# ACOUSTIC EMISSION AND STRAIN GAGE MONITORING OF PROTOTYPE RETROFIT FOR CALTRANS STRUCTURE B-22-26 R/L I-80 SACRAMENTO RIVER (BRYTE BEND) SACRAMENTO, CALIFORNIA

**by**


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## Introduction

The Bryte Bend Bridge carries I-80 traffic over the Sacramento River near Sacramento, California. The bridge consists of two 4050-foot trapezoidal steel boxes, 36 feet wide. Its approaches are 146.5-foot simple spans 8.5 feet deep with main spans of 370 feet and 281.5 feet in length at a depth of 15.5 feet. Flanges on the sloped side and vertical center web support the composite concrete deck. In the early 1990s in-depth inspection by Caltrans personnel led to the discovery of cracks in the web of the trapezoidal box at the lower attachment point for the stiffener crossframes. A crossframe is shown in Figure 1. The cracks typically initiate around the toe of the weld that joins the vertical stiffener to the web. These sites are located at the bottom left and right corners of the crossframe as seen in Figure 1. Repeated observations showed that the cracks were growing and new ones were being initiated. In 1993, and again in 1994, researchers from Northwestern University's Infrastructure Technology Institute (ITI) used acoustic emission and strain gage monitoring techniques to provide additional confirmation of the active fatigue nature of the cracks.

Figure 1. Typical Crossframe.

Caltrans embarked on a thorough analysis of the structure that resulted in the development of two approaches to crack-mitigating retrofits. Because of the complex nature of the structure and its response to live loading, Caltrans decided it would be prudent to perform a series of tests on the structure to gain a better understanding of the effects of the retrofits on structural performance.

To accomplish this effort, they contracted with ITI to perform extensive strain and acoustic emission tests on specific details in span 19 of the structure. Testing was to be performed both before and after installation of the prototype retrofits. The experimental effort included the installation of approximately 100 strain gages in key locations on two mid-span crossframes (3 and 4). Strain measurements were made with both live traffic loading and load testing with vehicles of known weight under bridge closure. Acoustic emission monitoring was applied using live traffic loading to the prototype installation sites both before and after completion of the planned modifications to ascertain the effects of the structural modifications on fatigue crack activity. The gages were installed during the week of September 9 and the initial (pre-installation) tests were run the week of September 16, 1996. Following installation of the prototype retrofits, the second series of tests were run during the week of November 9, 1996. This report describes the test procedures and summarizes the results.

**Acoustic Emission Testing**

The objective of the AE testing is to determine the effect of the retrofit on the activity of the fatigue cracks. Crack activity was measured before and after the installation of the retrofit modifications.

<u>Test Setup</u> ITI engineers applied acoustic emission monitoring to six crack sites. The sites were located at the right, center and left corner of crossframes 3 and 4 in span 19L. Each of these sites had active fatigue cracks. Since this bridge is an all-welded structure (no extraneous acoustic noise sources were located adjacent to the crack), we were able to apply the acoustic emission using a simple multi-channel approach with first hit channel (FHC) analysis. This approach was developed and proven during previous AE testing on this structure by ITI. The FHC analysis evaluates the order of receipt of an AE signal at each of the sensors in the array. When the sensor mounted on the crack is the first hit channel, the signal had to originate at the crack. All other first hits are the result of extraneous noise sources. The array consisted of six sensors. A sensor was located at the visible crack tip and five others were placed in an array surrounding the crack tip. The six-channel approach is an improvement over the original (1993/1994) test setup that employed only four channels in that it provides additional immunity to non-crack related acoustic emission sources. A photograph of a typical AE test setup is shown in Figure 2. Dunegan Engineering Consultants Inc. type SE375 375 kHz sensors were used for the guards and a M9250 broadband sensor was used for the crack sensor. Preamplifiers with 37 dB gain were used to drive a 250-foot multi-conductor shielded coaxial cable that led from the test site on the bridge to a motor home parked under the bridge where the AE monitoring system was located. Figure 3 shows the motor home (loaned by Caltrans) and the lift bucket that was used for quick access to the testing area. Figure 4 shows the AMS3 and associated equipment set up inside the motor home. Unity gain line driving amplifiers were used to interface between the strain gage signal conditioner/data logger (Somat 2100 field computer) and the same 250-foot cable that carried the strain data to the AE monitor. The AE and strain data were recorded and analyzed with a digital AE monitor (model AMS3) manufactured by Vallen Systeme GmbH in Icking, Germany.

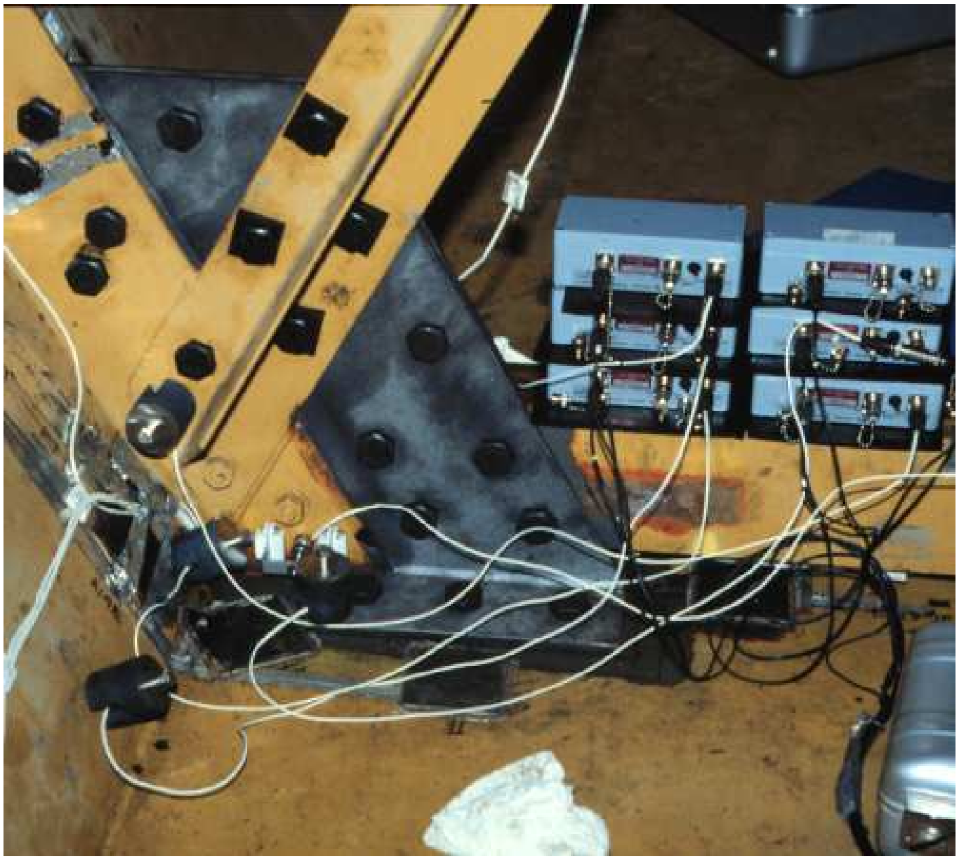

Figure 2. AE Setup.

Test Procedure Pencil lead breaks and simulated AE events, generated by pulsing each AE sensor and recording the received signal amplitude at each of the other five sensors, were used to verify AE system integrity and to balance system gain for each of the AE channels. These procedures were performed prior to each test run. Following the calibration and verification procedures data were recorded during live traffic loading for a test period of approximately 30 min. Typically, at least three data recording runs were made for each test site. The data were recorded directly on the hard drive of the AE monitoring system's PC and backed up on 100-Mb zip disks. Both conventional event based AE data and digitized wave form data were recorded. The event based data also included two channels of strain data recorded from the two strain gages mounted in the vicinity of each crack.

Results A recording threshold of 33dB was used for these tests. This threshold value is 7dB lower than the minimum threshold for reliable detection of early fatigue cracks in mild steel under high cycle fatigue conditions as determined in laboratory experiments. The low threshold setting insures a high probability of detection of crack-related AE activity. The high data throughput and dynamic range for the AMS3 system allows the use of these low threshold settings. Our experience has shown that the optimum approach to insure maximum detection probability is to use a low recording threshold and apply additional post-test thresholding or windowing to remove noise. The only penalty for this approach is large raw data files (typically

10 to 15 megabytes for 30 min. data recording time) which is no problem with the modern PC's capabilities.

Figure 3. Motor Home Used to House AE Instrumentation.

Figure 4.  AE Monitoring System.

First hit channel (FHC) analysis was used to determine the total number of crack-related hits per data recording session for any given test site.  Further analysis showed that the ratio of FHC at the crack sensor to total recorded hits was very consistent at a given test site.  This ratio expressed as a percentage is a measure of the total crack-related activity for a given crack site.  In Table 1 we see the percentage of crack-related activity as determined by FHC analysis for each of the six sites monitored.  The AE data were post-test filtered by raising the threshold to 39 dB to eliminate continuous low-level noise.  The percentage values shown in Table 1 are averaged for the multiple runs at each site (usually three or more tests of 30 min. duration).

Table 1.  Percent Total Crack Activity.

| Crossframe | Location | % Crack Activity Before Retrofit | % Crack Activity After Retrofit |
|---|---|---|---|
| 3 | R | 25.51 | 4.26 |
| 3 | C | 29.64 | 2.97 |
| 3 | L | 17.79 | 4.77 |
| 4 | R | 25.99 | 25.27 |
| 4 | C | 5.29 | 6.37 |
| 4 | L | 4.81 | 3.38 |

These results are shown in graphic form in Figure 5.

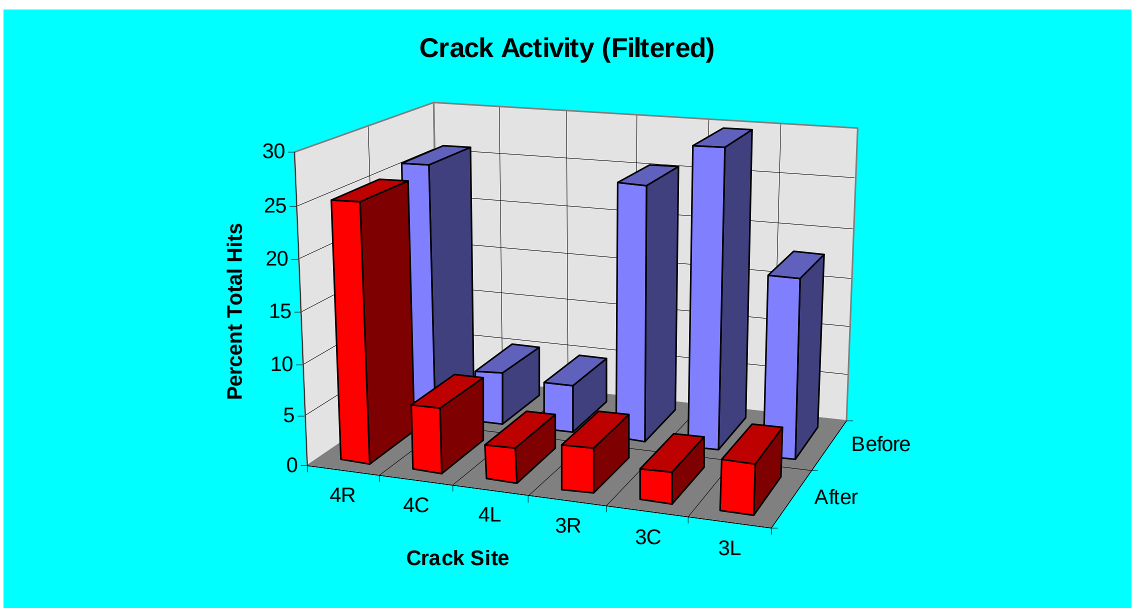


Figure 5.  Plot of AE Results for Crossframes 3 and 4.

Crossframe 3 was modified by placement of plates or shoes and knee braces at the outside corners and both sides of the center web. Crossframe 4 had the same modification with the additional feature of disconnecting the diagonal braces from their attachment points at the deck and reattaching them to an added upper horizontal cross member. The crack-related AE activity was clearly reduced by the addition of the modifications in crossframe 3. However, in crossframe 4, which had the modified diagonal stiffeners, the effect on AE activity is not measurable. These results indicate that the frame 3 type modification results in a marked reduction in crack activity as measured by AE while the frame 4 type modification has no measurable effect on the AE results.

**Strain Gage Monitoring**

A total of 92 strain gages were applied at locations specified by Caltrans prior to the pre-retrofit installation testing in September 1996. The location and numbering of each gage is detailed in Figure 8 and Appendix A. Detail A shows locations for gages 21-27 and 31-37 while detail B shows locations for gages 41-49. The objective of the strain gage installation and monitoring was to provide quantitative information about the strain distribution before and after the retrofit modifications.

Installation Pre-wired resistive foil-type strain gages mounted on weldable steel shims were chosen for this application. The gages were 350 ohm, self-temperature compensated for mild steel, and had a gage factor of 2.2. All gages were supplied by J.P. Technologies of San Bernardino, California (part #WSG-06-1-350-V3C-25). These gages permit simple and rapid field installation by means of a portable spot welding unit (Measurements Group, Raleigh, NC, model 700). Gage installation consists of four steps: surface preparation, attachment, protection, and wiring. Caltrans removed paint and scale at gage sites by grit blasting. ITI engineers performed final surface preparation by manually abrading with 400-grit silicon carbide paper and degreasing. Gages were attached by spot welding the gage shim to the bridge using multiple 30 joule spot welds. Spot welding is a permanent installation method which, if properly protected, will not degrade over time like some adhesives. Protection was an especially important consideration for this application because the gages also had to survive the retrofit process. A multi-layer system was chosen. Each gage was first covered with an adhesive Teflon patch to provide corrosion protection and a release surface so the other protective layers could be removed for inspection without damaging the gage. This was then followed by a thick layer of Dow Corning 732 RTV silicone, a 1/8-inch-thick neoprene rubber pad, and adhesive-backed aluminum tape. The gage's unique number was then written in permanent ink adjacent to the protected gage. The bulk of the wiring task was completed before installation began. Based on drawings and photographs, ITI engineers laid out a full-scale mock up of a crossframe in the lab. A photograph of the mock up is shown in Figure 6.

An individual screw terminal strip was labeled and placed at each gage location on the mock up. A board of labeled screw terminal strips was placed at the central instrumentation location. Shielded instrumentation leads were then labeled and run along the mock up, avoiding retrofit areas, from the gage sites to the central board. The individual leads were then bundled into a wiring harness for each crossframe and shipped to the bridge. Actual wiring of the gages

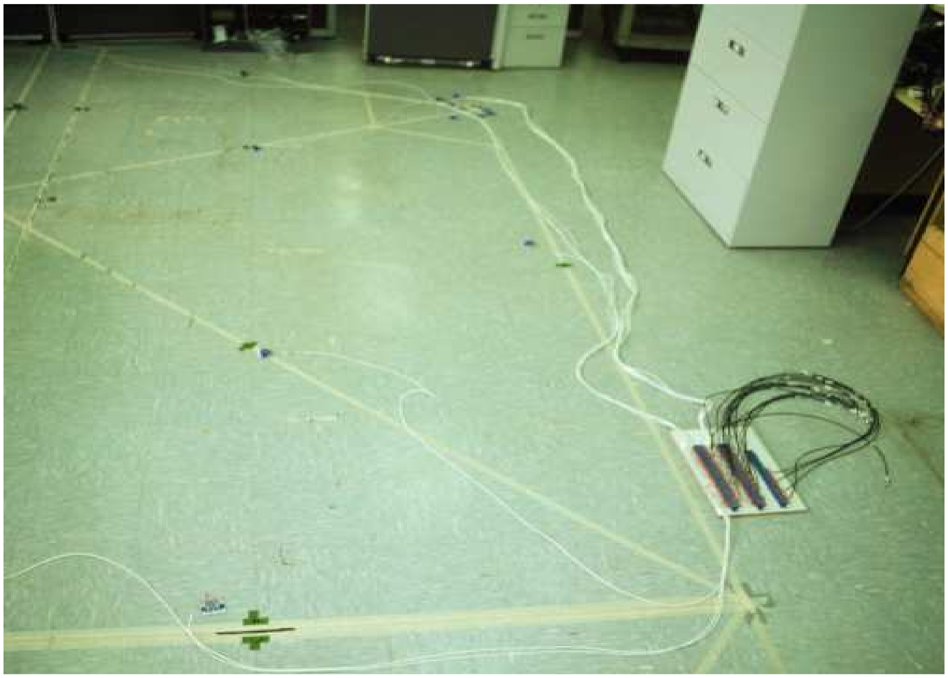

Figure 6. Crossframe Mock Up Used for Wiring Harness Development.

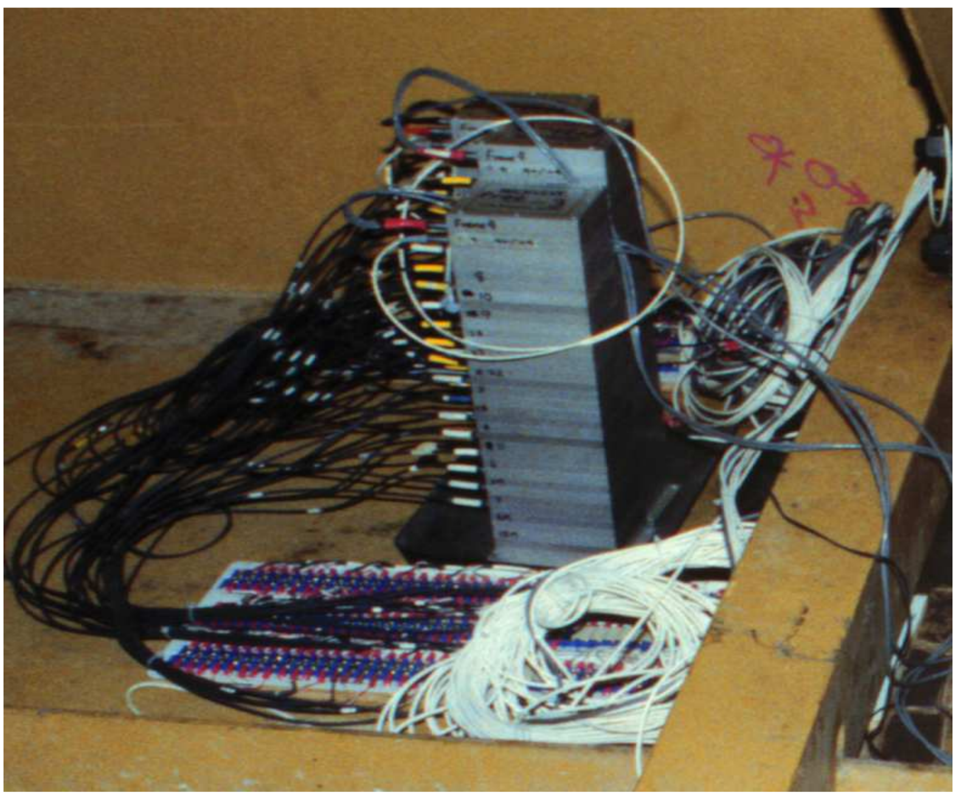

Figure 7. Somat 2100 “Stacks.”

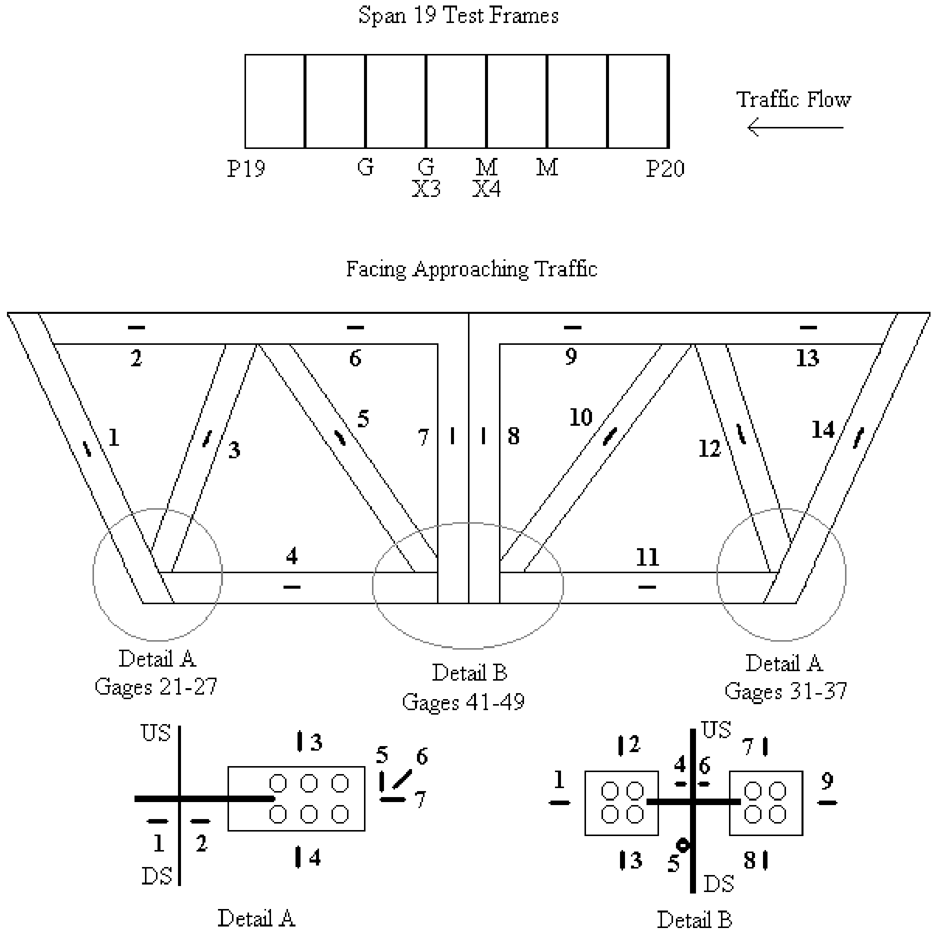


Figure 8. Location of Crossframes and Gage Layout.

consisted of unrolling and securing of the wiring harnesses, connecting the gage to its screw terminal strip, and connecting the instrumentation to the screw terminals of the central board.

Instrumentation All strain gage data were collected by means of Somat Corporation model 2100 field computers. The Somat 2100 is a modular signal conditioning, data reduction, and storage system in a rugged field-ready package. The configuration used on Bryte Bend consisted of three 2100 field computer “stacks” in a network configuration. A view of the three stacks is shown in Figure 7. Each stack processed 15 channels of data, permitting a total of 43 channels of strain data and two switch closure detection channels to be recorded simultaneously with a common time base. This network of processors was controlled by a simple serial port connection to a laptop computer. The strain gages were each connected to the Somats in a three-wire, quarter-bridge circuit. Each strain gage module is automatically calibrated against an internal precision resistor by means of software commands from the laptop computer. Caltrans placed tape switches on the deck over crossframes 3 and 4. These were connected to the two analog input channels on the Somat. These provided a “mark” in the data whenever a truck passed over a crossframe. The sampling rate used during all tests was 50 Hz, with the programmable low pass filters set to a 10-Hz cutoff. All gages and wiring were left in place as a permanent installation to facilitate future monitoring. Any instrumentation capable of reading 350-ohm resistive strain gages in a quarter-bridge configuration may simply be attached to the labeled screw terminals on central board.

Test Procedure Strain gages were monitored under both live traffic and controlled loading conditions before and after the retrofit modifications. Time history and rain flow data were recorded for select gages under live traffic loading during the week preceding each controlled load test. Time history runs were approximately 30 minutes long. Rain flow runs were approximately 24 hours long. The controlled load tests consisted of static and dynamic loading of the test span by trucks of known weights. The testing procedure specified by Caltrans was as follows:

**BRYTE BEND BRIDGE, SPAN 19 LEFT**
**BASIC LOAD TEST PLAN**
**SEPTEMBER 21 - NOVEMBER 16, 1996**

The basic load test plan will consist of three distinct portions done in sequence. This sequence will be run two times: once while readings are taken at frame #3, and once again at frame #4. There will be an approximate 20-minute break between these sequences to change strain recording computers from one frame to the next.

The load test sequence will be as follows:

1a) A single static three-axle truck will be placed along the shoulder (line b) and the rear axles of the truck will be positioned over crossframes 6, 5, 4, and 3 for strain readings at each frame;

1b) The truck will move to the number 3 lane (line a) and the rear axles of the truck will be positioned over crossframes 6, 5, 4, and 3 with strain readings recorded at each frame;

1c) The truck will move to the number 2 lane (line c) and the rear axles of the truck will be positioned over crossframes 6, 5, 4, and 3 with strain readings recorded at each frame.

In summary, a total of 12 placements will occur. At each placement, a strain reading will be recorded.

2) Next, two static five-axle trucks will be placed in the number 2 and 3 lanes over a test crossframe. At this placement, a strain reading will be recorded.

3) Finally, two dynamic five-axle trucks will be run at 55 mph in the number 2 and 3 lanes. During this run, strain readings will be recorded.

These tests will be performed during limited traffic control. The number 2 and 3 lanes will be closed off with traffic flow restricted to the number 1 lane. Trucks will be readied and instrumentation prepared for testing during these restricted flow times. When ready, traffic will be stopped in the number 1 lane and strain readings will commence. It is hoped that a full sequence can be completed with a single stop; however, it may be that we will have to suspend operations during the sequence to allow traffic queues to diminish. If this is the case, we will resume the sequence when traffic allows until complete. Erol Kaslan will coordinate traffic control and truck placement on the deck; Dan Hogan will coordinate strain readings with those inside the bridge.

Schedule of Events:

| | |
|---|---|
| 0630 | All parties will arrive at site (SHARP) |
| 0630-0700 | Traffic control will be set, test trucks positioned, and instrumentation readied for readings. Strip switches need to be installed on the deck and hooked up at this time. |
| 0700-0745 | First sequence of tests performed. |
| 0745-0815 | Instrumentation switched from frame #3 to frame #4. |
| 0815-0900 | Second sequence of tests performed. |
| 0900-0930 | Traffic control removed. |

This test procedure was followed without incident. The September 21 data file for crossframe 3, right bay load tests was corrupted. There is no data for 18 of the gages in that bay during load tests one through three. One additional test was performed on November 15. Dynamic test three was repeated with an additional three-axle truck, in the number three lane, following immediately behind the five-axle trucks.

<u>Results</u> All strain readings taken during the live traffic and controlled loading are included on the raw data zip disk accompanying this report. The files may be viewed with Somat TCS or EASE software. ASCII-format files can be provided upon request. Please note that live traffic data were recorded over a period of days with different gages monitored at different times. Static and dynamic controlled loading strain data are recorded on a common time base for each crossframe. Strain readings recorded during the static load tests are summarized in Appendix B. The dynamic test results are shown graphically in Appendix C. Truck weights and speeds were similar for all dynamic tests. Direct comparison between the peak strain values for each gage during the dynamic tests offers the most straightforward means to understand strain distribution before and after the retrofit modifications. All of the remaining comments apply only to the

dynamic tests. Dynamic test before and after readings for all gages are provided in tabular format in Appendix D. All changes in excess of 20 μstrain are detailed in Table 2.

Table 2. Gages Showing Significant Change (>20 strain) After Retrofit.

| **CROSSFRAME 3 TEST 3 (Dynamic)** | | | | |
|---|---|---|---|---|
| Gage # | Gage Description | Before | After | Change |
| 3 | Left Side Outer Diagonal Stiffener | -90 | -70 | 20 |
| 4 | Lower Left Side Horizontal Stiffener | 40 | 0 | 40 |
| 5 | Left Side Inner Diagonal Stiffener | -110 | -60 | 50 |
| 6 | Upper Left Inner Horizontal Stiffener | 20 | -60 | 80 |
| 21 | Left Web at "Shoe" Transverse | -50 | 10 | 60 |
| 27 | Left Flange at Shoe Rosette Transverse | -10 | 10 | 20 |
| 41 | Center "Shoe" Left Side Left Transverse | -20 | 10 | 30 |
| 43 | Center "Shoe" Left Side Longitudinal (DS) | 90 | -10 | 100 |
| 44 | Center "Shoe" Left Side Right Transverse | 20 | 0 | 20 |
| | | | | |
| **CROSSFRAME 4 TEST 3 (Dynamic)** | | | | |
| Gage # | Gage Description | Before | After | Change |
| 1 | Left side Web Stiffener | -10 | -30 | 20 |
| 3 | Left Side Outer Diagonal Stiffener | -150 | 0 | 150 |
| 4 | Lower Left Side Horizontal Stiffener | 50 | -10 | 60 |
| 5 | Left Side Inner Diagonal Stiffener | -80 | 10 | 90 |
| 8 | Right Center Vertical Stiffener | 10 | -30 | 40 |
| 9 | Upper Right Inner Horizontal Stiffener | -10 | 20 | 30 |
| 10 | Right Side Inner Diagonal Stiffener | 110 | 90 | 20 |
| 11 | Lower Right Side Horizontal Stiffener | 20 | -10 | 30 |
| 12 | Right Side Outer Diagonal Stiffener | -140 | -90 | 50 |
| 21 | Left Web at "Shoe" Transverse | -50 | -30 | 20 |
| 22 | Left Flange at "Shoe" Transverse | 40 | -40 | 80 |
| 23 | Left Flange at "Shoe" Longitudinal (US) | 100 | 120 | 20 |
| 24 | Left Flange at "Shoe" Longitudinal (DS) | 80 | 110 | 30 |
| 27 | Left Flange at Shoe Rosette Transverse | -20 | -40 | 20 |
| 31 | Right Web at "Shoe" Transverse | -100 | 90 | 190 |
| 32 | Right Flange at "Shoe" Transverse | 110 | 10 | 100 |
| 37 | Right Flange at Shoe Rosette Transverse | 0 | -20 | 20 |
| 41 | Center "Shoe" Left Side Left Transverse | 0 | -50 | 50 |
| 44 | Center "Shoe" Left Side Right Transverse | 10 | -50 | 60 |
| 46 | Center "Shoe" Right Side Left Transverse | -70 | -20 | 50 |
| 47 | Center "Shoe" Right Side Longitudinal (US) | 90 | 110 | 20 |
| 49 | Center "Shoe" Right Side Right Transverse | -10 | -80 | 70 |

The measured response of crossframes 3 and 4 are similar before the retrofit for all gages monitored. All monitored crossframe 3 gages inside the corners spanned by the gusset plates

(3X21, 3X22, 3X44) show dramatic reductions to near zero strain. These gages are the closest to the cracks. Most gages elsewhere in the crossframe show reduced strain magnitude or are driven into mild compression. The only exceptions to this are gages 3X21, 3X27, and 3X41 which show a load reversal to only 10 µstrain tension. One notable change involves gages 3X42 and 3X43, the left center upstream and downstream longitudinal floor gages. Before the retrofit they showed 90 µstrain tension each. After the retrofit 3X42 increases slightly to 100 µstrain while 3X43 reverses to 10 µstrain compression. This asymmetry after the retrofit suggests bending in the floor near the shoe. This effect was not present in the other shoe monitored in this crossframe.

Crossframe 4’s strain measurements are more complex. Unlike in crossframe 3, crossframe 4 gages inside the corners spanned by the gusset plates (4X21, 4X22, 4X31, 4X32, 4X44, 4X45, 4X46) do not show reductions to near zero strain. In the left corner gage 4X21 shows a slight reduction in compression while 4X22 shows a reversal into slight compression. In the right corner gage 4X31 shows a very dramatic strain reversal into tension while 4X32 shows a reduction in tension to near zero. In the middle corners, gage 4X44 shows a reversal from near zero tension to moderate compression while gages 4X45 and 4X46 show moderate reductions in tension. Longitudinal floor gage readings changed little and showed no large asymmetry. Cross member gages in the left bay (4X3, 4X5) showed dramatic reductions to near zero. Cross member gages in the right bay (4X10, 4X12) showed slight reductions with the inner in tension and the outer in compression. Horizontal stiffener gages 4X4, 4X9, 4X11 reversed into compression. Gage 4X1 (left side web stiffener) showed a change from 10 µstrain to 30 µstrain compression. Gage 4X14 (right side web stiffener) showed no change. Gage 4X7 (left center vertical stiffener) showed an increase from 20 µstrain to 40 µstrain compressive, while gage 4X8 (right center vertical stiffener) shows a load reversal from 10 µstrain tension to 30 µstrain compression. These two gages are mounted on stiffeners on opposite sides of the same center web.

**Summary**

Acoustic emission (AE) and strain monitoring techniques have been applied to the two retrofit designs that are candidate fatigue-crack mitigation approaches for the Bryte Bend bridge. The AE results clearly show that one design approach (crossframe 3) markedly reduces the measurable crack activity while the design used on crossframe 4 makes no measurable difference in AE as observed before and after installation. The strain data agree with these findings. The addition of the shoes in the outside corners and center has greatly reduced the strain in the bottom flange and web area that are in the vicinity of the cracks on crossframe 3. However, the crossframe 4 modification that consisted of disconnection of the diagonal braces from the deck and reattachment to an additional horizontal cross member, in addition to the shoes in the corners, does not reduce these strains and in some cases actually increases them and switches them from compression to tension. These tests would appear to indicate that the modification to crossframe 3 is more effective in mitigating the fatigue cracks.