

Noise Localization via Acoustic Emission Monitoring on a Rolling Leaf Bascule Bridge

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EXECUTIVE SUMMARY

Acoustic emission (AE) testing was used to identify the source of audible “bangs” generated during opening and closing of a large, double-leaf rolling-lift bascule bridge. The data were analyzed using a combination of well-established AE techniques, including first hit analysis (FHA), planar location analysis, and linear location analysis. The FHA results indicate that the audible noises originate along the interface between the bascule girder and the curved forging on which the leaf rolls during opening and closing. More specifically, planar location analysis strongly suggests that the bangs occur along this interface near the point of contact between the curved upper forging and the flat bottom forging as the bascule girder rolls along.

Planar micro-location analysis at a single tested location specifically ruled out the bolts (both tapped and turned) that connect the bascule girder to the curved forging as the source of the AE activity. Rather, the AE events are distributed along the interface between the bascule girder and curved forging. Furthermore, first-hit and linear location analyses ruled out the pinion bearing, machinery strut, and flat bottom forging along which the bascule rolls during lifts as the source of the bangs.

EQUIPMENT AND METHODS

All acoustic emission tests performed during this study were made using a six channel AMSY-5 monitor, VS375-RIC 375 kHz-resonant piezoelectric transducers with integral preamplifiers, and MAG4R magnetic sensor hold downs, all from Vallen-Systeme GmbH of Icking, Germany. AE sensors were acoustically coupled to the structure with Dow Corning high vacuum silicone grease and the bridge paint was not removed. Our testing method was consistent with that described in the project proposal and prior noise localization studies performed by ITI¹. Additionally, two Kaman Instrumentation KD-2300 1SU eddy-current displacement sensors and two Schaevitz Accustar II electronic clinometers were affixed to the bridge and connected to the AMSY-5’s parametric inputs in order to provide additional information during AE monitoring. A digital video (DV) camcorder was used to record all testing runs.

The DV tapes were transferred to a PC for processing. They were edited into discrete files for each test run, each containing only the scenes when the AE system was active. The audio track was then extracted to wav-format digital sound files and edited with a graphical audio editing application to obtain the time index of each audible bang. The bangs were clear and distinct, both to the human ear and when the audio waveform was plotted. However, there is no method to discern a bang originating from the bascule girder under test versus the other side. Based on the list of bang time indices and the known time indices of the AE calibration pulses at the beginning of each test, the time index offset between the AE data and audio track was calculated, allowing direct comparison of the two.

The AMSY-5 was configured with an instrument recording threshold of 50.1 dB, a gain setting of 34, and transient waveform recording enabled on channels 1 & 2. Due to the extremely numerous and energetic acoustic sources created at the contact point between the curved and flat forgings during a normal open-

¹“Evaluation of the Segmental Casting Attachments”, Prine & Oleksy, 1994

ing, extensive post-processing filtering was employed to eliminate all but the sources of audible bangs. Through several trial iterations and comparison with the DV audio track, a post-processing filter excluding all events except those with amplitudes of 95 dB or greater and an energy of 600,000 AE energy units or greater was selected. This filter choice was validated by comparison of filtered events with audible bangs logged from the audio track extracted from digital video recorded during testing.

TESTS PERFORMED

ITI engineers performed ten test runs over two days. Each run included acoustic emission monitoring during a full opening and closing of the bridge leaf under testing. Two of the ten runs were performed on the quiet east leaf as a control. The experimental design of these tests was guided by the stated goal of our proposal: to determine the physical location of the source of the audible bangs emitted during bridge movement. Based on initial data and conversations with the design engineers, the number and focus of the tests was expanded to address specific concerns such as displacement of the curved forging and correlation of events with bridge position. Table 1 summarizes the test runs. AE arrays A–D will be described with the various analyses for which they were respectively employed. On some runs, bascule girder tilt and sub-mil resolution displacement data were taken to provide insight into the mechanism producing the bangs. This was done above and beyond our original commitment to locate the source of the bangs.

Table 1: Summary of test runs. Displacement Locations 2–4 indicate that a displacement transducer was installed at the bascule girder/curved forging interface directly “above” (i.e., toward the pinion) the AE transducer at Location 2–4. Displacement Locations 2A and 4B represent locations outside the AE array, chosen for proximity to the contact area when the leaf was fully open or closed, where only displacement data were taken.

Test Run	Date	Time	Location	AE Array	Displacement Locations	Tilt
1	9/18/08	11:42	W leaf, S bascule girder	A	2, perpendicular 2	N
2	9/18/08	12:40	W leaf, S bascule girder	A	2, perpendicular 2	N
3	9/18/08	16:50	W leaf, S bascule girder	A	2, 4	N
4	9/18/08	17:07	W leaf, S bascule girder	A	2, 4	N
5	9/18/08	17:48	W leaf, S bascule girder	A	2A, 4B	N
6	9/19/08	9:05	W leaf, N & S bascule girders	B	2A, 3	N
7	9/19/08	10:48	W leaf, S bascule girder	C	4B, 3	Y
8	9/19/08	12:21	W leaf, S bascule girder	D	4B, 3	Y
9	9/19/08	14:27	E leaf, N bascule girder	A	3, 4	Y
10	9/19/08	14:50	E leaf, N bascule girder	A	3, 2A	Y

We used a coordinate system with the origin at the point of contact between the bascule girder and bottom forging when the leaf is fully closed. For consistency with the standard Cartesian system, the bascule girder translates in the negative direction along the x -axis as the leaf opens. Figure 1 shows an overview of the bascule girder/track area with the primary (Array A) sensor locations and coordinate system.

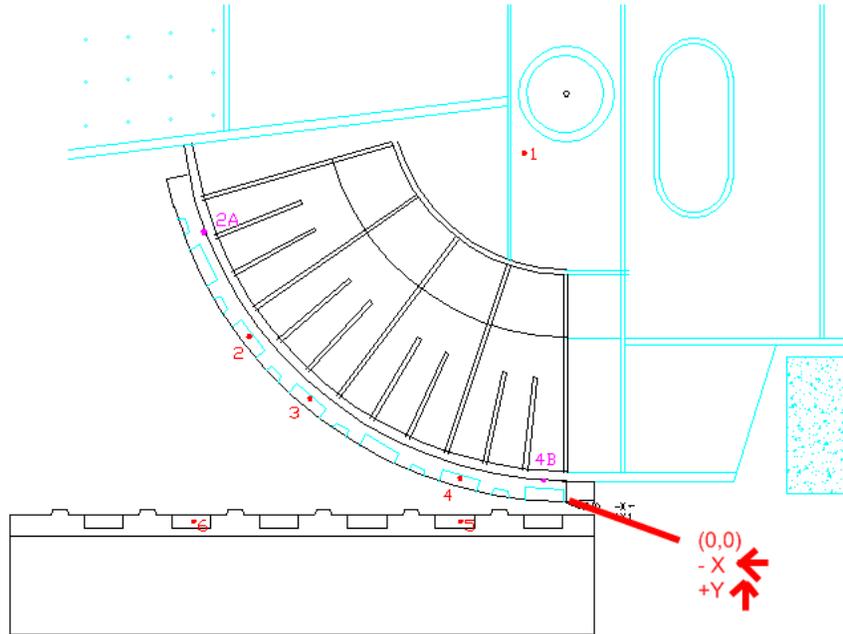


Figure 1: Overview of bascule girder/track area showing primary (Array A) sensor locations and the coordinate system used in analysis. Note that for planar location along the bascule girder, the coordinate system rotates and translates with the movement of the bridge; i.e., the coordinate system is defined by sensors 2, 3, and 4. Locations 2A and 4B were used exclusively for the displacement measurements described in Analysis #5.

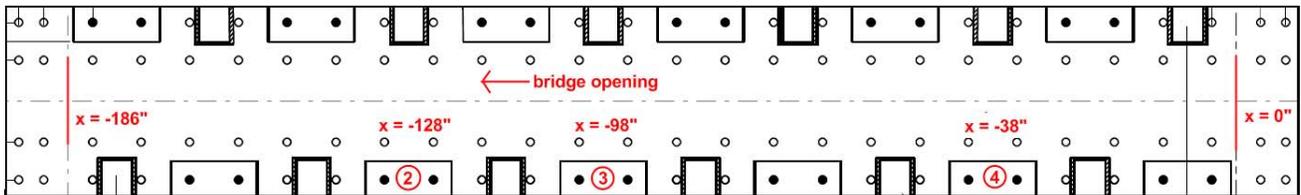


Figure 2: Reflected view of AE transducer locations and one-dimensional coordinate system used in “un-rolled” linear location analysis along the curved upper forging bolted to the bascule girder. Dimensions represent distances along the arc of the forging, not chord distances. Overview of bascule girder/track area showing primary (Array A) sensor locations and the coordinate system used in analysis. Note that for planar location along the bascule girder, the coordinate system rotates and translates with the movement of the bridge; i.e., the coordinate system is defined by sensors 2, 3, and 4.

ANALYSIS #1: FIRST-HIT CHANNEL

As stated in our original proposal, audible noises in large steel structures are extremely difficult to localize by means of audible sound. This is because steel provides an excellent path for sound. Steel can carry and re-radiate sound over great distances. Furthermore, because the velocity of sound in steel is over 17 times faster than in air, re-radiated sound from the steel can appear to originate from multiple sources. ITI approaches the sound localization problem in steel structures by applying AE monitoring to localize the sound. The AE technique uses high-frequency contact sensors coupled to the steel structure. Processes such as stick-slip in bearings and bolt fretting typically produce acoustic energy in a very broad spectrum. The logic behind this application of AE monitoring to the noise localization problem is that the high frequencies (a few hundred kilohertz) are carried with little attenuation in steel but are quickly attenuated in air. Therefore, an array of high frequency sensors attached to the structure can accurately determine the location of the source by simple time-of-arrival measurement. This approach, coupled with high-pass filtering, eliminates the confusing airborne low frequency sound and generally produces unambiguous source location.

This general time of arrival technique is known as “first hit analysis” (FHA). When a discrete physical process, such as stick-slip, produces acoustic energy, it propagates outward as sound waves along all available paths in the structure. Each discrete physical process generating bursts of acoustic energy corresponds to the AE term “event.” When sound waves from an event reach an AE transducer and its amplitude is above the recording “threshold,” it is termed a “hit” and the AE monitor records information about that sound wave for a set period of time. This means that on our six channel monitor, one event can cause from one to six hits to be logged for a single event. We can determine which sensor is the “first hit” based on time of arrival. Logically, the source of the sound will be closest to the sensor with a first hit for that event. Our choice of sensor layout combined with the geometry of the structure and the average of first hits per lift cycle at each sensor can be used to determine the location of the acoustic source.

Our primary sensor layout for FHA was Array “A,” shown in Figure 3. This is the configuration included in our initial testing proposal. One AE sensor was placed on the bascule girder near the pinion gear, three on the curved upper forged track, and two on the lower straight forged track. This testing was performed on one bascule girder on each leaf. We compared the average number of first hits per lift cycle on the west-south bascule girder, which exhibits the audible bangs, to the east-north bascule girder, which is quiet and serves as a baseline for normal operation. Figures 4 and 5 clearly show that the source of the bangs is a region including the curved outer periphery of the bascule girder and the curved forging.

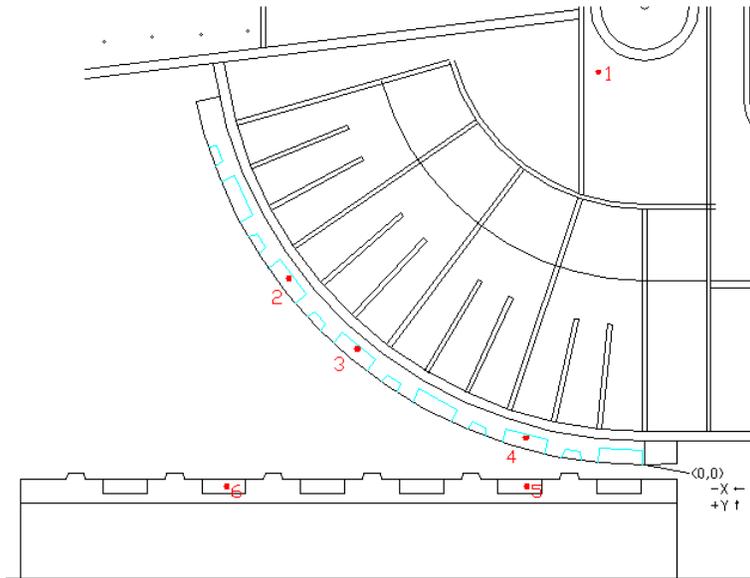


Figure 3: AE array “A” was deployed similarly on the west leaf, south bascule girder and east leaf, north bascule girder. This array was used for first-hit channel analysis.

Table 2: First-hit analysis of high-energy AE events (energy > 600,000 AE energy units)

Channel	Total hits (percentage of total hits) on west-south bascule during Runs 1–5	Average hits per cycle during Runs 1–5	Total hits on east-north bascule (Runs 9–10)
1	4 (2.0%)	1	0
2	53 (26.8%)	11	0
3	58 (29.3%)	12	0
4	83 (41.9%)	17	0
5	0 (0.0%)	0	0
6	0 (0.0%)	0	0

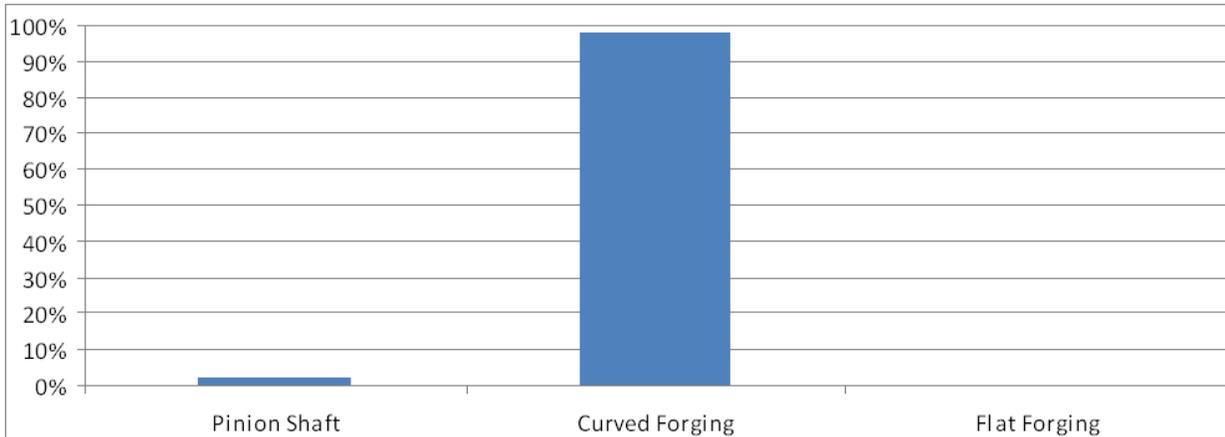


Figure 4: Results of first-hit analysis on the west leaf, south bascule girder. 98% of high-energy AE events hit Channels 2, 3, or 4 first, indicating that they originated near the curved forging-bascule girder interface. The balance originate near the pinion shaft; no high-energy AE events originate from the flat forging.

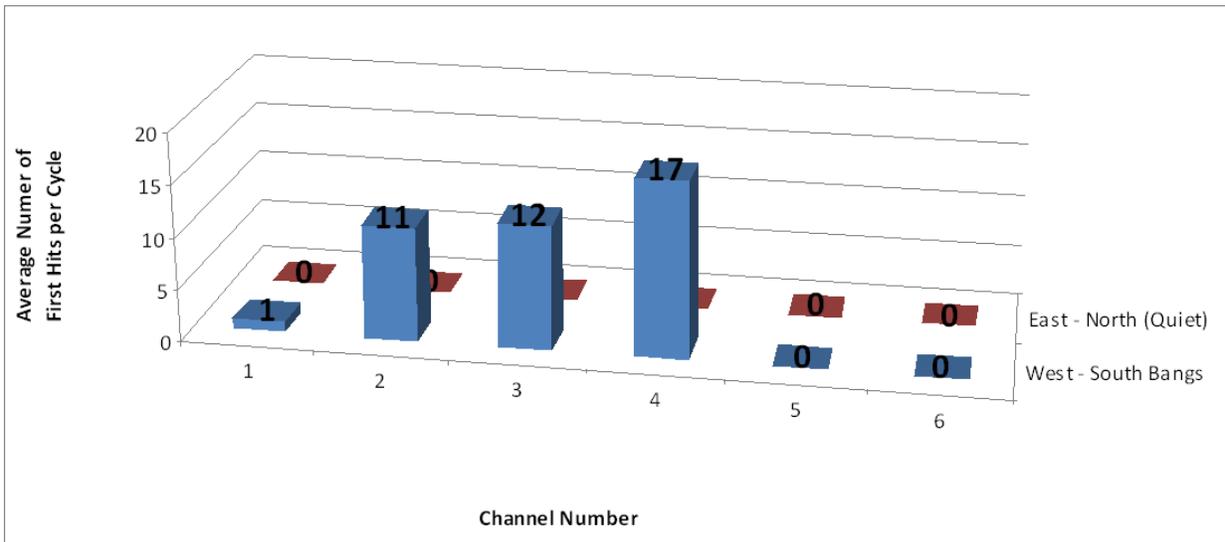


Figure 5: Comparison of first-hit results from high-energy AE events on the noisy west-south bascule girder and the quiet east-north bascule girder. Nearly all the high-energy AE events on the noisy bascule girder hit Channel 2, 3, or 4 first, indicating the events originated near the curved forging-bascule girder interface. No high-energy AE events were recorded on the quiet bascule girder.

ANALYSIS #2: NORTH VS. SOUTH BASCULE GIRDER AE ACTIVITY

In this analysis we attempted to determine if the audible bangs were produced at one or both bascule girders on the west side of the bridge. Additionally, we sought to quantify the ratio of bangs produced on the south bascule girder versus those produced on the north bascule girder. The sensor layout shown in Figure 6 was applied to the south bascule girder on the west leaf. Sensors 5 & 6 were placed on the machinery strut, a large transverse beam between the bascule girders. Sensor 5 was at the south end of the floor beam, just behind the bascule girder and Sensor 6 was at the midpoint of the floor beam.

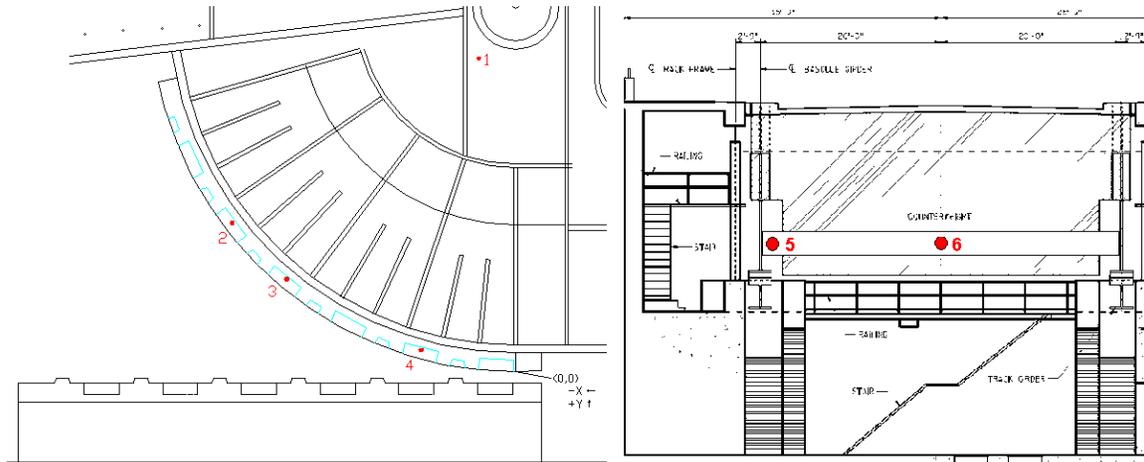


Figure 6: AE array “B” was deployed on the west leaf, with AE Sensors 1–4 on the south bascule girder and Sensors 5 and 6 on the transverse machinery strut. This array was used for comparison of AE activity from the north vs. south bascule girders.

It was hoped that the acoustic signals of the audible bangs would be of high enough amplitude that they would be consistently measurable at the midpoint of the floor beam, 20 feet from each bascule girder. By looking at the first-hit counts at Sensors 5 and 6, we could then quantify the relative acoustic activity originating from each bascule girder. However, when the energy filter corresponding to our best understanding of the AE characteristics of the audible bangs was applied, the results were inconclusive. This may be attributed to attenuation of the acoustic signals along the 20 foot path between Sensors 5 and 6 or the existence of other AE sources or other propagation paths along the structure. A more definitive test would have been to have AE sensors on both bascule girders, but we did not have sufficient length cabling at the time of testing.

ANALYSIS #3: “UNROLLED” LINEAR LOCATION ALONG BASCULE GIRDER

Acoustic emission monitoring can be used to locate acoustic sources in one, two, or three dimensions by analysis of geometry, the speed of sound in the material, and the signal arrival times at each sensor. For this test we performed the simplest location analysis in one dimension by “unrolling” the curved upper forging on the bascule girder and treating it as if it was a straight rod. This is a valid assumption due to the geometry and our use of guard sensors to eliminate extraneous sources; the sensor layout is shown in Figure 7.

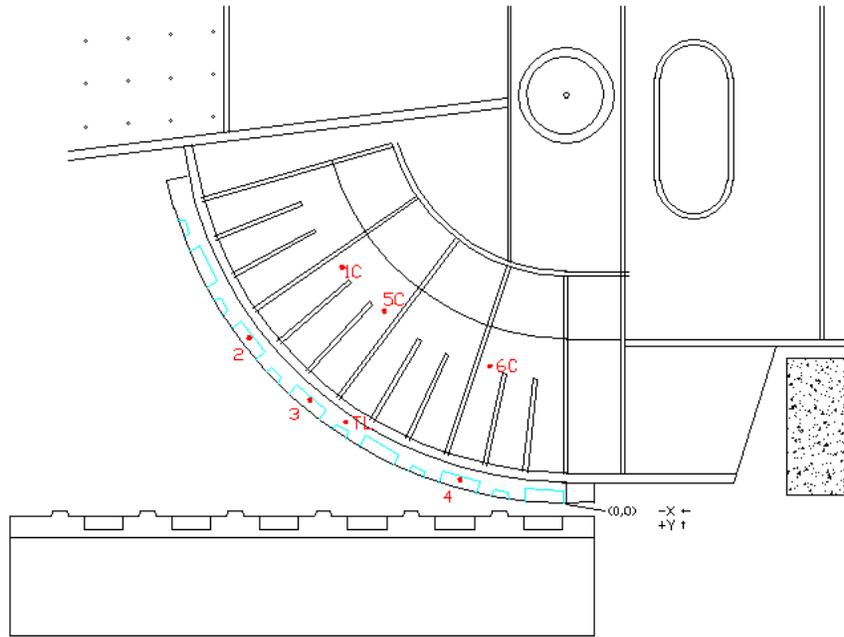
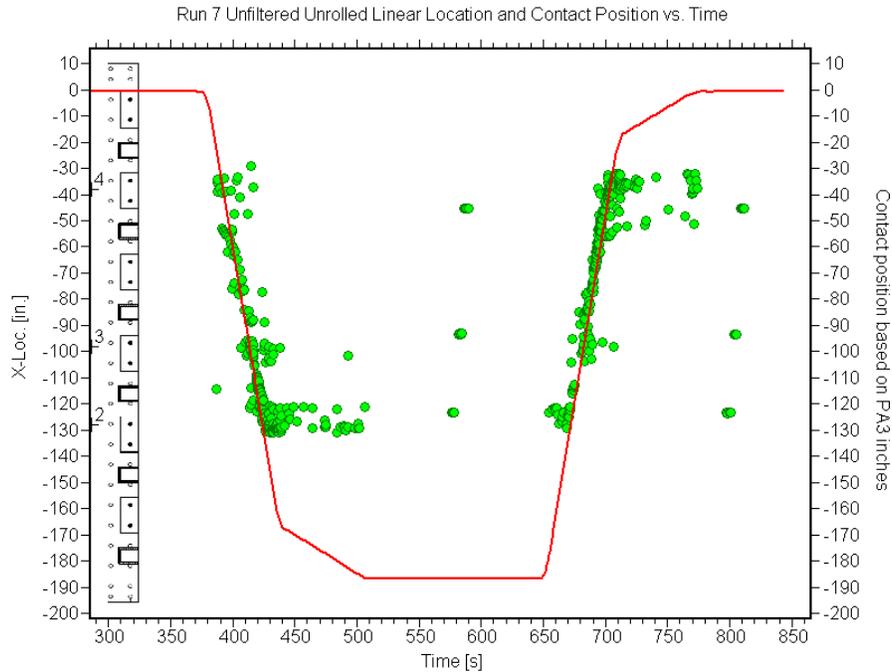


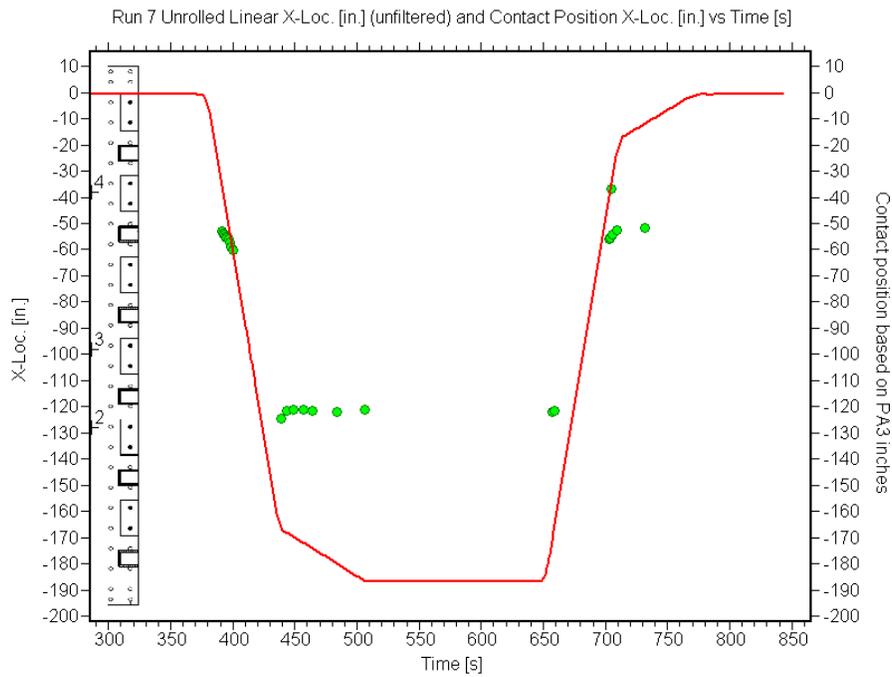
Figure 7: AE array “C” was deployed on the west leaf, south bascule girder for linear location analysis by “unrolling” the curved upper forging on the bascule girder. The three sensors closest to the pinion were used as guard sensors to intercept noise not coming from the curved forging.

Figure 8 shows the location of AE hits along the “unrolled” upper forging along with the position of the contact area as the bridge opens and closes.

Additionally, we performed planar location analysis on the data from Run 7. In this configuration, Channels 1, 5, and 6 were used in combined guard/normal mode; that is, AE events that reached those channels first were rejected outright, eliminating any noise from the pinion, while events that reached those channels after reaching Channels 2, 3, or 4 were located using the time-of-arrival data from all channels. The results, shown in Figure 9, indicate that the bulk of the locatable events originate along the arc of the bascule girder and curved forging. While the precision of the planar location results was reduced due to the complicated geometry of the bascule girder/curved forging interface, the location results seem to strongly support the hypothesis that the bangs originate somewhere along the bottom arc of the bascule girder.

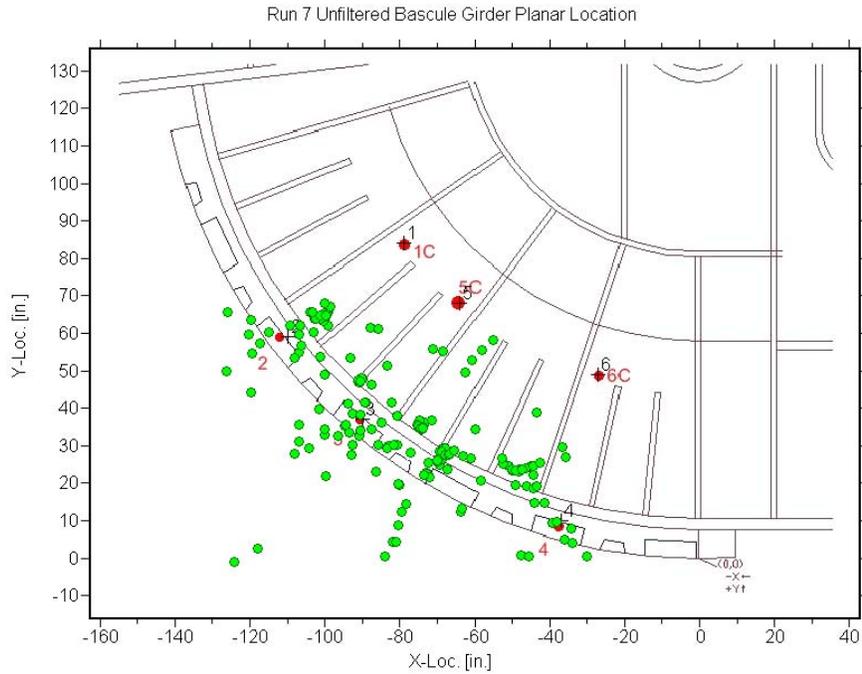


(a) Unfiltered

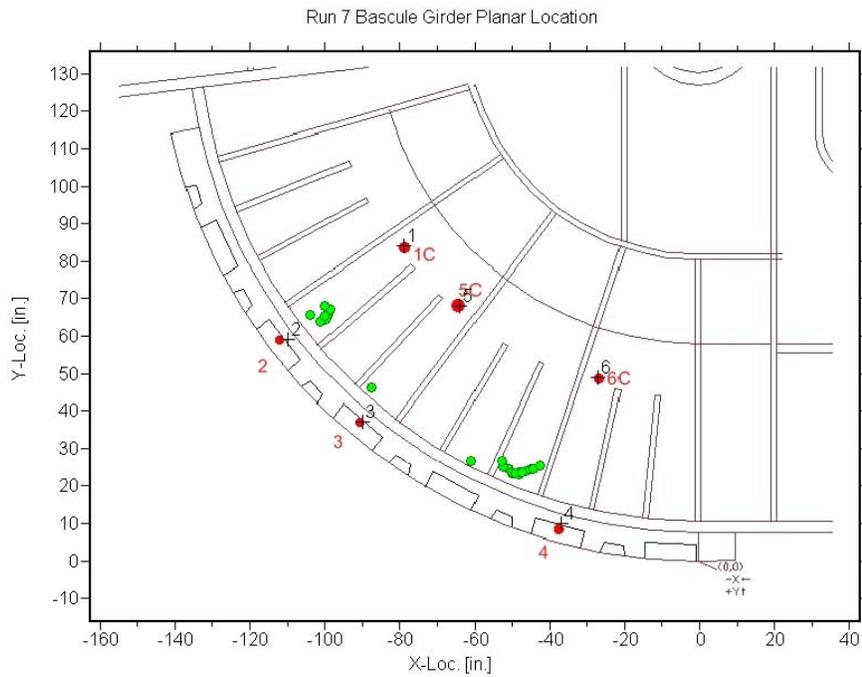


(b) Filtered, minimum energy of 600,000 AE energy units

Figure 8: Linear location along the upper forging during opening and closing of the west leaf in Run 7, unfiltered (a) and filtered (b).



(a) Unfiltered



(b) Filtered, minimum energy of 600,000 AE energy units

Figure 9: Planar location along the upper forging during opening and closing of the west leaf in Run 7, unfiltered (a) and filtered (b).

ANALYSIS #4: MICRO-LOCATION AROUND BOLTS ON BASCULE GIRDER

An AE test run was performed at the location shown in Figure 10 on the west-south bascule girder to determine if the bolts connecting the bascule girder to the curved forging were the source of the audible bangs. Transducers 1–4 were placed on the outside of the bascule girder between the bolts as shown in Figure 11.

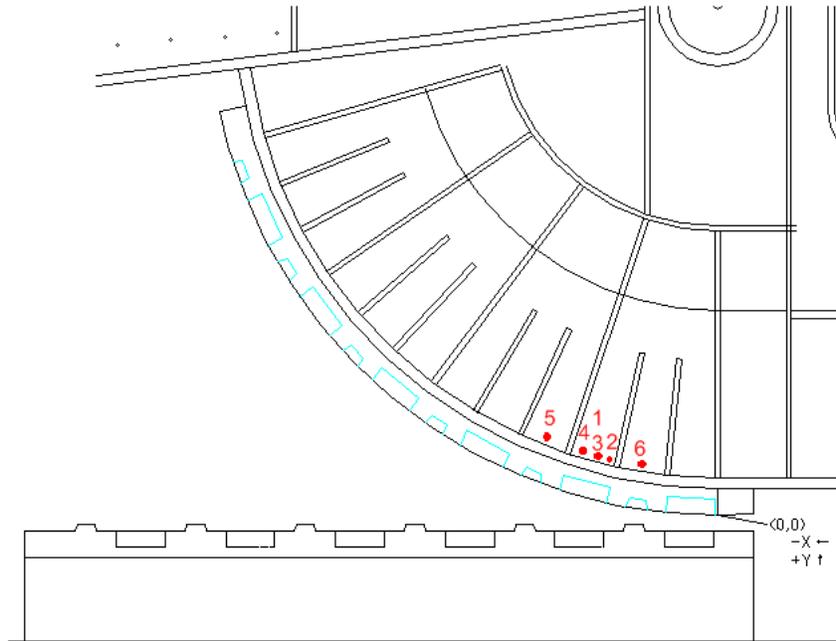


Figure 10: AE array “D” was deployed on the west leaf, south bascule girder for micro-localization of AE activity around the bolts connecting the curved upper forging to the bascule girder.

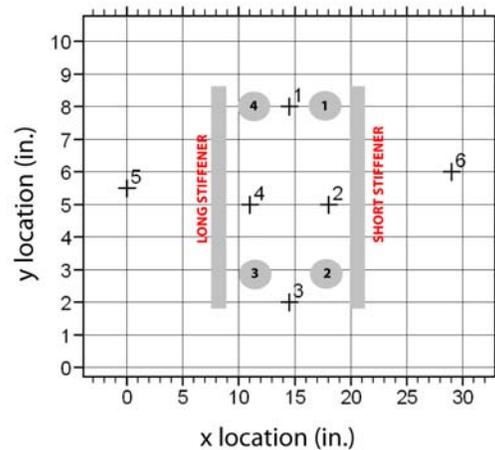


Figure 11: Photograph and drawing of array of AE transducers on bascule girder bolts near Location 4

AE Transducers 5 and 6 were placed approximately fifteen inches to the left and right of Transducers 4 and 2, respectively, on the opposite sides of the two radial stiffeners adjacent to the bolt grouping. Figure 11 shows the approximate relative positions of the AE transducers and radial stiffeners on the bascule girder. The right stiffener is the shorter of the two types of radial stiffeners on the bascule girder. The left stiffener is the full-length type.

Ultimately, no high-energy AE events (energy greater than 600,000 AE energy units) were recorded within the micro-location array. If the turned or tapped bolts were the source of the audible bangs, high-energy AE events would almost certainly have been detected near the bolts themselves. The complete absence of high-energy AE during Run 8 seems to rule out the bolts as the source of the audible bangs.

ANALYSIS #5: DISPLACEMENT MEASUREMENTS

As a supplement to AE measurements, we applied two displacement sensors across the gap between the bascule girder and the curved forging. This was done to monitor relative motion between the two members, which have been the source of acoustic events on other similar bridges that we have tested. The displacement sensors were applied to various locations along the gap with the temporary magnetic-mount fixture shown in Figures 12 and 13. These non-contact eddy current displacement sensors have resolution and frequency response well in excess of the recording capabilities of the auxiliary parametric inputs to the AE system to which they were attached, so any sensor-related error is insignificant.

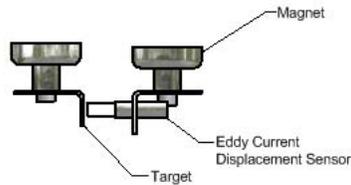


Figure 12: Sketch of eddy-current displacement sensor with magnetic mounts

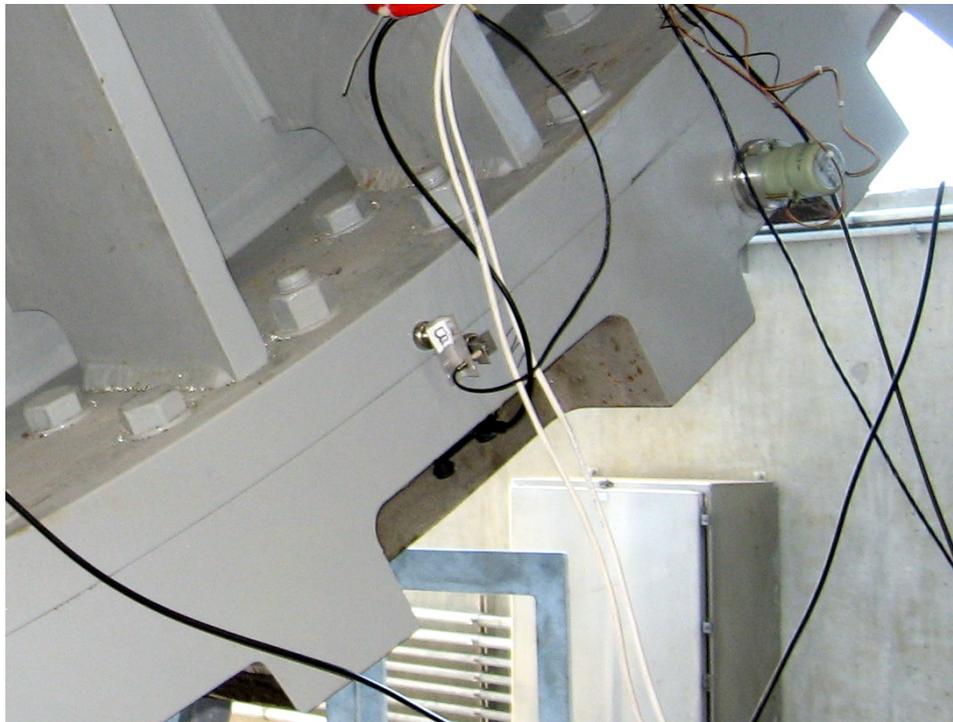


Figure 13: Eddy-current displacement sensor pair (metal bracket with inverted B on label) deployed across bascule girder-curved forging interface. The electronic clinometer (tiltmeter), a greyish cylinder magnetically mounted to the curved bottom forging, is also visible. All instrument cables were tied off to clamps on the bascule girder for strain relief.

A typical open and close cycle is shown in Figures 14 and 15 with one sensor placed parallel across the gap and the other sensor placed perpendicularly across the gap at Location 2, approximately 132 in (along the arc of the bascule girder) from the resting contact point. Both plots are typical, repeatable, and return to zero, in the same manner as other measurements taken on the west end of bridge, south girder. The perpendicular displacements were under eight mils peak-to-peak, so only parallel placements were measured during the subsequent Runs 3–10.

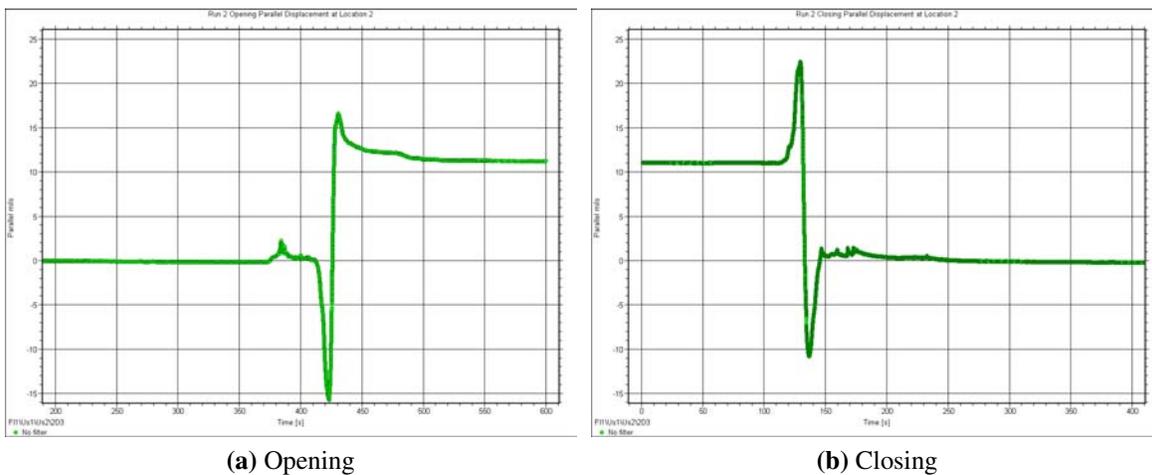


Figure 14: Parallel displacement at Location 2, Run 1

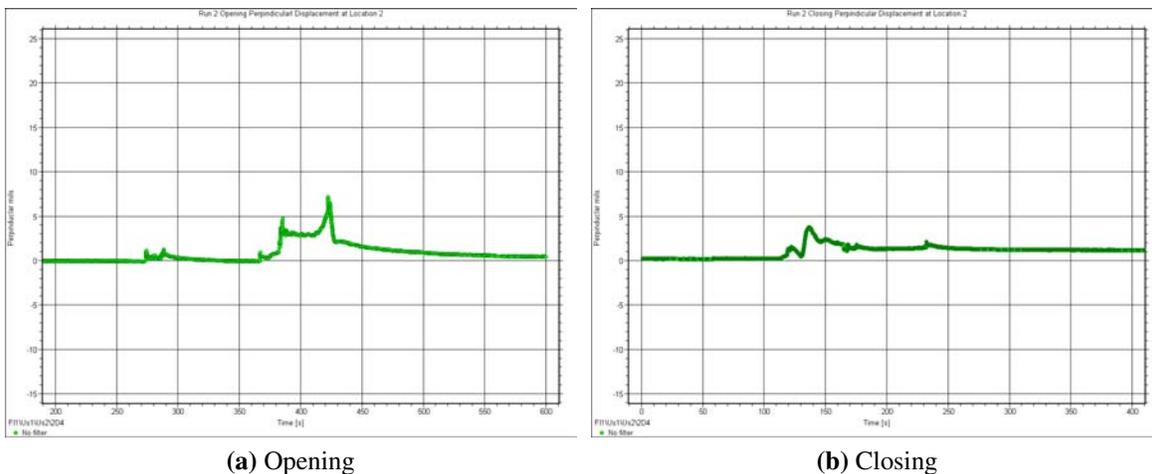


Figure 15: Perpendicular displacement at Location 2, Run 1

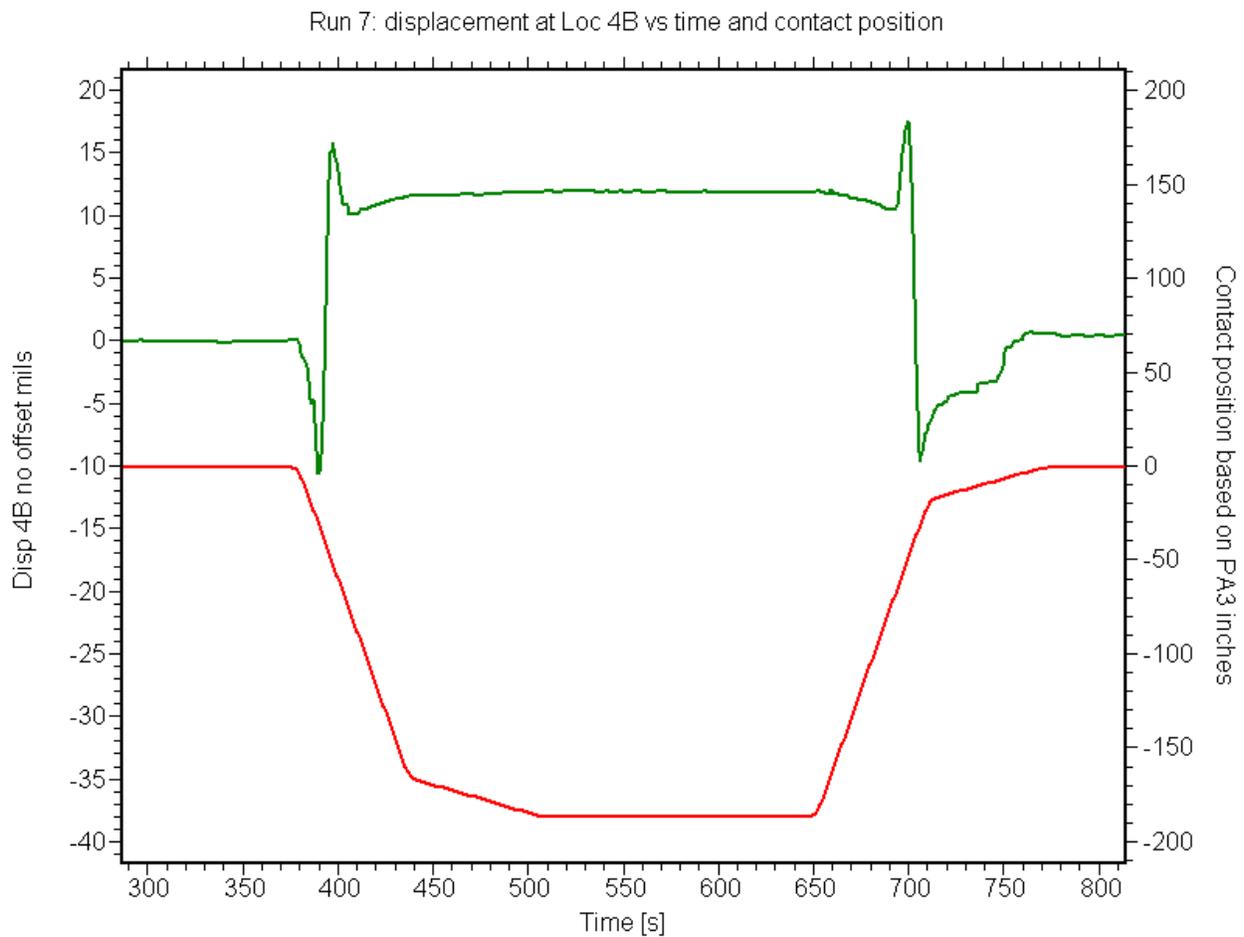
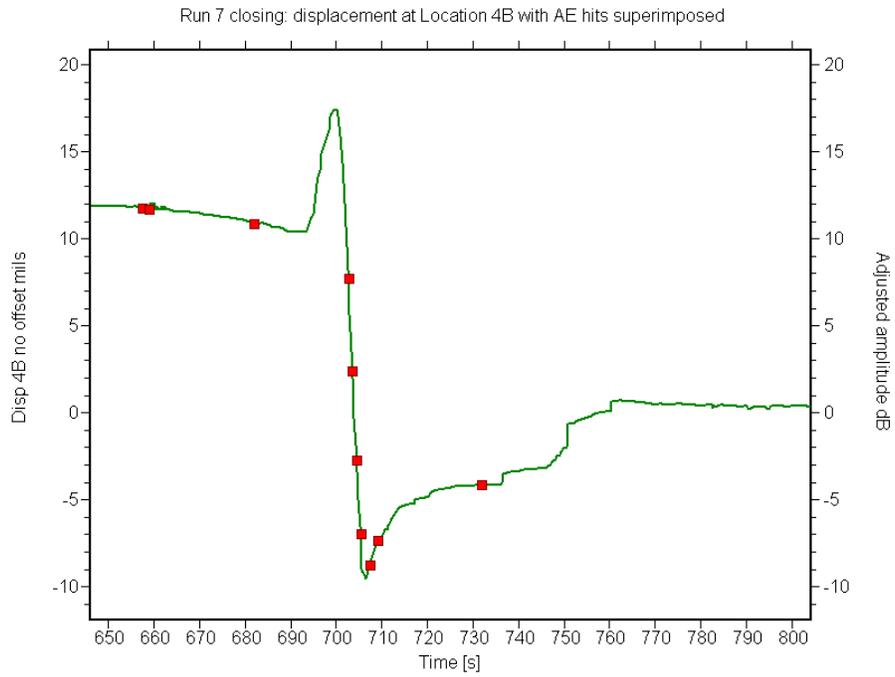


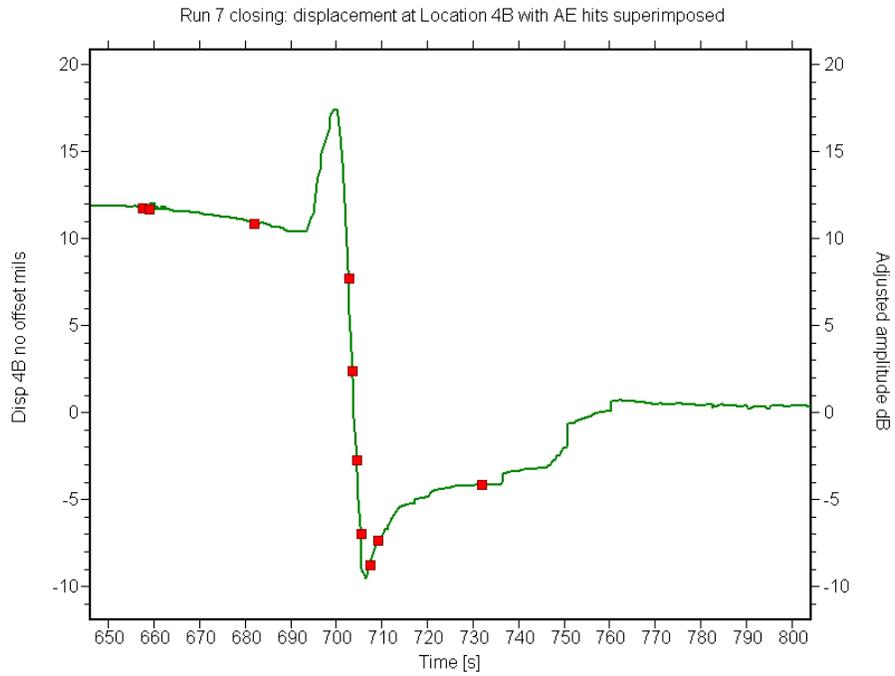
Figure 16: Superposition of parallel displacement at Location 4B ($x = -12$ in) and contact position during Run 7. Parallel displacement (green line) is given in mils. Contact position (red line, scale on right side of graph) is given in inches (arc length) along the rolling surface where $x = 0$ represents the contact position when the leaf is fully closed. This repeatable, quasi-static behavior, is typical of all the test runs on the west leaf, south bascule girder.

Apparent Relation of Displacement and AE Events

Displacements showed a rough correlation with AE events, as shown in Figures 17 and 18, wherein AE events can be seen near step-like jumps in the displacement record. This is consistent with stick-slip behavior between the bascule and curved forging being the source of the audible bangs. The red AE event points show that an event meeting out filter criteria occurred. The AE amplitudes themselves are meaningless, as they have been modified to follow the displacement plot for illustrative purposes.



(a) Opening



(b) Closing

Figure 17: Run 7 parallel displacement at Location 4B with AE events with energy greater than 600,000 AE energy units superimposed. AE amplitudes have been arbitrarily offset to generally follow the displacement plot for comparison purposes; the amplitudes displayed are meaningless.

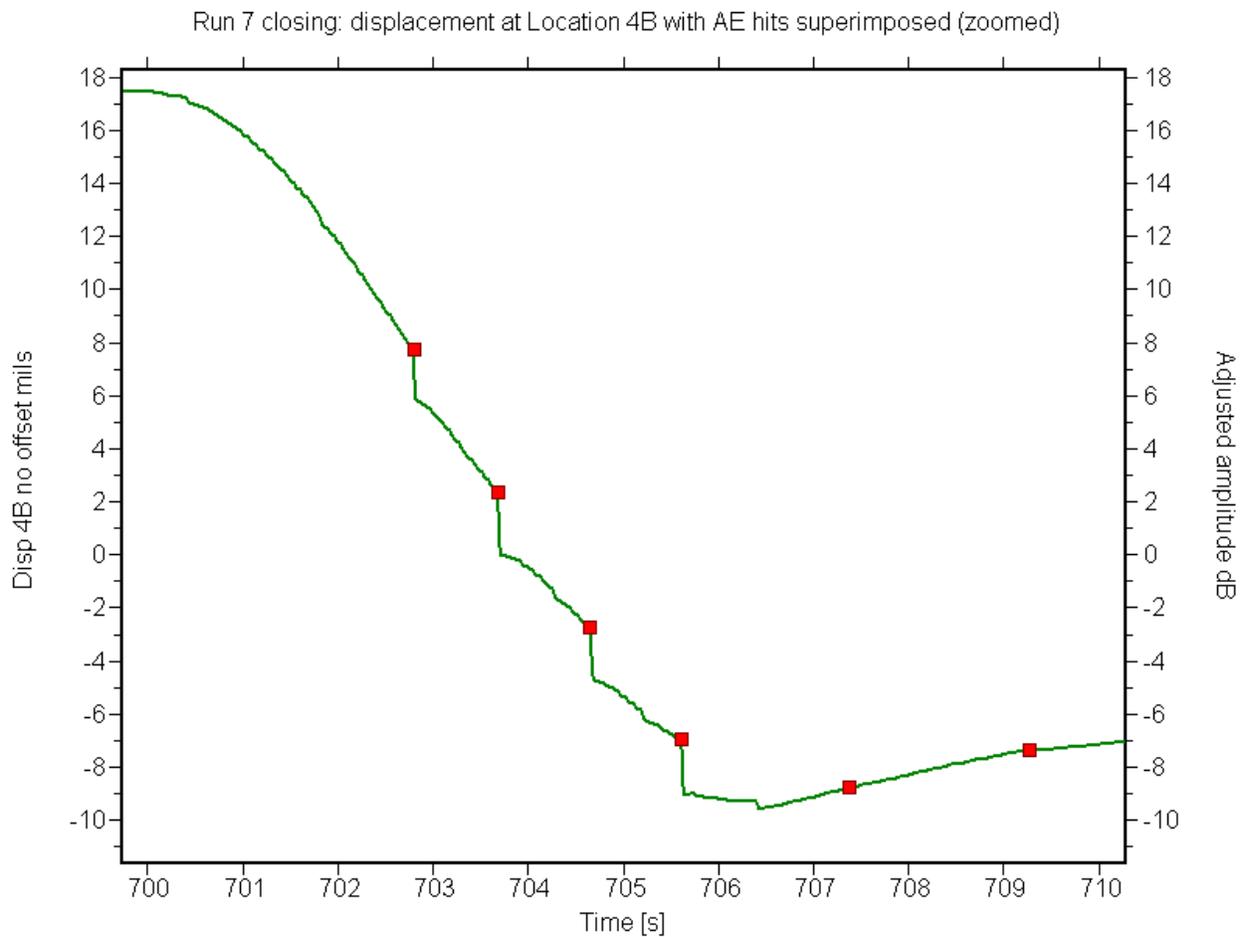


Figure 18: Close-up of Run 7 closing parallel displacement at Location 4B with AE events with energy greater than 600,000 AE energy units superimposed. As with Figure 17, the AE amplitudes have been arbitrarily offset and are meaningless. Note that each “jump” in the displacement data is accompanied by a high-energy AE event; this is typical of most of the events shown in Figure 17.

CONCLUSIONS

Acoustic emission monitoring was carried out during ten lift cycles of a large, double-leaf rolling-lift bascule bridge over two days to identify the source of loud “bangs” that occurred during opening and closing, particularly on the west leaf. The recorded data were analyzed using several well-established techniques, including first-hit analysis, linear location analysis, and planar location analysis. The results strongly suggest that the source of the audible bangs is along the interface between the bascule girder and the curved forging bolted to it.

First-hit analysis specifically ruled out the flat bottom forging on which the bascule girder rolls as the source of the bangs: no high-energy AE events typical of the audible bangs were recorded along the bottom forging. Likewise, very few high-energy AE events originated near the pinion drive shaft bearing area, eliminating that as the source of the audible bangs.

Planar micro-location about the array of turned and tapped bolts connecting the bascule girder and curved upper forging in one “bay” between radial stiffeners yielded no high-energy AE events. Data from this This seems to rule out the bolts themselves as the source of the bangs.

Linear and planar location analyses on the bascule girder and curved upper forging showed that a large number of high-energy AE events originate near the bascule girder/curved forging interface. Temporal comparison of the AE data with sub-mil resolution displacement data along the interface indicate a possible connection between AE events and local jumps in displacement data. This supports the hypothesis that the source of the bangs is highly localized stick-slip behavior along small patches along the interface. This behavior would be consistent with previous work² by ITI engineers on noise localization on large movable structures.

Finally, the number of high-energy AE events for the west and east leaves followed the same pattern as audible bangs heard by human observers: the east leaf is much “quieter” than the west leaf, yielding neither audible bangs nor high-energy AE events.

²D. Prine, “Acoustic Emission Monitoring of Bridges and Other Large Civil Structures”, 2005