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Field Instrumentation and Monitoring of Eyebars within the Southeast Anchorage of the Walt Whitman Bridge - Final Report

Robert G. Connor

Ian C. Hodgson

Carl A. Bowman

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Robert J. Connor
Ian C. Hodgson
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ATLSS is a National Center for Engineering Research on Advanced Technology for Large Structural Systems

117 ATLSS Drive
Bethlehem, PA 18015-4729

Phone: (610)758-3525
Fax: (610)758-5902

www.atlss.lehigh.edu
Email: inatl@lehigh.edu

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Executive Summary

As part of a comprehensive inspection and evaluation of the main cables on the Walt Whitman Bridge over the Delaware River at Philadelphia, PA, field instrumentation and remote monitoring of several eyebars was conducted. Specifically, four eyebars in the south east anchorage were instrumented and monitored. Stress-range histograms and continuous time history data were recorded over several weeks. The effort is being led by the firm of Weidlinger and Associates of New York City. All field work was conducted between December 2002 and January 2003 by personnel from the ATLSS Engineering Research Center at Lehigh University, Bethlehem, PA.

The measurements indicate that live load stress ranges in the eyebars are low (less than 1.0 ksi) and that changes in the ambient temperature have a small influence on the stress range in the cable over the temperature ranges measured. The measurements are used to estimate the stress ranges in the strands and main cable. Further details related to the instrumentation and a discussion of the results, are presented in this report.

1.0 Background

The Walt Whitman Bridge connects the City of Philadelphia in Pennsylvania with Gloucester City in New Jersey and carries seven lanes of Interstate I-76 over the Delaware River (See Figure 1). The bridge was designed by Othmar Ammann and opened to traffic on May 16, 1957. The main suspended span and anchor spans are 2000 ft and 700 ft respectively. There are two 23-1/8 inch diameter main cables containing 11,396 individual wires for a net cable area of 343.84 in^2. Hence, each strand is 9.29 in^2.

In order to better define the magnitudes of live load stresses in the cables, establish the effects of temperature, and perform an accurate fatigue assessment, field instrumentation and monitoring was conducted.

Figure 1 – Walt Whitman Bridge over the Delaware River

2.0 Instrumentation Plan and Data Acquisition

2.1 General

The main cable is split into 37 strands that are attached to 37 individual eyebars. Each eyebar anchors two half strands that loop around the eyebar within cast sheaves that serve as the strand shoes which are held to the eyebar by a large diameter pin. Hence, changes in cable axial force are proportional to changes in axial force in the eyebars. Although it is not practical to instrument the cable itself, individual eyebars are solid prismatic members that can be easily instrumented. Furthermore, the eyebars can be instrumented in such a way to ensure only axial forces are measured. Figure 2 is photograph of the eyebar anchorage assembly within the southeast anchorage.

Figure 2 – Photograph of portion of eyebar assembly in southeast anchorage

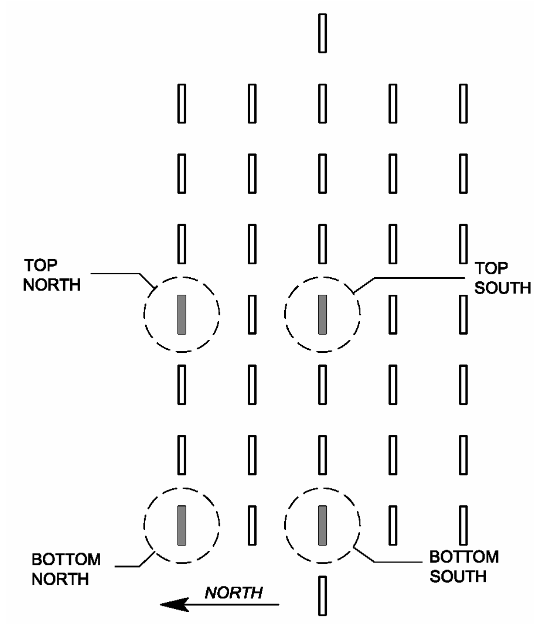

Figure 3 – Layout of eyebars in southeast anchorage indicating instrumented eyebars

The eyebars selected for instrumentation are indicated in Figure 3. The eyebars to be instrumented were selected by Weidlinger Associates while on site. Each eyebar is 13" x 2¼" inches in cross section and is solid steel. The area of each eyebar at the section where the strain gages are attached is 29.25 in^2. The centerline of the sheave is about 30 ½" above the surface of the concrete, on average. Hence, the ratio of the strand area to the eyebar area is about 3.14 (29.25 in^2 / 9.29 in^2 = 3.14)

Two biaxial bondable resistance strain gages were installed directly opposite each other as shown in Figure 4. The gages were then wired as full-bridge circuits so that only axial strains in the eyebar could be measured. In addition, the circuit was fully temperature compensated. This means that temperature changes of the eyebar itself did not produce a change in strain within the circuit and only mechanical strains applied to the eyebars were measured. Changes in force applied by the main cable due to fluctuations in cable temperature however were measured.

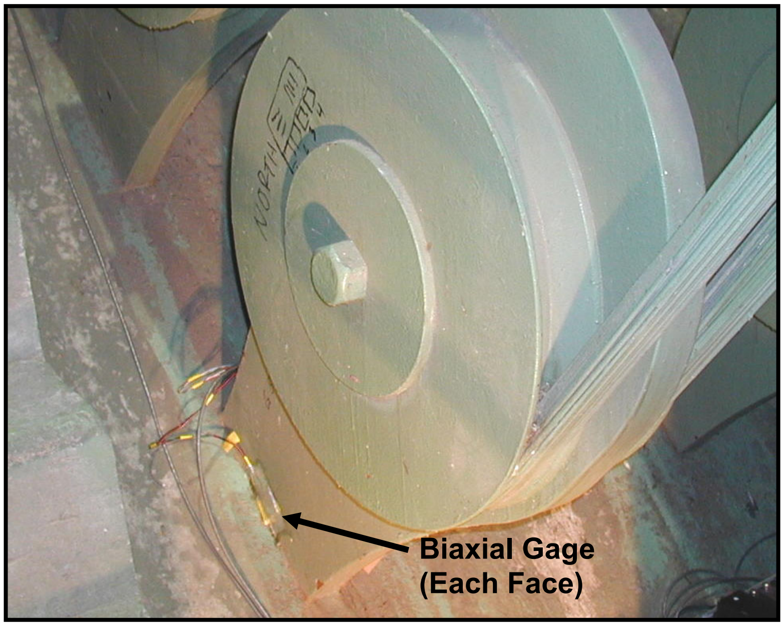

Figure 4 – Photograph of portion of eyebar assembly in southeast anchorage

Data were collected using a Campbell Scientific CR9000 Data Logger. This is a high-speed, multi-channel, 16-bit digital data acquisition system. Using a laptop computer, real-time review of the data was possible during monitoring while on site. Hence, sensors could be checked in real-time to ensure proper operation. A photograph of the data acquisition system can be seen in Figure 5.

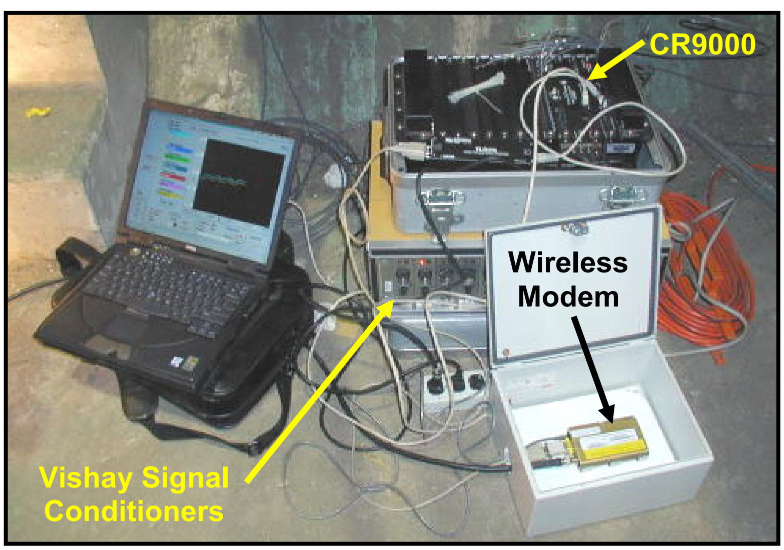

Figure 5 – Photograph of data acquisition system installed near eyebars

During the remote monitoring phase, program upload and data download were achieved using a wireless modem that was connected to the CR9000 (See Figure 5). The antenna for the modem was mounted within the anchorage on a safety railing near the eyebars. Data were automatically downloaded from the bridge to the ATLSS Bridge Server located at Lehigh University every two hours. Hence, the data could be regularly examined to ensure operation of the equipment and near real-time review. The process was fully automated by the server.

As previously discussed, all strain gages were biaxial bondable resistance strain gages. The gages were produced by Measurements Group and were type CEA-06-250UT-350. The gages were driven with an excitation of 10 volts DC to maximize the signal to noise ratio. To ensure a stable noise-free signal, signal conditioning was provided by Vishay Model 2120 signal conditioners. A thermocouple was used to measure the temperature of the eyebars. The ambient temperature within the anchorage and the outside air temperature were not monitored.

Power for the data acquisition system was provided by the Delaware River Port Authority within the anchorage. The data acquisition system was placed adjacent to the lower eyebars, covered with a plastic tarp to protect the equipment from any water leakage, and left in place for the duration of the monitoring program.

2.2 Monitoring Program

Although installation of the instrumentation was completed on December 18, 2002, monitoring did not begin until the morning of December 27, 2002. Table 1 summarizes the data collected. This allowed sufficient time to ensure that the equipment was working properly and that the wireless connection was in operation. Data collection began at 11:15 AM on December 27, 2002 and continued until 9:40 AM January 17, 2003. (*The first monitoring period identified in Table 1 was disregarded due to the problem with the strain gage installed on the bottom north eyebar. As a result, only data from the second period are discussed herein.*).

File Name	Start	Finish	Days	Type of Data
First Period				
Five_min	12/23/02 9:20 AM	12/27/02 10:05 AM	4.03	Min, Max, & Avg. every 5 min
RAIN	12/23/02 9:20 AM	12/27/02 10:00 AM	4.03	Rainflow histo. every 10 min
TIME_HST	-	-	-	Contin. time history @ 20 Hz
Second Period				
Five_min	12/27/02 11:15 AM	1/17/03 9:40 AM	20.93	Min, Max, & Avg every 5 min
RAIN	12/27/02 11:15 AM	1/17/03 9:40 AM	20.93	Rainflow histo. every 10 min
TIME_HST	12/27/02 11:10 AM	1/8/03 8:15 PM	12.38	Contin. time history @ 20 Hz

Table 1 – Summary of data collected during monitoring program
(*For descriptions of data collected see following sections*)

The strain gages installed on the bottom north eyebar failed sometime during the first monitoring period. However, data were recorded from all four eyebars during the on-site monitoring and at the beginning or the first monitoring period. As will be discussed, these data were used to establish that the behavior of all four eyebars was consistent.

2.3 Data Collection

Data were sampled at a frequency of 20 Hz for each eyebar continuously. Three separate data files were recorded during the monitoring program. Although the data used to develop each file was sampled at 20 Hz, the data were recorded at different rates for each table. The data stored in each file are discussed below.

2.3.1 Continuous Time History Data

In order measure the live-load response of the eyebars, continuous time history data were collected from all instrumented eyebars. This data is useful for determining if the response of all four eyebars is consistent and hence representative of the entire eyebar group. The data can also be used to observe the response of the eyebars due to the passage of heavy vehicles, the daily positioning of the movable barrier, and overall response of the eyebar. Data were sampled and recorded continuously at a rate of 20 Hz until the memory card was filled on the data logger.

2.3.2 Five Minute Data Sampling

Although the continuous time history data described above are very useful, the resulting files are very large (over 1 GB). In order to obtain similar data in a much more compact format, an additional file was recorded. The minimum, maximum, and average stress measured over a five minute interval were recorded. These data are a reasonable representation of the continuous time history data described above, from a maximum stress range standpoint during a particular five-minute interval. It must be noted that stress-time history plots of this data are not actually continues, but rather discrete points of data plotted at five-minute intervals.

2.3.3 Stress-range Histograms

Stress-range histograms were developed continuously using the rainflow cycle counting method for the eyebars. The histogram table was updated every ten minutes and ran continuously so that all cycles were counted. Stress-range cycles less than 0.25 ksi were ignored and the bin size or interval was set at 1.0 ksi. The sampling rate used to develop the stress-range histograms was 20 Hz.

In addition, stress-range histograms were developed for the strands using continuous time history data after all data were collected. This additional effort was undertaken after it was determined that histograms developed initially (*described in the paragraph above*) were not of sufficient refinement. These histograms were updated every 60 minutes. Stress-range cycles less than 0.25 ksi were ignored and the bin size or interval was set at 0.25 ksi so that more accurate histogram could be developed for the strands.

3.0 Validity of Measurements

The distance between the top of the concrete and the centerline of the strain gages was held constant at one inch. However, the distance between the centerline of the eyebar pin and the gages varied for each eyebar due to slight variability in the height of the concrete surface. The distance from the centerline of the eyebar pin to each strain gage is summarized in Table 2. As can be seen, the variability is relatively small.

Location	Distance from Gage to C.L. Eyebar Pin (in)
Top North	29 3/8
Bottom North	27 5/8
Top South	33 5/8
Bottom South	31

Table 2 – Distance from strain gage to centerline of eyebar pin

Strain gages were installed about one inch above the concrete at each eyebar in order to ensure that the gages were as far as possible from the head of the eyebar. This was done to minimize any shear lag effects that may bias the measurements. The stress field near the eyebar head is very complex due to the hole, variation in cross section, and bearing stresses at the pin.

In order to obtain the force in the eyebar, it must be ensured that the gages were installed in a "nominal" stress field. If the head of the eyebar influenced the stress at the location of the gages, then the force in the eyebar cannot be calculated by simply multiplying the measured stress by the cross sectional area of the eyebar at the gage.

To verify the stress field in the eyebar, a simple finite element model of a typical eyebar was developed using geometry provided by Weidlinger Assoc. The model is shown in Figure 6. FE_Map was used for pre- and post-processing and the finite element solver used was ABAQUS. Twenty node 3-D solid elements were used to model the eyebar.

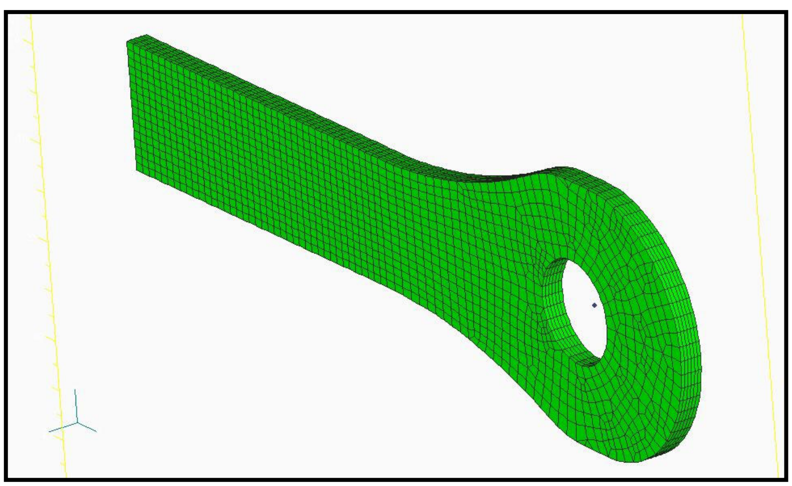

Figure 6 – Finite element model of typical eyebar

Nodal loads were applied at the hole in the eyebar on the side where the pin would bear on the edge of the hole. The magnitude of the load selected was arbitrary since the relative stress distribution was of interest near the gage. The nodes of the eyebar were assumed to be pinned an arbitrary distance of six feet from the centerline of pin to simulate the embedment into the concrete anchorage.

The results of the analysis indicate that the gages were installed sufficiently far from the eyebar head and pin to assume a nominal stress field. In fact, at the section where the strain gages were place, the strains only varied by about 3% across the section. Figure 7 is a plot of the longitudinal stress contours on the eyebar surface. The average location of the strain gages from the centerline of the pin is also shown and confirms the nominal stress field. Hence, the force in the eyebar can be accurately obtained by multiplying the measured stresses by the nominal cross sectional area of the eyebar at the gage.

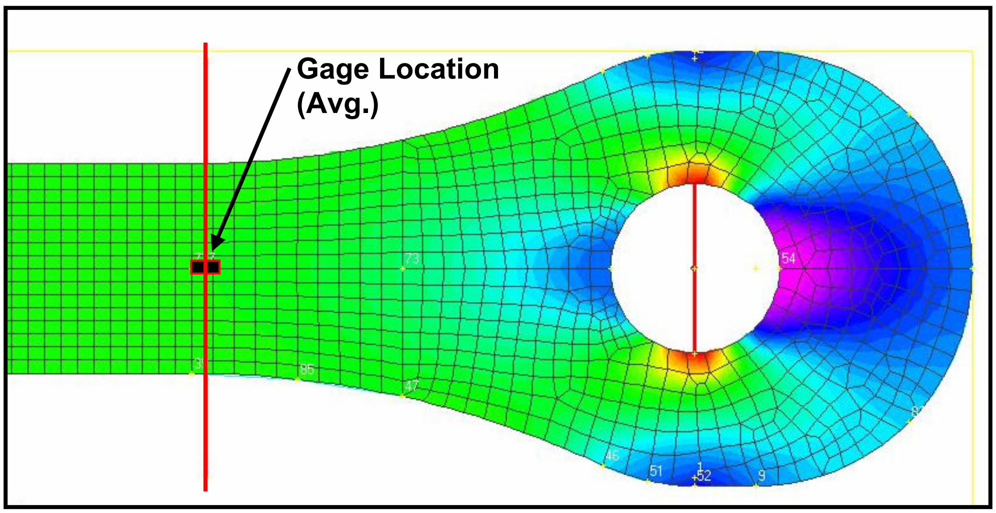

Figure 7 – Plot of longitudinal stress contours for a typical eyebar
Note the strain gage is located in a uniform stress field.

4.0 Results

The results of the monitoring program are discussed in this section. Overall, stresses produced by live loads and daily thermal cycles were small in the eyebars. The maximum stress range did not exceed 1.0 ksi in any of the instrumented eyebars. Stress ranges in the strands were subsequently calculated from the measurements made on the eyebars.

4.1 Eyebar Stresses

As previously discussed, strain gages installed on the bottom north eyebar failed sometime after monitoring began in December 2002. However, data were successfully collected from all four eyebars for a period of 17 hours beginning at 3:30 PM on December 17, 2002. Hence, an evening and morning rush hour were recorded. The data confirm that the response of all four eyebars is essentially uniform. A selected portion of the time history is plotted in Figure 8. Note that the "peak-to-peak" response of all four eyebars is about the same for each event. Hence, although the strain gages on the bottom north eyebar failed, the data from the other three eyebars accurately represents the response of the fourth eyebar. Furthermore, it is reasonable to assume that the response of the instrumented eyebars can be used to reasonably represent the response of any eyebar in the group.

4.2 Strand Stresses

As previously discussed, the ratio of the areas of the eyebar to the individual strands is 3.14. From statics, it is clear that the force in the eye bar is equal to the force in the strand. However, due to the differences in the area of the eyebar and the area of the strand, the stresses in each element are not equal. Assuming linear elastic behavior, the stress in the strand is equal to 3.14 times the stress in the eyebar. Hence, the magnitude of the stress-range histograms measured in the eyebars must be scaled in order to establish the stress-range histograms for the strands.

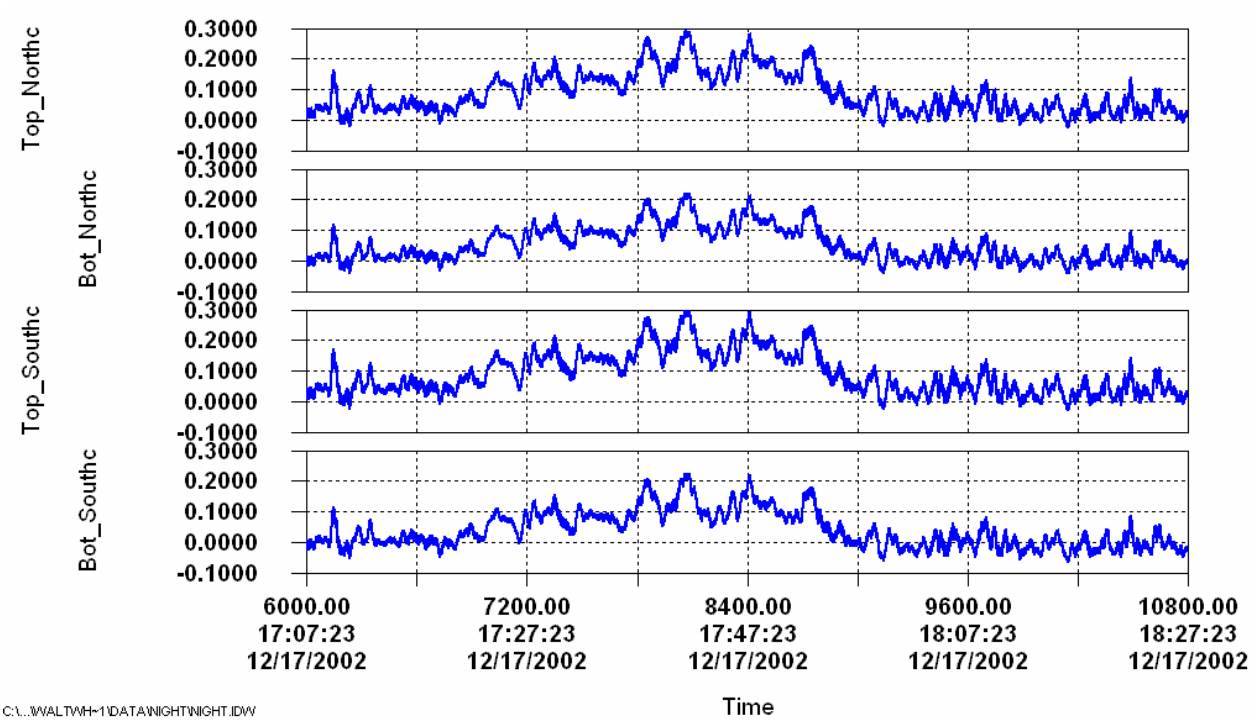

Figure 8 – Selected portion of time history response of all four instrumented eyebars during first night of monitoring (December 17, 2003)

Figure 9 is a time history plot of the entire monitoring period from December 27, 2002 to January 17, 2003 for the temperature of the eyebars and the stress in the top south eyebar. The data were collected at five-minute intervals. Hence, although the data appear continuous, the graph is actually comprised of individual data spaced at five-minute intervals. Because of the volume of data plotted, the graph appears continuous.

The data presented are the average of the five-minute interval. Each of the bold triangles on the horizontal axis represents 12:00 AM of the given day. As can be seen, there is a daily cyclic stress due to temperature fluctuations of the bridge. The magnitude of the daily stress range is small, and about 0.1 ksi. As expected, the temperature of the eyebar within the anchorage is relatively stable, as indicated by Figure 9. (*Note that this is the temperature of the eyebar itself and not the ambient air temperature within the anchorage.*) The distinct peaks or spikes shown in Figure 9 are produced by individual trucks or groups of trucks crossing the bridge. (*Recall that the sample interval is five minutes in Figure 9. Hence, individual heavy trucks, if passing during the sample, will appear as "spikes".*)

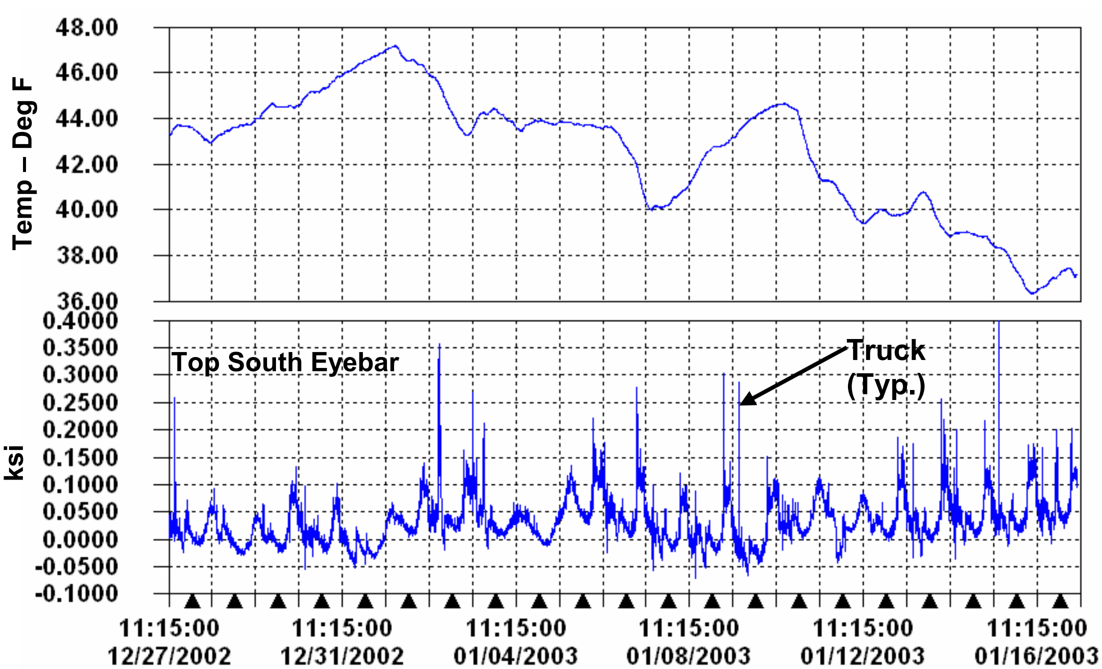

Figure 9 – Response of top south eyebar during second monitoring period from December 27, 2002 to January 17, 2003
(Data collected at five-minute intervals)

Continuous time history data were also collected for a period of just less than 12.38 days before the memory card filled on January 8, 2003, as indicated in Table 1. The size of the file was 1.34 GB. This file is very difficult to work with due to the large size. However, the data were reviewed and found to be consistent with the data recorded every five minutes and with the stress-range histograms. These data were subsequently used to develop stress-range histograms for the strands, as will be discussed.

A very small portion of the continuous time history data for the top south and top north eyebars are presented in Figure 10. These data were collected on December 30, 2002. The event shown is from a single heavy truck or group of trucks crossing the bridge. Note that the length of time to complete the cycle is around 70 seconds, which is consistent with the amount of time needed to cross the suspended spans. The total stress range is less than 0.5 ksi.

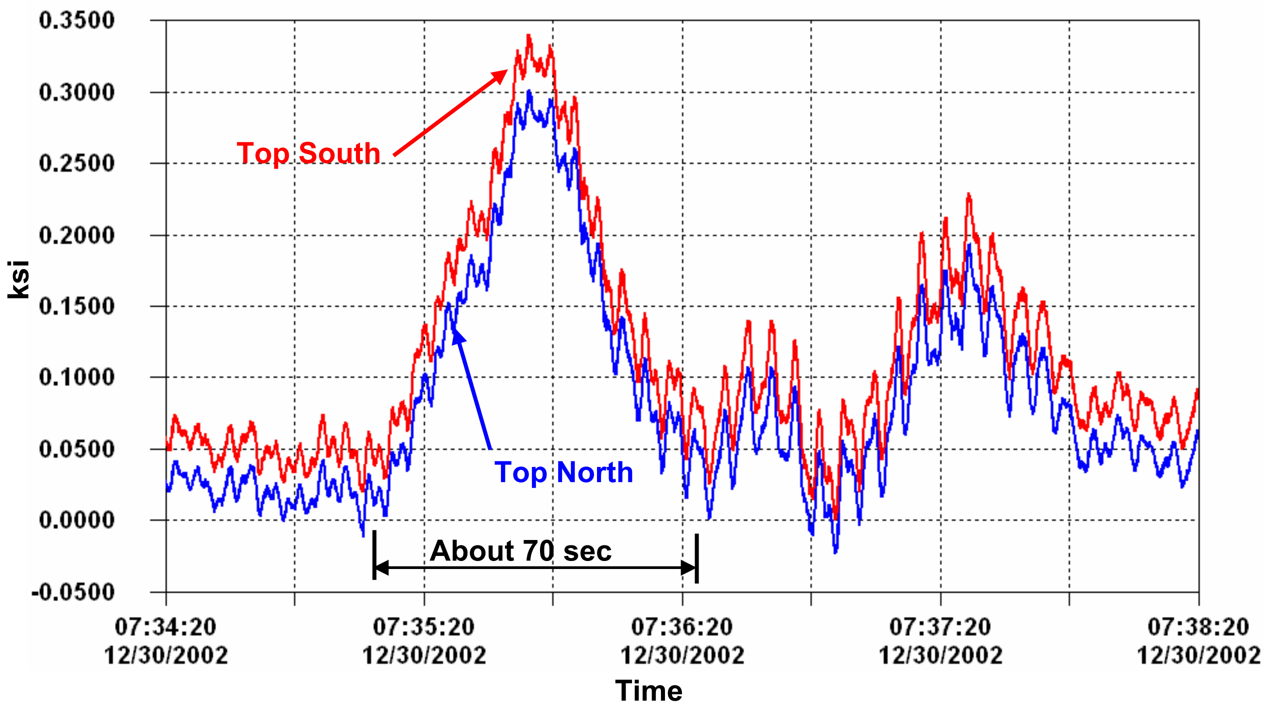

Figure 10 – Response of selected eyebars during the passage of trucks

As previously discussed, the "bins" of the stress-range histogram developed on site were broken into intervals of 1.0 ksi and stress ranges less than 0.25 ksi were not included in the count. Hence, the lowest bin included cycles between 0.25 ksi and 1.0 ksi. Because stress ranges greater than 1.0 ksi were never measured, all cycles counted fell within the first "bin". Because all cycles fell within a single bin, the average stress range of that bin is equivalent to the effective stress range (S_{reff}). In this case, the effective stress range would be calculated as:

$$S_{reff} = \left(\frac{0.25ksi + 1.0ksi}{2.0} \right) \approx 0.63ksi$$

The stress range histograms were developed continuously over a period of 20.93 days. Table 3 summarizes the results of the histograms developed for the eyebars. The scatter in the number of cycles counted is not surprising since all of the cycles were very small and either fell within the bin or were to small to be counted (*i.e., less than 0.25 ksi*). Due to small variations in the magnitude of the stress range produced in individual eyebars, some cycles may not be counted. For example, if a given event produced a stress range of 0.3 ksi in the top south eyebar, then the cycle would be counted.

However, if the same event only produced 0.2 ksi in the bottom south eyebar, a difference of only 0.1 ksi, the cycle would not be counted since the threshold for a stress range cycle to be counted was 0.25 ksi.

Location	S_{reff} (ksi)	Total Cycles	Cycles/day[1]
Top North	0.63	99	5
Top South	0.63	145	7
Bottom South	0.63	51	3

Note 1 – Cycles per day rounded to next higher full cycle

Table 3 – Summary of stress-range histograms collected for eyebars
December 27, 2002 through January 17, 2003

After the data were collected, reviewed, and stress-range histograms developed, it was thought that the histograms could simply be "scaled" up to develop the equivalent histograms for the strands attached to the instrumented eyebars. However, because all cycles fell into one bin, simply multiplying the histogram data by the scale factor of 3.14 would result in an overly conservative estimate of the fatigue damage in the strands.

In order to develop more meaningful and accurate stress-range histograms for the strands, it was decided to discard the stress-range histograms developed directly using the data logger. New histograms were then developed using the 12.38 days of continuous time history data also collected (See Table 1). This time history data could be scaled using the factor of 3.14 and then input to an algorithm used to develop new histograms using the rainflow cycle counting method. To develop these histograms, a more refined bin size and threshold cutoff was used to produce more accurate histograms. This turned out to be a very tedious process, but was quite effective. The results of this analysis are presented in Table 4 and are more representative of the cyclic stress history of the strands. The data in Table 4 are reasonable consistent, although the effective and maximum stress range for the bottom south bar are lower than the other two. The reason for this is not known. Assuming these data are representative of usual conditions, an accurate fatigue assessment of the strands can be made.

Stress Range Bin			Number of Cycles per Bin		
Min	Max	Avg.	Bottom South	Top South	Top North
0	0.25	0.125	0	0	0
0.25	0.5	0.375	3795	4808	4183
0.5	0.75	0.625	473	803	627
0.75	1	0.875	61	128	88
1	1.25	1.125	7	28	19
1.25	1.5	1.375	1	4	3
1.5	1.75	1.625	0	1	1
		S_{reff}	0.44 ksi	0.47 ksi	0.46 ksi
		S_{Max}	1.5 ksi	1.75 ksi	1.75 ksi
		N_{total}	**4,337**	**5,771**	**4,920**
		Cycles/day	**350**	**466**	**397**

Table 4 – Summary of stress-range histograms developed for strands using
12.38 days of continuous time history data

5.0 Summary

Remote monitoring of selected eyebars within the southeast anchorage of the Walt Whitman Bridge was conducted over period of several weeks. Continuous time history data were collected as well as stress-range histograms. The results of the monitoring indicate that stress ranges are relatively low in the eyebars due to live loads. The stress ranges due to daily thermal cycles of the bridge superstructure were also small during the monitoring period. Stress-histograms were developed for the strands using continuous time history data collected on the eyebars. The maximum effective stress range was 0.47 ksi at an equivalent of 466 cycles per day.