INSTRUMENTATION AND MONITORING OF I35W ST. ANTHONY FALLS BRIDGE

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Abstract

The I35W St. Anthony Falls Bridge, constructed to replace the steel truss bridge that collapsed in 2007, contains over 500 instruments to monitor the structural behavior. Numerical models of the bridge are being developed and calibrated to the collected data obtained during truck load testing and environmental loading. The data obtained over the first few years of monitoring will be correlated with the calibrated models and used to develop the baseline bridge behavior. This information will be used to develop a system to monitor and interpret the long-term behavior of the bridge. This paper describes the instrumentation, preliminary results from the data and model calibration, and plan for developing the long-term monitoring capabilities.

Introduction

The I35W St. Anthony Falls Bridge, constructed to replace the steel truss bridge that collapsed in 2007, consists of two parallel bridges to carry northbound and southbound traffic. The four-span bridges consist of prestressed concrete box girders. Three of the spans were fabricated with cast-in-place concrete. The fourth span, the river span (i.e., Span 2), was fabricated with match-cast precast segmental construction. To accelerate the construction of the replacement bridge, the design-build approach was used. The proposal from the design-build team of Flatiron-Manson in conjunction with Figg Bridge Engineers featured the incorporation of a "smart-bridge" system. This system included instruments to monitor the structural behavior of the bridge, as well as instruments to control the anti-icing and lighting systems. Photographs of the bridge nearing completion of construction are shown in Figure 1. Figure 2 shows elevation views of the bridge which indicate the primary instrumented sections of the bridge and the variation in the cross-sectional shape of the boxes along the length of the bridge.

The University of Minnesota (UMN) is involved in the collection and interpretation of the data obtained from the more than 500 sensors installed within the bridge as part of the "smart-bridge" system. In addition to using the information obtained to better understand the behavior of prestressed concrete box girder bridges, the UMN researchers are developing a system which can be used by the Minnesota Department of Transportation to conduct long-term monitoring of the bridge.

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Description of Instrumentation

This section contains a brief description of the types of sensors installed in the bridge followed by the quantities of each instrument in parentheses. Sensors include a CorSenSys system (4), an example of which is shown in Figure 3, to monitor the corrosion susceptibility of the reinforcement within the deck. Information from this system can be used to determine when the deck needs to be resurfaced to prevent the chlorides from reaching the reinforcement layer and initiating corrosion. Additional instrumentation includes: strain gages to measure the deformations of the bridge (24 resistive, 195 vibrating wire [VW], 12 fiber optic); accelerometers to measure the vibrations of the bridge and to relate those measurements to structural deformations if possible (26); linear potentiometers to measure displacements of the expansion joints in the structure (12), and thermistors to measure the thermal gradients through the bridge cross section (243, including the thermistors associated with the VW gages). The vibrating wire strain gages and thermistor data are recorded statically at four to twenty-four times per day; whereas the accelerometer, resistive gage, and linear potentiometer data are recorded at up to 200 Hz continuously during the day, and then processed daily to save a shorter period of data coincident with the VW data, and the asynchronous major events of the day.

The strain, temperature, and vibration measuring systems in the bridge are distributed in several sections throughout each span of the bridge. A few sections are more heavily instrumented in order to investigate more detailed response which can be compared to the limited set of information obtained in the other sections of the bridge. The exterior box of the southbound (SB) river span (Span 2) contains three different types of systems (i.e., VW and fiber optic strain gages and accelerometers) that provide some redundancy and enable the evaluation of the relative effectiveness of the three different types of systems for consideration in future bridge monitoring implementations. Examples of the more heavily instrumented sections are shown in Figures 4 through 6.

Figure 4 shows the cross section of the SB bridge at midspan of Span 2 which has the largest number of VW gages. The gages oriented in the longitudinal direction, shown as solid circles in the figure, enable the measure of the longitudinal curvatures at midspan and the distribution of the strains across the top flange of the bridge. Pairs of transverse gages, shown as solid rectangles, are located to investigate the transverse curvatures at five locations across that section. The open circles in the figure indicate locations of additional sets of thermistors, with the numbers in the circles indicating the number of thermistors through the thickness at each location.

Figure 5 shows the SOFO (fiber optic) sensors which were located in Span 2 of the SB exterior box. These twelve gages were oriented in pairs at six locations distributed along the length of the span. Whereas VW strain gages have very short gage lengths (i.e., ~6 in. [~150mm]), the SOFO gages measure strains over 13 ft [4m] gage lengths. The sets of SOFO gages are expected to provide information on the overall curvature across the span which may be used to determine the deflections of the SB river span.

Accelerometers are located below the deck near midspan of each of the boxes. In the exterior box of SB Span 2, 14 accelerometers can be reconfigured in different orientations at different locations. Figure 6 shows the typical location of the accelerometers below the center of the deck (in all spans) and attached near the corner of the flange in Span 2 (i.e., typical configuration of 13 of the 14 accelerometers in Span 2). The accelerometers were attached near the corner of the flange to better measure the overall dynamics of the span without the influence of the local deck vibrations. The 13 accelerometers in Span 2 are currently distributed fairly uniformly along the length, with one gage at midspan of the deck to replicate the configuration in the other spans.

Truck Load Tests

Prior to opening the bridge to traffic, a series of static and dynamic truck load tests were conducted on the evenings of September 14 and 17, 2008. The loads were provided by a series of eight heavily loaded sand trucks which were carefully weighed and measured before the tests. The vehicles each weighed approximately the same and had a combined weight of approximately 400 kips (1,800 kN). The trucks were positioned in a series of different pre-established configurations on the bridge. For the static tests, the trucks were stationed at each of the pre-established locations long enough to typically capture three readings. Several of these tests were also repeated over the course of the evening as time permitted. One of the configurations (ST I) is shown in Figure 7, for which case the eight trucks were positioned across the width of the bridge.

These tests provided valuable information used to calibrate numerical models of the bridge subjected to known loads at known locations. This information also provided a “baseline” for the measured behavior of the bridge. If desired, future truck tests could be conducted to compare the results to the initial baseline tests.

Finite Element Method (FEM) Model

Finite element models were developed to provide means to interpret the data obtained from the bridge. The most current FEM model was created in ABAQUS using continuum (solid) quadratic 20-node elements with reduced integration. The benefits of the solid elements included the ability to accurately model the geometry of the complex cross-sectional shape and to simulate the thermal gradient through the section (node by node). The scope of the initial model was limited to the continuous three-span section of the southbound bridge, as shown in Figure 8, where most of the instrumentation was located. Boundary conditions were chosen to approximate the physical constraints on the bridge including Piers 2 and 3 (assumed fixed at the base and pinned at the top), with longitudinal expansion joints modeled at Abutment 1 and Pier 4. To model the steel and prestress present in the bridge, all post-tensioning tendons (with the exception of the draped external tendons) were approximated as shells embedded in the top and bottom flanges. Mild steel was assumed to be uniformly distributed throughout the section by adjusting the modulus of elasticity of the concrete to account for the additional stiffness introduced by the reinforcement.

All of the concrete in the FEM model was assumed to be normal-weight concrete. The specified material properties for the cast-in-place and precast concrete were initially used. Studies are currently underway at the University of Minnesota using concrete samples obtained from the bridge during construction to investigate the measured material properties of the bridge including modulus of elasticity, creep, shrinkage, and coefficient of thermal expansion. The results of these studies may be used to further refine the numerical models.

Calibration of FEM Model

The results of the truck load tests were used to calibrate the FEM model. The results of the FEM model were compared to the measured data for the various configurations and positions of the static truck tests. Figure 9 shows the longitudinal strains and deformed configuration of the midspan cross section of SB Span 2 (magnified 2500 times) with loading to simulate truck orientation ST I (as shown in Fig. 7). Figure 10 shows the longitudinal mechanical strains obtained from the FEM model at the top of the deck and 6 in (150mm) below the top of the deck, relative to the VW strain gages assumed to be embedded at 6 in. (150mm) below the top of the deck. From the figure, it is evident that the trends in the measured data are similar to those obtained from the FEM model. The measured data better matched the FEM model results predicted to occur slightly lower in the section (e.g., at 7 in. [180mm] below the top of the deck). Differences between the measurements and the model may be attributed to sources including differences in the as-built and assumed cross section of the structure (e.g., the deck thickness was estimated to vary by approximately 1in.), and potential errors associated with the as-built locations of the sensors embedded within the structure.

In addition to calibrating the FEM model with the truck load tests, studies are underway to calibrate the model with the measured results due to environmental effects including the effect of the thermal gradient on the structure. Figure 11 shows thermal gradients measured through the cross section of the bridge obtained at four times over an 18 hour period. The effect of solar radiation has a dramatic effect on the thermal gradient through the section particularly in the April to late June time frame.

Following calibration, the FEM model can be used to investigate potential damage scenarios and how they might manifest themselves in the measured data.

Effects due to Temperature

To illustrate the effects of temperature on the response of the bridge, the measured strains obtained at the top and bottom of the box section near midspan of SB Span 2 are shown in Figure 12 over a twelve hour period during the course of one of the truck tests. Note that the strain values in the plot were arbitrarily zeroed on September 1, 2008; it is the changes in strain that can be determined from the plot that are of importance. The peaks in the plot represent the strains when the load was positioned locally with respect to the instrumentation. It should be emphasized that the truck tests took place over the course of an evening, from approximately 5:00 pm to 5:00 am, so the effects of the solar radiation should have been minimized. From the figure, however, the temperature variation during that time frame can be noted by the change in the readings of the bridge when it was unloaded. From this figure it is evident that the trucks caused a maximum local strain change of approximately 20με in the top gage readings.

Figure 13 shows the data from the same strain gages (i.e., in the top and bottom of the box section near midspan of SB Span 2) that were measured four times a day (i.e., midnight, 6:00 am, noon and 6:00 pm) over a ten month period (arbitrarily zeroed on September 1, 2008). As evident in the figure, the daily changes in total strain of the top gages (~100με) due to the thermal gradient and temperature changes were nearly five times the magnitudes of those obtained during the truck load test with the eight trucks stationed across the bridge at this section (i.e., ~20με). The seasonal changes in total strain were more than 500με for the same gages.

Besides having a significant effect on the strain measurements, the temperature changes also appear to affect other bridge properties including the modal frequencies. Preliminary data obtained from the accelerometer at midspan of Span 2 was used to determine the modal frequencies. To obtain this data, input averaging of 20 points was used on the dynamic data collected at 200 Hz over an approximately half hour period to obtain greater resolution in the frequencies in the 0 to 5 Hz range where the structural frequencies were expected to reside. The resulting Fast Fourier Transform (FFT) applied to the data showed three strong peaks at approximately 0.8 Hz, 1.5 Hz, and 2.3 Hz as shown in Figure 14, which compared reasonably well with the data obtained from the FEM model. In the FEM model, the frequencies around 0.8 Hz and 1.5 Hz represented bending modes, while the mode at 2.3 Hz was associated with a torsional mode. The FFTs were then applied to the data bimonthly, to investigate the consistency in the three noted frequencies over time. Figure 15 shows a sample of these results. The variation of the modal frequencies for the first mode is shown compared with the bridge temperature at the time of measurements. Data obtained for the other modes showed similar variations with respect to temperature. It appears that there is some correlation between temperature and bridge modal frequencies. As the temperature increased, all modal frequencies were observed to decrease. Further studies regarding this behavior are currently underway.

Plan for Development of Long-Term Monitoring System

The data obtained over the first few years of monitoring the I35W St. Anthony Falls Bridge will provide a “baseline” that describes what is considered “normal” behavior of the bridge; however using the baseline data to establish absolute maximum and minimum bounds on the expected behavior of the bridge is not sufficient to identify abnormal behavior. As evident in the discussion of the measured data above, the environmental effects (i.e., temperatures and thermal gradients) have a significant impact on the bridge response. As noted in Figures 12 and 13 showing the top longitudinal strain data measured near midspan of SB Span 2, the thermal effects were observed to be approximately 25 times larger than the effect of eight fully loaded sand trucks stationed across midspan of the SB bridge. In order to provide a useful long-term bridge monitoring system, it is important to be able to discern the relationship between the thermal effects and the behavior of the bridge. The desire is to provide a range of "moving" bounds that are related to the range of expected results associated with the measured thermal gradients. The FEM model which has been calibrated to both the truck load data and the data associated with thermal effects will serve as a useful tool in this regard. Any changes in expected behavior outside of the "moving" bounds will provide a means to signal when the response of the bridge may need further investigation or when maintenance needs to be performed.

One of the challenges is that no "turn-key" system for monitoring bridges such as this exists. The monitoring system has to be created where the inputs from the bridge (i.e., measured temperature distributions and expected traffic loads) can be combined with other information (e.g., measured strains) to identify anomalies in behavior. In order to provide a range of "moving" bounds, the calibrated FEM model will be used to establish relationships between the thermal gradient effects and the expected responses from the sensor data. As an example, a "look-up" table may be developed that could correlate the measured data obtained from the thermistors to the measured data from the other types of sensors (e.g., strain gages and linear potentiometers).

Figure 16 shows a schematic that illustrates the plan for the structural monitoring system under development. In the schematic, the raw *data* from the multiple dynamic and static acquisition systems is collected and *analyzed* or processed. The outputs of the processed data are then considered either *model input* (e.g., thermal effects) or *response* (i.e., measured responses of the bridge associated with the measured model inputs). The *model input* is used to determine *expected response* (e.g., expected bridge curvatures, deflections, etc.), by means of a "*passive*" or "*active model.*" A "look-up" table, as described above, is an example of a "*passive*" *model*. An example of an "*active*" *model* would be a study with the calibrated FEM model to investigate an intermittent load test of the bridge. The *expected responses* from the *active* or *passive models* would be *compared* to the measured "*response*" of the bridge. The system would then *output* the results of the comparison to the bridge management engineer. Example outputs include notifications when the measured *responses* are out of range of the *expected responses* which may warrant further examination.

The system will also be designed to notify the bridge management engineer when any problems are encountered with the data collection system, such that steps may be readily taken to avoid the loss of information. One of the challenges with the large volume of data collected with the system is the large amount of storage required to retain data. The system under development will be designed to cull the collected data to maintain sufficient information to ensure gradual changes in behavior are documented without causing overwhelming long-term storage demands.

Summary

A long-term structural monitoring system is being developed by the UMN for the I35W St. Anthony Falls Bridge. This structure contains over 500 instruments which includes sensors to monitor corrosion susceptibility, accelerations, strains, and movements at the piers and abutments. Numerical models of the bridge have been developed and calibrated to the collected data obtained from truck load tests, while studies are currently underway to calibrate the model to environmental (thermal) loading. The data obtained over the first few years of monitoring will be correlated with the calibrated models and used to develop the baseline bridge behavior. Because the thermal effects have such a significant impact on the response of the bridge, one of the challenges in developing the long-term structural monitoring system is the creation of "moving bounds" to distinguish when the response of the bridge is out of the expected range. The long-term monitoring system is being designed as a tool for bridge management engineers to investigate when the response of the bridge requires further evaluation and when maintenance may need to be performed.

Acknowledgments

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Unit Conversion

1 in. = 25.4 mm
1 k = 4.448 kN

FIGURE 1: PHOTOS OF THE I35W ST. ANTHONY FALLS BRIDGE DURING CONSTRUCTION

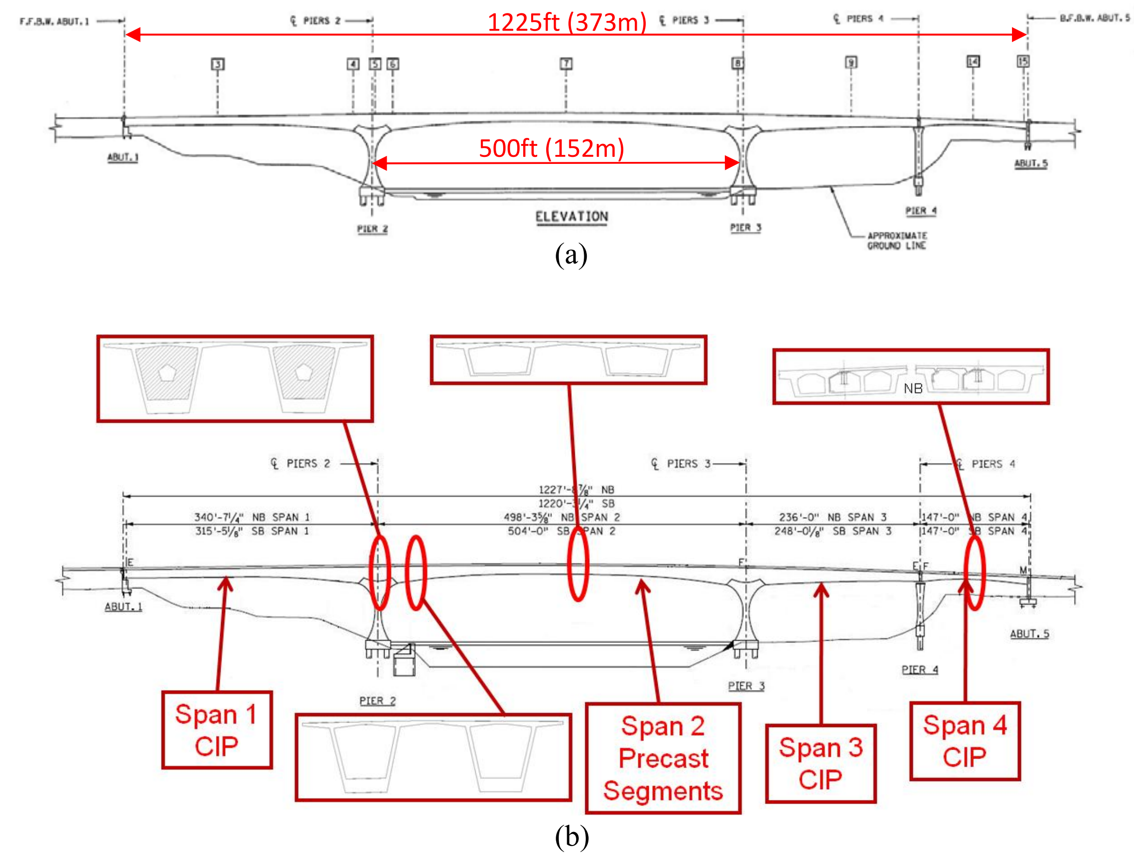

FIGURE 2: ELEVATION VIEWS INDICATING (a) INSTRUMENTED LOCATIONS AND (b) CROSS-SECTIONAL SHAPES ALONG THE BRIDGE

FIGURE 3: EXAMPLE OF CORSENSYS CORROSION SENSOR INSTALLATION

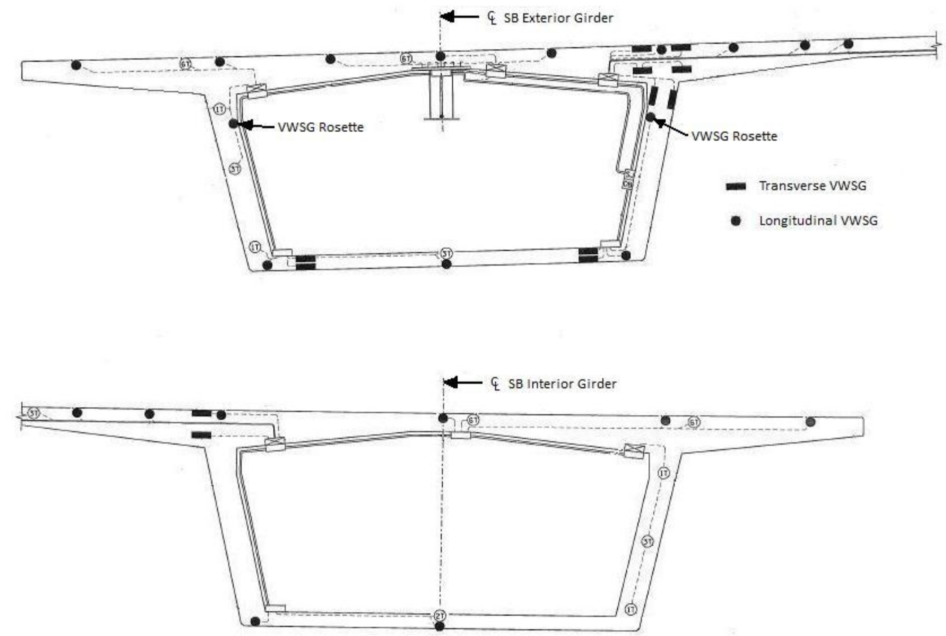

FIGURE 4: VIBRATING WIRE STRAIN GAGE LAYOUT FOR MIDSPAN OF SPAN 2 OF SOUTHBOUND BRIDGE (LOCATION 7SB)

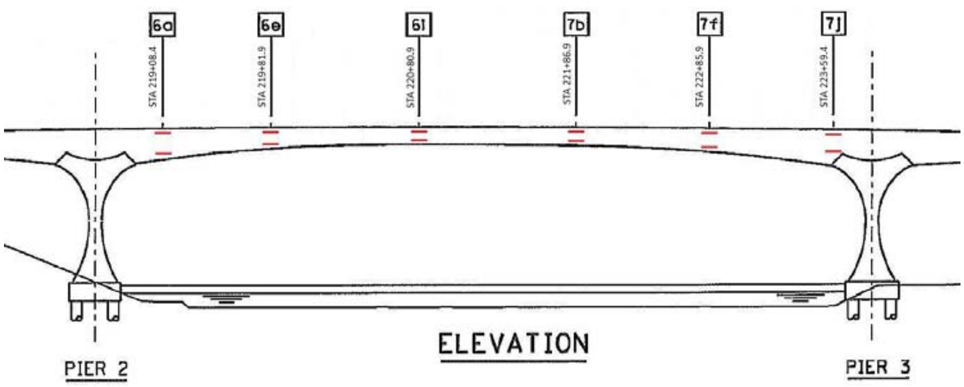

FIGURE 5: SOFO SENSOR LOCATIONS ALONG LENGTH OF SPAN 2 OF SOUTHBOUND BRIDGE EXTERIOR BOX

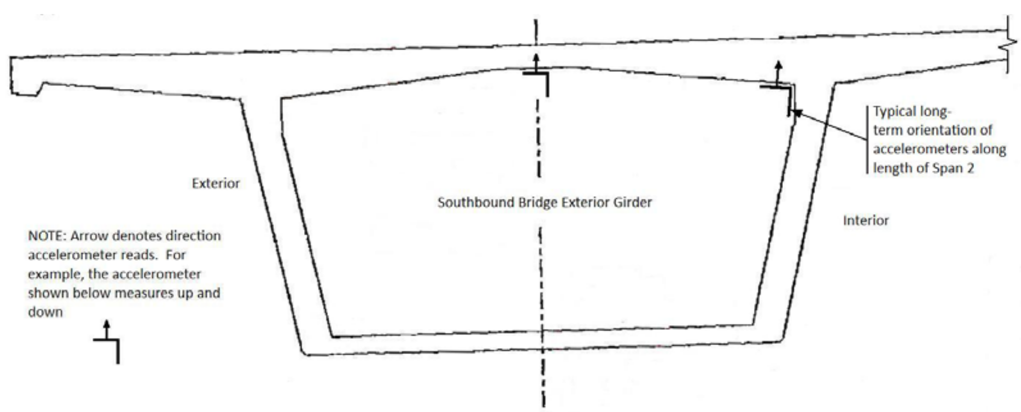

FIGURE 6: ACCELEROMETER LAYOUT IN THE SOUTHBOUND BRIDGE

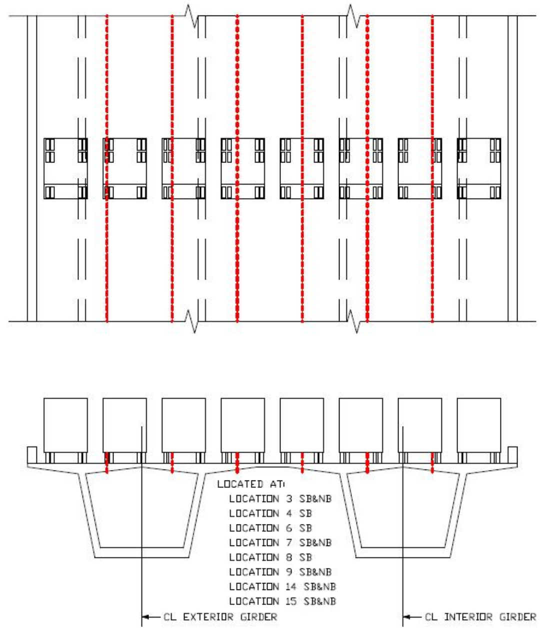

FIGURE 7: TRUCK ORIENTATION ST I

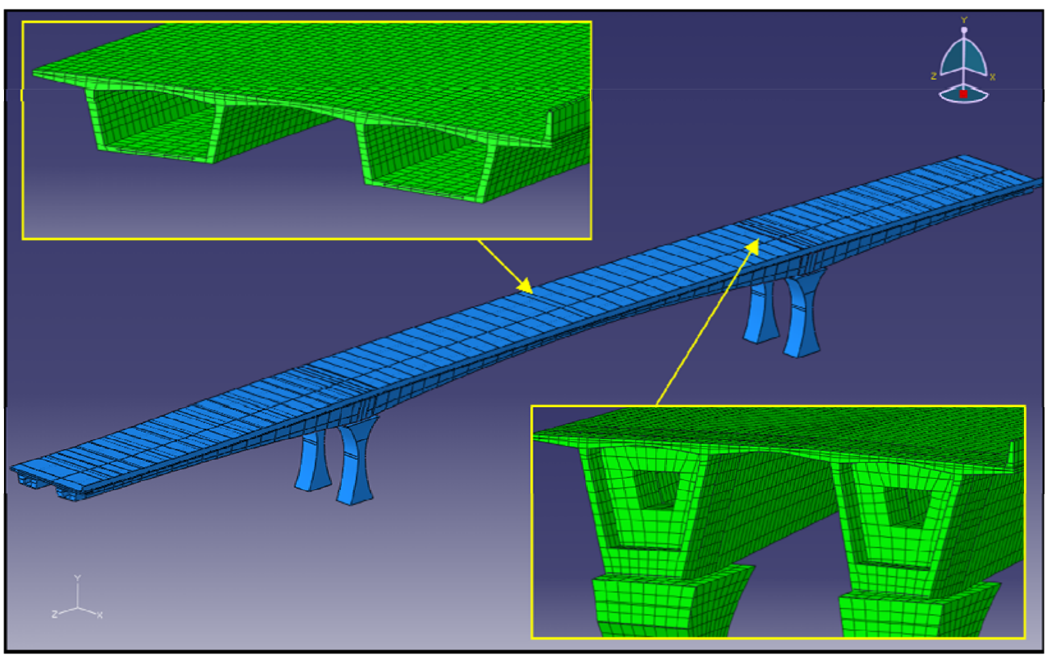

FIGURE 8: FINITE ELEMENT MODEL OF I35W ST. ANTHONY FALLS BRIDGE

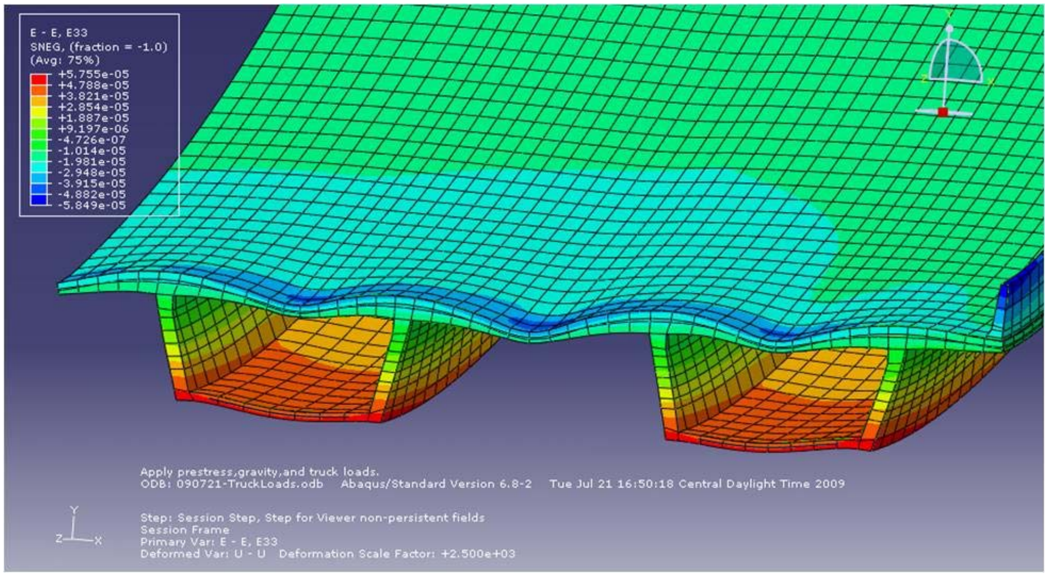

FIGURE 9: LONGITUDINAL STRAINS AT MIDSPAN OF SPAN 2 UNDER TRUCK TEST STI-7SB (DEFORMATIONS MAGNIFIED BY 2500)

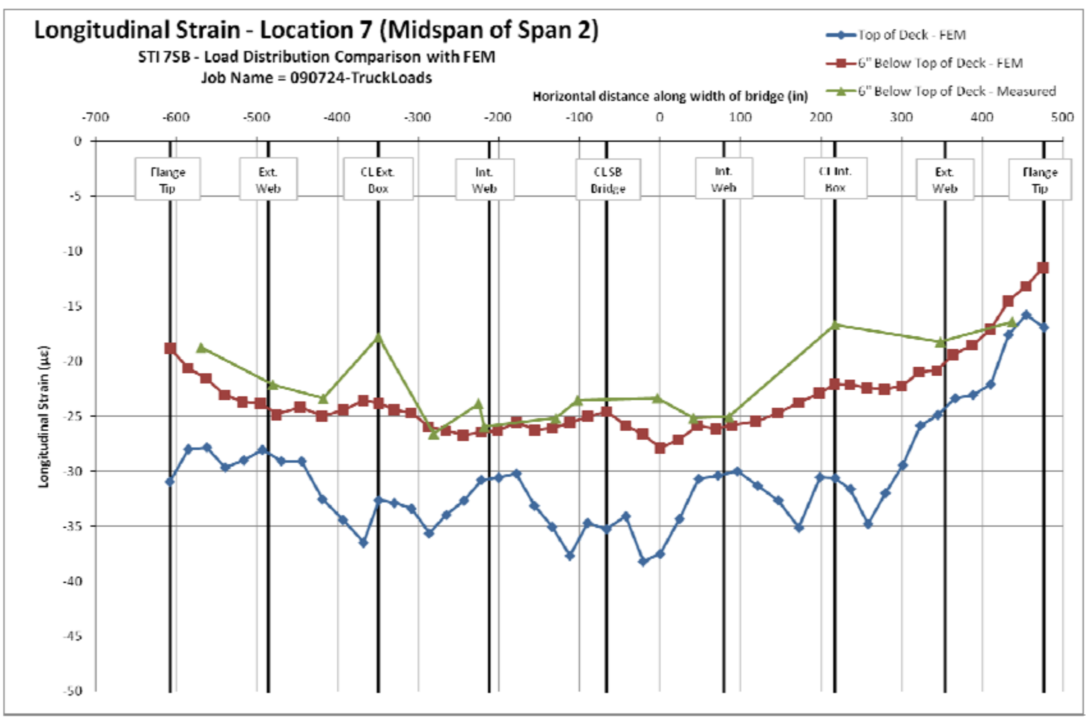

FIGURE 10: LONGITUDINALMECHANICAL STRAINS ACROSS SECTION (MIDSPAN OF SB SPAN 2)

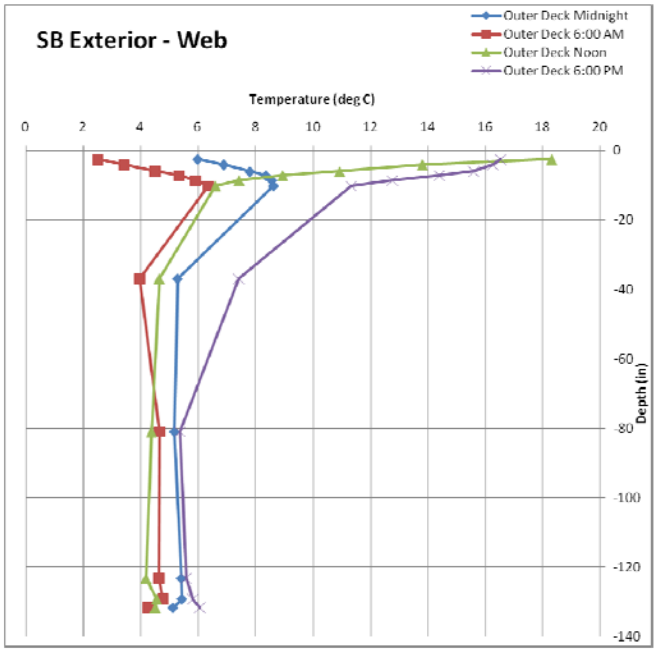

FIGURE 11: MEASURED THERMAL GRADIENTS THROUGH THE SECTION DEPTH OF WEB (MIDSPAN OF SB SPAN 2) 4/9/2009

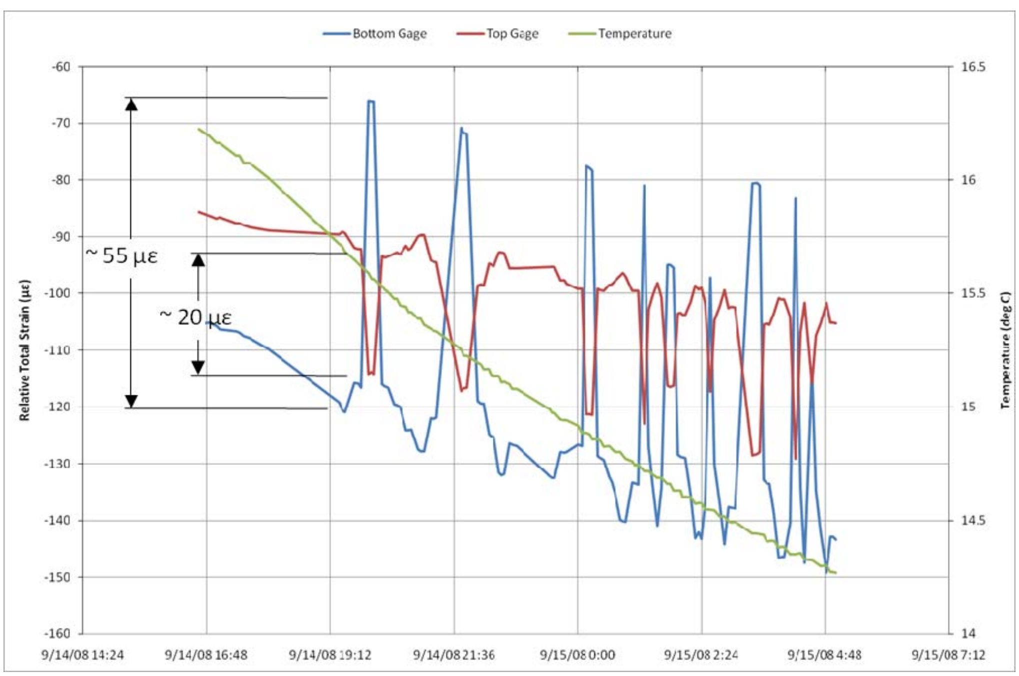

FIGURE 12: MEASURED TOP AND BOTTOM TOTAL STRAINS (MIDSPAN OF SB SPAN 2) AND TEMPERATURE VARIATION VS. TIME DURING TRUCK TESTS

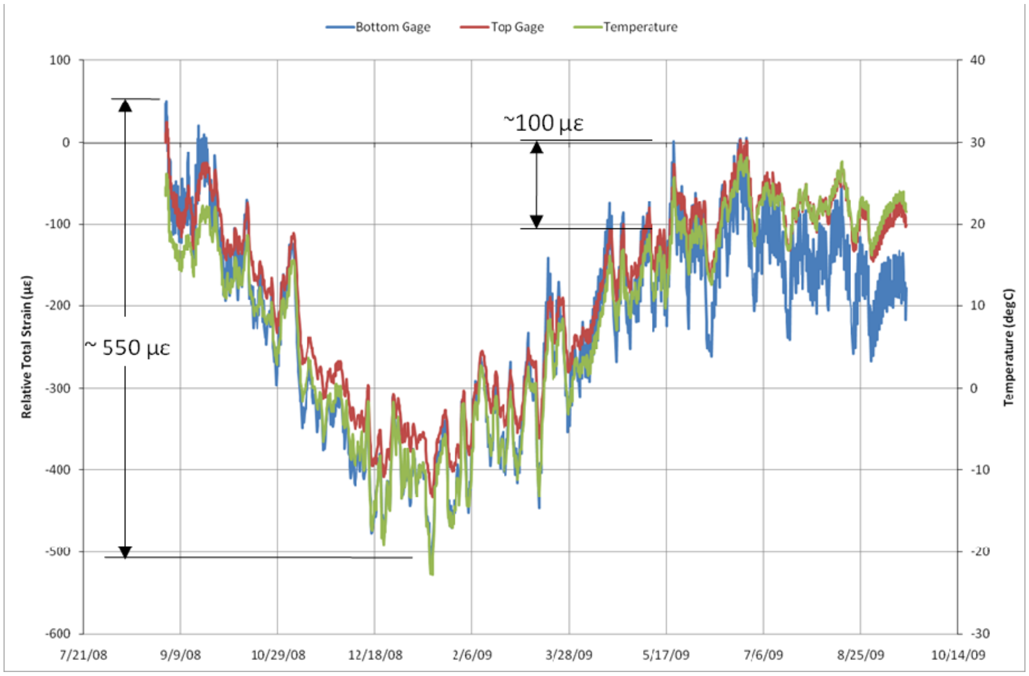

FIGURE 13: MEASURED TOP AND BOTTOM TOTAL STRAINS (MIDSPAN OF SB SPAN 2) VS. TIME (OVER 12 MONTH PERIOD)

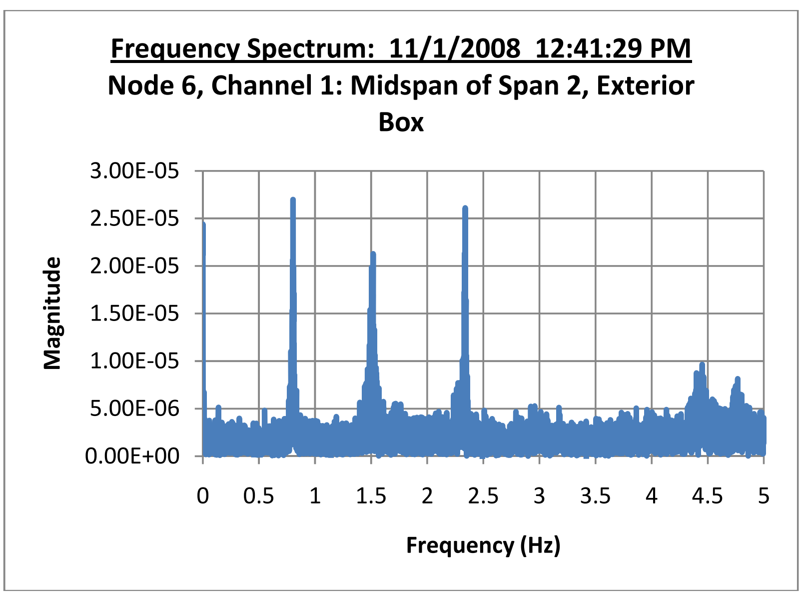

FIGURE 14: MODAL FREQUENCIES OF SPAN 2 ON 5/9/2009

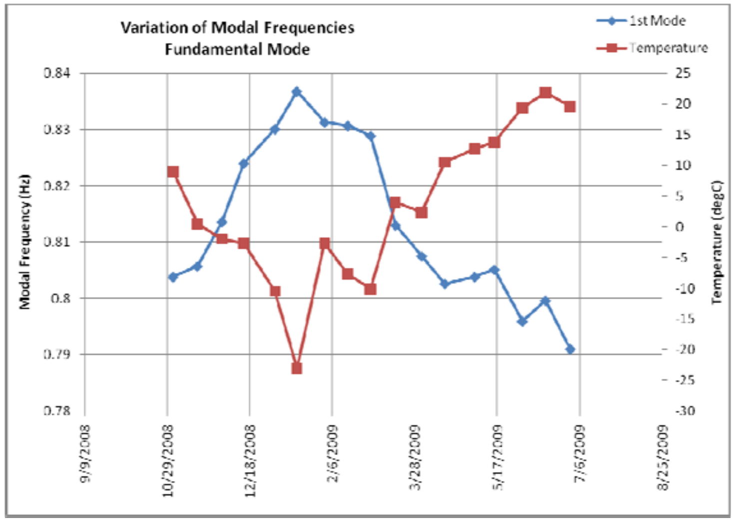

FIGURE 15: MODAL FREQUENCIES OF SPAN 2 (OVER EIGHT MONTH PERIOD)

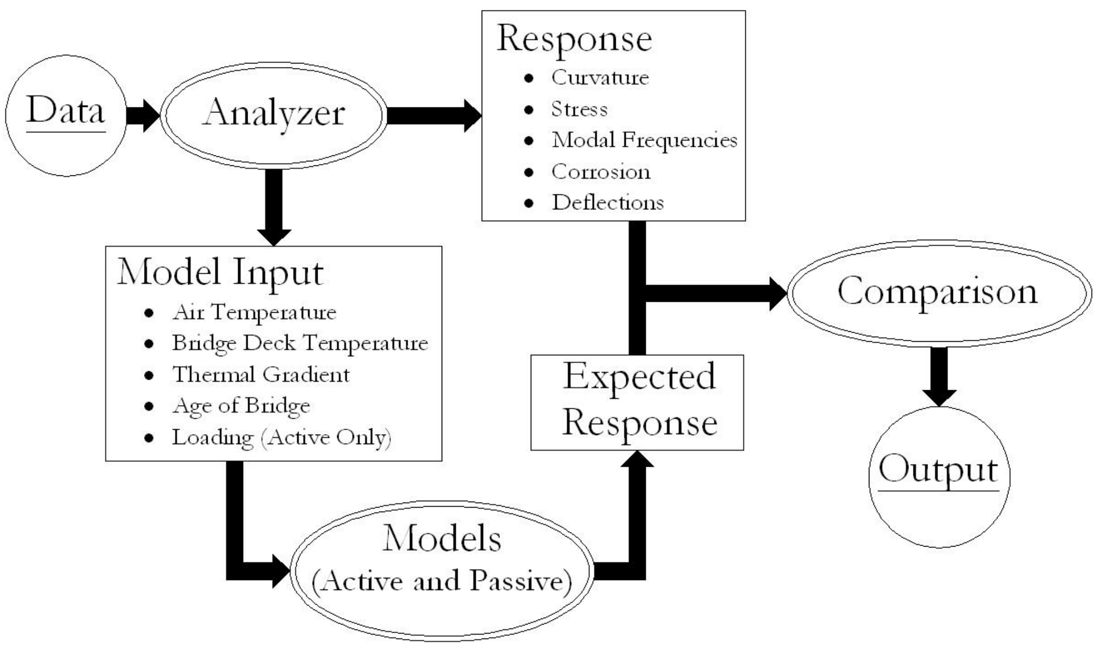

FIGURE 16: SCHEMATIC FOR DEVELOPMENT OF STRUCTURAL MONITORING SYSTEM