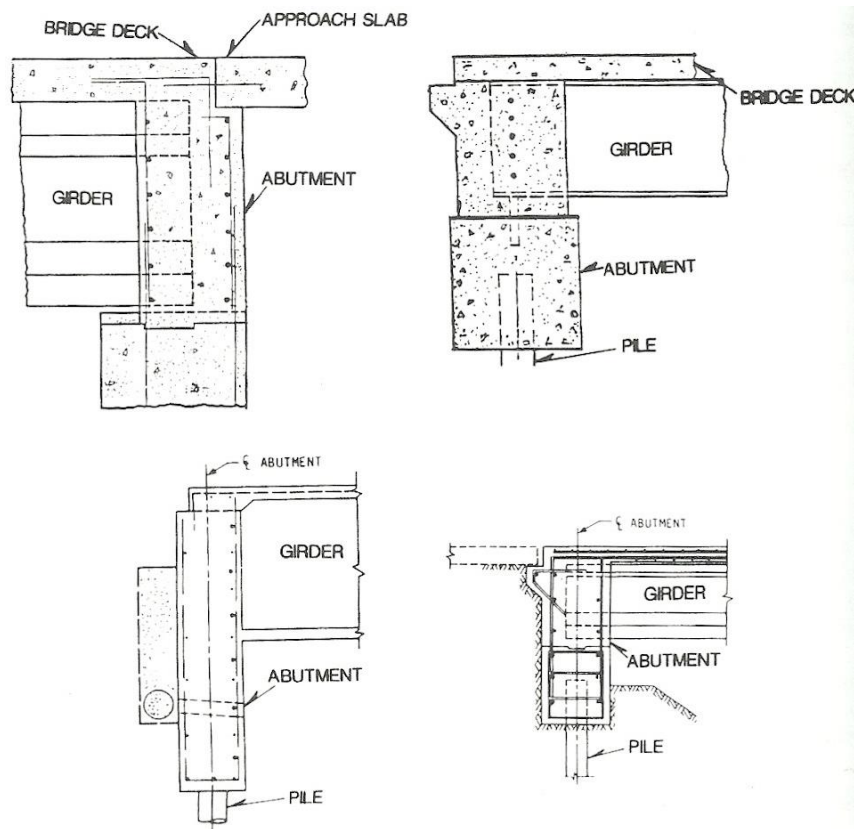
bridge superstructure and abutments. The connection details between the superstructure and abutments vary depending on the individual states or agencies and according to the bridge material. Some examples of abutment configuration for various states are shown in Figure 2.3 (Soltani 1992). The abutments can be supported on spread footings or on driven piles or drilled shafts. It is also common to structurally connect an approach slab to many integral abutment bridges. This connection allows for a smooth transition between the bridge and approach embankment. A notable variation of the integral abutment bridge design is a semi-integral abutment bridge. In this bridge configuration, expansion joints in the deck are still eliminated but girder bearings are still placed at the abutments. The important improvement from a conventional bridge is that the superstructure extends over the top of the abutment, thus protecting the bearing and reducing long-term maintenance costs (Horvath 2000).



**Figure 2.1** Cross Section of Bridge with Expansion Joints



**Figure 2.2** Abutment Detail of Bridge with Expansion Joints



**Figure 2.3** Integral Abutment Details

The desirable attributes of integral bridges are accompanied by some concerns about relatively high unit stresses. Many integral bridge components function under loading conditions that result in high stress levels. However, many bridge engineers would still rather build a cheaper integral bridge and design for the higher stresses rather than design and build costly jointed bridges with lower stress levels. The Tennessee DOT, for example, applies integral abutment bridge designs whenever bridge conditions will permit. The Tennessee DOT's design policy states, "When the total anticipated movement at an abutment is less than two (2) inches [50 mm] and the abutment is not restrained against movement, no joint will be required and the superstructure and abutment beam will be constructed integrally." They have determined that the toleration of these high stresses in some cases results in relatively minor structural distress. Some causes of concern due to these high stresses include visible distress in steel piles, minor cracks in bridge abutment wingwalls, and pile cap cracking. These problems have been found to be correctable with more generous wingwall reinforcement, providing more substantial pile cap connection reinforcement, and orienting steel H-piles with the weak axis normal to the direction of the bridge longitudinal movement. In addition, precast prestressed concrete and prefabricated steel superstructures are a viable way to overcome problems associated with the initial concrete shrinkage of superstructures that exists in cast-in-place bridges. Some additional damage may be caused by the pavement growth/pressure phenomenon that should be appropriately considered in the design of an integral bridge. When properly designed, these bridges can usually withstand the pressures generated by both pavements and bridges (Burke 2009).

## 2.2 GEOTECHNICAL ISSUES WITH INTEGRAL ABUTMENT BRIDGES

According to John S. Horvath of The Manhattan College School of Engineering (2000), there are two commonly encountered problems inherent in the design of integral abutment bridges that are not structural in nature but, rather, geotechnical. The cyclic loading of the bridge superstructure due to daily changes in temperature causes the abutments to rotate about the base and translate into the soil, thus developing considerable lateral earth pressure on the abutments. The magnitude of these soil pressures can approach or reach the passive state in the summer when bridge expansion is highest. Passive earth pressures are large in magnitude and may exceed the normally consolidated at-rest state for which an abutment should normally be designed by at least an order of magnitude. Failure to design the abutment for the larger pressures that develop during bridge thermal expansion can cause structural damage to the abutment. Adversely, the cost to properly design the abutment subjected to these higher forces will increase. In winter months, the bridge contracts and the pressure on the abutments can develop into the active condition. As the abutment moves away from the soil, a wedge of soil is commonly displaced near the top of the abutment. As a result, a void may form beneath the approach slab (if used) and settlement results in a bump at the end of the bridge. Over time, the movement of the soil toward the abutment results in a buildup of lateral earth pressure as the soil becomes effectively wedged behind the abutment. This phenomenon is referred to as “ratcheting” and may result in eventual failure of the abutment or the approach slab. Both these problems have a common source to which Horvath proposes possible geotechnical solutions involving a “compressible inclusion” behind the abutment. This compressible inclusion would create an allowance for expansion and lateral earth pressure without the problems caused by movement and settlement of the backfill material. A simply structural solution would be to shorten the abutment height. In this case, the lateral earth pressures would continue to increase in the summer, but the total resultant force and flexural stresses would be lessened. Some experiences with the application of a compressible inclusion show that this does not eliminate the tendency for the material to slump toward the abutment in the winter months when the bridge contracts and the abutment moves away from the backfill. In order to eliminate both problems, Horvath proposes the use of a mechanically stabilized earth wall or a geofoam compressible inclusion. In his opinion, the best way to apply the geofoam is described as a wedge-shaped mass that would effectively create a geofoam wall next to the abutment. Using this geofoam configuration would help with both the settlement behind the abutment and the tendency toward ratcheting behavior (Horvath 2000).

A number of limitations and guidelines that have been presented in order to avoid passive pressure as well as relatively high-pile stresses, are available. Practices to minimize the development of passive pressure include limiting the length, skew, abutment type, abutment details, and backfill material. The use of approach slabs is encouraged, in addition to the use of a well-drained granular backfill protected by approach slab curbs, turn-back wingwalls, and embankment-supported stub abutment types. The issue of high-pile stresses is addressed by using a single row of slender vertical piles, with steel H-piles expressed as the most suitable for longer applications (>300 ft). Orienting these piles with the weak axis normal to the direction of flexure, as well as providing pre-bored holes filled with granular material, also help control this issue. The use of an abutment hinge, and limiting the pile type, bridge length, and skew (typically less than 30°) of the structure, are encouraged to limit pile flexure. Most of the usual steel or well-reinforced prestressed concrete piles can be used for short integral bridges (<300 ft). The use of semi-integral abutments is a viable solution to limit these effects. Other slight concerns include minor wingwall cracks, which can be corrected with more generous wingwall reinforcement, and pile cap cracking, which has been eliminated by providing greater pile cap connection reinforcement and by rotating steel H-piles to place the weak axis normal to the direction of longitudinal bridge movement (Burke 2009).

## 2.3 DESIGN DETAILS

In 1992, the Transportation Research Record contained a “Performance Evaluation of Integral Abutment Bridges” by Alan A. Soltani and Anant R. Kukreti, which focused specifically on bridges with no skew (90° bridges). It contains a questionnaire issued to every department of transportation across the United States in which 29 of the 38 responding states indicated use of integral abutment bridges. Most of these states had developed their own specific guidelines regarding allowable bridge lengths, but these guidelines are largely empirical and based on observed past performance. The study shows that design practices used by many states may be too conservative, and much longer bridges could be constructed with little impact to their performance. The design and construction details of five states considered to be pioneers in their implementation of integral abutment bridges were further evaluated and will be discussed below.

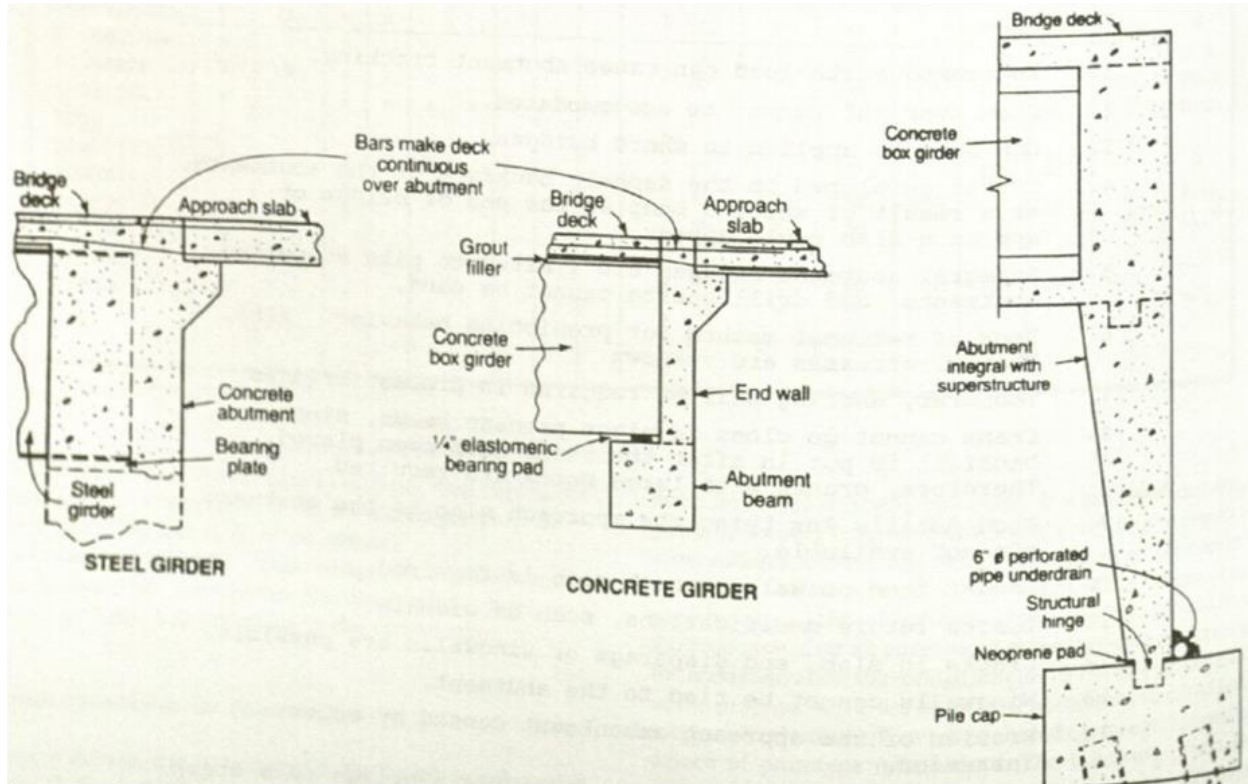
### 2.3.1 Tennessee

Tennessee has had extensive experience and is the apparent forerunner in the use of relatively long-span integral abutment bridges. The longest of these, constructed around 1992, consisted of a 416-ft steel bridge, a 460-ft cast-in-place concrete bridge, and a 927-ft prestressed concrete bridge. The performance of these bridges is noted to be better than expected. When designing a bridge, the Tennessee DOT reports, “We design Tennessee bridges in concrete for a temperature range of 20 to 90° F, and steel superstructure bridges for a range of 0 to 120° F. Based on these ranges and thermal coefficients of expansion for respective materials, we design for 0.505 inch of movement per 100 feet of span in concrete, and 0.936 inch of movement per 100 feet of span in steel.” Another design detail that is employed by the Tennessee DOT is the use of a compression seal between the approach slab and deck if the interface is concrete pavement approaching a concrete deck. No special treatment is used where the interface is asphalt to concrete. The Tennessee DOT acknowledges that this may result in some local pavement failure and a bump at the end of the bridge, but considers this a minor problem in comparison with joint maintenance.

The Tennessee DOT also offers these explanations about its efforts regarding how to eliminate expansion joints:

1. “We take advantage of pile translation and rotation capabilities.”
2. “By modifying foundation conditions, if feasible.”
3. “By taking advantage of reduced modulus of elasticity of concrete for long-term loads (1,000,000 versus 3,000,000 psi).”
4. “By allowing hinges to form naturally or constructing them.”
5. “Employing expansion bearing, where necessary.”

Figure 2.4 illustrates typical details of integral abutment bridge construction in Tennessee (Soltani 1992).



**Figure 2.4** Tennessee Abutment Details

### 2.3.2 California

The performance of integral abutment bridges in the state of California during the 1971 San Fernando earthquake contributed greatly to their increased popularity. During this earthquake, integral abutment bridges suffered less damage and performed better overall in comparison with bridges with jointed abutments. Consequently, since 1971, it has been general practice in California to implement jointless design in highway structures. As a result, most structures shorter than 350 feet since that time have been jointless. California also has over 100 jointless structures with lengths greater than 350 feet. Even on most structures with expansion joints, the abutments are designed without joints. Because water intrusion is the main problem with this design in California, the California DOT designs the connection of the approach slab directly to the abutment and extends it over the wingwalls. An underlying drainage system is also typically provided (Soltani 1992).

### 2.3.3 South Dakota

South Dakota has extensive experience using integral abutment bridges, particularly for steel bridges. They are also one of the first states to conduct a full-scale testing program to evaluate the performance of integral abutment bridges. A full-scale model was constructed and tested to simulate different stages of construction. At each stage, the specimen was subjected to a series of movements designed to simulate expansion and contraction caused by daily temperature variations. Based on the test results, the following conclusions were obtained:

1. The induced movement and shear force in the girder, caused by temperature changes alone, are usually smaller than the overstress allowance made by AASHTO for combine loadings.



2. The integral abutment acts as if it were a rigid body.
3. Thermal movements larger than 0.5 inches may cause yielding in the steel piling.

The researchers stated that the last conclusion may require further experimentation to verify as it contradicts the successful practices of Tennessee and North Dakota, which recommend 7 inches and 4 inches of expansion, respectively. In addition, one notable conclusion was that the stresses at various parts of the specimen were of greater magnitude during expansion than during contraction. This is attributed to the passive resistance of the backfill to expansion as well as the fact that the active soil pressure actually helps contraction (Soltani 1992).

### 2.3.4 North Dakota

North Dakota has been constructing integral abutment bridges for more than 30 years. They were also the only state as of 1992 to attempt to eliminate the passive soil pressure behind the abutments. A field study was conducted in which a compressible material was placed in the webs of the abutment piles as shown in Figure 2.5 (Soltani 1992). The bridge was 450-ft long, made up of six 75-ft spans, had integral abutments, piers, concrete box girders, and a concrete deck. The North Dakota DOT used the following equations to calculate temperature change and the resultant change in length.

$$\Delta T = T_1 - T_2 + \frac{(T_3 - T_1)}{3} \quad \text{and} \quad \Delta L = L \alpha \Delta T$$

Where

$T_1$  = air temperature at dawn on the hottest day

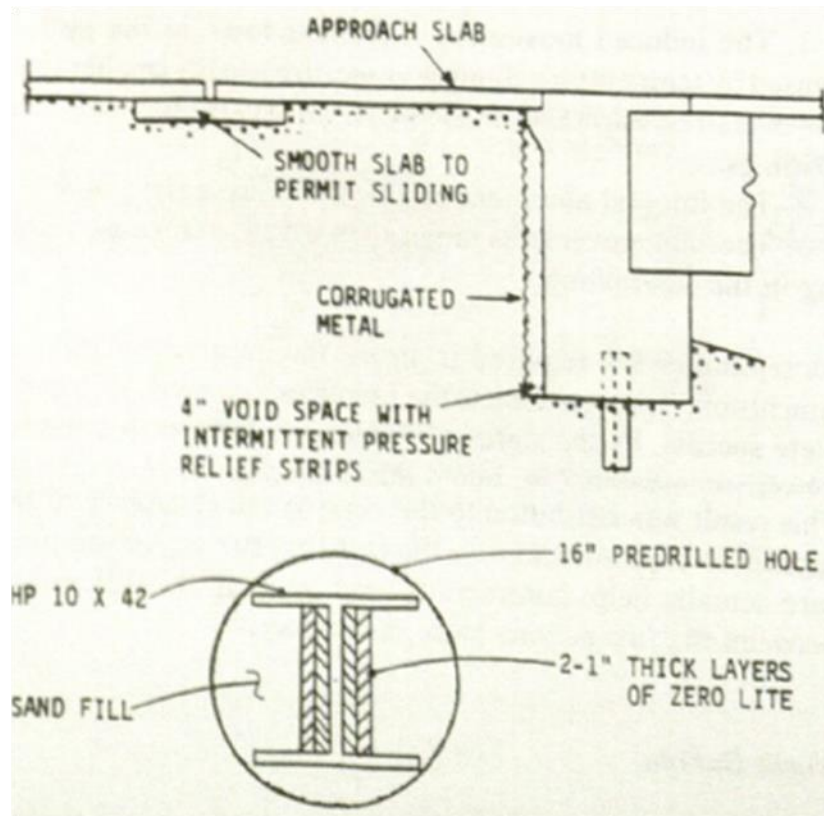
$T_2$  = air temperature at dawn on the coldest day

$T_3$  = maximum air temperature on the hottest day.

$L$  = original length of the bridge and

$\alpha$  = coefficient of thermal expansion of the bridge deck material

Observations from this study led to conclusions by the North Dakota DOT that the total change in bridge length did not result in equal movement at each abutment and that the stress at the top of the pile is sufficient to initiate yield stress in the steel but not enough to cause a plastic hinge to form (Soltani 1992).



**Figure 2.5** North Dakota Integral Abutment System with Pressure Relief Strips

### 2.3.5 Iowa

Iowa has been constructing integral abutments on concrete bridges since 1964. One of the first bridges built in this state was a 230-ft long bridge with no skew. Inspection of this bridge shows no major cracks or apparent distress in the abutment walls, wingwalls, and beams caused by thermal movement. The Iowa DOT reported that inspection on 20 integral abutment bridges was performed approximately five years after construction. Some bridges had skew angle of up to 23 degrees. Inspections were terminated because no problems were found related to lack of expansion joints in the superstructure. Iowa's designs are based on an allowable bending stress of 55% of yield plus a 30% overstress, because the loading is caused by temperature effects. The movement in the piles is found by a rigid joint analysis, which considers the relative stiffness of the superstructure and the piling. The piles are assumed to have an effective length of 10.5 feet. The soil resistance is not considered. The Iowa DOT analysis shows that the pile deflection is approximately  $\frac{3}{8}$  inch (Soltani 1992).

## 2.4 COMPARISON OF EUROPEAN AND U.S. INTEGRAL ABUTMENT BRIDGE DESIGN

An international survey conducted in 2007 gathered information from seven European countries to compare the various design requirements and restrictions of various countries. England, Finland, France, Ireland, Luxembourg, Germany, and Sweden responded to the survey. The responses from France were excluded because they did not construct bridges that were considered to be true fully integral abutment bridges. Luxembourg was also excluded from the survey results due to their small size and limited bridge population. The summarized results of this survey are shown in Figure 2.6 (White 2007).

| Criteria                                                                    | England      | Finland                | Ireland      | Germany | Sweden                 |
|-----------------------------------------------------------------------------|--------------|------------------------|--------------|---------|------------------------|
| Use Fully Integral Abutment Bridges?                                        | Yes          | Yes                    | Yes          | Yes     | Yes                    |
| Maximum Skew Angle?                                                         | 30°+         | 30°                    | 30°+         | None    | None                   |
| Steel Pile Foundation Used?                                                 | Yes          | Yes                    | Yes          | Rarely  | Yes                    |
| Steel Pipe Pile Filled with Reinforced Concrete?                            | Rarely       | No                     | Yes          | Rarely  | Yes                    |
| Reinforced Concrete Pile Foundation Used?                                   | Yes          | Rarely                 | Yes          | Yes     | No                     |
| Prestressed Piles Used?                                                     | Rarely       | No                     | Rarely       | No      | Yes                    |
| Spread Footing Used?                                                        | Yes          | No                     | Yes          | Yes     | Yes                    |
| Use Active Soil Pressure, Full Passive Soil Pressure, or Other Requirement? | Other Reqmt. | Depends on Span length | Other Reqmt. | Passive | Depends on Span length |
| Approach Slabs Recommended?                                                 | No           | Yes                    | No           | Yes     | Varies                 |
| Wingwalls Permitted to be Cast Rigidly with Abutment Stem?                  | Yes          | Yes                    | Yes          | Yes     | Yes                    |
| Use Semi-Integral Abutment Bridges?                                         | Yes          | Yes                    | Yes          | No      | Yes                    |
| Maximum Skew Angle?                                                         | 30°+         | 30°                    | 30°+         | -       | None                   |
| Steel Pile Foundation Used?                                                 | Yes          | Yes                    | Yes          | -       | Yes                    |
| Steel Pipe Pile Filled with Reinforced Concrete?                            | Rarely       | No                     | Yes          | -       | Yes                    |
| Reinforced Concrete Pile Foundation Used?                                   | Yes          | Rarely                 | Yes          | -       | -                      |
| Prestressed Piles Used?                                                     | Rarely       | No                     | Rarely       | -       | Yes                    |
| Spread Footing Used?                                                        | Yes          | Yes                    | Yes          | -       | Yes                    |
| Use Active Soil Pressure, Full Passive Soil Pressure, or Other Requirement? | Other Reqmt. | Depends on Span length | Other Reqmt. | -       | Depends on Span length |
| Approach Slabs Recommended?                                                 | No           | Yes                    | No           | -       | Varies                 |
| Wingwalls Permitted to be Cast Rigidly with Abutment Stem?                  | Yes          | Yes                    | Yes          | -       | Yes                    |

**Figure 2.6** Summary of European Integral Abutment Bridge Survey

The European survey data were compared with recent survey data of state agencies within the United States. This comparison provides useful insight into design requirements and restrictions based on the field experience of different countries. Integral abutment design details regarding the foundation, backfill, approach slabs, wingwalls, and beam design were extensively compared and are further explained below.

### 2.4.1 Foundation

None of the responses to the European survey indicated that pile foundations are always required for fully integral abutment bridges. When spread footings were used, however, no problems were reported due to the rotational restraint of the abutment stem. The survey also indicated that steel piles were rarely used in Europe. When steel piles were used, they were typically symmetrical cross-shaped piles with the

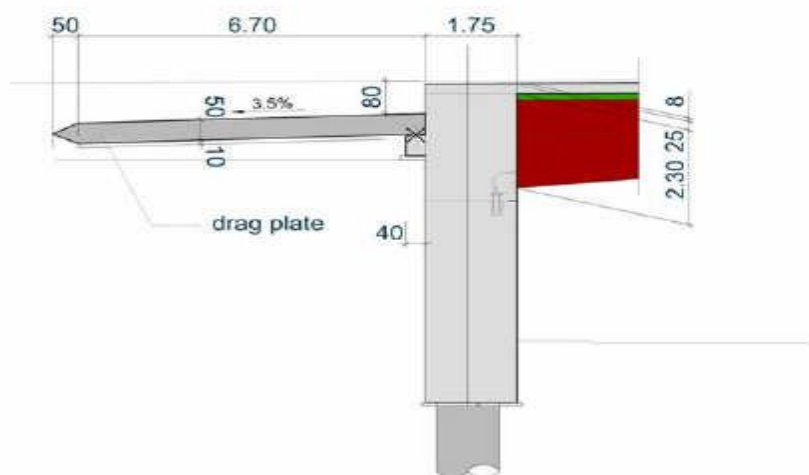
exception of England and Ireland, which typically used steel H-piles oriented with the strong axis perpendicular to the direction of bridge expansion. The most common piles used in European integral abutment bridges were steel pipe piles filled with reinforced concrete. This is in stark contrast to the requirements of many state agencies within the United States. In the United States, where more than 70% of state agencies reported steel H-piles to be the most commonly used pile for integral abutment bridges. Regarding pile orientation, 33% of state agencies required the H-piles to be oriented with the strong axis perpendicular to the direction of bridge expansion, while 46% required the weak axis of H-piles to be oriented perpendicular to the direction of bridge expansion (White 2007).

## 2.4.2 Backfill

The most common backfill material both in Europe and in the United States is well compacted gravel or sand. In the United States, 69% of responding state agencies required a well compacted granular backfill, while 15% require the backfill to be loose in an effort to reduce forces on the moving abutment stem. None of the European countries required the use of an elastic material behind the abutments. However, in the United States, 23% of respondents indicated the use of some type of compressible material behind the abutment stem. The responses of European countries varied concerning the design soil pressure behind the abutment. Some adopted a similar policy to the U.S. and account for the full passive pressure, while others employ formulas in their design codes that estimate the soil pressure behind an integral abutment bridge to be between the at rest pressure and the full passive pressure. In the United States, 59% of the states surveyed accounted for the full passive pressure in their design (White 2007).

## 2.4.3 Approach Slabs

According to the European survey, approach slabs are not required to be used with integral abutment bridges, but were indicated by most countries to be desirable. The length of the approach slab used in those countries ranged from 10-25 feet. Most state agencies in the United States require approach slabs to be used with integral abutment bridges in order to reduce the impact forces on the bridge. Of those states that require use of an approach slab, 46% reported that settlement of the approach slab is a maintenance problem. Use of a buried approach slab or ‘drag plate’ makes this settlement easier to repair and may eliminate this concern. An example of a drag plate used in Germany is shown in Figure 2.7 (White 2007).



**Figure 2.7** Example of a “Drag Plate” Used in Germany

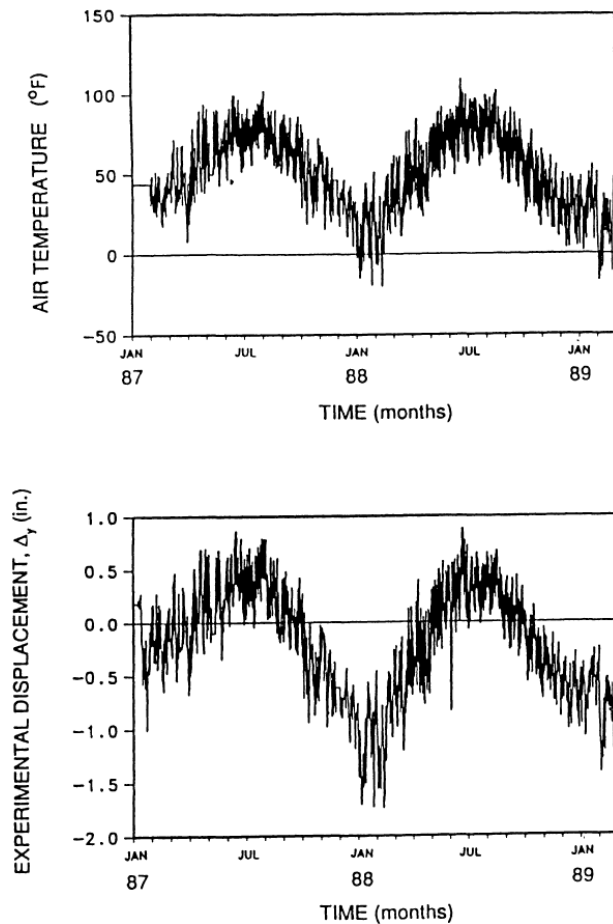
#### **2.4.4 Beam Design**

In the European survey, respondents indicated that steel beams, cast-in-place concrete beams, and precast/prestressed concrete beams were all permitted for integral abutment bridges. The predominate beam used was said to be made of precast/prestressed concrete. Cast-in-place reinforced concrete beams were seldom used, except for short-span 3-sided frame structures. These types of structures are seldom constructed in the United States. In the European survey, only Finland reported a maximum span length or total bridge length with steel beams or precast/prestressed concrete beams. The maximum limit for both these types of beams was reported to be 230 feet. In European countries, the maximum skew angle varied for different types of beams when limits were given. For steel beams and cast-in-place concrete beams, the maximum allowable skew angle was reported to be 30°, and for precast/prestressed concrete beams the maximum allowable skew angle was reported to be 60°. Sweden was the only European country surveyed to indicate a maximum roadway grade, which was given to be 4% for all three types of beams considered. State agencies in the United States specified more limits to length and skew angle than European countries. For steel beams, maximum span lengths ranged from 225-1000 feet and maximum total bridge length ranged from 500-2000 feet. For precast/prestressed concrete beams, agencies reported maximum span lengths between 20-650 feet and maximum total bridge length from 500-3800 feet. For both steel and precast/prestressed beams, state agencies reported maximum skew angles ranging from 15°-70°, and maximum degree of curvature ranging from 0°-10°. Most European countries permit the use of line girder analysis techniques to design the bridge beams, although they are analyzed for both a simple span condition and a fixed condition to determine the maximum positive moment at the mid-span and the maximum end moments at the abutments, respectively. 3-D modeling is also used in varying degrees among European countries. In the United States, state agencies are split between the use of line-girder techniques and 3-D modeling.

The design details of semi-integral abutment bridges were also compared between European countries and the United States with a very similar comparison observed to that of fully integral abutment bridges (White 2007).

### **2.5 GENERAL BEHAVIOR OF INTEGRAL ABUTMENT BRIDGES**

In a publication for the Virginia Transportation Research Council (VTRC), the general behavior of integral abutment bridges is expressed in an extensive literature review, which will be summarized here. Daily and seasonal variations in ambient temperatures are shown to affect integral abutment bridges. The extreme temperature variations control the extreme displacements of integral abutment bridges. This can be seen in Figure 2.8 (Arsoy 1999). The material and geometry of the bridge are also factors contributing to the displacement of integral bridges.



**Figure 2.8** Relationship Between Air Temperature and Horizontal Bridge Displacement

In addition to dead and live loads, integral abutment bridges are subject to further secondary loads due to creep, shrinkage, thermal gradients, differential settlements, buoyancy loads, and pavement growth. The effects of shrinkage and creep can be estimated using the Freyermuth method. It has been found that the greatest effect of shrinkage is apparent on the positive moment of single spans and on the continuity connection at abutment of continuous spans. Maximum shrinkage moments take place within 30 days of form removal, but creep effects continue for longer periods of time. In continuous single-span bridges, creep effects are greater than shrinkage effects.

Temperature gradients developed in the bridge cross section may be quite complicated, and these gradients generate secondary bending moments within the cross section of the bridge. The secondary moments generated by temperature gradients can be calculated as prescribed by AASHTO. In the VTRC report, it is stated that in moderate climates, the moments generated by thermal gradients can be neglected.

Differential settlement is an additional source for secondary bending moments in integral abutment bridges. Differential settlements can be estimated using simple procedures as defined by AASHTO. Typically, if the differential settlements are less than 1.5 inches (38mm), then the induced moments can be ignored.

In locations where the bridge may have the possibility of becoming submerged, buoyancy loads may appear. Integral abutment bridges are likely to be subjected to uplift forces when fully submerged. Hence, integral abutment bridges should either be limited to areas where the bridge height is higher than the maximum expected flood level, or the buoyancy loads should be considered in the bridge design.

Pavement growth can introduce an additional longitudinal compressive force into the bridge superstructure. Designers should therefore consider the pressure generated by pavement growth. The pavement growth phenomenon can gradually close pressure relief joints, which then create longitudinal compressive forces as pavement undergoes further expansion cycles. The VTRC report mentioned a case of severe abutment damage in a bridge with no pressure relief joints. According to the numerical analysis performed, the damage was caused by pavement growth, which introduced excessive longitudinal pressures on the abutments.

Steel H-piles are the most common pile type used for integral abutment bridges and they are typically oriented to facilitate weak axis bending. For a given deflection, weak axis bending generated less stress in the piles than strong axis bending does. Foundation piles for integral abutment bridges must also be able to carry the necessary vertical loads while also being subjected to temperature-induced displacements. The vertical load carrying capacity of the piles may be reduced due to lateral displacements. The ability of piles to accommodate lateral displacements plays a crucial role in determining the maximum possible length of integral abutment bridges. The VTRC report expresses the possibility of predrilled, oversized holes filled with loose sand after the piles have been driven as an alternative way to minimize the pile stresses and thereby maintain the vertical load carrying capacity as the bridge displaces. It has been found that predrilling greatly increases the vertical load carrying capacity of the piles. Predrilled length must then be considered. For an HP 10X42 steel H-pile, 6-10 feet of predrilled length was necessary in order to take full advantage of predrilling.

Earth pressures on the abutment are also considered in the VTRC report. Depending on the amount of temperature-induced displacement of the abutments, the earth pressures on the abutment can be as low as the minimum active pressure or as high as the maximum passive pressure. Many engineers prefer to use Rankine or Coulomb calculations for passive pressure because of their simplicity. These methods are generally conservative for bridge abutment applications. Tests have shown that turn-back (U-shaped) wingwalls result in greater earth pressures than transverse wingwalls.

A common problem occurring with integral abutment bridges is the development of a bump at the end of the bridge. This bump can be caused by cyclic compression or settlement of the backfill between the approach and the abutment. This produces a void below the approach at the abutment, which results in a bump at the end of the bridge. The VTRC report gives the following list of measures that have been effective in preventing and mitigating the approach settlement problem (Arsoy 1999).

1. Settlements should receive prime attention during design. Analysis should be performed and sufficient geotechnical data should be obtained.
2. An efficient drainage system should be included in the design.
3. Adequate compaction specifications and procedures should be employed. However, using a very dense backfill in the close proximity of the abutment is not likely to help reduce settlement. This is due to the cyclic nature of the abutment movement that tends to loosen dense backfill and also to densify loose backfill.
4. If significant settlement of the foundation soil is likely, soil improvement should be considered. To reduce loads on the foundation soil, the embankment may be constructed of lightweight materials.

5. Recognize that integral abutment bridges require continuous, yet reduced, maintenance. This maintenance may include asphalt overlays, slab jacking, and approach slab adjustment or replacement.

An additional investigation into the design details of integral abutment bridges focused on the deck-stringer-abutment continuity details. This study produced some useful insights about the behavior of integral abutment bridges in regards to cracking. Both longitudinal and transverse cracking were observed in approach slabs of an integral abutment bridge. The transverse cracking can occur from heavy vehicular live loads, settlement of the backfill soil, and void development under the approach slabs. Longitudinal cracking in the approach slab also develops when voids form under the approach slab. Most backfill materials are not perfectly elastic, which results in void formation with the cyclic movement of the abutments due to daily and annual temperature fluctuations. It was suggested that the performance of integral abutment bridges could be improved by incorporating a compressible elastic material as an incompressible inclusion, as was mentioned previously. Other cracking patterns were also observed in the decks of integral abutment bridges. Diagonal cracks were seen to occasionally develop at the acute corners of the bridge deck, and straight cracks were also observed over previously placed concrete end diaphragms. Transverse cracks at relatively uniform spacing may also occur as a result of insufficient continuous temperature and shrinkage reinforcement in the deck slabs over the end diaphragms.

Connections between the abutments and the bridge superstructure can be stressed and crack if there is a significant change in temperature during the initial concrete setting. To prevent the occurrence of stressing/cracking, the following procedures were suggested (Roman 2002).

1. Place continuity connection at sunrise.
2. Place deck slabs and continuity connections at night.
3. Place continuity connections after deck slab placement.
4. Use crack sealers

## **2.6 RESEARCH PROJECTS**

### **2.6.1 Fennema, et al. (2005)**

This project conducted a comparison between predicted and measured responses of an integral abutment bridge in Pennsylvania. The monitored bridge was a three-span, composite structure with four prestressed, concrete I-girders bearing on reinforced concrete piers and abutments. The south abutment was constructed with no expansion joint at the abutment and bore directly on rock. The north abutment was a standard Pennsylvania DOT integral abutment bearing on a single row of eight HP 12X74 piles. The bridge was thoroughly instrumented with vibrating wire based instruments and monitored between November 24, 2002, and March 24, 2003. Three levels of comparative numerical analysis were employed to determine the movements and behavior of integral abutment bridges due to thermal loads. Level 1 was an analysis of the behavior of the laterally loaded piles alone with no abutment or superstructure. Level 2 consisted of a two-dimensional, three-bent numerical model developed in STAAD Pro composed of frame members and soil springs. Level 3 analysis used a three-dimensional finite element model developed in STAAD Pro consisting of frame members, plate elements, and soil springs. Detail was given regarding the development of each level of analysis and the results obtained. Key conclusions drawn include the following (Fennema 2005):

1. Development of multilinear soil springs from  $p$ - $y$  curves is a valid approach
2. 2D numerical models are sufficiently accurate to determine pile response



3. The primary mode of movement of the integral abutment is rotation about the base of the abutment, not longitudinal displacement of the abutment
4. The girder-abutment connection is best approximated as hinged

### **2.6.2 Abendroth, et al. (2007)**

The details of the first integral abutment bridge in the state of Iowa to use precast, prestressed concrete (PC) piles in the abutment are contained in this report sponsored by the Iowa Highway Research Board and the Iowa Department of Transportation. The bridge was constructed in 2000 and consists of a 110-ft long, 30-ft wide, single-span precast, prestressed concrete girder superstructure with a 20° skew angle. The top of each pile was wrapped with a double layer of carpet in an attempt to create a pinned type of connection. The bridge was fitted with a variety of strain gauges, displacements sensors, and thermocouples. The data obtained showed that the published AASHTO guidelines regarding thermal gradients were in agreement with the recorded values. The effectiveness of the carpet wrap was debatable, but it was concluded that the connection should not be assumed as a pinned connection for this type of configuration. Data indicated the development of pile cracking and an accompanying change in behavior was evident. Excavation confirmed the presence of a pile crack, suggesting periodic inspection of the abutment piles in order to prevent long-term corrosion of the prestressing strands.

In connection with observation and instrumentation of the bridge, the details of a nationwide survey investigating the use of precast, prestressed concrete piles was included. The survey indicated that out of the 88% of respondents who had designed integral abutment bridges, 23% allowed the use of PC piles with integral abutment bridges. Seventy percent of respondents designed integral abutment bridges but did not allow the use of PC piles. Reasons for not permitting PC piles included lack of ductility from PC piles, insufficient research, PC piles not readily available, PC piles not being economical, and negative opinions of bridge contractors (Abendroth 2007).

### **2.6.3 Civjan, et al. (2007)**

An extensive parametric analysis was performed on a zero skew, three-span bridge in Massachusetts. The bridge was extensively instrumented and subsequently monitored for four years. 2D and 3D finite element models were used to create an equivalent model, which was compared to the field data in a separate publication. Loose and dense backfill conditions were evaluated in this investigation because of their effect on the abutment soil springs used in the model. The assumed soil properties covered a reasonable range of conditions and were meant to provide representative upper and lower bounds of typical backfill material. The effects of the parameters selected relate to deformations of the abutment, pile deformations, maximum moments in the abutment piles, and pressures developed by the abutment backfill. These are descriptors of bridge behavior. Regarding abutment displacement and rotation, it was shown by the finite element model that an applied temperature differential causes an imposed distortion of the bridge at the girder location, while soil conditions control the response of the rest of the structure. When expansion occurs, the deflection at the base of the abutment is largely controlled by the backfill conditions, but during contraction, the soil conditions or construction practices at the abutment piles affect the results most. The study concluded that the behavior of integral abutment bridges was greatly affected by the soil-structure parameters. Due to the variability of final soil conditions, conservative design assumptions are warranted. Another conclusion stated that lower pile restraint results in a decrease in both abutment rotation and pile moment during contraction, but during bridge expansion, the resulting backfill pressures would increase. Also, during expansion, denser backfill properties result in greater abutment rotation, decreased pile moment, and greater soil pressure behind the abutments (Civjan 2007).

#### **2.6.4 Olson, Long, et al. (2009)**

Researchers conducted a literature review regarding other states' limitations and guidelines pertaining to the use of integral abutment bridges. A survey of states with similar climates, as well as those states considered well-experienced with integral abutments, was also conducted. Two-dimensional modeling was conducted using FTOOL and LPILE software. Three-dimensional finite element modeling was also performed using SAP 2000. The modeling was based upon the current guidelines of the Illinois DOT. Different pile types and sizes, span lengths, skew angles, and girder material (steel vs. concrete) were compared through modeling to develop useful graphs summarizing allowable lengths and skew angles of details commonly used in the state of Illinois. Based on the modeling conducted, several conclusions and recommendations were made. Notable findings include the recommendation of compacting the granular backfill used directly behind the abutment backwall, as well as suggested maximum lengths and skew angles for some commonly used piles. To increase the length and skew limitations in Illinois, the following options were recommended: (1) Predrill the pile locations to a depth of 8 feet; (2) Reduce the depth of pile embedment in the pile cap to 6 inches, effectively introducing a hinge at the pile-to-pile cap interface; or (3) incorporate a mechanical hinge at the cold joint between the pile cap and the abutment. The Virginia DOT incorporates such a hinge using "strips of high durometer neoprene along either side of the dowels along the centerline of the integral abutment" (Olson 2009).

#### **2.6.5 Shah (2007)**

This study focused on the finite element analysis of integral abutment bridges with some emphasis on the complex soil interactions that occur in response to thermally induced deformations. A basic overview of integral abutment bridges, their geometry, history, and advantages, are stated. The soil-structure interaction is considered a critical design issue. A literature review is also contained that focuses on the past numerical models of integral abutment bridges. The studies presented deal heavily with the effects and behavior of the backfill soil that interacts with the integral abutment. A bridge with typical geometry and length for the state of Kansas was selected for finite element modeling with ABAQUS software. The bridge structure was modeled and the soil reaction was modeled using nonlinear springs. The complete details of this model are contained within the report, along with graphical results of different soil properties considered. The study concluded that "the overall behavior of integral abutment bridges is significantly affected by the type of soil adjacent to the abutment." Analysis indicated linear response to the selected temperature ranges. In response to thermal loads considered, an increase in relative compaction of the soil behind the abutment from 90% to 96% decreases the pile top displacement and maximum bending moment, increases the maximum compressive stresses in the girders, and increases the soil pressure on the abutment. Findings also indicated that translation of the abutment is 3.46 times larger than rotation for a relative compaction of 90%, rotation is larger than translation by 1.44 times for a relative compaction of 96% with  $\Delta T = 60^\circ\text{F}$ , but that difference entirely diminishes for a compaction of 96% and a  $\Delta T = 100^\circ\text{F}$ . The largest difference in maximum bending moments between central and end piles was found to occur for a relative compaction of 96% and a  $\Delta T = 60^\circ\text{F}$ . Although the abutment was assumed to be a rigid body, the thermal gradient within the abutment led to bending of the abutment. Throughout all the testing considered, none of the loading scenarios resulted in passive failure of the soil behind the abutment (Shah 2007).

#### **2.6.6 Arenas, et al. (2012)**

A study was conducted for the Virginia Center for Transportation Innovation and Research focusing specifically on integral abutment bridges with foundation piling in the backfill of Mechanically Stabilized Earth (MSE) walls with a "U-back" configuration. This indicates that the MSE wall has three faces. The study also focused on several unknowns and points of controversy in the design of integral abutment

bridges. The study included the implementation of many numerical analyses and subsequent monitoring to verify them, as well as a nationwide survey of departments of transportation. The nationwide survey received 21 usable responses from various states. The survey included questions about general bridge issues, piles, MSE walls, abutments, approach slabs, and other miscellaneous details. The Utah Department of Transportation (UDOT) was one of the agencies that responded to the survey. UDOT was identified as one of the agencies that used a combination of active and passive pressures in the calculation of earth pressure behind the abutment. This practice was also used by the majority of those who responded. A few notable conclusions made by this study include (Arenas 2013):

- Steel pipe sleeves filled with sand do not reduce forces and moments in the piles because of the tendency to densify with cyclic loading due to thermal response.
- The peak earth pressure behind the abutment can increase up to 60% after the first year but increases by less than 6 additional percentage points during the following year. The earth pressure buildup is due mainly to soil settlement and rearrangement behind the abutment.
- It was recommended that H-piles oriented for weak-axis bending with webs perpendicular to the bridge alignment be used for bridges with less than 20° skew to decrease bending moment in the longitudinal direction.

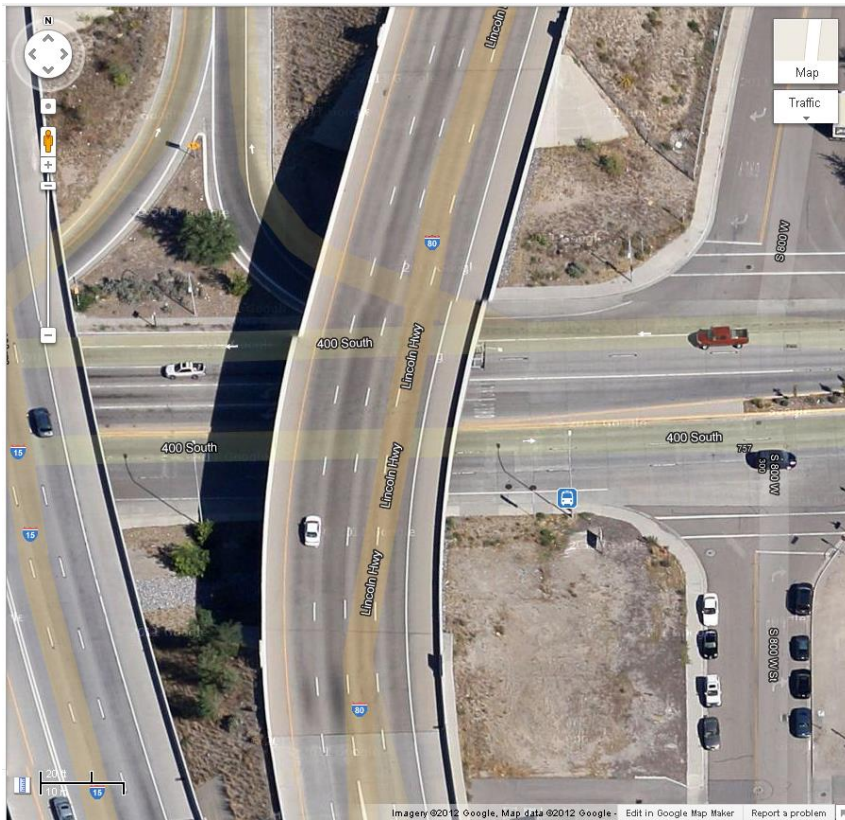


### 3. THERMAL ANALYSIS

The thermal monitoring and analysis that was conducted on a three-span, integral abutment bridge, located in Salt Lake City, Utah, is described in Chapter 3. A description of the test bridge is presented, followed by a description of the survey conducted to obtain data regarding the temperature-induced movement of the bridge. The results obtained through this year-long survey are presented, along with supplementary data from a day-long survey. In addition, a comparison of a three-dimensional survey that was conducted by NV5 is also presented. Chapter 3 concludes with a discussion on average bridge temperature measurements and the guidelines presented in the AASHTO LRFD specifications for a typical Utah bridge, followed by a summary of the thermal analysis.

#### 3.1 400 SOUTH STREET BRIDGE DESCRIPTION

The bridge monitored for this study is a three-span, integral abutment bridge, located in Salt Lake City, Utah. The bridge was built in 1999 and is part of the Lincoln Highway/I-80 that crosses over heavily travelled 400 South Street at approximately 800 West Street, directly east of the I-15 corridor. The bridge accommodates four lanes of traffic: two lanes of northbound traffic that depart from I-15 and two lanes of incoming traffic from 500 South Street. These four lanes of traffic merge into I-80 westbound towards the Salt Lake City International Airport. The Average Daily Traffic (ADT) on the 400 South Street Bridge is approximately 29,447 vehicles with an Average Daily Truck Traffic (ADTT) of 6%. An aerial view of the bridge can be seen in Figure 3.1.



**Figure 3.1** Aerial View of the 400 South Street Bridge

The deck of the bridge is curved, while the girders beneath are in three separate, straight segments. The girders in each segment are placed at a skewed angle that accommodates the curved deck above. Three spans comprise the overall bridge and are defined as Span 1, Span 2, and Span 3. Span 1 is defined as the southernmost span, Span 2 is the middle span, and Span 3 is the northern span. Figure 3.2 shows a plan view of the bridge, as well as the nomenclature designated for the spans and corners of the bridge. An elevation view of the full bridge is shown in Figure 3.3.

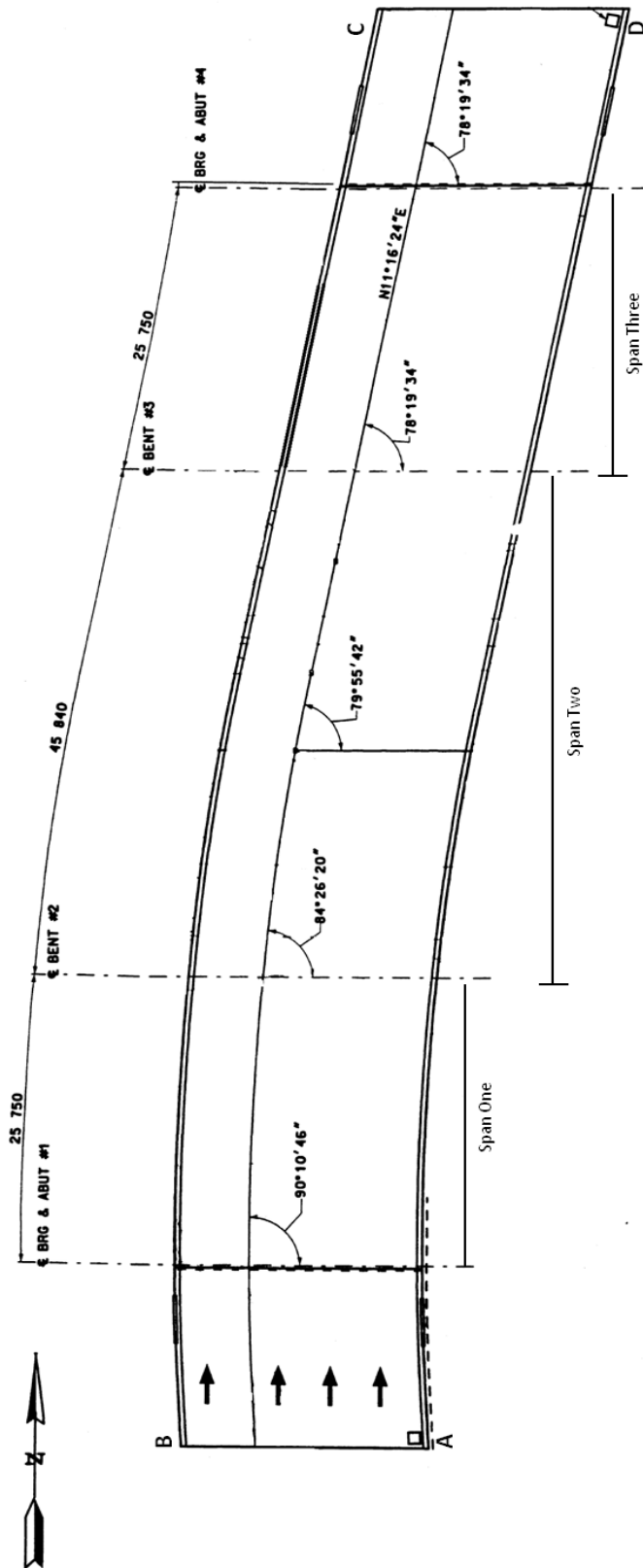


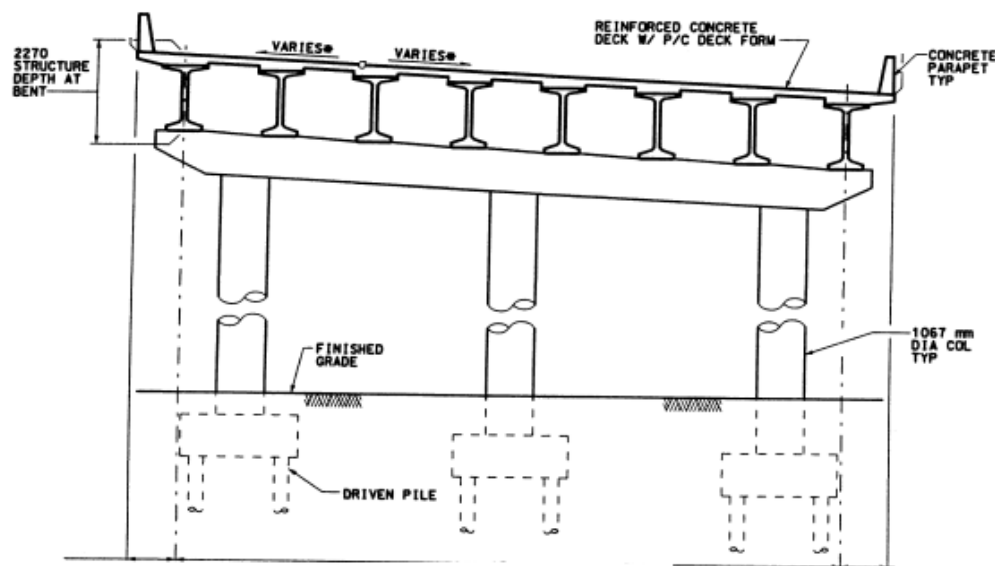
Figure 3.2 Plan View of 400 South Street Bridge (Dimensions in Millimeters)



**Figure 3.3** Photograph of 400 South Street Bridge in Elevation View

The overall length of the bridge between the integral abutments is 97.3 m (320 ft). Span 1 (south) and Span 3 (north) each measure 25.8 m (84.5 ft) long and Span 2 (middle) measures 45.8 m (150.4 ft) in length. Span 1 has a skew angle of 0.2 degrees, Span 2 has a skew angle of approximately 5.6 degrees, and Span 3 has a skew angle of approximately 11.7 degrees. The bridge also has an overall angle of curvature of approximately 16 degrees and a radius of curvature of 257 m (843 ft). The total width of the bridge is 21.3 m (70 ft) with an actual road width of 20.4 m (67 ft). Concrete parapets 432 mm (18 in.) wide are located at each side along the full length of the bridge.

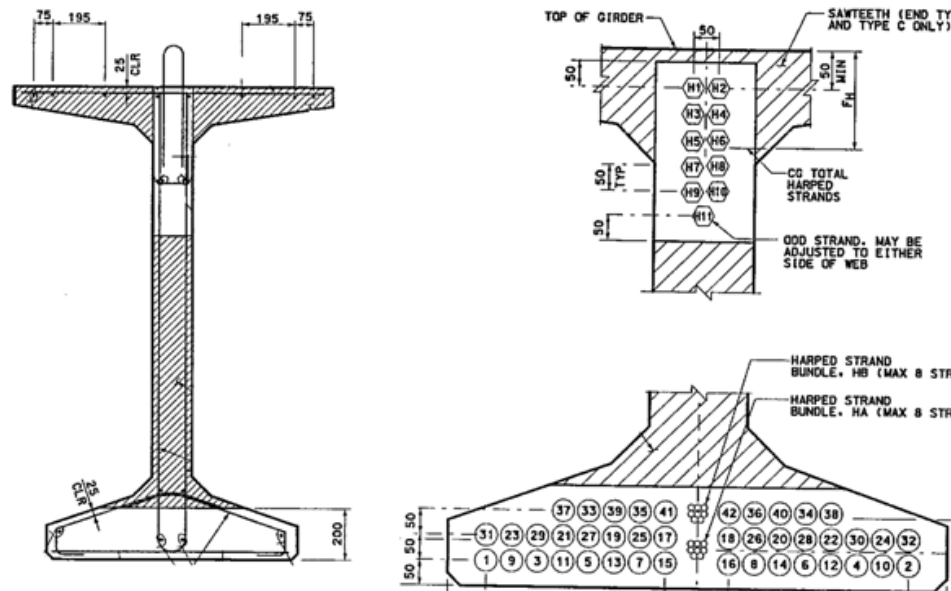
The deck of the 400 South Street Bridge is constructed of reinforced concrete. The average deck thickness is 200 mm (8.0 in.). The elevation view of the bridge at the bents, including the bridge deck, is shown in Figure 3.4. The specified concrete compressive strength ( $f'_c$ ) of the bridge deck is 28 MPa (4000 psi).



**Figure 3.4** Cross-Sectional View of the 400 South Street Bridge at the Bent (Dimensions in Millimeters)

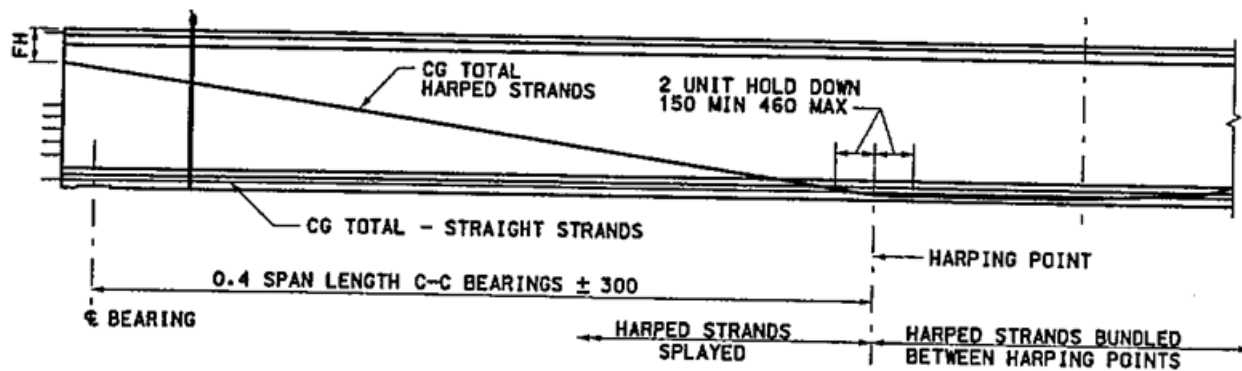


The 400 South Street Bridge consists of eight AASHTO-PCI W1850MG prestressed concrete girders per span, each with a depth of 1850 mm (72 in.). The girders are spaced across the width of the bridge at 2.8 m (9.1 ft) for Span 1, 2.7 m (8.9 ft) for Span 2, and 2.7 m (8.9 ft) for Span 3. The prestressed concrete used a minimum compressive strength at release of 38 MPa (5500 psi) and a 28-day minimum compressive strength of 52 MPa (7500 psi). For the prestressing strands, 15.2 mm (0.6 in.) diameter, seven-wire low relaxation strand with an ultimate stress at failure of 1860 MPa (270 ksi) was used. Figure 3.15 shows a cross-sectional view of the girder with a detailed view of the location of the reinforcement.



**Figure 3.5** Girder Cross Section and Detail View of Prestressing strand Template (Dimensions in Millimeters)

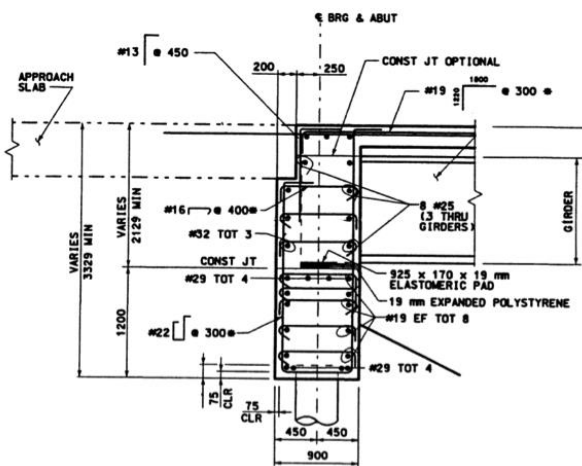
The prestressed concrete girders used contain both harped strands and straight strands. At the girder ends, the centroid of the harped prestressing strands is located 60 mm (2.36 in.) below the top of the girder for girders located in Span 1 and Span 3, and 135 mm (5.31 in.) below the top of the girder for girders located in Span 2. The harping point is located 10.3 m (33.8 ft) from the ends of the girders in Span 1 and Span 3 and 18.34 m (60.16 ft) from the girder ends in Span 2. In Span 1 and Span 3, two strands per bundle were used with a final total harped strand force of 340 kN (76.4 kips) per bundle. In Span 2, eight strands per bundle were used with a final total harped strand force of 1172 kN (263.5 kips) per bundle. At the girder ends, the centroid of the straight prestressing strands is located 50 mm (1.97 in.) above the bottom of the girder for girders located in Span 1 and Span 3 and 100 mm (3.94 in.) above the bottom of the girder for girders located in Span 2. In Span 1 and Span 3, 12 straight strands were used with a final total straight strand force of 2040 kN (458.6 kips). In Span 2, 38 straight strands were used with a final total straight strand force of 5563 kN (1250.6 kips). The location of the harped and straight strands is shown in Figure 3.6.



**Figure 3.6** Profile View of Girder End with Location of Strands Shown  
(Dimensions in Millimeters)

The bridge is supported at the ends using integral abutments with dimensions of 0.9 m (3.0 ft) thick by 3.33 m (11.0 ft) in height. Each abutment is supported by 12 324 mm (12 in.) diameter driven piles spaced at 1.8 m (6 ft). The driven piles supporting the north abutment each have an allowable pile load of 623 kN (140 kips), and those at the south abutment have an allowable pile load of 534 kN (120 kips). Figure 3.7 shows the dimensions of the abutment, as well as the configuration of the reinforcing steel.

The bridge is supported between Span 1 and Span 2 and between Span 2 and Span 3, by two bent caps measuring 1.5 m (5.0 ft) wide by a minimum dimension of 1.5 m (5.0 ft) tall, which are supported on three 1.1 m (3.5 ft) diameter reinforced concrete columns. Each column is supported by a reinforced concrete foundation 1.5 m (5.0 ft) square with a minimum depth of 1.5 m (5.0 ft). The foundations are each supported by eight 406 mm (16 in.) diameter driven steel piles, each with an allowable pile load of 1335 kN (300 kips).



**Figure 3.7** Detail View of Abutment with Reinforcing Shown and Photo of Actual Abutment  
(Dimensions in Millimeters)

## 3.2 BRIDGE SURVEY

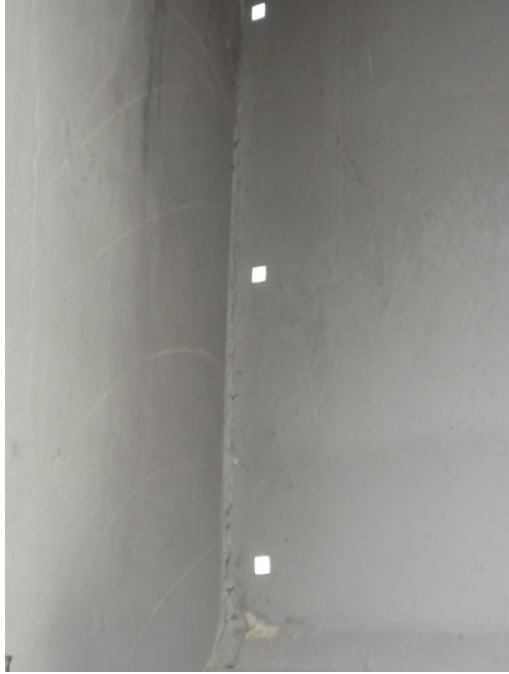
### 3.2.1 Monthly Survey

In order to obtain the data required to quantify basic span movement, the bridge was instrumented with 32 Sokkia RS30N reflective targets placed strategically at various locations along the bridge. These targets measure 30 mm (1.18 in.) square. The targets can be seen in Figure 3.8. Eight targets were attached near the joints at the approach slab such that one target was positioned on each side of the joint at all four corners of the bridge. The corners are labeled A, B, C, and D in Figure 3.2. The next 12 targets were used by placing three targets in a vertical line on each of the exterior girders directly adjacent to each abutment. The targets placed in groups of three were approximately located at the top, middle, and bottom of the section. Figure 3.9 shows the arrangement of the survey targets at one location. The locations of these target groups are represented by points 1 and 4, as labeled in Figure 3.10. The remaining 12 targets were used by placing three targets in a vertical line in the middle of the pier diaphragm directly above each side of both bents. The locations of these target groups are marked as points 2 and 3 in Figure 3.10. The configuration shown in Figure 3.10 is of the east side of the bridge. The west side of the bridge is instrumented similarly.

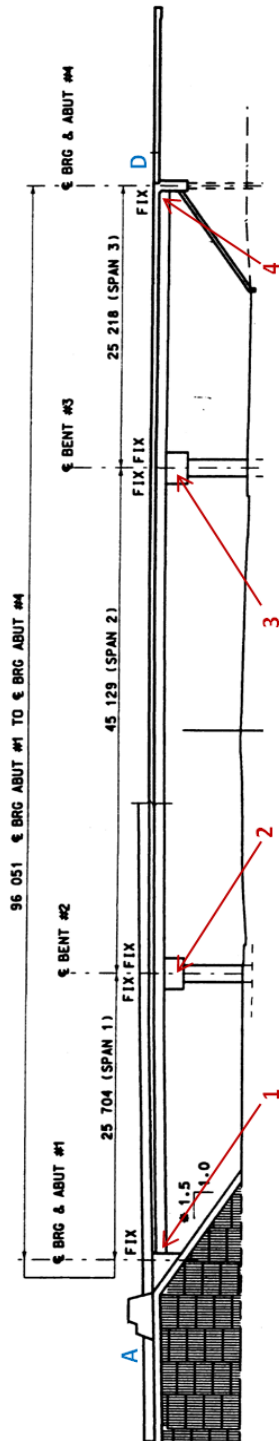
Four specific base stations were identified for measurement readings. Each base station was located so that the survey of the targets placed in each quadrant of the bridge would be obtained. These base stations were permanently located over the duration of the project with a rebar stake and cap. The locations of each station can be seen in Figure 3.11. Station 1 was placed at the southeast corner of the bridge, Station 2 was located near the southwest corner, Station 3 at the northwest corner, and Station 4 at the northeast corner.



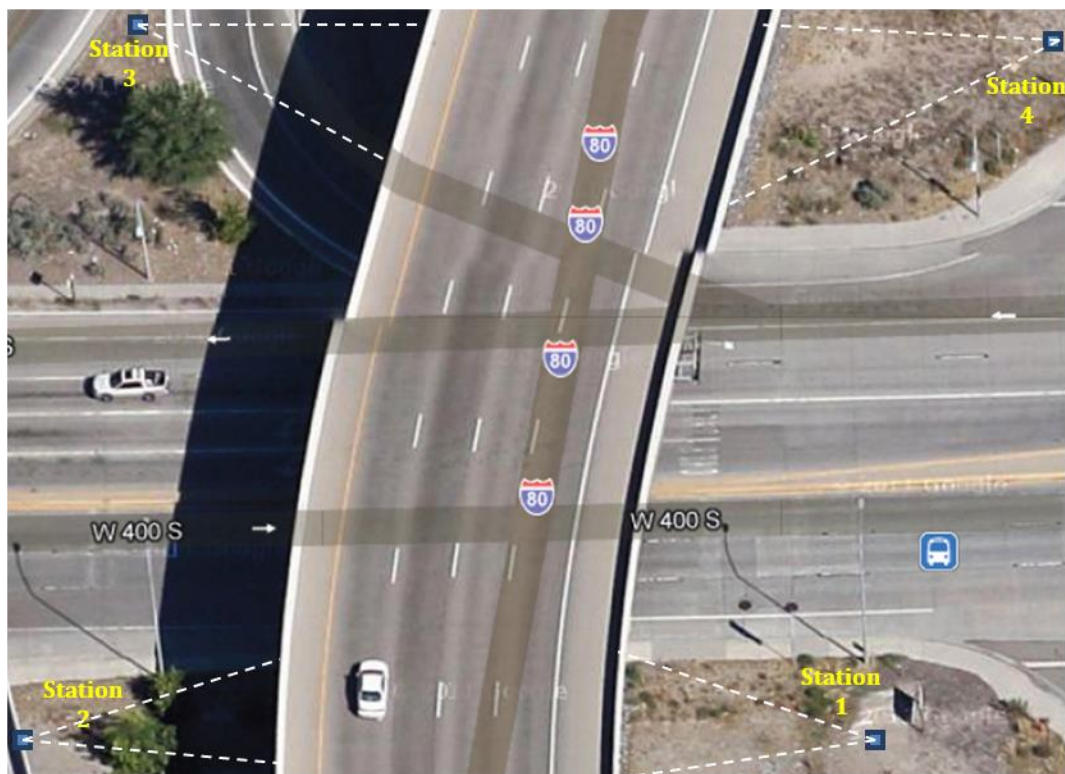
**Figure 3.8** Survey Target



**Figure 3.9** Survey Target Placement



**Figure 3.10** Profile View of 400 South Street Bridge with Locations of Survey Targets Shown and Numbered (Dimensions in Millimeters)



**Figure 3.11** Locations of Survey Base Stations

The survey of the 36 contact targets was conducted using a Topcon GTS-303D total station and a tripod. At each marked base station, the total station was carefully set up and leveled directly over the rebar caps. The targets attached to the bridge girders and bents were then surveyed. The distances to each survey target for the quadrant of the bridge in question were recorded, as well as the horizontal angle to each target. As there were six targets per quadrant (abutment and bents), six distances and six horizontal angles were recorded at each station surveyed. The survey process was repeated at each of the four base stations, producing 24 measurements of length and 24 horizontal angles. The positioning of the stations was limited by the surroundings of the bridge such that the joints on the approach slab at each corner could not be surveyed using the total station. Instead, starting in January, the distance between the survey targets located on either side of the expansion joint were measured with a measuring tape. These values were recorded in addition to the data collected from the total station at each quadrant of the bridge. An example of the configuration of the survey targets at the expansion joints can be seen in Figure 3.12.

Because the movement of the integral abutment bridge was primarily governed by changes in ambient temperature, a simple configuration was devised in order to collect survey and temperature data for the bridge. The survey was conducted at approximately the same time of morning on a monthly basis. In order to be as consistent and reliable as possible, temperature data were collected from the nearby National Weather Service station at Salt Lake City International Airport. For each monthly reading, the average temperature over the total time required to perform the survey was taken and then recorded.



**Figure 3.12** Survey Targets at Approach Slab

### 3.2.2 Full-Day Survey

A full-day survey was conducted on October 18, 2012, for the east side of the 400 South Street Bridge. The east side was selected because data for Span 2 were desired and could not be collected on the west side. The full-day survey used the same procedure discussed for the monthly surveys and added an additional base station used to calculate values for Span 2.

The full-day survey was conducted using the same total station and base stations used for the monthly surveys. An infrared thermometer was used to measure the temperature of the bridge deck. Once the bridge deck temperature was obtained, a round of survey measurements began. The total station was set up and leveled at Station 1 and the targets for that quadrant were surveyed in the same manner as the monthly surveys. Once the points from Station 1 were measured, the total station was moved to Station 3 and the process was repeated. Following the measurements at Station 3, the total station was moved to a different tripod set up in the median of 400 South Street directly east of the bridge. This tripod remained in the same location for the duration of this survey. From this point, the targets on either side of Span 2 could be seen and measured, providing survey data for Span 2 that were previously unavailable. This completed a round of survey measurements. This was then repeated each hour until there was insufficient daylight to read the targets.

### 3.3 MEASURED SPAN LENGTH

Using the recorded distances and angles measured from the periodic bridge surveys, a calculation of the changes in lengths of Span 1 and Span 3 was performed using the law of cosines shown as Equation 1.

$$c = \sqrt{a^2 + b^2 + 2ab\cos\theta} \quad (\text{Eq. 1})$$

where,

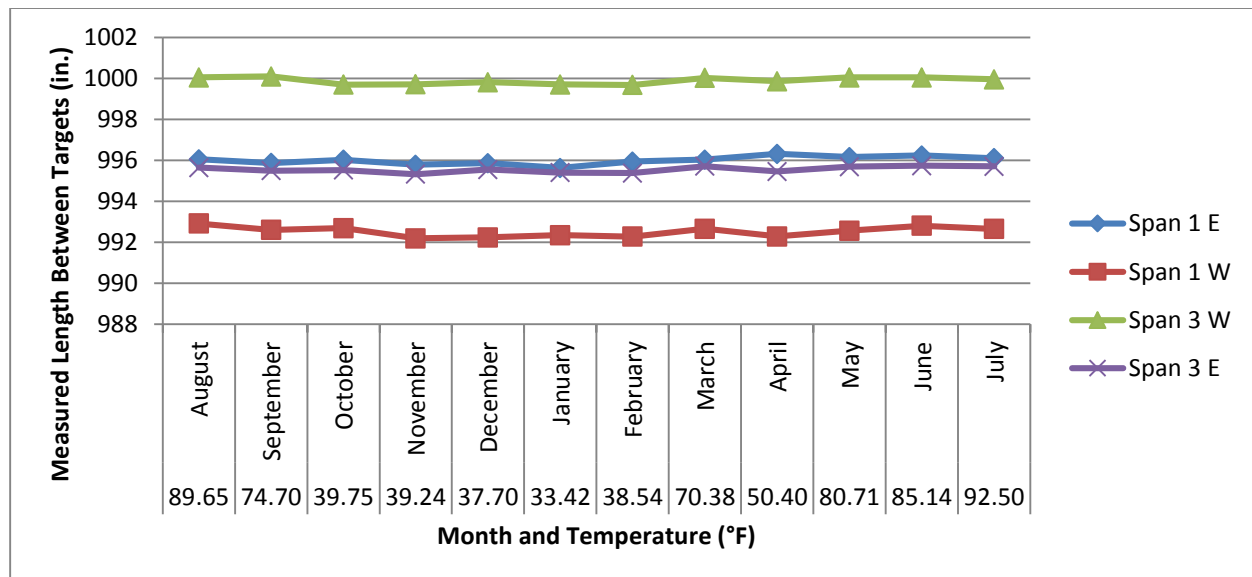
- $c$  = distance between targets
- $a$  = distance to first target from station
- $b$  = distance to second target from station
- $\theta$  = angle between  $a$  and  $b$

This equation was used to calculate the distance between targets (span elongation or shortening) placed on the pier diaphragm and those on the nearest abutment.

The survey only provided the distance between targets. No data were recorded that permitted the determination of direction of movement or determination of the center of gravity of the movement.

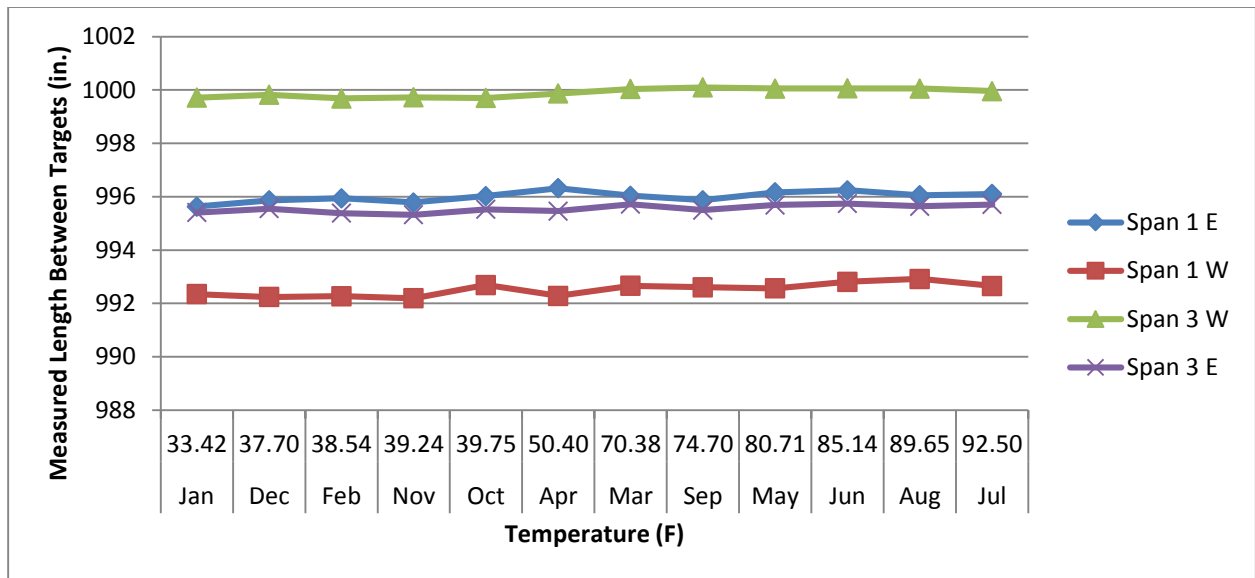
### 3.4 READINGS FROM MONTHLY SURVEY

Calculations using Equation 1 allowed for a direct comparison of change in axial span length with temperature. The results for the monthly survey can be seen for all spans in Figures 3.13 and 3.14 and for each side of Span 1 and Span 3 in Figures 3.15 through 3.18. Figures 3.15 through 3.18 are plotted on an identical scale for ease of comparison.

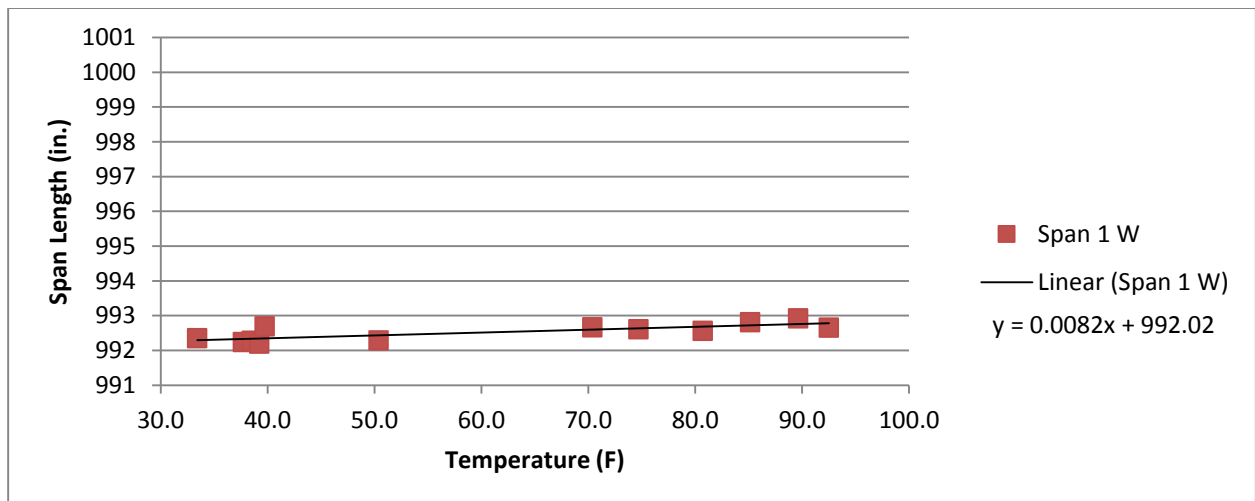


**Figure 3.13** Measured Lengths Between Survey Targets in Chronological Order

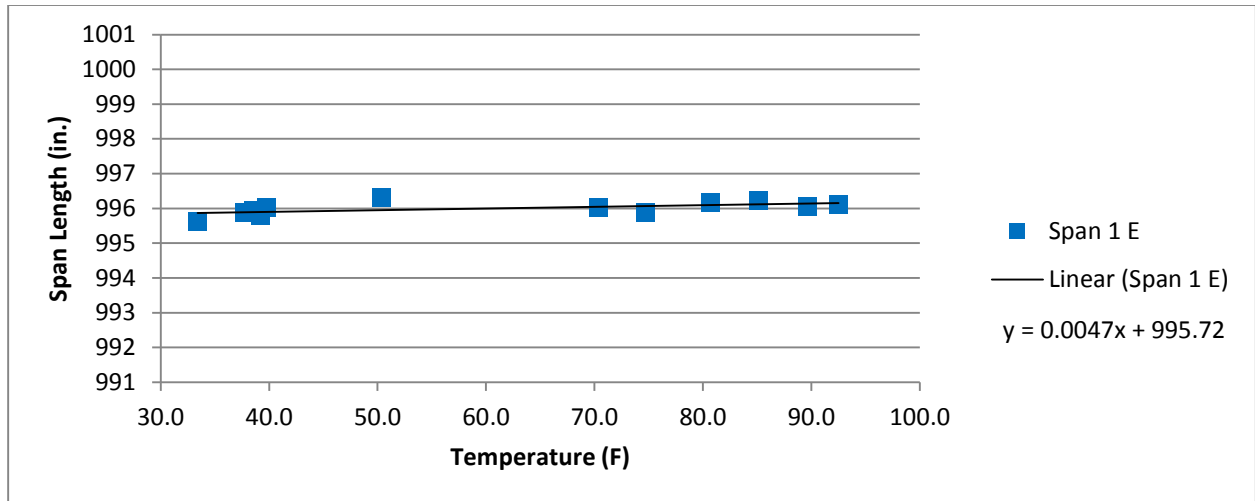




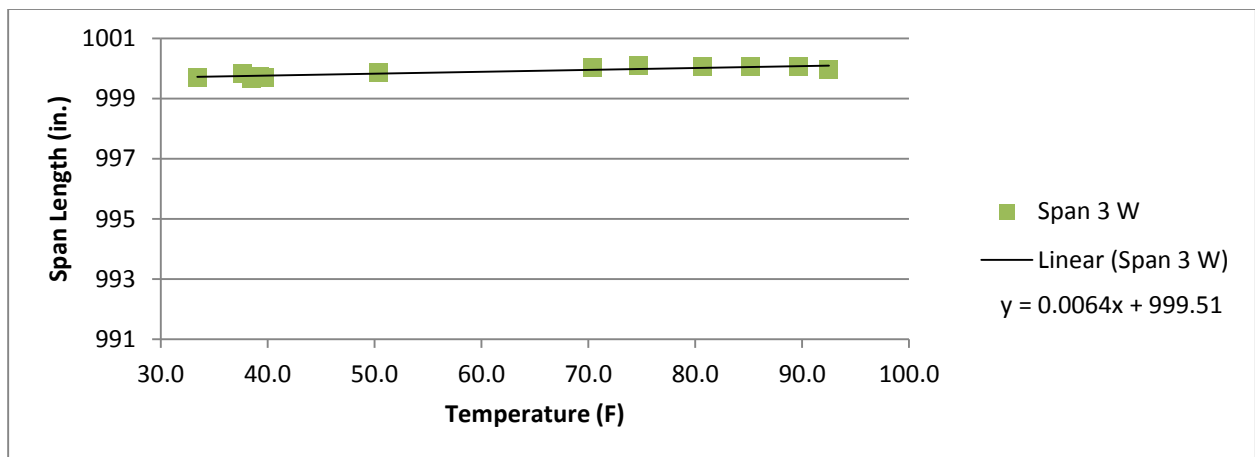
**Figure 3.14** Measured Lengths Between Survey Targets in Order of Increasing Temperature



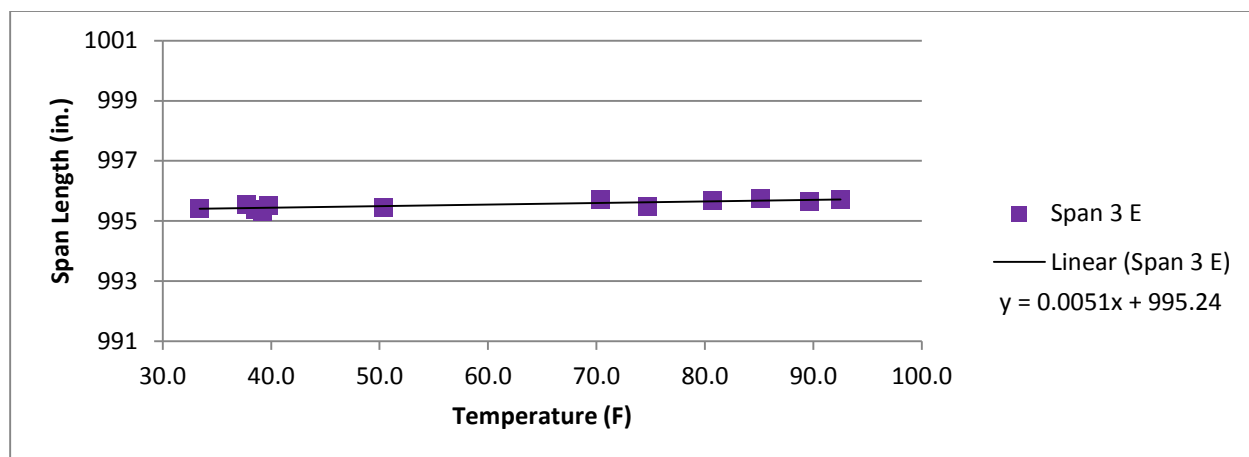
**Figure 3.15** Change in Measured Span Length for the West Side of Span 1 in Order of Increasing Temperature



**Figure 3.16** Change in Measured Span Length for the East Side of Span 1 in Order of Increasing Temperature



**Figure 3.17** Change in Measured Span Length for the West Side of Span 3 in Order of Increasing Temperature

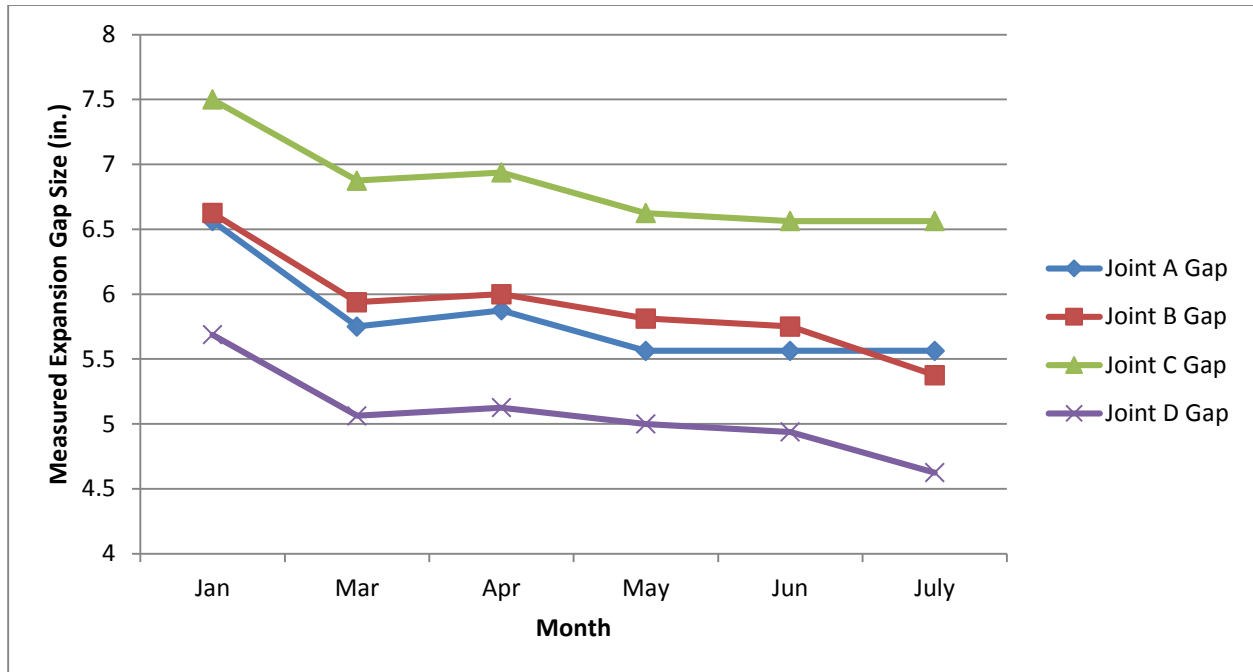


**Figure 3.18** Change in Measured Span Length for the East Side of Span 3 in Order of Increasing Temperature

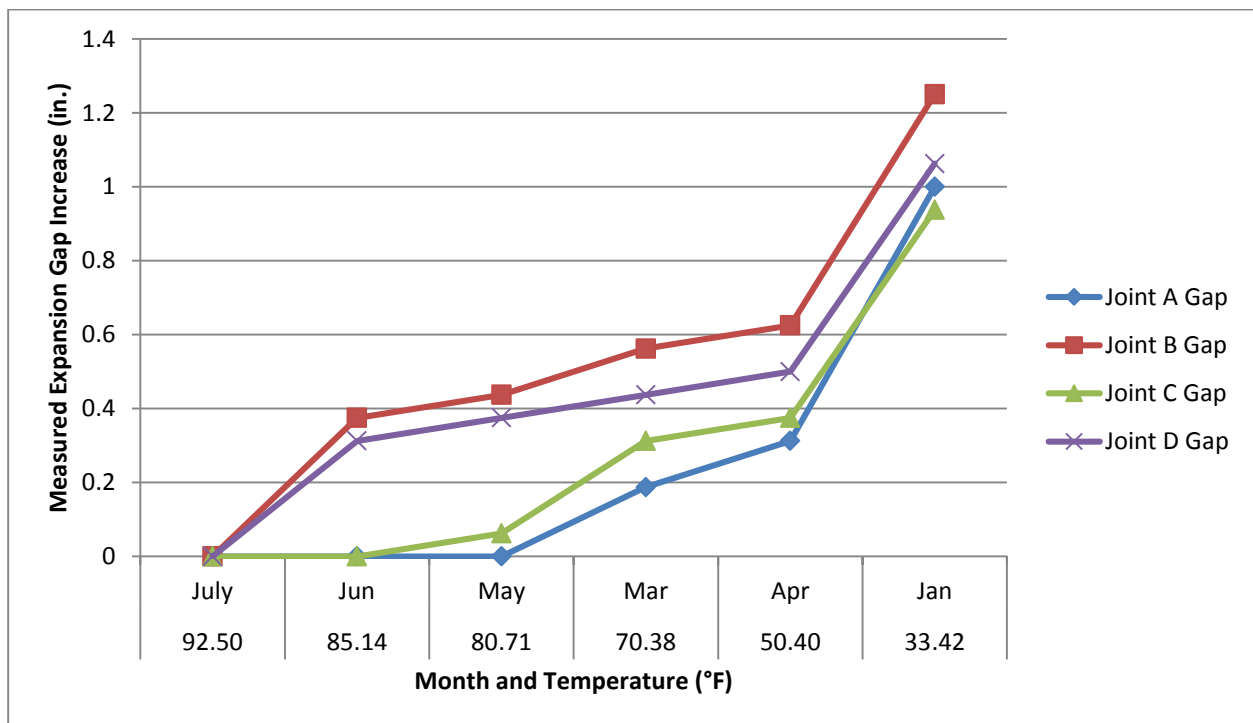
The survey results depicted graphically in Figures 3.13 and 3.14 show that a relatively small amount of movement occurred in the bridge spans. The average difference between the maximum recorded length measured and the minimum recorded length measured was 17.52 mm (0.690 in.) for the east side of Span 1, 18.42 mm (0.725 in.) for the west side of Span 1, 10.51 mm (0.414 in.) for the west side of Span 3, and 10.67 mm (0.420 in.) for the east side of Span 3. In general, the measured lengths obtained increased as the ambient temperature recorded increased.

This same increasing trend can be easily seen in Figures 3.15 through 3.18. The slope of the data trend lines shown in Figures 3.15 through 3.18 indicate that the west side of Span 1 expands more than the east side of Span 1. The same is true for Span 3, in that the west side experienced slightly larger movement than the east side. However, the difference between the magnitudes of the two slopes is smaller for Span 3 in comparison with Span 1. This indicates the presence of a moment in the abutment due to unequal expansion on the east and west sides of the bridge.

As mentioned previously, targets were placed on either side of the expansion gap and measured with a measuring tape at the time of the monthly survey starting in January. Figure 3.12 shows the configuration of the targets at the expansion gaps. A graph of the expansion gap movement recorded for targets placed at corners A, B, C, and D is shown in Figures 3.19 and 3.20.



**Figure 3.19** Measured Gap at Joints A, B, C, and D in Chronological Order



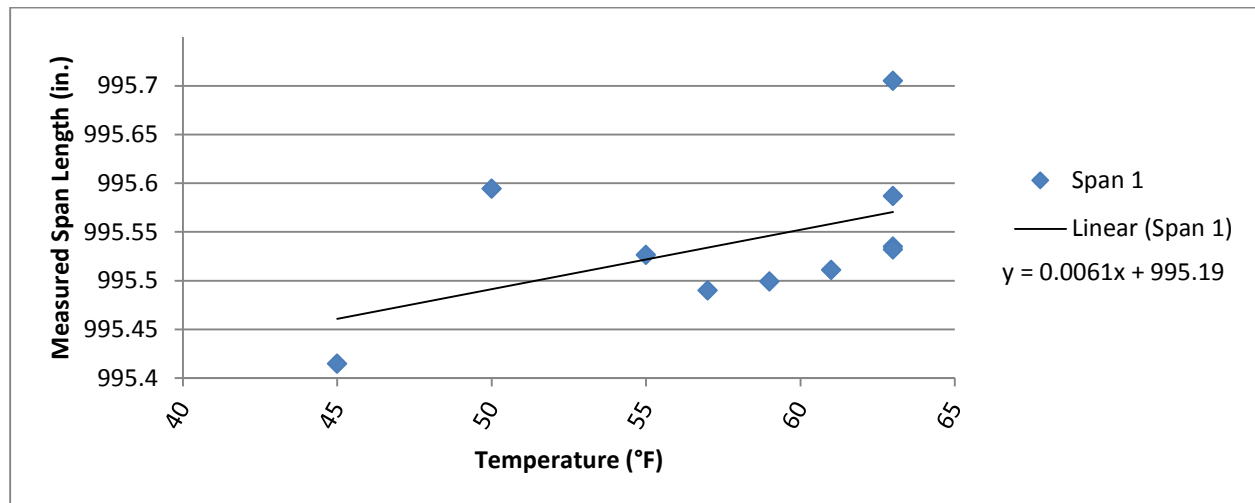
**Figure 3.20** Measured Gap at Joints A, B, C, and D in Increasing Order from Minimum

Figure 3.19 clearly shows an increase in expansion gap size measured as the recorded ambient temperature decreases. The movements of the expansion gaps at opposite corners appear to exhibit similar movements. This can be seen in Figure 3.19 when comparing the movement of the Joint B gap with that of Joint D. The same correlation can be made between the Joint B gap and the Joint C gap. The similar

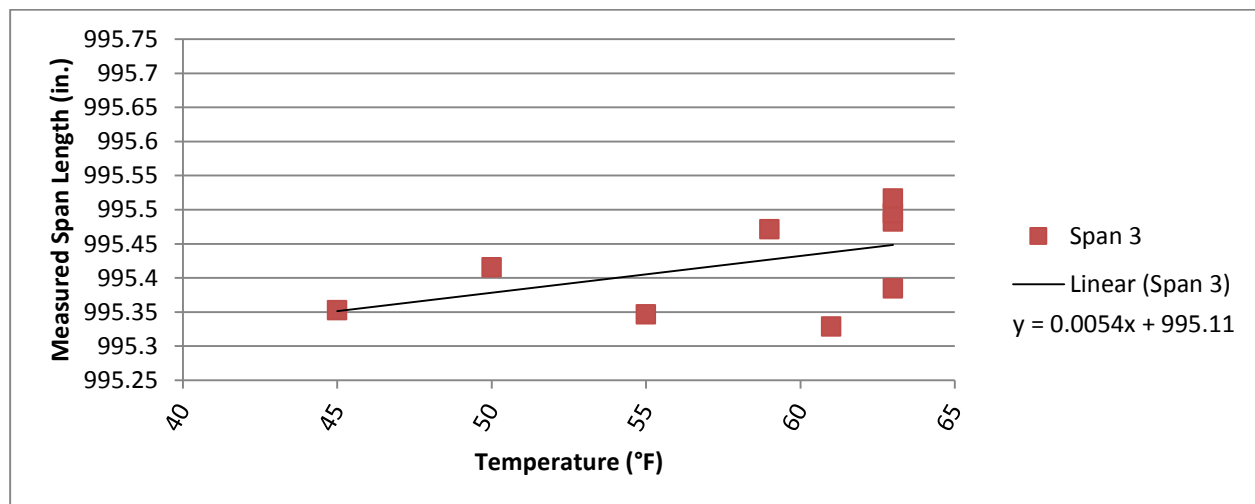
trend line slopes in Figures 3.16 and 3.17 also support this observation. This behavior supports the presence of bending moment occurring within the bridge abutments as a result of unequal movements at the east and west sides of each abutment.

### 3.5 HOURLY READINGS FROM DAY-LONG SURVEY

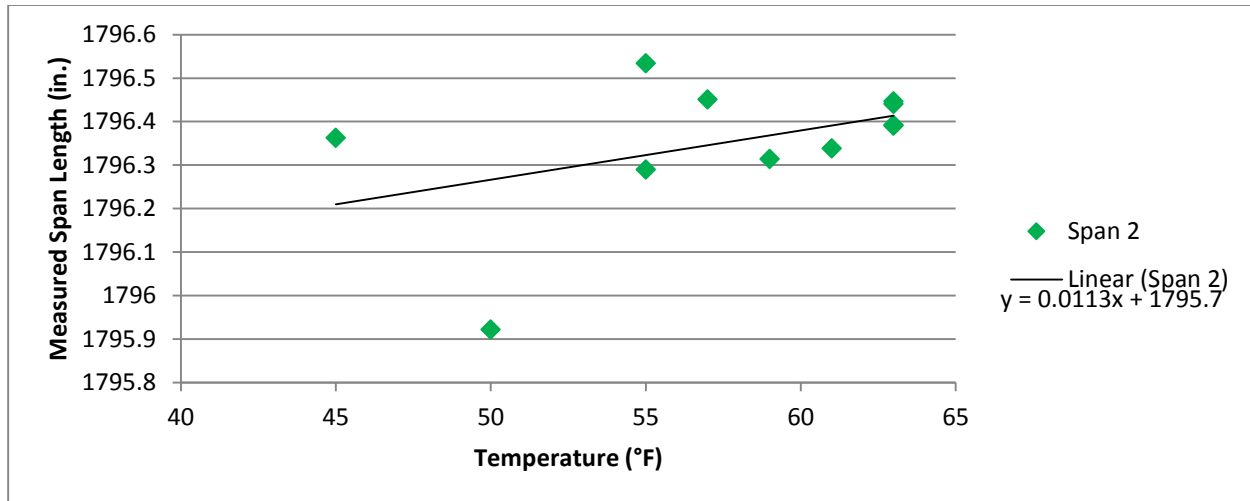
Similar calculations were made using Equation 1 with the data collected hourly during the full-day survey. These results are shown graphically in Figures 3.21, 3.22, and 3.23.



**Figure 3.21** Span 1 Measured Lengths Between Survey Targets for Day-Long Survey



**Figure 3.22** Span 3 Measured Lengths Between Survey Targets for Day-Long Survey



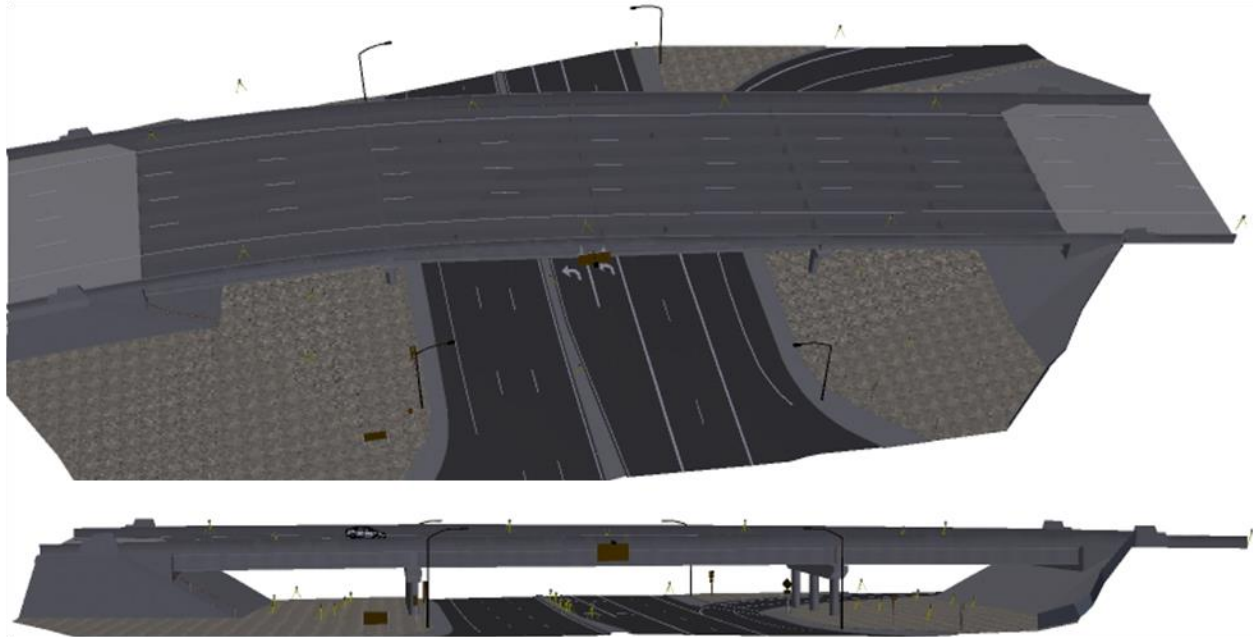
**Figure 3.23** Span 2 Measured Length Between Survey Targets for Day-Long Survey

Figures 3.21, 3.22, and 3.23 show a relatively small amount of movement in the bridge spans. For the full-day survey, the measured difference between the maximum recorded length and the minimum recorded length was 7.38 mm (0.29 in.) for Span 1, 15.55 mm (0.61 in.) for Span 2, and 4.78 mm (0.19 in.) for Span 3. In general, the measured lengths obtained increased as the ambient temperature increased throughout the day, with a slight time lag. The slope of the data trend lines shown in Figures 3.15 through 3.18 also indicate greater rate of expansion in Span 3 than observed in Span 1, again indicating that the conditions for Span 3 are different than those of Span 1.

### 3.6 NV5 MATERIAL

In order to quantify the global bridge movement of the bridge, an investigation by NV5 was performed in which a three-dimensional survey of the bridge was conducted. The three-dimensional survey was performed in conjunction with a standard survey with the level. Both surveys were conducted in February 2012. The goal was to perform two scans of the bridge. The original scan would serve as the baseline scan performed during a relatively cold period of time. It was anticipated that a second scan would be performed during the summer and serve as the bridge condition during a hot period of time. The original scan by NV5 successfully developed a three-dimensional model of the bridge with many more displacement points that could be used for comparison. Figure 3.24 shows the three-dimensional model developed by NV5.

After evaluating the NV5 data and discussing the requirements for the second scan, it was decided to forgo the second scan planned for the summer. This decision was based on the relatively small changes in movement that were measured with the level readings and the precision capabilities of the NV5 system.



**Figure 3.24** 3D Bridge Model Developed by NV5

### 3.7 AVERAGE BRIDGE TEMPERATURE IN UTAH

In parallel with the work on the 400 South Street Bridge, research was also being conducted on a separate bridge (Rodriguez 2012) that helped define average bridge temperatures in the State of Utah. Thermocouples were installed through the depth of an integral abutment bridge located on Interstate 15 over Cannery Road near Perry, Utah. Thermocouples installed throughout the depth of the bridge allowed for the calculation of average maximum and minimum temperatures for a typical Utah bridge. Based on guidelines presented in the AASHTO LRFD Bridge Design Specifications (2010), the average temperature was calculated from recorded temperatures using Equation 2.

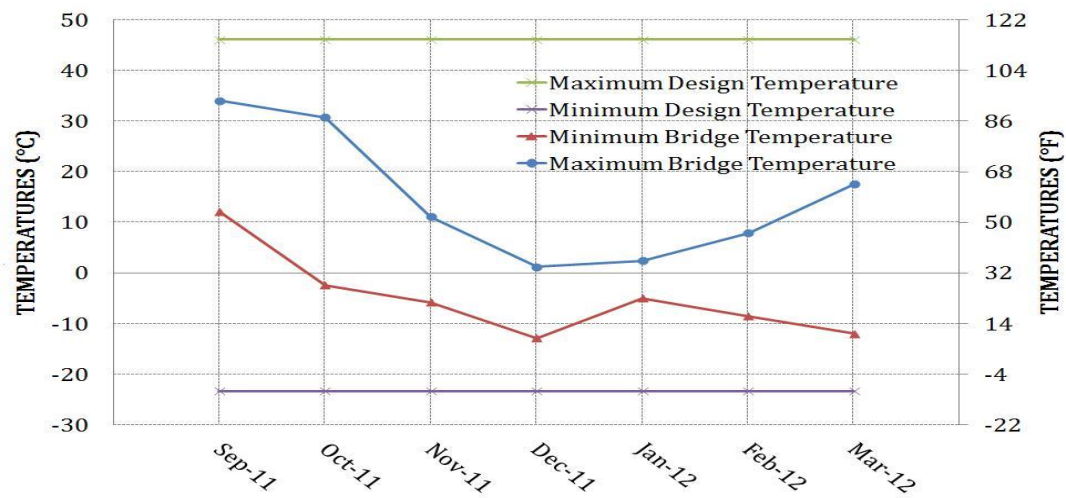
$$T_{avg} = \frac{\sum A_i * E_i * \alpha_i * T_i}{\sum A_i * E_i * \alpha_i} \quad (\text{Eq. 2})$$

where

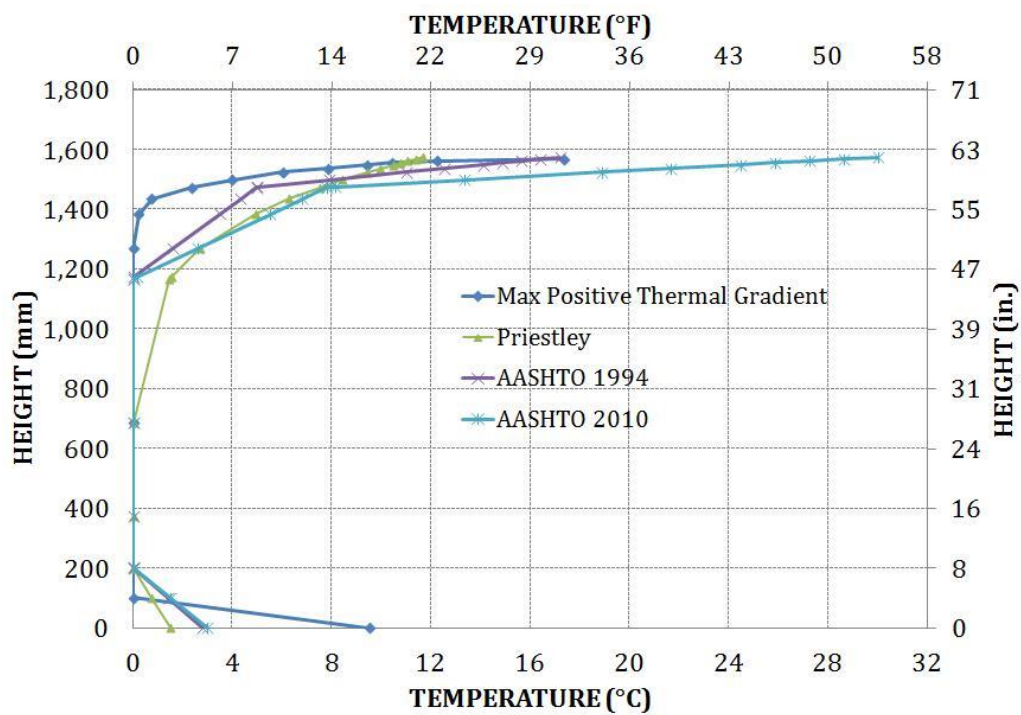
- $T_{avg}$  = average of the bridge temperature over the bridge cross section;
- $A_i$  = Area of the bridge cross section of the  $i$ -th segment;
- $E_i$  = Modulus of elasticity of the cross section of the  $i$ -th segment;
- $\alpha_i$  = Coefficient of thermal expansion of the material used for the  $i$ -th segment;
- $T_i$  = Temperature of the cross section of the  $i$ -th segment.

Using Equation 2, the data collected every 15 minutes from the bridge thermocouples were used to calculate average bridge temperature. The resulting average bridge temperatures obtained are shown in Figure 3.25 (Rodriguez 2012). A comparison of the measured maximum temperature gradient determined for a typical Utah Bridge is also shown in Figure 3.26 (Rodriguez 2012). The figures show that the AASHTO LRFD average bridge temperature limits, as well as the prescribed design temperature gradient,

accurately encompass the measured data. The reader is referred to the publication by Rodriguez (2012) for additional information.



**Figure 3.25** Monthly Measured Mean Temperature for a Utah Bridge



**Figure 3.26** Maximum Positive Thermal Gradient for a Utah Bridge on September 25



### 3.8 SUMMARY

The 400 South Street Bridge in Salt Lake City was monitored for changes in displacement due to temperature. In addition, a full bridge scan by NV5 was conducted. A comparison of measured average bridge temperatures and positive temperature gradients of a typical Utah Bridge with the AASHTO LRFD specifications was performed. A summary of the research findings is provided below.

- Based on the survey data collected, a small amount of movement due to changes in temperature was observed in each of the spans of the 400 South Street Bridge. However, despite the small movement, damage occurred in the north abutment.
- According to the periodic monthly survey, slightly more movement occurs on the west side of Span 1 than on the east side. There was also slightly more movement observed on the east side of Span 3 than on the west side. The full-day survey showed similar magnitudes in Span 1 and Span 3.
- The survey data showed that opposite corners of the bridge expanded and contracted differently, indicating the potential presence of an overall twisting motion. This non-uniform expansion and contraction could potentially be inciting a moment at the north abutment.
- According to temperature measurements on a typical Utah bridge, the maximum and minimum average design temperatures are indicative of the average bridge temperatures occurring in Utah. These maximum and minimum temperatures are predicted within the AASHTO LRFD specifications. In addition, temperature gradient measurements are also within the recommendations provided by AASHTO.
- The three-dimensional survey conducted by NV5 did not have enough accuracy to perform a second test.



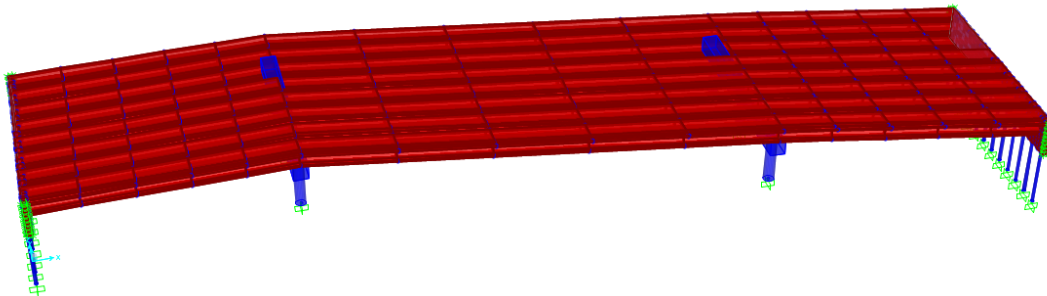
## 4. FINITE ELEMENT ANALYSES

### 4.1 FINITE ELEMENT MODEL

A description of the finite element analyses conducted for the 400 South Street Bridge is contained in Section 4. A description of the initial detailed solid model used to identify locations of stress concentrations is first presented. A simplified model of the 400 South Street Bridge follows. Data concerning change in span length with temperature are then included. A description of a parametric study conducted to further identify bridge parameters influencing the spalling of the abutments is included. The findings of these tests are also presented. A summary of the findings of the finite element analyses concludes Section 4.

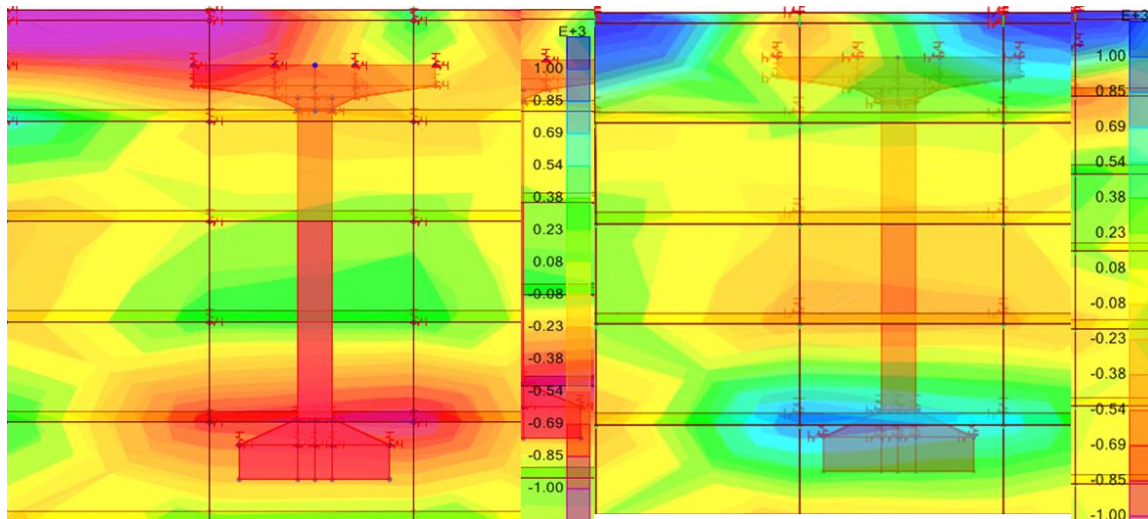
#### 4.1.1 Detailed Solid Model

A detailed finite element model of the 400 South Street Bridge was created using SAP2000 (Computers and Structures, Inc.) software. The model was developed using solid elements for the girders, abutments, bents, and bridge deck. The columns and piles were modeled using frame elements. The bridge girders were modeled using the specified prestressed concrete properties with an ultimate compressive strength ( $f'_c$ ) of 52 MPa (7500 psi). The cast-in-place concrete used to model the deck, abutments, bents, and columns was assigned an ultimate compressive strength of 28 MPa (4060 psi). A modulus of elasticity of 24900 MPa (3670 ksi) was used for the cast-in-place concrete and a modulus of Elasticity of 33900 MPa (5000 ksi) was used for the prestressed concrete. The concrete-filled driven piles below the abutments were modeled using frame elements. The piles were modeled using circular steel sections with an outside diameter of 324 mm (12.8 in.). The wall thickness of the piles was increased from the actual pile thickness of 10 mm (0.39 in.) to 31.9 mm (1.26 in.) using transformed section properties and the modular ratio. Surface springs were placed on the abutment face in the longitudinal direction in order to simulate the soil-abutment interaction. A spring stiffness of 150 pcf was used based on typical properties of granular backfill. Springs were assigned as compression and tension springs on the surface of the abutment. No springs were placed on the piles. A view of this model can be seen in Figure 4.1.

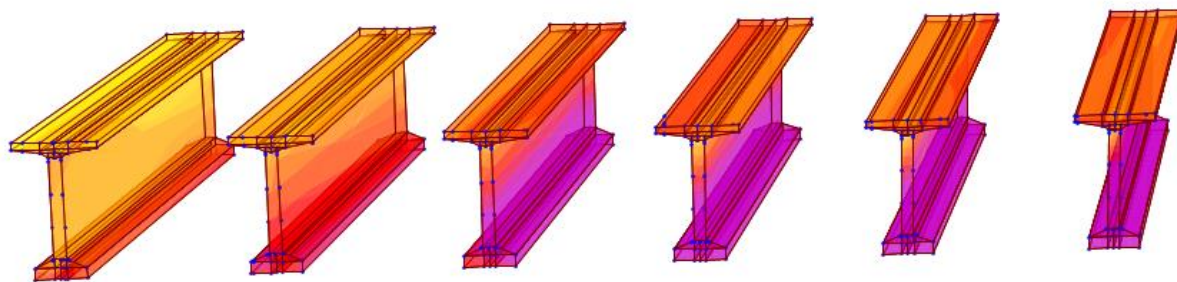


**Figure 4.1** 3D View of Solid SAP Model

Once the solid version of the SAP model was created, a uniform temperature load of 10° C (50° F) was applied to the concrete girders and deck of the bridge model. The calculated changes in stress for the abutment was then plotted as color contours on each of the solid elements used to model the abutment. These contours show the principal stresses in the abutment. The highest concentrations of stresses appeared as purple and red areas. These calculated stress concentrations were localized about the bottom girder flange, which coincides with the same locations as the observed spalling on the 400 South Street Bridge. An example of the stress contours observed can be seen in Figure 4.2.



**Figure 4.2** View of Model Abutment with Stress Contours Around Girder Bottom



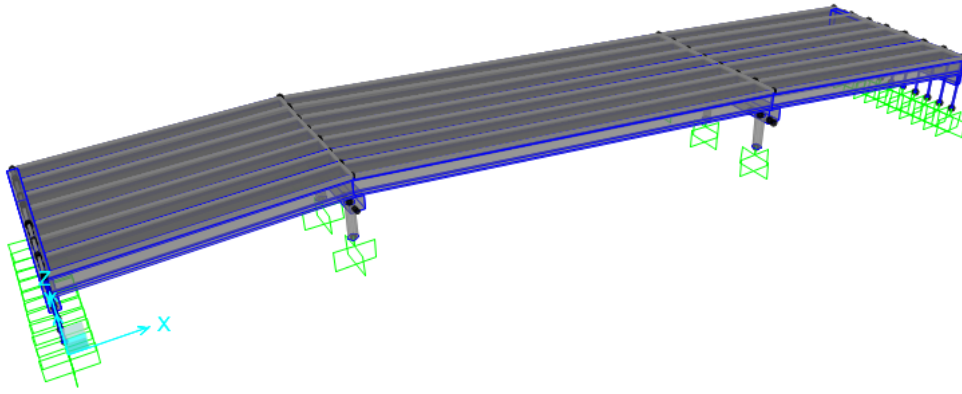
**NE**

**Figure 4.3** View of Stress Contours on Model Girders

Figure 4.3 shows the change in girder stresses at the north abutment of the bridge. For this figure, the girder on the right is at the northwest corner and the girder on the left is at the northeast corner. The figure shows that the calculated girder stresses progressively decrease when moving from the northwest corner to the northeast corner. In comparison, the stresses in the girder at the northwest are more than double those in the northeast girder.

#### 4.1.2 Simplified Finite-Element Model

In order to investigate the important bridge properties that resulted in the observed stress concentrations, a simplified model of the 400 South Street Bridge was constructed using SAP 2000. For the simplified model, frame elements were used to model all of the components of the bridge except the deck, which was modeled using solid elements. This simplified version of the model allowed for parametric studies of bridge parameters that influence the changes in moments in the bridge abutments. The frame elements used to model the bridge abutments were assigned line springs with a stiffness of 29.2 kN/m (2000 lb/ft), which corresponds to the stiffness applied to the detailed model. A graphical representation of this model can be seen in Figure 4.4.



**Figure 4.4** View of the Simplified SAP Model Using Frame Elements

Once the simplified finite-element model was developed, a series of temperature loads were applied uniformly on the concrete girders and deck. The applied temperatures corresponded to the measured temperature values recorded during the monthly surveys discussed in Section 3. The minimum recorded temperature was used as a base temperature. The temperature loads were then determined by calculating the difference between the temperature readings for each month compared with the minimum recorded temperature. This resulted in 11 values of temperature changes that were subsequently placed on the bridge model. The change in span length could then be determined using the deflections produced by the simplified SAP model. These changes in span length were compared with theoretical values calculated using Equation 3.

$$\Delta = \alpha * \Delta T * L$$

**(Eq. 3)**

where,

$\Delta$  = change in span length

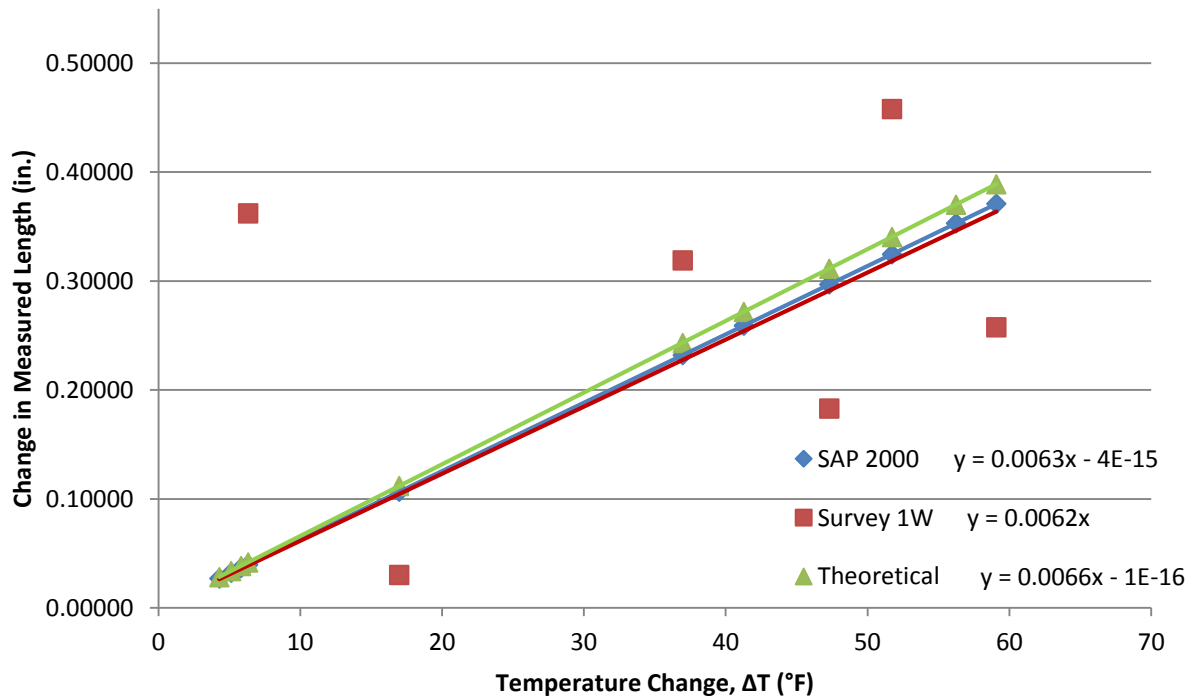
$\alpha$  = coefficient of thermal expansion

$\Delta T$  = change in temperature

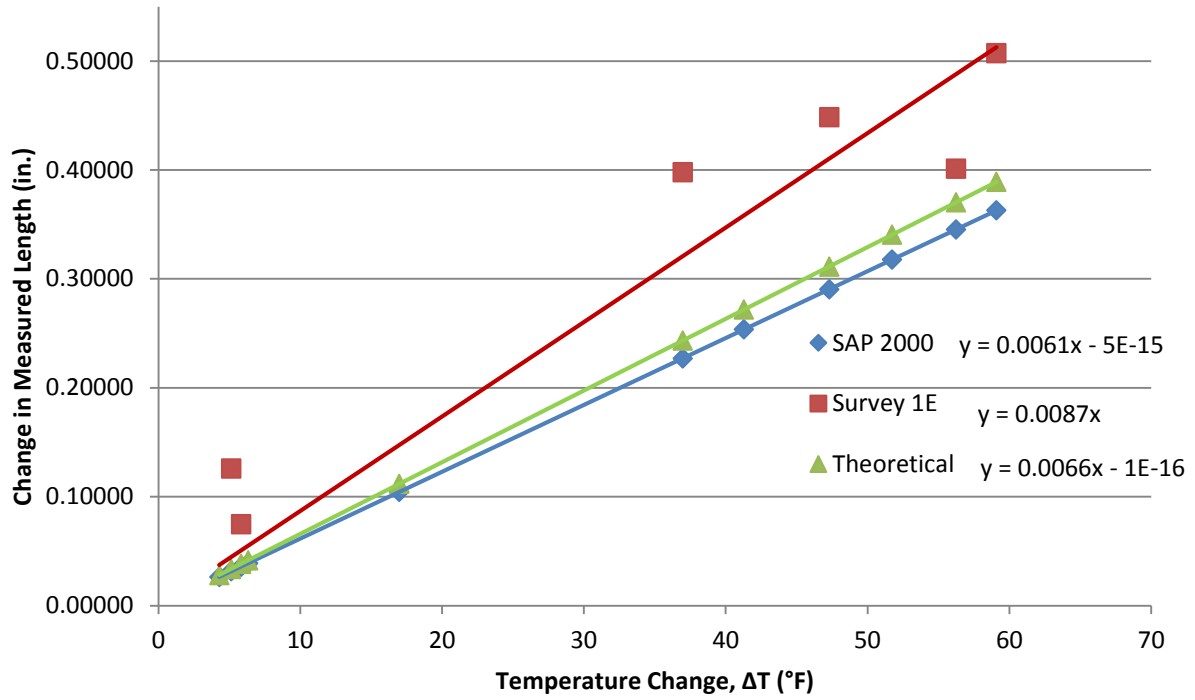
L = length of span

This equation was evaluated for spans one and three with  $\alpha=6.5 \times 10^{-6} \text{ } ^\circ\text{F}^{-1}$  and  $L=84.41 \text{ ft}$  for Span 1 and  $L=84.69 \text{ ft}$  for Span 3. The values used for  $\Delta T$  were the temperature change values (in  $^\circ\text{F}$ ) recorded for each month relative to the minimum recorded temperature. This comparison can be seen in Figures 4.5 through 4.8.

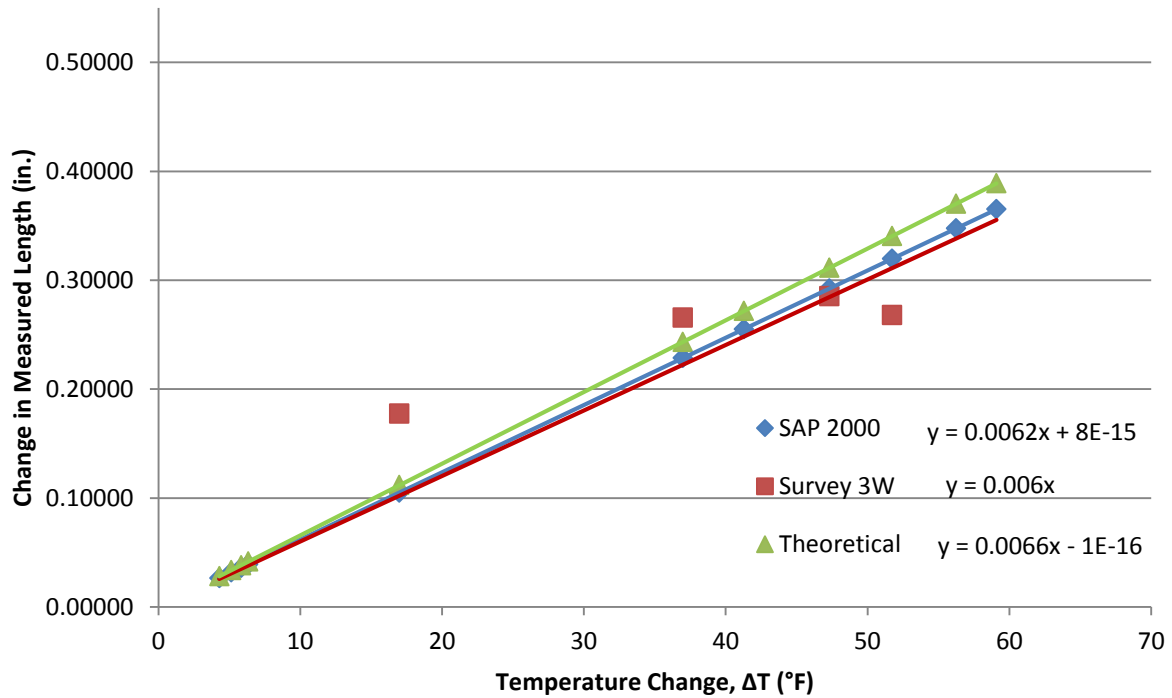
A comparison of trend lines in Figures 4.5 through 4.8 is very similar. In each case, it is observed that the values of change in calculated length obtained in SAP are lower than those predicted by Equation 3. This signifies that the SAP model represents conditions that are slightly restrained. This agrees with the expected conditions of the 400 South Street Bridge. The measured data in each plot are reasonably predicted by the finite-element model and simply supported conditions. Figure 4.9 shows the behavior of the east and west sides of Span 1 and Span 3 compared to one another.



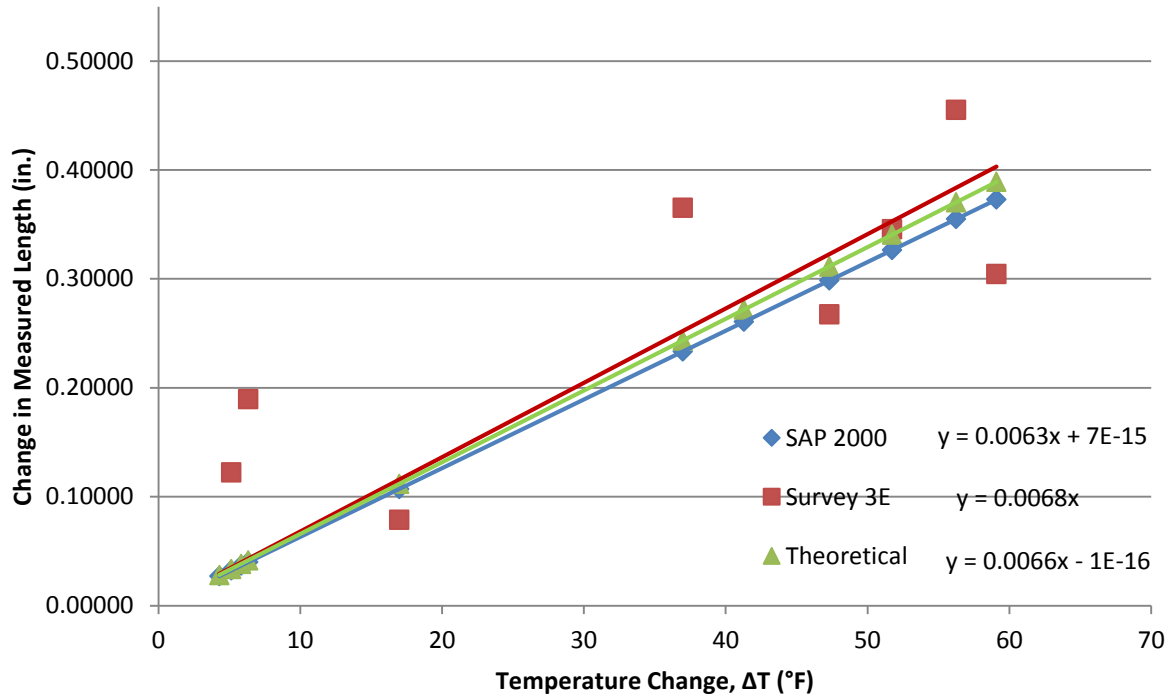
**Figure 4.5** Comparison of SAP and Theoretical Values for the West Side of Span 1



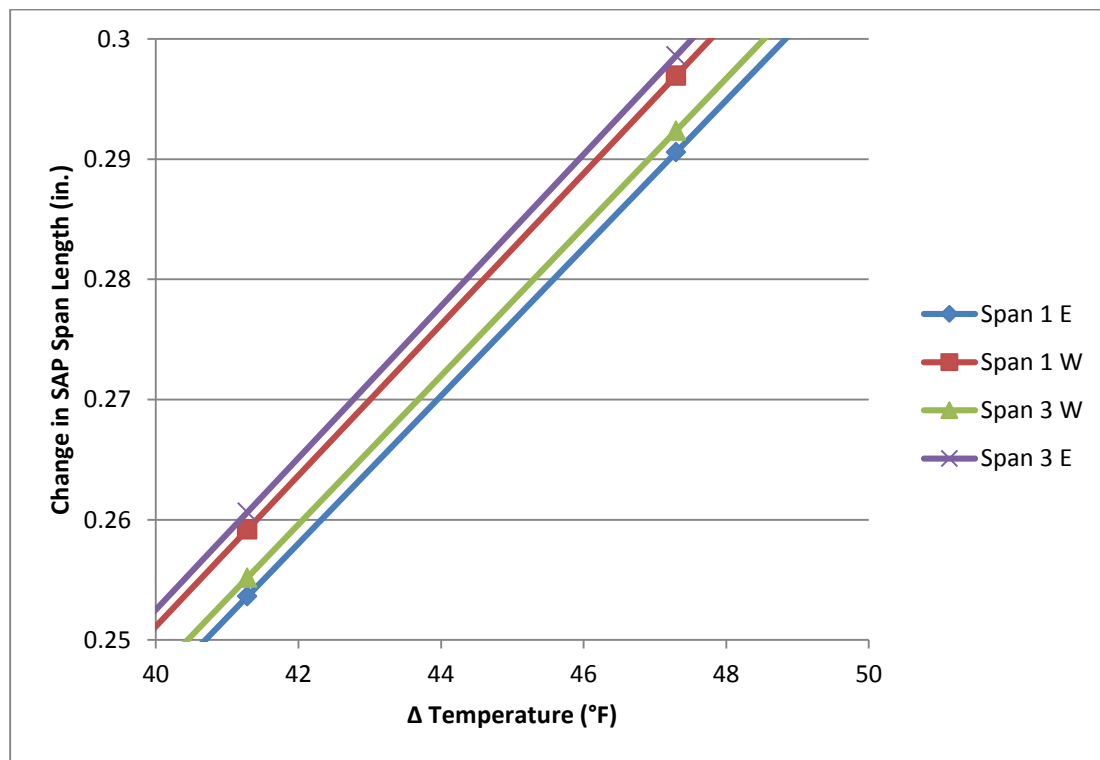
**Figure 4.6** Comparison of SAP and Theoretical Values for the East Side of Span 1



**Figure 4.7** Comparison of SAP and Theoretical Values for the West Side of Span 3



**Figure 4.8** Comparison of SAP and Theoretical Values for the East Side of Span 3



**Figure 4.9** Measured Changes in Span Length According to SAP 2000



In Figure 42 it can be seen that the east side of Span 3 and the west side of Span 1 exhibit very similar behavior. This can also be concluded about the west side of Span 3 and The east side of Span 1. This relationship is the same as was observed from the survey data discussed in Chapter 3. As a result, it can be concluded that the same trend of non-uniform expansion and contraction was observed from the SAP model data that was observed in the monthly surveys.

#### 4.1.3 Abutment Lateral Displacement

Calculating the transverse abutment force due to temperature effects can be done using Equations 4 through 8. As the skew angle increases, the transverse abutment force increases.

$$\Delta = \frac{P_l * L}{A * E} \quad (\text{Eq. 4})$$

$$P_l = \frac{\Delta * A * E}{L} \quad (\text{Eq. 5})$$

$$P_l = \frac{\alpha * \Delta T * L * A * E}{L} \quad (\text{Eq. 6})$$

$$P_l = \alpha * \Delta T * A * E \quad (\text{Eq. 7})$$

$$P_l = \alpha * \Delta T * A * E \quad (\text{Eq. 8})$$

where,

$\Delta$  = change in span length

$P_l$  = lateral force

$L$  = length of span

$A$  = Area of abutment

$E$  = Modulus of elasticity

$\alpha$  = coefficient of thermal expansion

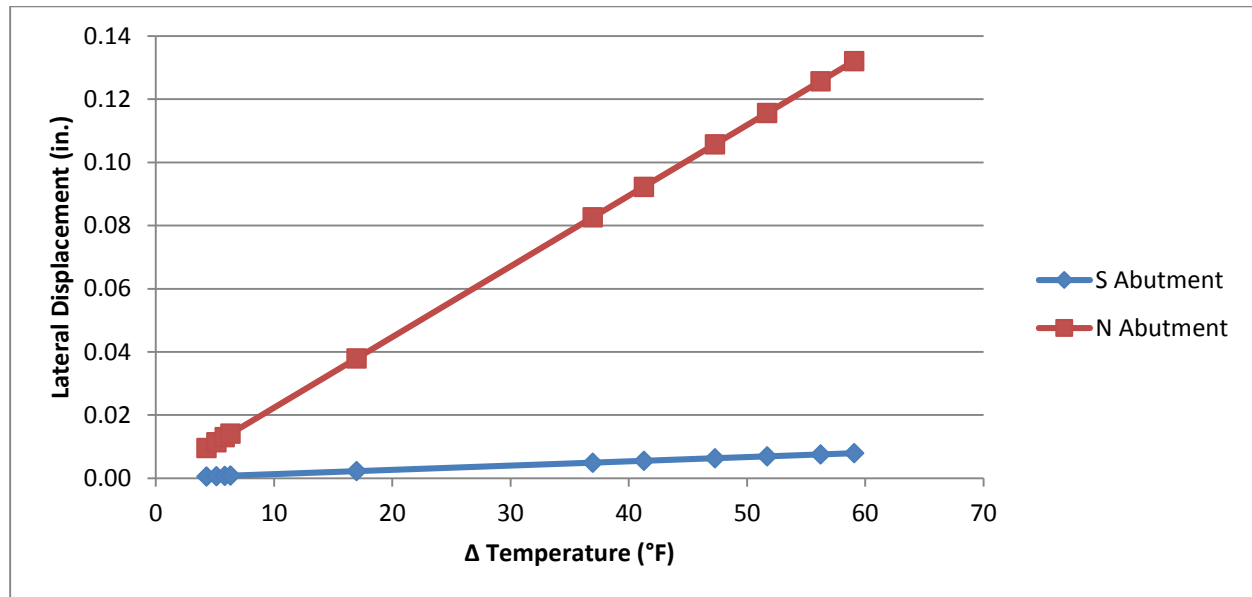
$\Delta T$  = change in temperature

$P_t$  = transverse force

Using the same simplified model described in Section 4.1.2, bridge behavior about the lateral deflection of the abutments was obtained. Lateral displacement corresponds to displacement in the transverse

direction of the SAP model. Figure 4.10 shows a comparison of the lateral deflections of the north and south abutments obtained from the SAP model. Figure 4.10 also shows that the north abutment displaces laterally much more than the south abutment does. This unbalanced movement is the main contributing factor to the non-uniform change in span length that can be seen in Figure 4.8.

These observed trends from the SAP model data support the correlation between the survey results and the finite-element model results. Using the same simplified SAP model, a series of parametric studies was then conducted.



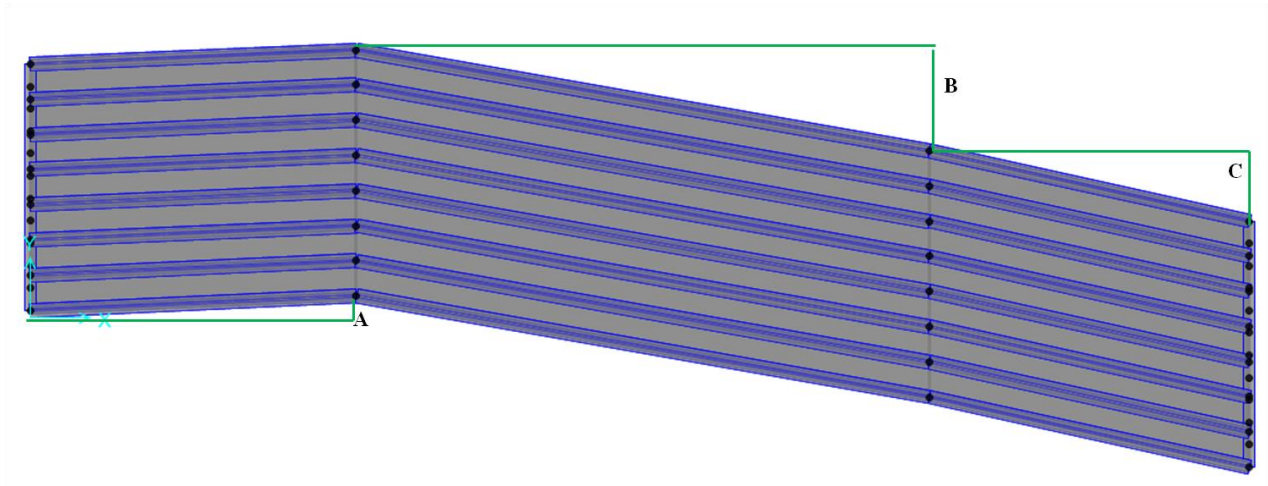
**Figure 4.10** Comparison of Modeled Lateral Deflections of the Bridge Abutments

## 4.2 PARAMETRIC STUDY

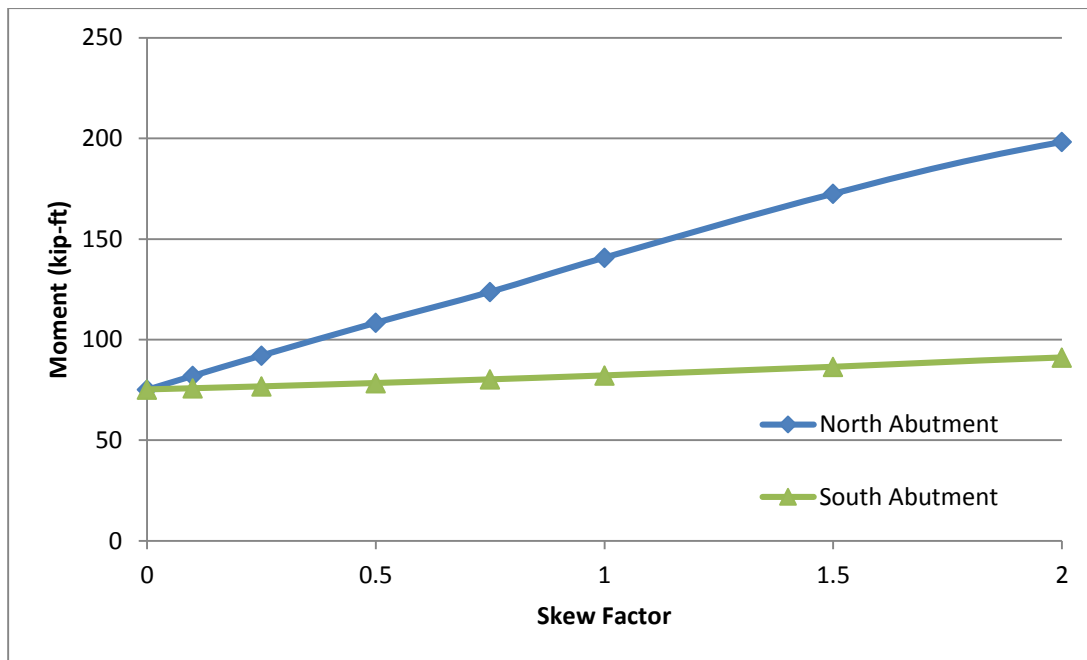
In an effort to further identify bridge parameters influencing the spalling observed on the abutment of the actual bridge, a series of parametric studies were conducted using SAP 2000. These studies were used to investigate the influence of skew angle and span length on the weak-axis bending moment in the abutment.

### 4.2.1 Effect of Abutment and Pier Offset

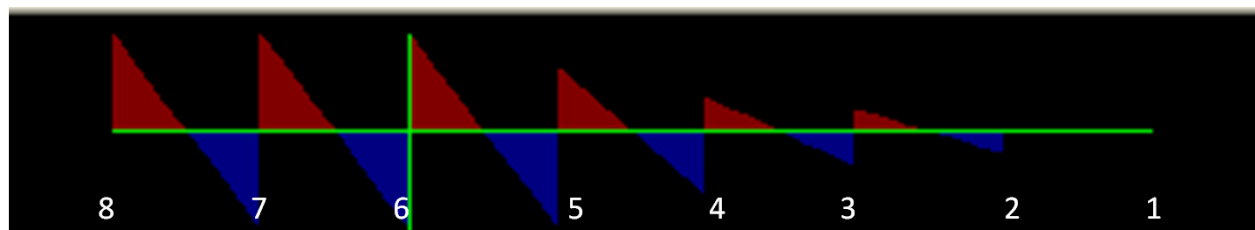
The first series of parametric tests provided an additional validation of the as-is model, as well as an investigation of the influence of the overall abutment offset of the bridge. This was achieved by a series of evaluations conducted using the simplified model of the bridge that used beam elements for the girders and abutments. The actual abutment offset of the bridge was multiplied by factors ranging from 0.10 to 5.0. The offsets used are labeled as A, B, and C in Figure 4.11. The offset values A, B, and C were multiplied by the factors from 0.1 to 5.0 to produce a series of skew angles occurring in the bridge spans that were factors of the actual bridge geometry. The actual geometry of the bridge was therefore represented by a factor of 1.0. A temperature differential of 50° F was uniformly applied to the girders and deck of the bridge model. For each offset factor, the maximum weak-axis bending moment in the abutment was found obtained the SAP model. Figure 4.12 shows the increase in moment on the skewed (north) abutment. These results agree with the observed spalling of the northern abutment and also serve as a secondary qualitative validation of the SAP model.



**Figure 4.11** Labeled Abutment Offsets of the Bridge



**Figure 4.12** Increase in Absolute Maximum Weak-axis Bending Moment of the Abutments for Parametric Study of Full Bridge Geometry



**Figure 4.13** Moment Diagram for the North Abutment for the Actual Bridge Geometry

Figure 4.13 shows the moment diagram obtained from the SAP model for the multiplication factor of 1.0, representing the actual bridge geometry. The maximum moment was observed between girders 5 and 6 and between girders 7 and 8. The girders are numbered, with the girder on the east side of the bridge being number 1 and the west most girder being number 8. This agrees with the actual location of the most extreme spalling on the 400 South Street Bridge.

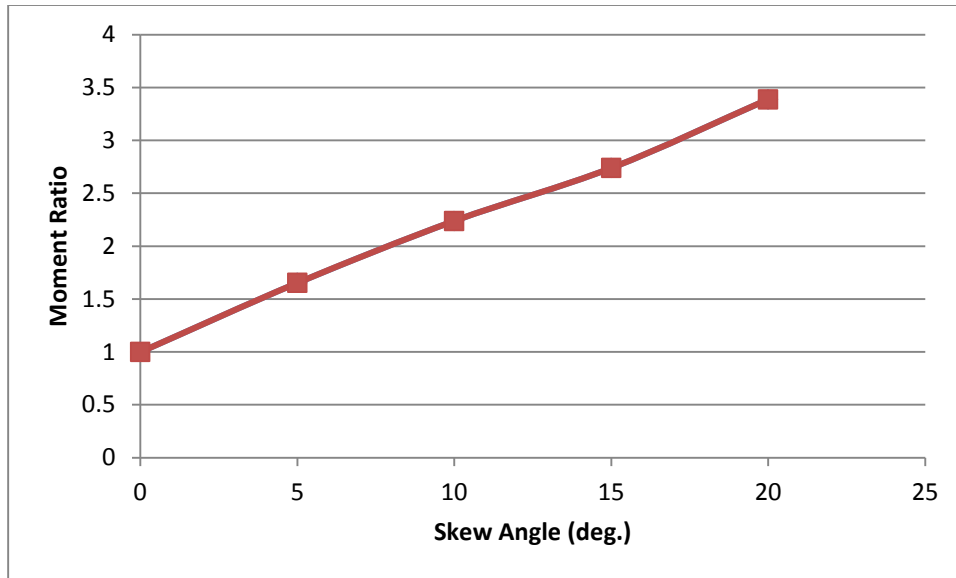
#### 4.2.2 Effect of Skew

Using the same bridge components described for the full-scale model of the bridge, a model was created to test the effects of skew angle. A single span version of the bridge consisting of eight girders and the concrete deck supported by abutments and piles was created. The same configuration of soil springs as previously described was applied to the abutments. The temperature differential applied to the girders and deck was again 50° F. A straight version of this model was evaluated and then the skew angle was increased in 10° increments by rotating the abutments. Figure 4.14 shows an example of this model with a skew angle of 10°.

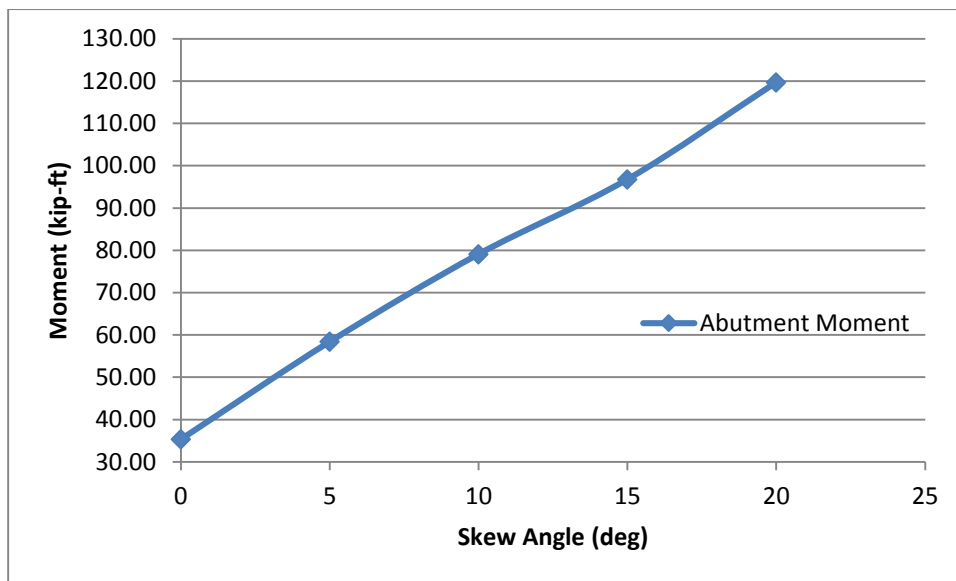


**Figure 4.14** Parametric Skew Model with Skew Angle of 10°

The finite-element model results calculated from this study were used to calculate an increase in abutment moment as a function of skew angle. This calculated weak-axis moment could then be compared with the cracking moment of the abutment. The moment values recorded from the skewed models were compared with the moment in the abutments from the straight version of the same model. By dividing the moment from the skewed models by the moment from the zero-skew model, a moment ratio was found. The results from the parametric skew test can be seen graphically in Figures 4.15 and 4.16.



**Figure 4.15** Moment Ratio Results of a Parametric Study of Skew Angle

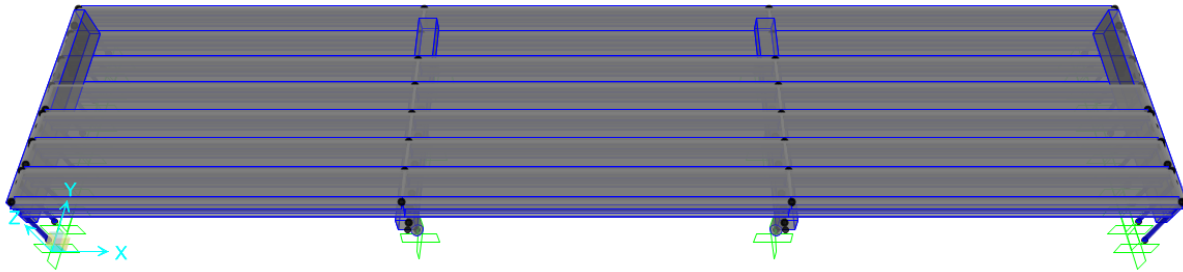


**Figure 4.16** Comparison of Absolute Maximum Weak-Axis Bending Moment in the Abutment with Calculated Cracking Moment for a Parametric Study of Skew Angle

Figure 4.15 shows a large increase in moment as skew angle increases. The amount of moment in the 20° skew model is more than three times that of the model without skew. According to this study, for each 5° increase in skew, a 50% to 65% increase in moment is seen in the abutment. This shows a very strong relationship between the amount of moment in the bridge abutments and the skew angle of the abutments. Figure 4.16 shows the increase in weak-axis bending moment in the abutment as skew angle is increased.

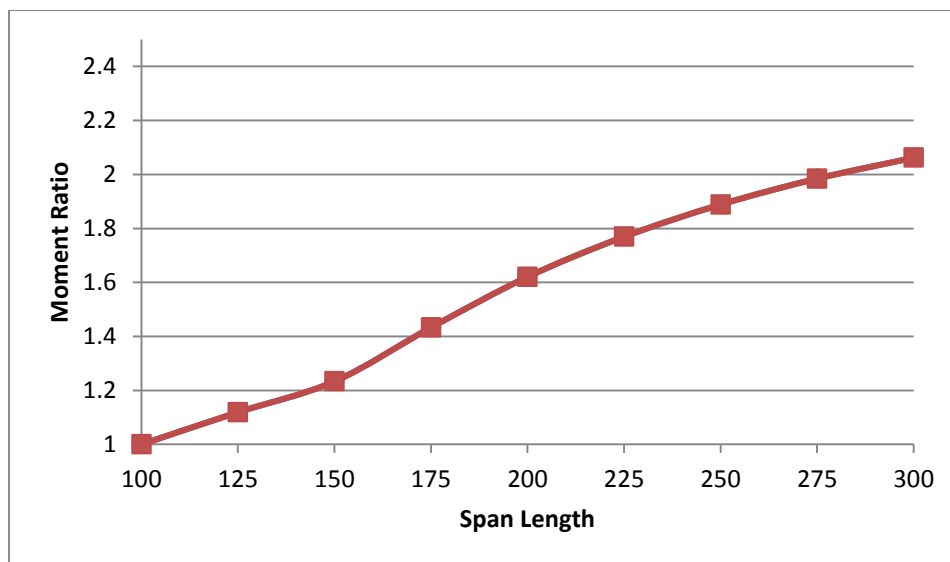
### 4.2.3 Effect of Span Length

A second parametric study was conducted using the same components as the models previously described in a configuration designed to test the effects of span length. A three-span model of similar configuration to that of the actual bridge was used. Each of the three spans was modeled with equal lengths. A sample view of this arrangement can be seen in Figure 4.17.

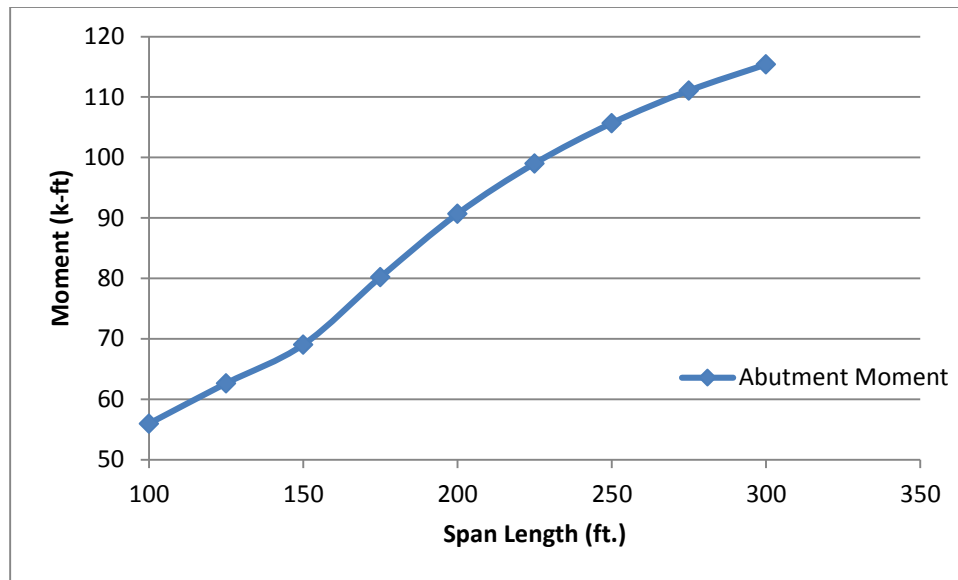


**Figure 4.17** Three-span Parametric Length Model

Tests were performed using a range of span lengths from 100 feet to 300 feet in 25-ft increments. The weak-axis bending moment in the abutment was recorded for each configuration and used to calculate a moment ratio for each length test. The results show a clear increase in moment ratio as the span length increases. The results from these tests can be seen in Figures 4.18 and 4.19.



**Figure 4.18** Moment Ratio Results of a Parametric Study of Span Length

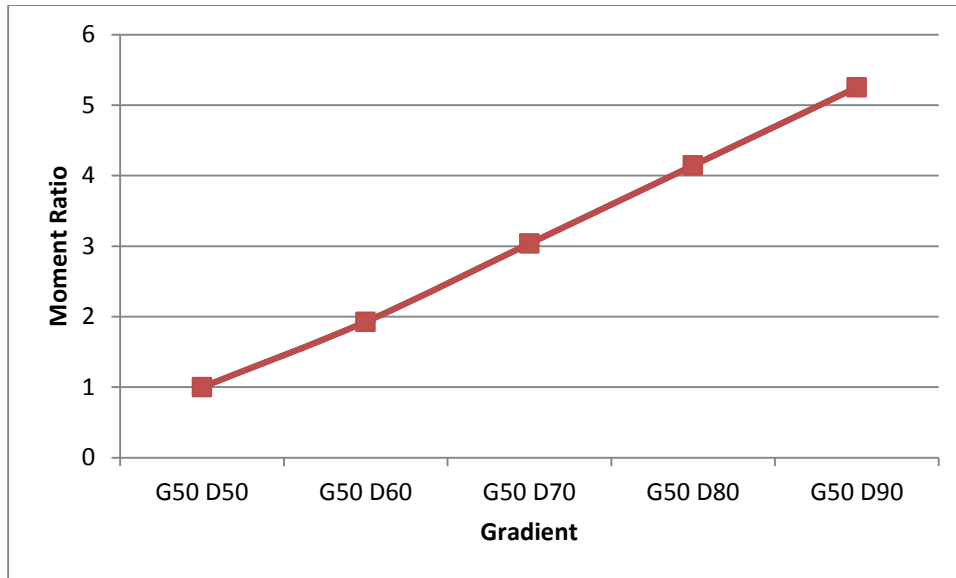


**Figure 4.19** Comparison of Absolute Maximum Weak-Axis Bending Moment in the Abutment with Calculated Cracking Moment for a Parametric Study of Length

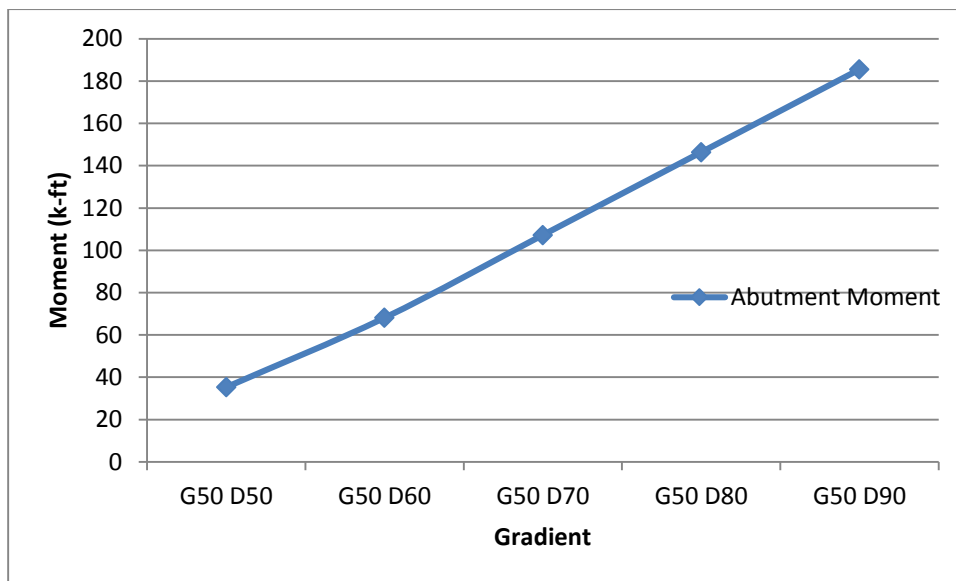
According to the test results shown in Figure 4.18, by doubling the span length, an approximately 60% increase in moment is seen in the abutment. Figure 4.19 shows the calculated abutment moments from the model.

#### 4.2.4 Effect of Temperature Gradient

An investigation regarding the effect of temperature gradient over the bridge cross-section was carried out using a single-span model of a length of 100 feet. The model was constructed similar to the zero-skew model used in the parametric investigation of skew angle described in Section 4.2.3. The geometry of the bridge model remained constant for this test while the difference between the temperature loads applied to the deck and the girders was increased. The first evaluation was performed without any gradient and a temperature load of 50° F. The temperature load on the deck was then increased in increments of 10° F while the girder temperature loads remained the same. The moment in the abutments as a function of temperature gradient was compared with the values obtained from the uniform temperature loading to get a moment ratio based on temperature gradient. The results from this test are shown in Figures 4.20 and 4.21.



**Figure 4.20** Moment Ratio Results from a Parametric Study of Temperature Gradient



**Figure 4.21** Comparison of Absolute Maximum Weak-Axis Bending Moment in the Abutment with Calculated Cracking Moment for a Parametric Study of Length

The results shown in Figure 4.20 show a large increase in the moment in the abutment as the temperature gradient within the bridge increases. According to the data from this test, a 20° F increase in temperature difference between the girders and deck of the bridge causes an approximately 200% increase in the moment observed in the abutment. Figure 4.21 shows that a large temperature gradient can develop moments within the abutments sufficient to cause cracking. In combination with other parameters, even smaller temperature gradients can lead to conditions involving cracking.



### 4.3 SUMMARY

A solid model was created using SAP 2000 that showed stress concentrations in the same locations that damage occurred on the 400 South Street Bridge. A simplified version of the SAP model was subsequently created using frame elements. This model showed that as overall conditions approach the actual geometry of the 400 South Street Bridge, the moment in the abutment approaches a calculated cracking moment. A parametric study was then performed to attempt to isolate the effects of skew, span length, and temperature gradient. A summary of the research findings is provided below.

- The overall geometry of the 400 South Street Bridge is such that, according to the frame element model, the effects of skew, length, and temperature gradient cause moment in the abutment to approach the calculated cracking moment.
- The study of skew effect showed that for each 5° increase in skew, an approximately 50% to 65% increase in moment was observed in the abutment
- The study of the effects of length indicated that by doubling the span length, an approximately 60% increase in moment was calculated in the abutment.
- The study of temperature gradient effects showed that a 20° F increase in temperature difference between the girders and deck of the bridge causes an approximately 200% increase in the moment observed in the abutment.



## **5. SUMMARY AND CONCLUSIONS**

### **5.1 SUMMARY**

In an effort to understand the cause of the observed spalling at the north abutment of the integral abutment bridge over 400 South Street in Salt Lake City, Utah, the bridge was surveyed monthly to quantify its behavior. Span lengths of the bridge were surveyed monthly and recorded with the accompanying ambient air temperature at the time of the survey.

In addition to the monthly survey, multiple surveys were performed over one day. These two sources of bridge behavior were used to understand the overall response of the bridge to changes in temperature. The overall bridge behavior using the survey data was compared to a detailed finite-element model of the bridge. The finite-element model was shown to exhibit slightly restrained conditions compared with the unrestrained theoretical values. The model showed the same general trends observed in the monthly surveys. Locations of tensile stress concentrations were found to develop at the bottom girder flanges. A simplified modeling scheme was then used to perform a series of parametric studies investigating the effects of skew angle, span length, and temperature gradient on the weak-axis bending moment of the abutment. The relationship between these bridge parameters and the abutment weak-axis moment were obtained. The survey and finite-element results were used to make the following conclusions.

### **5.2 CONCLUSIONS AND RECOMMENDATIONS**

Based on the results from the survey data and finite-element analyses, several conclusions were obtained. Recommendations based on these conclusions are also presented.

1. Bridge Movement – In general, expansion and contraction of the 400 South Street Bridge was observed as temperature increased and decreased, respectively. The observed movements were unequal when comparing the east and west sides of the bridge. Through finite-element analyses, this unequal movement is believed to be a result of lateral movement at the skewed support of the north abutment. Reduction of the lateral movement would reduce tensile stress in the abutment.
2. Skew – As little as a 5° increase in skew angle can significantly increase the weak axis bending moment of the bridge abutment.
3. Length – As the span length increases by a factor of 2, an approximate 60% increase in weak-axis bending moment in the bridge abutments was observed.
4. Temperature Gradient – Temperature gradients, in combination with uniform temperature changes, influence the stresses in the bridge abutments. A 20° F increase in temperature difference between the girders and deck of the bridge can cause an increase in the stresses observed in the bridge abutments. The influence of temperature gradients on abutment stresses should be investigated.
5. The abutment cracking of the 400 South Street Bridge is likely a result of a combination of bridge parameters. These properties include a combination of skew, curvature, span length, and detailing. Integral abutment bridges with more than one of these conditions require additional design checks.
6. Finite element models can predict localized and global increases in demand on integral abutments



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## APPENDIX A: MONTHLY SURVEY DATA

|                            |
|----------------------------|
| <b>400 S Bridge Survey</b> |
|----------------------------|

Date: 26-Aug-11

Prism Height: 6 ft      Avg Temp 89.6 F

|                  |             |             |             |                 |            |            |
|------------------|-------------|-------------|-------------|-----------------|------------|------------|
| <i>Station 1</i> | Height:     | 6.650       |             |                 |            |            |
|                  |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism            | Reference   | 175.805     | 175.805     | -0.650          |            |            |
|                  |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b>  | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 1                |             |             |             | 227             | 52         | 45         |
| 2                | 124.025     | 122.425     | 19.875      | 228             | 0          | 5          |
| 3                | 79.340      | 77.735      | 15.865      | 247             | 0          | 25         |
| 4                | 79.080      | 77.820      | 14.085      | 246             | 56         | 45         |
| 5                | 78.740      | 77.795      | 12.155      | 246             | 56         | 45         |
| 6                | 54.160      | 49.725      | 21.465      | 278             | 30         | 0          |
| 7                | 54.975      | 52.235      | 17.145      | 323             | 25         | 20         |
| 8                | 54.525      | 52.425      | 14.990      | 323             | 22         | 30         |
| 9                | 53.965      | 52.705      | 11.595      | 323             | 17         | 35         |
| 10               |             |             |             | 6               | 43         | 40         |
|                  |             |             |             |                 |            |            |
| <i>Station 2</i> | Height:     | 6.030       |             |                 |            |            |
|                  |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism            | Reference   | 176.945     | 176.945     | -0.030          |            |            |
|                  |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b>  | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 29               |             |             |             | 6               | 26         | 35         |
| 30               | 65.355      | 62.010      | 20.630      | 44              | 46         | 30         |
| 31               | 64.935      | 62.135      | 18.855      | 44              | 51         | 50         |
| 32               | 64.410      | 62.355      | 16.130      | 44              | 51         | 25         |
| 33               | 69.500      |             |             | 81              | 52         | 25         |
| 34               | 95.110      |             |             | 105             | 29         | 30         |
| 35               | 94.810      |             |             | 105             | 29         | 40         |
| 36               | 94.405      |             |             | 105             | 29         | 40         |

| <b>400 S Bridge Survey</b> |             |             |             |                 |            |            |
|----------------------------|-------------|-------------|-------------|-----------------|------------|------------|
|                            |             |             |             |                 |            |            |
|                            |             |             |             |                 |            |            |
| Prism Height:              |             | 6 ft        |             |                 |            |            |
|                            |             |             |             |                 |            |            |
|                            |             |             |             |                 |            |            |
|                            |             |             |             |                 |            |            |
| Station 3                  | Height:     | 7.300       |             |                 |            |            |
|                            |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism                      | Reference   | 90.880      | 90.870      | -1.300          |            |            |
|                            |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b>            | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 20                         |             |             |             | 278             | 32         | 50         |
| 21                         |             |             |             | 278             | 39         | 25         |
| 22                         | 95.145      | 93.380      | 18.225      | 297             | 57         | 35         |
| 23                         | 94.720      | 93.315      | 16.275      | 297             | 58         | 35         |
| 24                         | 94.335      | 93.235      | 14.375      | 298             | 0          | 15         |
| 25                         | 74.685      | 70.765      | 23.885      | 321             | 2          | 20         |
| 26                         | 74.570      | 72.060      | 19.180      | 356             | 52         | 20         |
| 27                         | 74.185      | 72.210      | 17.020      | 356             | 47         | 55         |
| 28                         | 73.680      | 72.380      | 13.800      | 356             | 35         | 25         |
| 29                         |             |             |             |                 |            |            |
|                            |             |             |             |                 |            |            |
| Station 4                  | Height:     | 6.265       |             |                 |            |            |
|                            |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism                      | Reference   | 126.340     | 126.340     | -0.265          |            |            |
|                            |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b>            | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 10                         |             |             |             | 326             | 36         | 55         |
| 11                         | 73.050      | 70.485      | 19.200      | 354             | 41         | 10         |
| 12                         | 72.520      | 70.655      | 16.340      | 354             | 52         | 30         |
| 13                         | 72.085      | 70.860      | 13.235      | 355             | 2          | 55         |
| 14                         | 58.875      | 53.890      | 23.710      | 30              | 50         | 25         |
| 15                         | 72.600      | 70.185      | 18.570      | 67              | 3          | 5          |
| 16                         | 72.100      | 70.210      | 16.415      | 67              | 2          | 50         |
| 17                         | 71.670      | 70.195      | 14.465      | 67              | 2.5        | 27.5       |
| 18                         |             |             |             | 92              | 42         | 25         |
| 19                         |             |             |             | 92              | 49         | 30         |



**400 S Bridge Survey**

Date: 30-Sep-11

Prism Height: 6 ft      Avg Temp 74.7 F

|                  |             |             |             |                 |            |            |
|------------------|-------------|-------------|-------------|-----------------|------------|------------|
| <i>Station 1</i> | Height:     | 6.470       |             |                 |            |            |
|                  |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism            | Reference   | 175.685     | 175.685     | 0.470           |            |            |
|                  |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b>  | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 1                |             |             |             | 227             | 52         | 15         |
| 2                | 123.970     | 122.315     | 20.015      | 227             | 59         | 50         |
| 3                | 79.265      | 77.635      | 16.000      | 247             | 0          | 25         |
| 4                | 79.010      | 77.720      | 14.220      | 246             | 56         | 35         |
| 5                | 78.660      | 77.695      | 12.295      | 246             | 56         | 35         |
| 6                | 54.130      | 49.640      | 21.585      | 278             | 30         | 15         |
| 7                | 54.910      | 52.125      | 17.270      | 323             | 25         | 40         |
| 8                | 54.455      | 52.315      | 15.110      | 323             | 23         | 5          |
| 9                | 53.880      | 52.590      | 11.725      | 323             | 18         | 0          |
| 10               |             |             |             | 64              | 32         | 20         |
|                  |             |             |             |                 |            |            |
| <i>Station 2</i> | Height:     | 5.790       |             |                 |            |            |
|                  |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism            | Reference   | 176.885     | 176.880     | 0.210           |            |            |
|                  |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b>  | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| <b>29</b>        |             |             |             | <b>6</b>        | 26         | 25         |
| 30               | 65.355      | 61.940      | 20.835      | 44              | 45         | 15         |
| 31               | 64.930      | 62.065      | 19.065      | 44              | 50         | 35         |
| 32               | 64.390      | 62.280      | 16.335      | 44              | 50         | 30         |
| 33               | 69.485      | 64.405      | 26.085      | 81              | 51         | 10         |
| 34               | 95.050      | 92.860      | 20.285      | 105             | 30         | 20         |
| 35               | 94.740      | 92.855      | 18.795      | 105             | 30         | 0          |
| 36               | 94.325      | 92.865      | 16.545      | 105             | 30         | 15         |

| 400 S Bridge Survey |             |             |             |                 |            |            |
|---------------------|-------------|-------------|-------------|-----------------|------------|------------|
|                     |             |             |             |                 |            |            |
|                     |             |             |             |                 |            |            |
| Prism Height:       |             | 6 ft        |             |                 |            |            |
|                     |             |             |             |                 |            |            |
|                     |             |             |             |                 |            |            |
|                     |             |             |             |                 |            |            |
| Station 3           | Height:     | 7.240       |             |                 |            |            |
|                     |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism               | Reference   | 90.730      | 90.720      | 1.240           | -          |            |
|                     |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b>     | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 20                  |             |             |             | 278             | 32         | 10         |
| 21                  |             |             |             | 278             | 29         | 5          |
| 22                  | 95.055      | 93.285      | 18.265      | 297             | 57         | 25         |
| 23                  | 94.630      | 93.210      | 16.315      | 297             | 58         | 35         |
| 24                  | 94.245      | 93.135      | 14.420      | 298             | 0          | 10         |
| 25                  | 74.620      | 70.690      | 23.900      | 321             | 10         | 0          |
| 26                  | 74.495      | 71.975      | 19.210      | 356             | 52         | 5          |
| 27                  | 74.115      | 72.125      | 17.055      | 356             | 47         | 55         |
| 28                  | 73.605      | 72.295      | 13.830      | 356             | 35         | 10         |
| 29                  |             |             |             |                 |            |            |
|                     |             |             |             |                 |            |            |
| Station 4           | Height:     | 6.605       |             |                 |            |            |
|                     |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism               | Reference   | 126.200     | 126.200     | 0.605           | -          |            |
|                     |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b>     | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 10                  |             |             |             | 326             | 37         | 25         |
| 11                  | 72.870      | 70.395      | 18.825      | 354             | 41         | 20         |
| 12                  | 72.350      | 70.565      | 15.965      | 354             | 52         | 50         |
| 13                  | 71.930      | 70.770      | 12.865      | 355             | 3          | 15         |
| 14                  | 58.640      | 53.805      | 23.315      | 30              | 50         | 30         |
| 15                  | 72.400      | 70.075      | 18.190      | 67              | 3          | 50         |
| 16                  | 71.915      | 70.100      | 16.040      | 67              | 3          | 35         |
| 17                  | 71.485      | 70.085      | 14.090      | 67              | 0          | 10         |
| 18                  |             |             |             | 92              | 42         | 35         |
| 19                  |             |             |             | 92              | 50         | 30         |

**400 S Bridge Survey**

Date: 2-Nov-11

Prism Height: 6 ft      Avg Temp 39.75 F

|                  |             |             |             |                 |            |            |
|------------------|-------------|-------------|-------------|-----------------|------------|------------|
| <i>Station 1</i> | Height      | 6.195       |             |                 |            |            |
|                  |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism            | Reference   | 175.820     | 175.820     | -0.195          |            |            |
|                  |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b>  | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 1                |             |             |             | 227             | 49         | 15         |
| 2                | 124.055     | 122.385     | 20.290      | 227             | 57         | 25         |
| 3                | 79.400      | 77.710      | 16.300      | 246             | 58         | 40         |
| 4                | 79.140      | 77.800      | 14.515      | 246             | 54         | 25         |
| 5                | 78.785      | 77.770      | 12.590      | 246             | 54         | 25         |
| 6                | 54.330      | 49.725      | 21.895      | 278             | 29         | 10         |
| 7                | 55.100      | 52.225      | 17.575      | 323             | 24         | 25         |
| 8                | 54.630      | 52.410      | 15.415      | 323             | 21         | 35         |
| 9                | 54.045      | 52.690      | 12.025      | 323             | 16         | 45         |
| 10               |             |             |             | 6               | 41         | 25         |
|                  |             |             |             |                 |            |            |
| <i>Station 2</i> | Height      | 5.755       |             |                 |            |            |
|                  |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism            | Reference   | 176.900     | 176.900     | 0.245           |            |            |
|                  |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b>  | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 29               |             |             |             | 6               | 25         | 45         |
| 30               | 65.475      | 62.055      | 20.890      | 44              | 42         | 0          |
| 31               | 65.050      | 62.175      | 19.120      | 44              | 47         | 20         |
| 32               | 64.510      | 62.395      | 16.390      | 44              | 47         | 5          |
| 33               | 69.595      | 64.500      | 26.140      | 81              | 46         | 40         |
| 34               | 95.140      | 92.940      | 20.335      | 105             | 27         | 50         |
| 35               | 94.835      | 92.940      | 18.850      | 105             | 27         | 50         |
| 36               | 94.415      | 92.945      | 16.590      | 105             | 28         | 0          |

| <b>400 S Bridge Survey</b> |             |             |             |                 |            |            |
|----------------------------|-------------|-------------|-------------|-----------------|------------|------------|
|                            |             |             |             |                 |            |            |
|                            |             |             |             |                 |            |            |
| Prism Height:              |             | 6 ft        |             |                 |            |            |
|                            |             |             |             |                 |            |            |
|                            |             |             |             |                 |            |            |
|                            |             |             |             |                 |            |            |
| Station 3                  | Height      | 7.465       |             |                 |            |            |
|                            |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism                      | Reference   | 90.865      | 90.850      | -1.465          |            |            |
|                            |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b>            | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 20                         |             |             |             | 278             | 31         | 25         |
| 21                         |             |             |             | 278             | 39         | 10         |
| 22                         | 95.095      | 93.360      | 18.075      | 297             | 57         | 55         |
| 23                         | 94.675      | 93.290      | 16.125      | 297             | 59         | 0          |
| 24                         | 94.295      | 93.220      | 14.225      | 298             | 0          | 30         |
| 25                         | 74.650      | 70.785      | 23.720      | 321             | 3          | 25         |
| 26                         | 74.555      | 72.090      | 19.020      | 356             | 51         | 35         |
| 27                         | 74.175      | 72.230      | 16.860      | 356             | 47         | 25         |
| 28                         | 73.680      | 72.405      | 13.640      | 356             | 34         | 45         |
| 29                         |             |             |             |                 |            |            |
|                            |             |             |             |                 |            |            |
| Station 4                  | Height      | 6.680       |             |                 |            |            |
|                            |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism                      | Reference   | 126.195     | 126.190     | -0.680          |            |            |
|                            |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b>            | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 10                         |             |             |             | 326             | 35         | 15         |
| 11                         | 72.960      | 70.500      | 18.780      | 354             | 38         | 55         |
| 12                         | 72.445      | 70.675      | 15.925      | 354             | 50         | 10         |
| 13                         | 72.030      | 70.880      | 12.820      | 355             | 0          | 30         |
| 14                         | 58.710      | 53.895      | 23.285      | 30              | 47         | 15         |
| 15                         | 72.465      | 70.150      | 18.150      | 67              | 0          | 40         |
| 16                         | 71.980      | 70.180      | 15.995      | 67              | 0          | 15         |
| 17                         | 71.555      | 70.165      | 15.050      | 66              | 57         | 5          |
| 18                         |             |             |             | 92              | 40         | 5          |
| 19                         |             |             |             | 92              | 48         | 40         |

**400 S Bridge Survey**

26-Nov-

Date: 11

Prism Height: 6 ft      Avg Temp 39.24

|                  |             |             |             |             |                 |            |
|------------------|-------------|-------------|-------------|-------------|-----------------|------------|
| <i>Station 1</i> | Height      | 6.395       |             |             |                 |            |
|                  |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> |                 |            |
| Prism            | Reference   | 175.690     | 175.690     | 0.395       |                 |            |
|                  |             |             |             |             | <b>Hz Angle</b> |            |
| <b>Target #</b>  | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>  | <b>Min</b>      | <b>Sec</b> |
| 1                |             |             |             | 227         | 51              | 20         |
| 2                | 124.045     | 122.375     | 20.265      | 227         | 59              | 30         |
| 3                | 79.400      | 77.720      | 16.265      | 247         | 0               | 45         |
| 4                | 79.140      | 77.800      | 14.480      | 246         | 56              | 35         |
| 5                | 78.775      | 77.765      | 12.559      | 246         | 56              | 45         |
| 6                | 54.320      | 49.725      | 21.860      | 278         | 30              | 35         |
| 7                | 55.090      | 52.225      | 17.535      | 323         | 24              | 55         |
| 8                | 54.625      | 52.415      | 15.380      | 323         | 22              | 10         |
| 9                | 54.040      | 52.690      | 11.940      | 323         | 17              | 20         |
| 10               |             |             |             | 6           | 41              | 55         |
|                  |             |             |             |             |                 |            |
| <i>Station 2</i> | Height      | 5.560       |             |             |                 |            |
|                  |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> |                 |            |
| Prism            | Reference   | 177.005     | 177.005     | 0.440       |                 |            |
|                  |             |             |             |             | <b>Hz Angle</b> |            |
| <b>Target #</b>  | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>  | <b>Min</b>      | <b>Sec</b> |
| 29               |             |             |             | 6           | 26              | 5          |
| 30               | 65.585      | 62.055      | 21.230      | 44          | 43              | 55         |
| 31               | 65.150      | 62.180      | 19.450      | 44          | 49              | 5          |
| 32               | 64.600      | 62.395      | 16.725      | 44          | 48              | 45         |
| 33               | 69.725      | 64.505      | 26.475      | 81          | 48              | 5          |
| 34               | 95.215      | 92.945      | 20.670      | 105         | 27              | 15         |
| 35               | 94.900      | 92.940      | 19.190      | 105         | 27              | 10         |
| 36               | 94.480      | 92.950      | 16.930      | 105         | 27              | 20         |

| <b>400 S Bridge Survey</b> |             |             |             |                 |            |            |
|----------------------------|-------------|-------------|-------------|-----------------|------------|------------|
|                            |             |             |             |                 |            |            |
|                            |             |             |             |                 |            |            |
| Prism Height:              |             | 6 ft        |             |                 |            |            |
|                            |             |             |             |                 |            |            |
|                            |             |             |             |                 |            |            |
|                            |             |             |             |                 |            |            |
| Station 3                  | Height      | 7.190       |             |                 |            |            |
|                            |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism                      | Reference   | 90.865      | 90.860      | -<br>1.190      |            |            |
|                            |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b>            | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 20                         |             |             |             | 278             | 30         | 50         |
| 21                         |             |             |             | 278             | 38         | 25         |
| 22                         | 95.170      | 93.355      | 18.495      | 297             | 56         | 50         |
| 23                         | 94.740      | 93.285      | 16.540      | 297             | 58         | 20         |
| 24                         | 94.355      | 93.210      | 14.645      | 297             | 59         | 40         |
| 25                         | 74.780      | 70.780      | 24.140      | 321             | 2          | 50         |
| 26                         | 74.660      | 72.085      | 19.440      | 356             | 50         | 0          |
| 27                         | 74.270      | 72.230      | 17.280      | 356             | 47         | 0          |
| 28                         | 73.750      | 72.400      | 14.055      | 356             | 34         | 25         |
|                            |             |             |             |                 |            |            |
|                            |             |             |             |                 |            |            |
| Station 4                  | Height      | 6.655       |             |                 |            |            |
|                            |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism                      | Reference   | 126.345     | 126.340     | -<br>0.655      |            |            |
|                            |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b>            | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 10                         |             |             |             | 326             | 36         | 10         |
| 11                         | 72.990      | 70.495      | 18.905      | 354             | 40         | 0          |
| 12                         | 72.465      | 70.665      | 16.050      | 354             | 51         | 35         |
| 13                         | 72.050      | 70.875      | 12.945      | 355             | 1          | 45         |
| 14                         | 58.760      | 53.895      | 23.410      | 30              | 48         | 10         |
| 15                         | 72.495      | 70.155      | 18.280      | 67              | 1          | 5          |
| 16                         | 72.010      | 70.180      | 16.125      | 67              | 1          | 0          |
| 17                         | 71.580      | 70.165      | 14.180      | 66              | 57         | 40         |
| 18                         |             |             |             | 92              | 40         | 40         |
| 19                         |             |             |             | 92              | 49         | 15         |

**400 S Bridge Survey**

Date: 2-Jan-12

Prism Height: 6 ft      Avg Temp 37.7

|                  |             |             |             |                 |            |            |
|------------------|-------------|-------------|-------------|-----------------|------------|------------|
| <i>Station 1</i> | Height      | 6.560       |             |                 |            |            |
|                  |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism            | Reference   | 175.810     | 175.810     | 0.560           | -          |            |
|                  |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b>  | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 1                |             |             |             | 227             | 50         | 5          |
| 2                | 124.010     | 122.370     | 20.090      | 227             | 50         | 30         |
| 3                | 79.360      | 77.710      | 16.100      | 246             | 59         | 35         |
| 4                | 79.100      | 77.795      | 14.315      | 246             | 56         | 10         |
| 5                | 78.755      | 77.775      | 12.385      | 246             | 56         | 15         |
| 6                | 54.250      | 49.725      | 21.690      | 278             | 29         | 20         |
| 7                | 55.040      | 52.225      | 17.370      | 323             | 25         | 15         |
| 8                | 54.575      | 52.415      | 15.210      | 323             | 22         | 30         |
| 9                | 54.000      | 52.690      | 11.820      | 323             | 15         | 50         |
| 10               |             |             |             | 6               | 41         | 5          |
|                  |             |             |             |                 |            |            |
| <i>Station 2</i> | Height      | 5.810       |             |                 |            |            |
|                  |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism            | Reference   | 177.020     | 177.020     | 0.190           |            |            |
|                  |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b>  | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 29               |             |             |             | 6               | 26         | 0          |
| 30               | 65.515      | 62.050      | 21.015      | 44              | 40         | 25         |
| 31               | 65.075      | 62.175      | 19.205      | 44              | 41         | 30         |
| 32               | 64.530      | 62.390      | 16.475      | 44              | 41         | 15         |
| 33               | 69.630      | 64.500      | 26.230      | 81              | 40         | 50         |
| 34               | 95.155      | 92.935      | 20.425      | 105             | 20         | 20         |
| 35               | 94.845      | 92.935      | 18.940      | 105             | 20         | 5          |
| 36               | 94.430      | 92.945      | 16.680      | 105             | 20         | 20         |

| <b><u>400 S Bridge Survey</u></b> |             |             |             |                 |            |            |
|-----------------------------------|-------------|-------------|-------------|-----------------|------------|------------|
|                                   |             |             |             |                 |            |            |
|                                   |             |             |             |                 |            |            |
| Prism Height:                     |             | 6 ft        |             |                 |            |            |
|                                   |             |             |             |                 |            |            |
|                                   |             |             |             |                 |            |            |
|                                   |             |             |             |                 |            |            |
| Station 3                         | Height      | 7.425       |             |                 |            |            |
|                                   |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
|                                   |             |             |             | -               |            |            |
| Prism                             | Reference   | 90.875      | 90.865      | 1.425           |            |            |
|                                   |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b>                   | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 20                                |             |             |             | 278             | 30         | 10         |
| 21                                |             |             |             | 278             | 38         | 5          |
| 22                                | 95.125      | 93.355      | 18.250      | 297             | 57         | 5          |
| 23                                | 94.700      | 93.285      | 16.300      | 297             | 57         | 35         |
| 24                                | 94.315      | 93.210      | 14.405      | 297             | 59         | 0          |
| 25                                | 74.705      | 70.780      | 23.895      | 321             | 2          | 20         |
| 26                                | 74.600      | 72.085      | 19.200      | 356             | 50         | 35         |
| 27                                | 74.210      | 72.230      | 17.040      | 356             | 46         | 40         |
| 28                                | 73.710      | 72.400      | 13.815      | 356             | 34         | 5          |
| 29                                |             |             |             |                 |            |            |
|                                   |             |             |             |                 |            |            |
| Station 4                         | Height      | 6.705       |             |                 |            |            |
|                                   |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
|                                   |             |             |             | -               |            |            |
| Prism                             | Reference   | 126.335     | 126.330     | 0.705           |            |            |
|                                   |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b>                   | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 10                                |             |             |             | 326             | 35         | 30         |
| 11                                | 72.975      | 70.495      | 18.880      | 354             | 39         | 5          |
| 12                                | 72.455      | 70.665      | 16.020      | 354             | 50         | 30         |
| 13                                | 72.040      | 70.870      | 12.910      | 355             | 0          | 55         |
| 14                                | 58.745      | 53.890      | 23.380      | 30              | 47         | 35         |
| 15                                | 72.480      | 70.145      | 18.245      | 67              | 1          | 20         |
| 16                                | 71.995      | 70.175      | 16.095      | 67              | 1          | 15         |
| 17                                | 71.570      | 70.160      | 14.140      | 66              | 58         | 0          |
| 18                                |             |             |             | 92              | 41         | 15         |
| 19                                |             |             |             | 92              | 49         | 50         |

|                                   |
|-----------------------------------|
| <b><u>400 S Bridge Survey</u></b> |
|-----------------------------------|



Date: 31-Jan-12

Prism Height: 6 ft      Avg Temp 33.41667

|                 |             |             |             |                 |            |            |        |
|-----------------|-------------|-------------|-------------|-----------------|------------|------------|--------|
| Station 1       | Height      | 6.390       |             | Expansion Gap   |            | 6.5625     | inches |
|                 |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |        |
| Prism           | Reference   | 175.805     | 175.805     | -0.390          |            |            |        |
|                 |             |             |             | <b>Hz Angle</b> |            |            |        |
| <b>Target #</b> | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |        |
| 1               |             |             |             | 227             | 51         | 45         |        |
| 2               | 124.035     | 122.370     | 20.245      | 227             | 59         | 55         |        |
| 3               | 79.390      | 77.710      | 16.245      | 247             | 0          | 30         |        |
| 4               | 79.130      | 77.795      | 14.465      | 246             | 56         | 50         |        |
| 5               | 78.780      | 77.775      | 12.540      | 246             | 56         | 55         |        |
| 6               | 54.315      | 49.725      | 21.845      | 278             | 29         | 25         |        |
| 7               | 55.080      | 52.220      | 17.515      | 323             | 25         | 5          |        |
| 8               | 54.610      | 52.410      | 15.360      | 323             | 21         | 55         |        |
| 9               | 54.030      | 52.685      | 11.965      | 323             | 17         | 0          |        |
| 10              |             |             |             | 6               | 42         | 40         |        |
|                 |             |             |             |                 |            |            |        |
| Station 2       | Height      | 5.650       |             | Expansion Gap   |            | 6.625      | inches |
|                 |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |        |
| Prism           | Reference   | 177.005     | 177.005     | 0.350           |            |            |        |
|                 |             |             |             | <b>Hz Angle</b> |            |            |        |
| <b>Target #</b> | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |        |
| 29              |             |             |             | 6               | 24         | 40         |        |
| 30              | 65.550      | 62.045      | 21.150      | 44              | 42         | 25         |        |
| 31              | 65.115      | 62.165      | 19.375      | 44              | 47         | 10         |        |
| 32              | 64.565      | 62.380      | 16.645      | 44              | 47         | 15         |        |
| 33              | 69.685      | 64.490      | 26.400      | 81              | 48         | 55         |        |
| 34              | 95.180      | 92.925      | 20.590      | 105             | 27         | 0          |        |
| 35              | 94.870      | 92.920      | 19.115      | 105             | 27         | 0          |        |
| 36              | 94.445      | 92.930      | 16.850      | 105             | 27         | 30         |        |

|                            |  |  |  |  |  |
|----------------------------|--|--|--|--|--|
| <b>400 S Bridge Survey</b> |  |  |  |  |  |
|                            |  |  |  |  |  |

|                            |             |             |             |                 |            |               |
|----------------------------|-------------|-------------|-------------|-----------------|------------|---------------|
| Prism Height:              |             | 6 ft        |             |                 |            |               |
|                            |             |             |             |                 |            |               |
|                            |             |             |             |                 |            |               |
|                            |             |             |             |                 |            |               |
| Station 3                  | Height      | 7.440       |             | Expansion Gap   |            | 7.5 inches    |
|                            |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |               |
| Prism                      | Reference   | 90.860      | 90.845      | -1.440          |            |               |
|                            |             |             |             | <b>Hz Angle</b> |            |               |
| <b>Target #</b>            | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b>    |
| 20                         |             |             |             | 278             | 29         | 35            |
| 21                         |             |             |             | 278             | 36         | 55            |
| 22                         | 95.130      | 93.365      | 18.235      | 297             | 53         | 25            |
| 23                         | 94.700      | 93.290      | 16.285      | 297             | 54         | 20            |
| 24                         | 94.320      | 93.215      | 14.385      | 297             | 55         | 30            |
| 25                         | 74.700      | 70.780      | 23.880      | 320             | 57         | 25            |
| 26                         | 74.585      | 72.075      | 19.185      | 356             | 47         | 10            |
| 27                         | 74.195      | 72.215      | 17.025      | 356             | 43         | 0             |
| 28                         | 73.695      | 72.390      | 13.800      | 356             | 30         | 55            |
| 29                         |             |             |             |                 |            |               |
|                            |             |             |             |                 |            |               |
| Station 4                  | Height      | 6.790       |             | Expansion Gap   |            | 5.6875 inches |
|                            |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |               |
| Prism                      | Reference   | 126.325     | 126.320     | -0.790          |            |               |
|                            |             |             |             | <b>Hz Angle</b> |            |               |
| <b>Target #</b>            | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b>    |
| 10                         |             |             |             | 326             | 36         | 5             |
| 11                         | 72.960      | 70.500      | 18.790      | 354             | 37         | 55            |
| 12                         | 72.440      | 70.670      | 15.930      | 354             | 49         | 45            |
| 13                         | 72.025      | 70.875      | 12.825      | 355             | 0          | 40            |
| 14                         | 58.715      | 53.895      | 23.295      | 30              | 46         | 40            |
| 15                         | 72.465      | 70.155      | 18.165      | 66              | 59         | 40            |
| 16                         | 71.985      | 70.180      | 16.005      | 66              | 59         | 25            |
| 17                         | 71.560      | 70.165      | 14.055      | 66              | 56         | 15            |
| 18                         |             |             |             | 92              | 38         | 50            |
| 19                         |             |             |             | 92              | 47         | 40            |
| <b>400 S Bridge Survey</b> |             |             |             |                 |            |               |

Date: 23-Feb-12

Prism Height: 6 ft      Avg Temp 38.53846 F

|                  |             |             |             |                 |            |            |
|------------------|-------------|-------------|-------------|-----------------|------------|------------|
| <i>Station 1</i> | Height      | 6.455       |             |                 |            |            |
|                  |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism            | Reference   | 175.770     | 175.770     | -0.455          |            |            |
|                  |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b>  | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 1                |             |             |             | 227             | 49         | 25         |
| 2                | 124.035     | 122.385     | 20.145      | 227             | 57         | 10         |
| 3                | 79.380      | 77.715      | 16.160      | 246             | 58         | 30         |
| 4                | 79.120      | 77.800      | 14.380      | 246             | 54         | 45         |
| 5                | 78.770      | 77.780      | 12.450      | 246             | 54         | 40         |
| 6                | 54.280      | 49.725      | 21.765      | 278             | 28         | 40         |
| 7                | 55.055      | 52.220      | 17.440      | 323             | 24         | 20         |
| 8                | 54.595      | 52.415      | 15.280      | 323             | 21         | 15         |
| 9                | 54.015      | 52.690      | 11.885      | 323             | 16         | 20         |
| 10               |             |             |             | 6               | 41         | 25         |
|                  |             |             |             |                 |            |            |
| <i>Station 2</i> | Height      | 5.705       |             |                 |            |            |
|                  |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism            | Reference   | 176.980     | 176.980     | 0.295           |            |            |
|                  |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b>  | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 29               |             |             |             | 6               | 27         | 5          |
| 30               | 65.515      | 62.035      | 21.070      | 44              | 46         | 35         |
| 31               | 65.080      | 62.160      | 19.290      | 44              | 51         | 55         |
| 32               | 64.535      | 62.375      | 16.560      | 44              | 51         | 35         |
| 33               | 69.670      | 64.510      | 26.315      | 81              | 51         | 20         |
| 34               | 95.210      | 92.975      | 20.510      | 105             | 29         | 10         |
| 35               | 94.895      | 92.970      | 19.025      | 105             | 29         | 20         |
| 36               | 94.480      | 92.985      | 16.760      | 105             | 29         | 20         |

|                                   |  |  |  |  |  |
|-----------------------------------|--|--|--|--|--|
| <b><u>400 S Bridge Survey</u></b> |  |  |  |  |  |
|                                   |  |  |  |  |  |

|                 |             |             |             |                 |            |            |
|-----------------|-------------|-------------|-------------|-----------------|------------|------------|
|                 |             |             |             |                 |            |            |
| Prism Height:   |             | 6 ft        |             |                 |            |            |
|                 |             |             |             |                 |            |            |
|                 |             |             |             |                 |            |            |
|                 |             |             |             |                 |            |            |
| Station 3       | Height      | 7.195       |             |                 |            |            |
|                 |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism           | Reference   | 90.840      | 90.835      | -1.195          |            |            |
|                 |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b> | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 20              |             |             |             | 278             | 30         | 55         |
| 21              |             |             |             | 278             | 38         | 25         |
| 22              | 95.170      | 93.365      | 18.470      | 297             | 57         | 20         |
| 23              | 94.745      | 93.290      | 16.520      | 297             | 58         | 45         |
| 24              | 94.355      | 93.215      | 14.620      | 298             | 0          | 0          |
| 25              | 74.775      | 70.775      | 24.120      | 321             | 2          | 35         |
| 26              | 74.650      | 72.080      | 19.415      | 356             | 51         | 35         |
| 27              | 74.255      | 72.225      | 17.255      | 356             | 47         | 10         |
| 28              | 73.745      | 72.400      | 14.035      | 356             | 34         | 45         |
| 29              |             |             |             |                 |            |            |
|                 |             |             |             |                 |            |            |
| Station 4       | Height      | 6.680       |             |                 |            |            |
|                 |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism           | Reference   | 126.245     | 126.245     | -0.680          |            |            |
|                 |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b> | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 10              |             |             |             | 326             | 35         | 10         |
| 11              | 72.975      | 70.490      | 18.885      | 354             | 38         | 45         |
| 12              | 72.455      | 70.660      | 16.025      | 354             | 50         | 50         |
| 13              | 72.035      | 70.865      | 12.920      | 355             | 1          | 30         |
| 14              | 58.735      | 53.875      | 23.390      | 30              | 47         | 50         |
| 15              | 72.480      | 70.145      | 18.255      | 67              | 1          | 20         |
| 16              | 71.995      | 70.175      | 16.100      | 67              | 0          | 55         |
| 17              | 71.570      | 70.155      | 14.150      | 66              | 57         | 45         |
| 18              |             |             |             | 92              | 40         | 55         |
| 19              |             |             |             | 92              | 49         | 10         |

**400 S Bridge Survey**

24-Mar-

Date:

12

Prism Height: 6 ft      Avg Temp 70.38095

|                  |             |             |             |                 |            |            |
|------------------|-------------|-------------|-------------|-----------------|------------|------------|
| <i>Station 1</i> | Height      | 6.410       |             |                 |            |            |
|                  |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism            | Reference   | 175.840     | 175.840     | -0.410          |            |            |
|                  |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b>  | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 1                |             |             |             | 227             | 51         | 30         |
| 2                | 124.055     | 122.400     | 20.195      | 227             | 59         | 5          |
| 3                | 79.405      | 77.730      | 16.215      | 247             | 0          | 0          |
| 4                | 79.140      | 77.810      | 14.430      | 246             | 55         | 55         |
| 5                | 78.785      | 77.790      | 12.500      | 246             | 55         | 55         |
| 6                | 54.300      | 49.725      | 21.815      | 278             | 30         | 0          |
| 7                | 55.075      | 52.220      | 17.490      | 323             | 25         | 30         |
| 8                | 54.605      | 52.410      | 15.330      | 323             | 22         | 35         |
| 9                | 54.025      | 52.690      | 11.940      | 323             | 17         | 40         |
| 10               |             |             |             | 6               | 43         | 20         |
|                  |             |             |             |                 |            |            |
| <i>Station 2</i> | Height      | 5.615       |             |                 |            |            |
|                  |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism            | Reference   | 177.030     | 177.030     | 0.385           |            |            |
|                  |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b>  | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 29               |             |             |             | 6               | 25         | 15         |
| 30               | 65.555      | 62.035      | 21.180      | 44              | 44         | 25         |
| 31               | 65.120      | 62.160      | 19.405      | 44              | 49         | 30         |
| 32               | 64.575      | 62.380      | 16.680      | 44              | 49         | 35         |
| 33               | 69.705      | 64.495      | 26.435      | 81              | 51         | 20         |
| 34               | 95.215      | 92.955      | 20.620      | 105             | 29         | 25         |
| 35               | 94.900      | 92.950      | 19.135      | 105             | 29         | 35         |
| 36               | 94.480      | 92.960      | 16.880      | 105             | 30         | 0          |

|                                   |  |      |  |  |  |
|-----------------------------------|--|------|--|--|--|
| <b><u>400 S Bridge Survey</u></b> |  |      |  |  |  |
|                                   |  |      |  |  |  |
|                                   |  |      |  |  |  |
| Prism Height:                     |  | 6 ft |  |  |  |

|                 |             |             |             |                 |            |            |
|-----------------|-------------|-------------|-------------|-----------------|------------|------------|
|                 |             |             |             |                 |            |            |
|                 |             |             |             |                 |            |            |
|                 |             |             |             |                 |            |            |
| Station 3       | Height      | 7.285       |             |                 |            |            |
|                 |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism           | Reference   | 90.860      | 90.850      | -1.285          |            |            |
|                 |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b> | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 20              |             |             |             | 278             | 29         | 30         |
| 21              |             |             |             | 278             | 36         | 50         |
| 22              | 95.155      | 93.370      | 18.355      | 297             | 54         | 55         |
| 23              | 94.730      | 93.300      | 16.405      | 297             | 56         | 5          |
| 24              | 93.345      | 93.225      | 14.505      | 297             | 57         | 20         |
| 25              | 74.725      | 70.770      | 24.000      | 321             | 0          | 35         |
| 26              | 74.610      | 72.065      | 19.305      | 356             | 50         | 0          |
| 27              | 74.220      | 72.210      | 17.150      | 356             | 45         | 50         |
| 28              | 73.710      | 72.385      | 13.920      | 356             | 33         | 5          |
|                 |             |             |             |                 |            |            |
|                 |             |             |             |                 |            |            |
| Station 4       | Height      | 6.615       |             |                 |            |            |
|                 |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism           | Reference   | 126.360     | 126.360     | -0.615          |            |            |
|                 |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b> | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 10              |             |             |             | 326             | 36         | 0          |
| 11              | 72.990      | 70.485      | 18.950      | 354             | 40         | 15         |
| 12              | 72.465      | 70.655      | 16.095      | 354             | 51         | 45         |
| 13              | 72.045      | 70.865      | 12.990      | 355             | 1          | 40         |
| 14              | 58.760      | 53.875      | 23.455      | 30              | 49         | 50         |
| 15              | 72.520      | 70.165      | 18.330      | 67              | 3          | 55         |
| 16              | 72.025      | 70.185      | 16.165      | 67              | 3          | 20         |
| 17              | 71.595      | 70.170      | 14.215      | 66              | 59         | 40         |
| 18              |             |             |             | 92              | 42         | 25         |
| 19              |             |             |             | 92              | 50         | 25         |

**400 S Bridge Survey**

Date: 5-May-12

Prism Height: 6 ft      Avg Temp 50.4

|                  |             |             |             |                 |            |            |
|------------------|-------------|-------------|-------------|-----------------|------------|------------|
| <i>Station 1</i> | Height      | 6.310       |             |                 |            |            |
|                  |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism            | Reference   | 176.010     | 176.010     | 0.310           |            |            |
|                  |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b>  | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 1                |             |             |             | 227             | 49         | 10         |
| 2                | 124.070     | 122.395     | 20.300      | 227             | 56         | 30         |
| 3                | 79.410      | 77.720      | 16.300      | 246             | 57         | 20         |
| 4                | 79.155      | 77.815      | 14.525      | 246             | 53         | 55         |
| 5                | 78.800      | 77.785      | 12.595      | 246             | 53         | 45         |
| 6                | 54.335      | 49.725      | 21.905      | 278             | 28         | 10         |
| 7                | 55.095      | 52.215      | 17.585      | 323             | 22         | 0          |
| 8                | 54.630      | 52.410      | 15.425      | 323             | 22         | 0          |
| 9                | 54.040      | 52.685      | 12.030      | 323             | 16         | 55         |
| 10               |             |             |             | 6               | 42         | 20         |
|                  |             |             |             |                 |            |            |
| <i>Station 2</i> | Height      | 5.670       |             |                 |            |            |
|                  |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism            | Reference   | 177.230     | 177.230     | 0.330           |            |            |
|                  |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b>  | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| <b>29</b>        |             |             |             | <b>6</b>        | 20         | 50         |
| 30               | 65.535      | 62.050      | 21.100      | 44              | 39         | 30         |
| 31               | 65.105      | 62.170      | 19.325      | 44              | 45         | 5          |
| 32               | 64.560      | 62.390      | 16.600      | 44              | 44         | 50         |
| 33               | 69.675      | 64.505      | 26.350      | 81              | 44         | 55         |
| 34               | 95.125      | 92.950      | 20.535      | 105             | 23         | 35         |
| 35               | 94.875      | 92.945      | 19.045      | 105             | 23         | 30         |
| 36               | 94.455      | 92.955      | 16.785      | 105             | 24         | 0          |

|                                   |  |      |  |  |  |
|-----------------------------------|--|------|--|--|--|
| <b><u>400 S Bridge Survey</u></b> |  |      |  |  |  |
|                                   |  |      |  |  |  |
|                                   |  |      |  |  |  |
| Prism Height:                     |  | 6 ft |  |  |  |
|                                   |  |      |  |  |  |
|                                   |  |      |  |  |  |

|                 |             |             |             |                 |            |            |
|-----------------|-------------|-------------|-------------|-----------------|------------|------------|
|                 |             |             |             |                 |            |            |
| Station 3       | Height      | 7.245       |             |                 |            |            |
|                 |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism           | Reference   | 90.810      | 90.805      | 1.245           | -          |            |
|                 |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b> | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 20              |             |             |             | 278             | 30         | 15         |
| 21              |             |             |             | 278             | 38         | 15         |
| 22              | 95.165      | 93.370      | 18.390      | 297             | 56         | 45         |
| 23              | 94.735      | 93.300      | 16.440      | 297             | 58         | 20         |
| 24              | 94.355      | 93.225      | 14.535      | 297             | 59         | 25         |
| 25              | 74.750      | 70.780      | 24.035      | 321             | 2          | 10         |
| 26              | 74.625      | 72.080      | 19.340      | 356             | 51         | 40         |
| 27              | 74.235      | 72.220      | 17.175      | 356             | 47         | 15         |
| 28              | 73.730      | 72.395      | 13.955      | 356             | 34         | 35         |
|                 |             |             |             |                 |            |            |
|                 |             |             |             |                 |            |            |
| Station 4       | Height      | 6.595       |             |                 |            |            |
|                 |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism           | Reference   | 126.301     | 126.305     | 0.595           | -          |            |
|                 |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b> | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 10              |             |             |             | 326             | 29         | 15         |
| 11              | 73.005      | 70.495      | 18.975      | 354             | 32         | 55         |
| 12              | 72.480      | 70.665      | 16.115      | 354             | 44         | 15         |
| 13              | 72.055      | 70.870      | 13.010      | 354             | 54         | 45         |
| 14              | 58.785      | 53.890      | 23.480      | 30              | 40         | 55         |
| 15              | 72.520      | 70.165      | 18.340      | 66              | 54         | 40         |
| 16              | 72.030      | 70.190      | 16.185      | 66              | 54         | 0          |
| 17              | 71.605      | 70.175      | 14.235      | 66              | 50         | 55         |
| 18              |             |             |             | 92              | 34         | 5          |
| 19              |             |             |             | 92              | 39         | 10         |

**400 S Bridge Survey**

Date: 1-Jun-12

Prism Height: 6 ft      Avg Temp 80.71429



|                  |             |             |             |                 |            |            |
|------------------|-------------|-------------|-------------|-----------------|------------|------------|
| <i>Station 1</i> | Height      | 6.530       |             |                 |            |            |
|                  |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism            | Reference   | 175.960     | 175.960     | -0.530          |            |            |
|                  |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b>  | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 1                |             |             |             | 227             | 55         | 40         |
| 2                | 124.005     | 122.370     | 20.085      | 228             | 2          | 55         |
| 3                | 79.390      | 77.740      | 16.090      | 247             | 6          | 30         |
| 4                | 79.140      | 77.835      | 14.310      | 247             | 2          | 40         |
| 5                | 78.780      | 77.800      | 12.385      | 247             | 2          | 30         |
| 6                | 54.335      | 49.815      | 21.695      | 278             | 38         | 20         |
| 7                | 55.180      | 52.375      | 17.370      | 323             | 26         | 55         |
| 8                | 54.725      | 52.565      | 15.210      | 323             | 24         | 5          |
| 9                | 54.150      | 52.845      | 11.820      | 323             | 19         | 10         |
| 10               |             |             |             | 6               | 40         | 0          |
|                  |             |             |             |                 |            |            |
| <i>Station 2</i> | Height      | 5.765       |             |                 |            |            |
|                  |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism            | Reference   | 177.020     | 177.020     | 0.235           |            |            |
|                  |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b>  | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| <b>29</b>        |             |             |             | <b>6</b>        | 24         | 35         |
| 30               | 65.495      | 62.035      | 21.010      | 44              | 43         | 45         |
| 31               | 65.065      | 62.160      | 19.230      | 44              | 49         | 5          |
| 32               | 64.525      | 62.380      | 16.505      | 44              | 49         | 5          |
| 33               | 69.635      | 64.490      | 26.265      | 81              | 50         | 5          |
| 34               | 95.170      | 92.950      | 20.445      | 105             | 28         | 30         |
| 35               | 94.870      | 92.955      | 18.960      | 105             | 28         | 30         |
| 36               | 94.450      | 92.960      | 16.700      | 105             | 28         | 30         |

|                                   |        |       |  |  |  |  |
|-----------------------------------|--------|-------|--|--|--|--|
| <b><u>400 S Bridge Survey</u></b> |        |       |  |  |  |  |
|                                   |        |       |  |  |  |  |
|                                   |        |       |  |  |  |  |
| Prism Height:                     |        | 6 ft  |  |  |  |  |
|                                   |        |       |  |  |  |  |
|                                   |        |       |  |  |  |  |
|                                   |        |       |  |  |  |  |
| <i>Station 3</i>                  | Height | 7.230 |  |  |  |  |

|                 |             |             |             |                 |            |            |
|-----------------|-------------|-------------|-------------|-----------------|------------|------------|
|                 |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism           | Reference   | 90.865      | 90.860      | -1.230          |            |            |
|                 |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b> | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 20              |             |             |             | 278             | 28         | 25         |
| 21              |             |             |             | 278             | 35         | 10         |
| 22              | 95.175      | 93.375      | 18.420      | 297             | 53         | 30         |
| 23              | 94.750      | 93.305      | 16.470      | 297             | 54         | 50         |
| 24              | 94.365      | 93.230      | 14.570      | 297             | 56         | 15         |
| 25              | 74.750      | 70.770      | 24.070      | 320             | 58         | 50         |
| 26              | 74.625      | 72.065      | 19.365      | 356             | 48         | 40         |
| 27              | 74.235      | 72.210      | 17.210      | 356             | 44         | 30         |
| 28              | 73.725      | 72.385      | 13.985      | 356             | 31         | 45         |
| 29              |             |             |             |                 |            |            |
|                 |             |             |             |                 |            |            |
| Station 4       | Height      | 6.660       |             |                 |            |            |
|                 |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism           | Reference   | 126.390     | 126.390     | -0.660          |            |            |
|                 |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b> | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 10              |             |             |             | 326             | 35         | 25         |
| 11              | 72.990      | 70.490      | 18.940      | 354             | 39         | 40         |
| 12              | 72.470      | 70.660      | 16.075      | 354             | 51         | 5          |
| 13              | 72.045      | 70.865      | 12.970      | 355             | 1          | 40         |
| 14              | 58.765      | 53.885      | 23.440      | 30              | 48         | 30         |
| 15              | 72.525      | 70.175      | 18.300      | 67              | 2          | 25         |
| 16              | 72.030      | 70.200      | 16.145      | 67              | 1          | 50         |
| 17              | 71.605      | 70.180      | 14.195      | 66              | 58         | 20         |
| 18              |             |             |             | 93              | 53         | 15         |
| 19              |             |             |             | 94              | 0          | 40         |

**400 S Bridge Survey**

26-Jun-

Date: 12

Prism Height: 6 ft      Avg Temp 85.14286

|           |        |       |  |  |  |  |
|-----------|--------|-------|--|--|--|--|
| Station 1 | Height | 6.515 |  |  |  |  |
|-----------|--------|-------|--|--|--|--|

|                 |             |             |             |                 |            |            |
|-----------------|-------------|-------------|-------------|-----------------|------------|------------|
|                 |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism           | Reference   | 175.700     | 175.700     | -0.515          |            |            |
|                 |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b> | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 1               |             |             |             | 227             | 50         | 55         |
| 2               | 124.065     | 122.425     | 20.110      | 227             | 58         | 10         |
| 3               | 79.390      | 77.740      | 16.105      | 246             | 58         | 50         |
| 4               | 79.130      | 77.820      | 14.330      | 246             | 55         | 25         |
| 5               | 78.775      | 77.795      | 12.395      | 246             | 55         | 25         |
| 6               | 54.260      | 49.730      | 21.710      | 278             | 28         | 45         |
| 7               | 55.040      | 52.225      | 17.385      | 323             | 25         | 30         |
| 8               | 54.585      | 52.415      | 15.225      | 323             | 22         | 35         |
| 9               | 54.005      | 52.695      | 11.830      | 323             | 17         | 40         |
| 10              |             |             |             | 6               | 43         | 45         |
|                 |             |             |             |                 |            |            |
| Station 2       | Height      | 5.825       |             |                 |            |            |
|                 |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism           | Reference   | 176.945     | 176.945     | 0.175           |            |            |
|                 |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b> | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 29              |             |             |             | 6               | 24         | 10         |
| 30              | 65.470      | 62.020      | 20.975      | 44              | 44         | 10         |
| 31              | 65.045      | 62.145      | 19.200      | 44              | 49         | 25         |
| 32              | 64.505      | 62.365      | 16.470      | 44              | 49         | 15         |
| 33              | 69.610      | 64.480      | 26.230      | 81              | 51         | 10         |
| 34              | 95.170      | 92.960      | 20.405      | 105             | 29         | 50         |
| 35              | 94.860      | 92.955      | 18.925      | 105             | 30         | 10         |
| 36              | 94.445      | 92.965      | 16.660      | 105             | 30         | 10         |

| <b>400 S Bridge Survey</b> |        |             |           |             |  |  |
|----------------------------|--------|-------------|-----------|-------------|--|--|
|                            |        |             |           |             |  |  |
|                            |        |             |           |             |  |  |
| Prism<br>Height:           |        | 6 ft        |           |             |  |  |
|                            |        |             |           |             |  |  |
|                            |        |             |           |             |  |  |
|                            |        |             |           |             |  |  |
| Station 3                  | Height | 7.420       |           |             |  |  |
|                            |        | <b>Dist</b> | <b>Hz</b> | <b>Vert</b> |  |  |

|                 |             |             |             |                 |            |            |
|-----------------|-------------|-------------|-------------|-----------------|------------|------------|
| Prism           | Reference   | 90.820      | 90.810      | -1.420          |            |            |
|                 |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b> | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 20              |             |             |             | 278             | 30         | 40         |
| 21              |             |             |             | 278             | 37         | 10         |
| 22              | 95.145      | 93.375      | 18.245      | 297             | 55         | 35         |
| 23              | 94.715      | 93.305      | 16.295      | 297             | 56         | 50         |
| 24              | 94.340      | 93.235      | 14.395      | 297             | 58         | 10         |
| 25              | 74.690      | 70.765      | 23.895      | 321             | 0          | 35         |
| 26              | 74.575      | 72.060      | 19.195      | 356             | 50         | 35         |
| 27              | 74.190      | 72.205      | 17.035      | 356             | 46         | 35         |
| 28              | 73.685      | 72.380      | 13.815      | 356             | 33         | 35         |
|                 |             |             |             |                 |            |            |
|                 |             |             |             |                 |            |            |
| Station 4       | Height      | 6.755       |             |                 |            |            |
|                 |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism           | Reference   | 126.250     | 126.245     | -0.755          |            |            |
|                 |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b> | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 10              |             |             |             | 326             | 35         | 15         |
| 11              | 72.965      | 70.490      | 18.835      | 354             | 39         | 20         |
| 12              | 72.445      | 70.665      | 15.975      | 354             | 51         | 0          |
| 13              | 72.030      | 70.870      | 12.870      | 355             | 1          | 25         |
| 14              | 58.720      | 53.885      | 23.340      | 30              | 48         | 45         |
| 15              | 72.495      | 70.175      | 18.200      | 67              | 2          | 30         |
| 16              | 72.005      | 70.195      | 16.045      | 67              | 2          | 0          |
| 17              | 71.580      | 70.180      | 14.095      | 66              | 58         | 25         |
| 18              |             |             |             | 92              | 41         | 25         |
| 19              |             |             |             | 92              | 49         | 5          |

**400 S Bridge Survey**

Date: 12-Jul-12

Prism Height: 6 ft      Avg Temp 92.5

|           |           |             |           |                 |  |  |
|-----------|-----------|-------------|-----------|-----------------|--|--|
| Station 1 | Height    | 6.580       |           |                 |  |  |
|           |           | <b>Dist</b> | <b>Hz</b> | <b>Vert</b>     |  |  |
| Prism     | Reference | 175.765     | 175.765   | -0.580          |  |  |
|           |           |             |           | <b>Hz Angle</b> |  |  |

| Target #  | Dist      | Hz      | Vert    | Deg      | Min | Sec |
|-----------|-----------|---------|---------|----------|-----|-----|
| 1         |           |         |         | 227      | 49  | 55  |
| 2         |           |         |         | 227      | 57  | 10  |
| 3         | 79.385    | 77.740  | 16.080  | 246      | 57  | 35  |
| 4         | 79.125    | 77.820  | 14.300  | 246      | 54  | 5   |
| 5         | 78.780    | 77.800  | 12.370  | 246      | 53  | 45  |
| 6         | 54.255    | 49.730  | 21.685  | 278      | 27  | 40  |
| 7         | 55.030    | 52.220  | 17.365  | 323      | 23  | 15  |
| 8         | 54.570    | 52.410  | 15.200  | 323      | 20  | 35  |
| 9         | 53.995    | 52.690  | 11.805  | 323      | 15  | 45  |
| 10        |           |         |         | 6        | 41  | 35  |
|           |           |         |         |          |     |     |
| Station 2 | Height    | 5.840   |         |          |     |     |
|           |           | Dist    | Hz      | Vert     |     |     |
| Prism     | Reference | 176.935 | 176.935 | 0.160    |     |     |
|           |           |         |         | Hz Angle |     |     |
| Target #  | Dist      | Hz      | Vert    | Deg      | Min | Sec |
| 29        |           |         |         | 6        | 24  | 10  |
| 30        | 65.440    | 62.005  | 20.720  | 44       | 44  | 45  |
| 31        | 65.015    | 62.130  | 19.145  | 44       | 49  | 45  |
| 32        | 64.470    | 62.345  | 16.415  | 44       | 49  | 45  |
| 33        | 69.590    | 64.485  | 26.165  | 81       | 51  | 40  |
| 34        | 95.160    | 92.960  | 20.355  | 105      | 29  | 40  |
| 35        | 94.860    | 92.965  | 18.865  | 105      | 29  | 30  |
| 36        | 94.440    | 92.970  | 16.605  | 105      | 29  | 35  |

| 400 S Bridge Survey |           |        |        |          |     |     |
|---------------------|-----------|--------|--------|----------|-----|-----|
|                     |           |        |        |          |     |     |
|                     |           |        |        |          |     |     |
| Prism Height:       |           | 6 ft   |        |          |     |     |
|                     |           |        |        |          |     |     |
|                     |           |        |        |          |     |     |
|                     |           |        |        |          |     |     |
| Station 3           | Height    | 7.575  |        |          |     |     |
|                     |           | Dist   | Hz     | Vert     |     |     |
| Prism               | Reference | 90.805 | 90.790 | -1.575   |     |     |
|                     |           |        |        | Hz Angle |     |     |
| Target #            | Dist      | Hz     | Vert   | Deg      | Min | Sec |

|                 |             |             |             |                 |            |            |
|-----------------|-------------|-------------|-------------|-----------------|------------|------------|
| 20              |             |             |             | 278             | 26         | 20         |
| 21              |             |             |             | 278             | 33         | 5          |
| 22              | 95.120      | 93.385      | 18.100      | 297             | 51         | 5          |
| 23              | 94.705      | 93.315      | 16.155      | 297             | 52         | 40         |
| 24              | 94.325      | 93.245      | 14.255      | 297             | 53         | 55         |
| 25              | 74.650      | 70.770      | 23.755      | 320             | 55         | 55         |
| 26              | 74.535      | 72.055      | 19.055      | 356             | 46         | 5          |
| 27              | 74.150      | 72.200      | 16.890      | 356             | 41         | 45         |
| 28              | 73.655      | 72.375      | 13.670      | 356             | 28         | 55         |
|                 |             |             |             |                 |            |            |
|                 |             |             |             |                 |            |            |
| Station 4       | Height      | 6.850       |             |                 |            |            |
|                 |             | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b>     |            |            |
| Prism           | Reference   | 126.385     | 126.385     | -0.850          |            |            |
|                 |             |             |             | <b>Hz Angle</b> |            |            |
| <b>Target #</b> | <b>Dist</b> | <b>Hz</b>   | <b>Vert</b> | <b>Deg</b>      | <b>Min</b> | <b>Sec</b> |
| 10              |             |             |             | 326             | 34         | 0          |
| 11              | 72.935      | 70.485      | 18.735      | 354             | 38         | 45         |
| 12              | 72.415      | 70.655      | 15.870      | 354             | 50         | 20         |
| 13              | 72.000      | 70.860      | 12.765      | 355             | 0          | 45         |
| 14              | 58.680      | 53.885      | 23.235      | 30              | 48         | 30         |
| 15              | 72.470      | 70.175      | 18.090      | 67              | 1          | 45         |
| 16              | 71.985      | 70.200      | 15.935      | 67              | 1          | 20         |
| 17              | 71.565      | 70.185      | 13.990      | 66              | 57         | 50         |
| 18              |             |             |             | 92              | 40         | 35         |
| 19              |             |             |             | 92              | 47         | 50         |
|                 |             | 3.000       |             |                 |            |            |

## APPENDIX B: FULL-DAY SURVEY DATA

### B-1: SPAN 1 RAW DATA

|               |        |        |        |          |     |     |
|---------------|--------|--------|--------|----------|-----|-----|
| Time: 9:20 AM |        | SE     |        |          |     |     |
|               |        | Temp   |        | 35.5     |     |     |
| Span 1        |        |        |        | Hz Angle |     |     |
| Target        | Dist   | Hz     | Vert   | Deg      | Min | Sec |
| 3             | 79.390 | 77.705 | 16.275 | 258      | 42  | 20  |
| 4             | 79.130 | 77.795 | 14.495 | 258      | 38  | 25  |
| 5             | 78.780 | 77.770 | 12.570 | 258      | 38  | 25  |
| 6             | 54.320 | 49.720 | 21.875 | 290      | 12  | 25  |
| 7             | 55.085 | 52.215 | 17.550 | 335      | 8   | 10  |
| 8             | 54.620 | 52.405 | 15.395 | 335      | 5   | 10  |
| 9             | 54.030 | 52.680 | 12.000 | 335      | 0   | 25  |

|                |        |        |        |          |     |     |
|----------------|--------|--------|--------|----------|-----|-----|
| Time: 10:30 AM |        | SE     |        |          |     |     |
|                |        | Temp   |        | 43.0     |     |     |
| Span 1         |        |        |        | Hz Angle |     |     |
| Target         | Dist   | Hz     | Vert   | Deg      | Min | Sec |
| 3              | 79.400 | 77.715 | 16.285 | 258      | 42  | 35  |
| 4              | 79.135 | 77.795 | 14.505 | 258      | 38  | 50  |
| 5              | 78.785 | 77.775 | 12.580 | 258      | 38  | 45  |
| 6              | 54.330 | 49.725 | 21.885 | 290      | 13  | 5   |
| 7              | 55.090 | 52.215 | 17.560 | 335      | 9   | 10  |
| 8              | 54.625 | 52.410 | 15.405 | 335      | 6   | 15  |
| 9              | 54.035 | 52.685 | 12.010 | 335      | 1   | 25  |

|                |        |        |        |          |     |     |
|----------------|--------|--------|--------|----------|-----|-----|
| Time: 11:30 AM |        | SE     |        |          |     |     |
|                |        | Temp   |        | 57.5     |     |     |
| Span 1         |        |        |        | Hz Angle |     |     |
| Target         | Dist   | Hz     | Vert   | Deg      | Min | Sec |
| 3              | 79.405 | 77.715 | 16.285 | 258      | 42  | 5   |
| 4              | 79.145 | 77.805 | 14.510 | 258      | 37  | 40  |
| 5              | 78.775 | 77.765 | 12.570 | 258      | 37  | 35  |
| 6              | 54.325 | 49.720 | 21.885 | 290      | 11  | 40  |
| 7              | 55.090 | 52.215 | 17.560 | 335      | 7   | 30  |
| 8              | 54.620 | 52.405 | 15.400 | 335      | 5   | 25  |
| 9              | 54.030 | 52.680 | 12.010 | 335      | 0   | 10  |

|                |        |        |        |           |     |     |
|----------------|--------|--------|--------|-----------|-----|-----|
| Time: 12:30 PM |        | SE     |        | Temp 61.5 |     |     |
| Span 1         |        |        |        | Hz Angle  |     |     |
| Target         | Dist   | Hz     | Vert   | Deg       | Min | Sec |
| 3              | 79.410 | 77.715 | 16.300 | 258       | 42  | 55  |
| 4              | 79.155 | 77.810 | 14.520 | 258       | 39  | 0   |
| 5              | 78.795 | 77.780 | 12.590 | 258       | 38  | 45  |
| 6              | 54.335 | 49.725 | 21.895 | 290       | 12  | 50  |
| 7              | 55.100 | 52.220 | 17.580 | 335       | 8   | 20  |
| 8              | 54.635 | 52.410 | 15.420 | 335       | 5   | 25  |
| 9              | 54.040 | 52.685 | 12.025 | 335       | 0   | 35  |

|               |        |        |        |           |     |     |
|---------------|--------|--------|--------|-----------|-----|-----|
| Time: 1:30 PM |        | SE     |        | Temp 70.5 |     |     |
| Span 1        |        |        |        | Hz Angle  |     |     |
| Target        | Dist   | Hz     | Vert   | Deg       | Min | Sec |
| 3             | 79.405 | 77.710 | 16.300 | 258       | 42  | 45  |
| 4             | 79.155 | 77.810 | 14.520 | 258       | 38  | 50  |
| 5             | 78.790 | 77.775 | 12.590 | 258       | 38  | 50  |
| 6             | 54.330 | 49.720 | 21.900 | 290       | 12  | 55  |
| 7             | 55.095 | 52.215 | 17.575 | 335       | 8   | 25  |
| 8             | 54.630 | 52.405 | 15.415 | 335       | 5   | 50  |
| 9             | 54.040 | 52.685 | 12.025 | 335       | 0   | 55  |

|               |        |        |        |           |     |     |
|---------------|--------|--------|--------|-----------|-----|-----|
| Time: 2:30 PM |        | SE     |        | Temp 69.5 |     |     |
| Span 1        |        |        |        | Hz Angle  |     |     |
| Target        | Dist   | Hz     | Vert   | Deg       | Min | Sec |
| 3             | 79.405 | 77.720 | 16.265 | 258       | 42  | 30  |
| 4             | 79.140 | 77.805 | 14.480 | 258       | 38  | 50  |
| 5             | 78.790 | 77.785 | 12.555 | 258       | 38  | 50  |
| 6             | 54.315 | 49.720 | 21.860 | 290       | 12  | 35  |
| 7             | 55.080 | 52.215 | 17.540 | 335       | 8   | 20  |
| 8             | 54.615 | 52.405 | 15.380 | 335       | 5   | 35  |
| 9             | 54.030 | 52.685 | 11.990 | 335       | 0   | 35  |



| Time: 3:30 PM |        | SE<br>Temp 68.5 |        |          |     |     |
|---------------|--------|-----------------|--------|----------|-----|-----|
| Span 1        |        |                 |        | Hz Angle |     |     |
| Target        | Dist   | Hz              | Vert   | Deg      | Min | Sec |
| 3             | 79.400 | 77.720          | 16.260 | 258      | 42  | 55  |
| 4             | 79.130 | 77.795          | 14.485 | 258      | 39  | 15  |
| 5             | 78.785 | 77.780          | 12.550 | 258      | 39  | 10  |
| 6             | 54.315 | 49.720          | 21.860 | 290      | 13  | 20  |
| 7             | 55.085 | 52.220          | 17.540 | 335      | 9   | 0   |
| 8             | 54.620 | 52.410          | 15.380 | 335      | 6   | 5   |
| 9             | 54.035 | 52.685          | 11.990 | 335      | 1   | 5   |

| Time: 4:30 PM |        | SE<br>Temp 66.5 |        |          |     |     |
|---------------|--------|-----------------|--------|----------|-----|-----|
| Span 1        |        |                 |        | Hz Angle |     |     |
| Target        | Dist   | Hz              | Vert   | Deg      | Min | Sec |
| 3             | 79.400 | 77.720          | 16.240 | 258      | 42  | 25  |
| 4             | 79.135 | 77.800          | 14.460 | 258      | 38  | 40  |
| 5             | 78.785 | 77.780          | 12.530 | 258      | 38  | 30  |
| 6             | 54.305 | 49.720          | 21.845 | 290      | 12  | 25  |
| 7             | 55.075 | 52.215          | 17.515 | 335      | 8   | 40  |
| 8             | 54.610 | 52.405          | 15.355 | 335      | 5   | 50  |
| 9             | 54.025 | 52.685          | 11.965 | 335      | 0   | 55  |

| Time: 5:30 PM |        | SE<br>Temp 60.0 |        |          |     |     |
|---------------|--------|-----------------|--------|----------|-----|-----|
| Span 1        |        |                 |        | Hz Angle |     |     |
| Target        | Dist   | Hz              | Vert   | Deg      | Min | Sec |
| 3             | 79.405 | 77.725          | 16.245 | 258      | 42  | 30  |
| 4             | 79.135 | 77.800          | 14.465 | 258      | 38  | 45  |
| 5             | 78.790 | 77.785          | 12.535 | 258      | 38  | 35  |
| 6             | 54.305 | 49.720          | 21.845 | 290      | 12  | 50  |
| 7             | 55.075 | 52.215          | 17.515 | 335      | 9   | 5   |
| 8             | 54.615 | 52.410          | 15.360 | 335      | 6   | 30  |
| 9             | 54.030 | 52.685          | 11.970 | 335      | 1   | 30  |

|               |        |                 |        |          |     |     |
|---------------|--------|-----------------|--------|----------|-----|-----|
| Time: 6:30 PM |        |                 |        |          |     |     |
|               |        | SE<br>Temp 52.0 |        |          |     |     |
| Span 1        |        |                 |        | Hz Angle |     |     |
| Target        | Dist   | Hz              | Vert   | Deg      | Min | Sec |
| 3             | 79.400 | 77.720          | 16.250 | 258      | 42  | 50  |
| 4             | 79.140 | 77.805          | 14.470 | 258      | 38  | 45  |
| 5             | 78.795 | 77.790          | 12.540 | 258      | 38  | 30  |
| 6             | 54.310 | 49.725          | 21.845 | 290      | 12  | 20  |
| 7             | 55.075 | 52.215          | 17.520 | 335      | 8   | 0   |
| 8             | 54.610 | 52.405          | 15.355 | 335      | 5   | 10  |
| 9             | 54.030 | 52.685          | 11.970 | 335      | 0   | 10  |

**B-2: SPAN 2 RAW DATA**

|              |            |
|--------------|------------|
| <b>Time:</b> | 8:00<br>AM |
|--------------|------------|

| <b>Prism:</b> | 388.340 | 388.335 | -2.125 | Hz Angle |     |     |
|---------------|---------|---------|--------|----------|-----|-----|
| <b>Target</b> | Dist    | Hz      | Vert   | Deg      | Min | Sec |
| 7             | 207.960 | 207.375 | 15.545 | 342      | 17  | 35  |
| 8             | 207.965 | 207.535 | 13.380 | 342      | 19  | 35  |
| 9             | 208.020 | 207.780 | 9.990  | 342      | 22  | 15  |
| 10            | 183.665 | 182.445 | 21.125 | 3        | 17  | 35  |
| 11            | 187.170 | 186.375 | 17.220 | 26       | 33  | 40  |
| 12            | 187.220 | 186.665 | 14.355 | 26       | 34  | 5   |
| 13            | 187.300 | 186.960 | 11.245 | 26       | 33  | 30  |
| 14            | 198.975 | 197.785 | 21.730 | 38       | 33  | 5   |

|              |            |
|--------------|------------|
| <b>Time:</b> | 9:20<br>AM |
|--------------|------------|

| <b>Prism:</b> | 388.340 | 388.335 | -2.120 | Hz Angle |     |     |
|---------------|---------|---------|--------|----------|-----|-----|
| <b>Target</b> | Dist    | Hz      | Vert   | Deg      | Min | Sec |
| 7             | 207.960 | 207.380 | 15.550 | 342      | 17  | 45  |
| 8             | 207.970 | 207.535 | 13.390 | 342      | 19  | 55  |
| 9             | 208.020 | 207.780 | 10.000 | 342      | 22  | 25  |
| 10            | 183.660 | 182.440 | 21.130 | 3        | 17  | 55  |
| 11            | 187.165 | 186.370 | 17.220 | 26       | 34  | 0   |
| 12            | 187.215 | 186.665 | 14.365 | 26       | 34  | 25  |
| 13            | 187.295 | 186.955 | 11.255 | 26       | 34  | 10  |
| 14            | 198.970 | 197.780 | 21.730 | 38       | 33  | 25  |

|              |             |
|--------------|-------------|
| <b>Time:</b> | 10:30<br>AM |
|--------------|-------------|

| <b>Prism:</b> | 388.280 | 388.270 | -2.100 | Hz Angle |     |     |
|---------------|---------|---------|--------|----------|-----|-----|
| <b>Target</b> | Dist    | Hz      | Vert   | Deg      | Min | Sec |
| 7             | 207.965 | 207.380 | 15.560 | 342      | 17  | 40  |
| 8             | 207.970 | 207.535 | 13.395 | 342      | 19  | 35  |
| 9             | 208.020 | 207.780 | 10.000 | 342      | 22  | 15  |
| 10            | 183.665 | 182.445 | 21.135 | 3        | 17  | 30  |
| 11            | 187.170 | 186.375 | 17.230 | 26       | 33  | 55  |
| 12            | 187.220 | 186.665 | 14.360 | 26       | 33  | 5   |
| 13            | 187.300 | 186.965 | 11.260 | 26       | 32  | 50  |
| 14            |         |         |        |          |     |     |

|              |             |
|--------------|-------------|
| <b>Time:</b> | 11:30<br>AM |
|--------------|-------------|

|               |         |         |        |          |     |     |
|---------------|---------|---------|--------|----------|-----|-----|
| <b>Prism:</b> | 388.275 | 388.270 | -2.095 | Hz Angle |     |     |
| <b>Target</b> | Dist    | Hz      | Vert   | Deg      | Min | Sec |
| 7             | 207.950 | 207.370 | 15.545 | 342      | 17  | 40  |
| 8             | 207.965 | 207.535 | 13.385 | 342      | 19  | 40  |
| 9             | 208.020 | 207.780 | 9.980  | 342      | 22  | 5   |
| 10            | 183.660 | 182.440 | 21.130 | 3        | 17  | 35  |
| 11            | 187.165 | 186.370 | 17.210 | 26       | 33  | 50  |
| 12            | 187.215 | 186.660 | 14.355 | 26       | 34  | 5   |
| 13            | 187.295 | 186.960 | 11.235 | 26       | 33  | 45  |
| 14            | 198.960 | 197.775 | 21.710 | 38       | 33  | 20  |

|              |             |
|--------------|-------------|
| <b>Time:</b> | 12:30<br>PM |
|--------------|-------------|

|               |         |         |        |          |     |     |
|---------------|---------|---------|--------|----------|-----|-----|
| <b>Prism:</b> | 388.275 | 388.270 | -2.145 | Hz Angle |     |     |
| <b>Target</b> | Dist    | Hz      | Vert   | Deg      | Min | Sec |
| 7             | 207.950 | 207.365 | 15.540 | 342      | 17  | 30  |
| 8             | 207.955 | 207.525 | 13.380 | 342      | 19  | 30  |
| 9             | 208.015 | 207.775 | 9.990  | 342      | 22  | 5   |
| 10            | 183.660 | 182.440 | 21.125 | 3        | 17  | 30  |
| 11            | 187.170 | 186.375 | 17.220 | 26       | 33  | 40  |
| 12            | 187.220 | 186.665 | 14.360 | 26       | 34  | 5   |
| 13            | 187.300 | 186.960 | 11.250 | 26       | 33  | 50  |
| 14            | 198.965 | 197.775 | 21.725 | 38       | 32  | 45  |

|              |         |
|--------------|---------|
| <b>Time:</b> | 1:30 PM |
|--------------|---------|

|               |         |         |        |          |     |     |
|---------------|---------|---------|--------|----------|-----|-----|
| <b>Prism:</b> | 388.270 | 388.265 | -2.120 | Hz Angle |     |     |
| <b>Target</b> | Dist    | Hz      | Vert   | Deg      | Min | Sec |
| 7             | 207.955 | 207.370 | 15.545 | 342      | 17  | 35  |
| 8             | 207.960 | 207.525 | 13.390 | 342      | 19  | 30  |
| 9             | 208.005 | 207.765 | 9.995  | 342      | 22  | 5   |
| 10            | 183.665 | 182.435 | 21.125 | 3        | 17  | 30  |
| 11            | 187.170 | 186.375 | 17.215 | 26       | 33  | 50  |
| 12            | 187.220 | 186.665 | 14.355 | 26       | 34  | 5   |
| 13            | 187.300 | 186.960 | 11.245 | 26       | 33  | 55  |
| 14            | 198.965 | 197.775 | 21.715 | 38       | 33  | 20  |

|              |         |
|--------------|---------|
| <b>Time:</b> | 2:30 PM |
|--------------|---------|

| Prism: 388.275 388.270 -2.145 |         |         |        | Hz Angle |     |     |
|-------------------------------|---------|---------|--------|----------|-----|-----|
| Target                        | Dist    | Hz      | Vert   | Deg      | Min | Sec |
| 7                             | 207.955 | 207.375 | 15.535 | 342      | 17  | 35  |
| 8                             | 207.965 | 207.535 | 13.385 | 342      | 19  | 25  |
| 9                             | 208.010 | 207.770 | 9.980  | 342      | 22  | 0   |
| 10                            | 183.655 | 182.435 | 21.120 | 3        | 17  | 30  |
| 11                            | 187.165 | 186.370 | 17.225 | 26       | 33  | 45  |
| 12                            | 187.215 | 186.665 | 14.360 | 26       | 34  | 10  |
| 13                            | 187.300 | 186.960 | 11.260 | 26       | 33  | 50  |
| 14                            | 198.965 | 197.775 | 21.725 | 38       | 33  | 15  |

|       |         |
|-------|---------|
| Time: | 3:30 PM |
|-------|---------|

| Prism: 388.275 388.270 -2.135 |         |         |        | Hz Angle |     |     |
|-------------------------------|---------|---------|--------|----------|-----|-----|
| Target                        | Dist    | Hz      | Vert   | Deg      | Min | Sec |
| 7                             | 207.960 | 207.380 | 15.540 | 342      | 17  | 25  |
| 8                             | 207.970 | 207.540 | 13.380 | 342      | 19  | 25  |
| 9                             | 208.025 | 207.785 | 9.985  | 342      | 21  | 55  |
| 10                            | 183.655 | 182.435 | 21.125 | 3        | 17  | 25  |
| 11                            | 187.170 | 186.375 | 17.220 | 26       | 33  | 40  |
| 12                            | 187.220 | 186.665 | 14.365 | 26       | 34  | 5   |
| 13                            | 187.300 | 186.960 | 11.265 | 26       | 33  | 45  |
| 14                            | 198.960 | 197.770 | 21.730 | 38       | 33  | 5   |

|       |         |
|-------|---------|
| Time: | 4:30 PM |
|-------|---------|

| Prism: 388.270 388.265 -2.140 |         |         |        | Hz Angle |     |     |
|-------------------------------|---------|---------|--------|----------|-----|-----|
| Target                        | Dist    | Hz      | Vert   | Deg      | Min | Sec |
| 7                             | 207.960 | 207.375 | 15.550 | 342      | 17  | 20  |
| 8                             | 207.955 | 207.525 | 13.385 | 342      | 19  | 20  |
| 9                             | 208.020 | 207.780 | 9.985  | 342      | 21  | 55  |
| 10                            | 183.655 | 182.435 | 21.120 | 3        | 17  | 20  |
| 11                            | 187.165 | 186.370 | 17.225 | 26       | 33  | 35  |
| 12                            | 187.215 | 186.665 | 14.355 | 26       | 34  | 0   |
| 13                            | 187.295 | 186.960 | 11.255 | 26       | 33  | 45  |
| 14                            | 198.960 | 197.770 | 21.735 | 38       | 33  | 5   |

|              |         |
|--------------|---------|
| <b>Time:</b> | 5:30 PM |
|--------------|---------|

| <b>Prism:</b> 388.275 388.270 -2.115 |         |         |        | Hz Angle |     |     |
|--------------------------------------|---------|---------|--------|----------|-----|-----|
| Target                               | Dist    | Hz      | Vert   | Deg      | Min | Sec |
| 7                                    | 207.955 | 207.375 | 15.545 | 342      | 17  | 50  |
| 8                                    | 207.970 | 207.540 | 13.380 | 342      | 19  | 30  |
| 9                                    | 208.025 | 207.785 | 9.995  | 342      | 22  | 10  |
| 10                                   | 183.660 | 182.440 | 21.120 | 3        | 17  | 35  |
| 11                                   | 187.170 | 186.375 | 17.220 | 26       | 34  | 0   |
| 12                                   | 187.215 | 186.665 | 14.360 | 26       | 34  | 15  |
| 13                                   | 187.300 | 186.965 | 11.255 | 26       | 34  | 0   |
| 14                                   | 198.970 | 197.780 | 21.725 | 38       | 33  | 25  |

|              |         |
|--------------|---------|
| <b>Time:</b> | 6:30 PM |
|--------------|---------|

| <b>Prism:</b> 388.275 388.270 -2.150 |         |         |        | Hz Angle |     |     |
|--------------------------------------|---------|---------|--------|----------|-----|-----|
| Target                               | Dist    | Hz      | Vert   | Deg      | Min | Sec |
| 7                                    | 207.955 | 207.370 | 15.540 | 342      | 17  | 45  |
| 8                                    | 207.965 | 207.535 | 13.370 | 342      | 19  | 40  |
| 9                                    | 208.025 | 207.785 | 9.995  | 342      | 22  | 15  |
| 10                                   | 183.660 | 182.440 | 21.125 | 3        | 17  | 35  |
| 11                                   | 187.170 | 186.375 | 17.215 | 26       | 34  | 0   |
| 12                                   | 187.300 | 186.665 | 14.355 | 26       | 34  | 30  |
| 13                                   | 187.300 | 186.960 | 11.250 | 26       | 34  | 5   |
| 14                                   | 198.970 | 197.775 | 21.735 | 38       | 33  | 30  |

|              |         |
|--------------|---------|
| <b>Time:</b> | 7:00 PM |
|--------------|---------|

| <b>Prism:</b> 388.275 388.270 -2.095 |         |         |        | Hz Angle |     |     |
|--------------------------------------|---------|---------|--------|----------|-----|-----|
| Target                               | Dist    | Hz      | Vert   | Deg      | Min | Sec |
| 7                                    | 207.955 | 207.370 | 15.540 | 342      | 17  | 20  |
| 8                                    | 207.980 | 207.550 | 13.385 | 342      | 19  | 10  |
| 9                                    | 208.025 | 207.785 | 9.975  | 342      | 22  | 0   |
| 10                                   |         |         |        |          |     |     |
| 11                                   | 187.170 | 186.375 | 17.225 | 26       | 33  | 45  |
| 12                                   | 187.220 | 186.665 | 14.365 | 26       | 34  | 5   |
| 13                                   | 187.300 | 186.960 | 11.260 | 26       | 33  | 50  |
| 14                                   |         |         |        |          |     |     |

### B-3: SPAN 3 RAW DATA

|        |        | NE<br>Temp 32.5 |        |          |     |     |
|--------|--------|-----------------|--------|----------|-----|-----|
| Span 3 |        | 9:20<br>AM      |        | Hz Angle |     |     |
| Target | Dist   | Hz              | Vert   | Deg      | Min | Sec |
| 11     | 72.940 | 70.490          | 18.740 | 354      | 32  | 30  |
| 12     | 72.425 | 70.665          | 15.880 | 354      | 43  | 45  |
| 13     | 72.010 | 70.870          | 12.775 | 354      | 54  | 15  |
| 14     | 58.690 | 53.890          | 23.245 | 30       | 41  | 0   |
| 15     | 72.445 | 70.150          | 18.105 | 66       | 54  | 30  |
| 16     | 71.965 | 70.175          | 15.950 | 66       | 54  | 10  |
| 17     | 71.545 | 70.160          | 14.005 | 66       | 50  | 45  |

|              |        | 7.375046        |        |          |     |     |
|--------------|--------|-----------------|--------|----------|-----|-----|
| 0.290356 in. |        | NE<br>Temp 43.5 |        |          |     |     |
| Span 3       |        | 10:30<br>AM     |        | Hz Angle |     |     |
| Target       | Dist   | Hz              | Vert   | Deg      | Min | Sec |
| 11           | 72.965 | 70.495          | 18.835 | 354      | 32  | 20  |
| 12           | 72.445 | 70.665          | 15.975 | 354      | 43  | 35  |
| 13           | 72.025 | 70.870          | 12.865 | 354      | 54  | 5   |
| 14           | 58.725 | 53.890          | 23.335 | 30       | 40  | 55  |
| 15           | 72.475 | 70.155          | 18.200 | 66       | 54  | 35  |
| 16           | 71.990 | 70.180          | 16.045 | 66       | 54  | 0   |
| 17           | 70.565 | 70.160          | 14.095 | 66       | 50  | 45  |

|        |        | NE<br>Temp 52.5 |        |          |     |     |
|--------|--------|-----------------|--------|----------|-----|-----|
| Span 3 |        | 11:30<br>AM     |        | Hz Angle |     |     |
| Target | Dist   | Hz              | Vert   | Deg      | Min | Sec |
| 11     | 72.945 | 70.490          | 18.760 | 354      | 32  | 30  |
| 12     | 72.425 | 70.660          | 15.900 | 354      | 44  | 5   |
| 13     | 72.010 | 70.865          | 12.795 | 354      | 54  | 20  |
| 14     | 58.695 | 53.885          | 23.265 | 30       | 41  | 15  |
| 15     | 72.460 | 70.155          | 18.125 | 66       | 54  | 35  |
| 16     | 71.970 | 70.175          | 15.975 | 66       | 54  | 20  |
| 17     | 71.550 | 70.160          | 14.025 | 66       | 51  | 0   |

|        |        | NE<br>Temp 59.0 |        |          |     |     |
|--------|--------|-----------------|--------|----------|-----|-----|
| Span 3 |        | 12:30<br>PM     |        | Hz Angle |     |     |
| Target | Dist   | Hz              | Vert   | Deg      | Min | Sec |
| 11     | 72.945 | 70.495          | 18.760 | 354      | 32  | 5   |
| 12     | 72.430 | 70.660          | 15.900 | 354      | 43  | 40  |
| 13     | 72.015 | 70.870          | 12.795 | 354      | 54  | 5   |
| 14     | 58.695 | 53.890          | 23.260 | 30       | 40  | 55  |
| 15     | 72.460 | 70.160          | 18.130 | 66       | 54  | 45  |
| 16     | 71.975 | 70.180          | 15.975 | 66       | 54  | 5   |
| 17     | 71.555 | 70.165          | 14.025 | 66       | 51  | 0   |

|        |        | NE<br>Temp 63.5 |        |          |     |     |
|--------|--------|-----------------|--------|----------|-----|-----|
| Span 3 |        | 1:30 PM         |        | Hz Angle |     |     |
| Target | Dist   | Hz              | Vert   | Deg      | Min | Sec |
| 11     | 72.990 | 70.490          | 18.935 | 354      | 32  | 45  |
| 12     | 72.465 | 70.660          | 16.070 | 354      | 43  | 50  |
| 13     | 72.045 | 70.870          | 12.965 | 354      | 53  | 50  |
| 14     | 58.760 | 53.885          | 23.430 | 30       | 40  | 50  |
| 15     | 72.505 | 70.160          | 18.300 | 66       | 54  | 0   |
| 16     | 72.020 | 70.185          | 16.145 | 66       | 53  | 50  |
| 17     | 71.590 | 70.170          | 14.195 | 66       | 50  | 15  |

|        |        | NE<br>Temp 67.5 |        |          |     |     |
|--------|--------|-----------------|--------|----------|-----|-----|
| Span 3 |        | 2:30 PM         |        | Hz Angle |     |     |
| Target | Dist   | Hz              | Vert   | Deg      | Min | Sec |
| 11     | 72.990 | 70.495          | 18.935 | 354      | 32  | 35  |
| 12     | 72.465 | 70.665          | 16.070 | 354      | 44  | 25  |
| 13     | 72.045 | 70.870          | 12.965 | 354      | 54  | 35  |
| 14     | 58.765 | 53.890          | 23.435 | 30       | 41  | 30  |
| 15     | 72.510 | 70.160          | 18.300 | 66       | 54  | 40  |
| 16     | 72.020 | 70.185          | 16.145 | 66       | 54  | 30  |
| 17     | 71.590 | 70.165          | 14.195 | 66       | 50  | 45  |



|        |        | NE<br>Temp 62.0 |        |          |     |     |
|--------|--------|-----------------|--------|----------|-----|-----|
| Span 3 |        | 3:30 PM         |        | Hz Angle |     |     |
| Target | Dist   | Hz              | Vert   | Deg      | Min | Sec |
| 11     | 72.975 | 70.490          | 18.870 | 354      | 32  | 30  |
| 12     | 72.455 | 70.660          | 16.015 | 354      | 44  | 15  |
| 13     | 72.035 | 70.870          | 12.905 | 354      | 55  | 10  |
| 14     | 58.735 | 53.885          | 23.370 | 30       | 41  | 40  |
| 15     | 72.490 | 70.160          | 18.235 | 66       | 55  | 10  |
| 16     | 72.005 | 70.185          | 16.085 | 66       | 55  | 10  |
| 17     | 71.575 | 70.170          | 14.135 | 66       | 51  | 35  |

|        |        | NE<br>Temp 61.5 |        |          |     |     |
|--------|--------|-----------------|--------|----------|-----|-----|
| Span 3 |        | 4:30 PM         |        | Hz Angle |     |     |
| Target | Dist   | Hz              | Vert   | Deg      | Min | Sec |
| 11     | 72.970 | 70.490          | 18.870 | 354      | 31  | 50  |
| 12     | 72.455 | 70.660          | 16.010 | 354      | 43  | 25  |
| 13     | 72.040 | 70.875          | 12.905 | 354      | 53  | 55  |
| 14     | 58.740 | 53.890          | 23.370 | 30       | 41  | 5   |
| 15     | 72.495 | 70.160          | 18.240 | 66       | 54  | 10  |
| 16     | 72.010 | 70.190          | 16.080 | 66       | 54  | 0   |
| 17     | 71.580 | 70.170          | 14.130 | 66       | 50  | 50  |

|        |        | NE<br>Temp 56.5 |        |          |     |     |
|--------|--------|-----------------|--------|----------|-----|-----|
| Span 3 |        | 5:30 PM         |        | Hz Angle |     |     |
| Target | Dist   | Hz              | Vert   | Deg      | Min | Sec |
| 11     | 72.960 | 70.495          | 18.810 | 354      | 32  | 55  |
| 12     | 72.440 | 70.660          | 15.950 | 354      | 43  | 55  |
| 13     | 72.025 | 70.870          | 12.840 | 354      | 54  | 25  |
| 14     | 58.710 | 53.885          | 23.310 | 30       | 41  | 35  |
| 15     | 72.475 | 70.160          | 18.175 | 66       | 55  | 10  |
| 16     | 71.990 | 70.185          | 16.020 | 66       | 54  | 55  |
| 17     | 71.565 | 70.170          | 14.065 | 66       | 51  | 30  |

|        |        | NE<br>Temp 49.0 |        |          |     |     |
|--------|--------|-----------------|--------|----------|-----|-----|
| Span 3 |        | 6:30 PM         |        | Hz Angle |     |     |
| Target | Dist   | Hz              | Vert   | Deg      | Min | Sec |
| 11     | 72.960 | 70.490          | 18.810 | 354      | 32  | 55  |
| 12     | 72.440 | 70.660          | 15.955 | 354      | 43  | 50  |
| 13     | 72.025 | 70.870          | 12.845 | 354      | 53  | 55  |
| 14     | 58.715 | 53.890          | 23.315 | 30       | 40  | 15  |
| 15     | 72.475 | 70.160          | 18.175 | 66       | 53  | 20  |
| 16     | 71.995 | 70.190          | 16.020 | 66       | 53  | 10  |
| 17     | 71.570 | 70.170          | 14.070 | 66       | 49  | 50  |