APPLICATION OF ACOUSTIC, STRAIN, AND OPTICAL SENSORS TO NDE OF STEEL HIGHWAY BRIDGES

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Application of Acoustic, Strain, and Optical Sensors to NDE of Steel Highway Bridges

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Abstract

Current bridge condition determination is based almost entirely on the use of visual inspection. This approach to bridge inspection provides data that is subjective and not traceable. Nondestructive evaluation (NDE) is a tool that in actuality is little used on bridges, but could eliminate much of the subjectivity of the input data for the bridge condition determination. A critical task for NDE on these structures is to detect and locate flaws that are growing which may eventually lead to serious impairment of the structures ability to perform its designed function. This problem area is the focus for a bridge NDE program currently being conducted by Northwestern's Infrastructure Technology Institute, (ITI). Under this program, all elements of the bridge inspection problem are being investigated by an interdisciplinary group consisting of members of Northwestern's faculty and BIRL staff. One of the major research areas of the program is the application of acoustic emission (AE) monitoring to steel bridges. AE monitoring is being combined with strain and optical sensors to develop a practical bridge inspection tool. This paper will presents the latest results of field tests conducted recently on bridges in California, and Wisconsin.

Introduction

Steel bridges may develop cracks in structural members resulting from a variety of causes. The cracks may have been produced during fabrication, or grow from fabrication flaws, or they may be the result of fatigue damage. Not all cracks grow to failure. Most NDE methods currently in use can detect, locate, and to some degree size a crack, but they cannot determine if the crack is growing. Acoustic emission (AE) monitoring has the capability of detecting crack growth in real-time. In fact, AE only responds to active flaws. This unique feature of AE makes it a prime candidate for crack characterization in highway bridges.

The acoustic emission (AE) monitoring discussed in this paper was done using a monitor that has 6 input channels and is computer based. This device is a hardened field portable unit. The key feature of this AE monitoring system is the powerful pattern recognition system that is applied in real time to the AE signals. This pattern recognition algorithm was originally developed for in-process weld monitoring. It is based on empirical results that key on signal characteristics which allow crack related information to be separated from a noisy background. The algorithm tests the rate of occurrence of the AE bursts and when a group of bursts is received that exceeds the pre-programmed rate limit (typically 3 Hz), the algorithm evaluates the locational spread of the group of signals. If the high rate group all came from a tightly clustered location (typically less than 1 inch spread), the algorithm counts this group as one indication. The algorithm has been successfully applied to in-process weld monitoring on virtually every type of weld process and material that is commonly encountered in heavy fabrication. Since 1982, the same approach has been successfully applied to the in-service monitoring of steel highway bridges. This approach is the only known way that AE can be successfully applied to bridge details that are adjacent to or part of bolted splices. The fundamental problem with AE monitoring of these details is the noise produced by the bolts. The bolt fretting imitates AE very well and if the area to be monitored is not locationally isolatable from the bolts, the noise rejection algorithm must be used to eliminate the irrelevant bolt noise.

The addition of strain gage monitoring in conjunction with the AE information provides additional useful information on a cracks nature. The strain gage data can indicate the magnitude of the live strains in the vicinity of the flaw being characterized. In the following sections we will discuss the application of this AE monitoring system to four different steel bridge NDE problems.

WIDOT Structure B-5-158, Green Bay, WI

Wisconsin Department of Transportation Bridge B-5-158 is located in the city of Green Bay in Brown County, Wisconsin. The structure carries east and westbound I-43 traffic over the Fox River at the southern end of Green Bay. Total length of the structure is 7982 feet including a 450 foot long tied arch. The bridge was constructed in 1980.

In-depth inspection of the bridge by WIDOT personnel detected visual cracks inside the tie girders in the tied arch. Figure 1 shows a close-up of this detail.

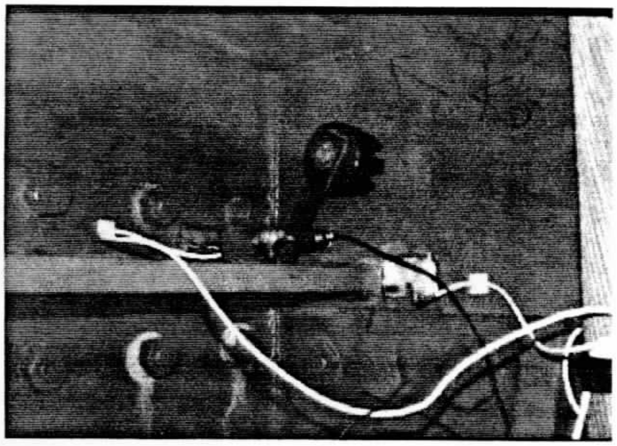

Figure 1 Close-up of Cracked Detail

The cracks were located in welds at the ends of 1 by 6 inch bars that join the bars to the hanger diaphragms at two sites. The bars, which serve as horizontal stiffeners, are welded to the inside of the tie girder at the point of attachment of the floor beams. The welds that join the 1 by 6 inch bars to the tie girder web and the hanger diaphragm were fabricated using shielded metal arc welding (SMAW) and have rough unfinished reinforcements which makes ultrasonic inspection very difficult to perform. The welds were supposed to have been full penetration and both visual as well as ultrasonic inspection indicate that this is not true.

WIDOT expressed an interest in gaining a better understanding of the nature of the visible cracks as well as additional information on the condition of the stiffener to web welds. Following discussions between BIRL and WIDOT this project was initiated. The test program utilized a combination of acoustic emission and strain gage monitoring to provide the needed information on live load and crack activity. The tests were performed by BIRL with assistance from The Kentucky Transportation Center (KTC).

On May 3, 1993 BIRL commenced testing. Test sites included hangers 4 and 6 on both the north and south tie girders. A total of six sites were monitored (the west side of hanger 4 on the north girder, the east side of hanger 6 on the south girder, and the east and west sides of hanger 6 on the north and hanger 4 on the south girder). These sites included all of the known cracks, sites that were adjacent to known cracks but with no known cracks, and sites that had no known cracks present either in or adjacent to the test site. The acoustic emission setup monitored both the stiffener to diaphragm and stiffener to web welds at each test site. Two strain gages were monitored at each of the test sites. Testing continued through May 13, 1993. Traffic location U14, top. This crack was approximately 3/4 inch long. The test results are summarized in Table 2 below.

TABLE 2 I-680 (B-28-253)

TEST SITE	AE RESULTS	STRAIN GAGE
L11	No Flaw Activity	80 μin./in. max.
U14	2 Flaw Indications	360 μin./in. max.

The U14 Flaw indications were at the end of the weld and near its midpoint. The AE indications coupled with relatively high live stresses indicates that this site (U14) has an active fatigue crack and should be closely watched.

Caltrans Structure B-22-26 R/L, (Bryte Bend) Sacramento, CA

The Bryte Bend Bridge carries I-80 traffic over the Sacramento River near Sacramento CA. The bridge consists of two 4050' trapezoidal steel boxes, thirty six 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. A view of the internal construction of the trapezoidal box is shown in Figure 4. 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 cross frames. BIRL engineers applied acoustic emission and strain gage monitoring to three crack sites to determine the nature of the cracks. Since this bridge is an all welded structure, we were able to apply the acoustic emission using a simple guard channel approach (no extraneous noise sources were in the immediate vicinity of the crack). This approach also allowed us to circumvent source location problems caused by dispersive acoustic propagation that result from the thin plate (3/8") used on this bridge. The guard channel setup consisted of 4 sensors. A sensor was located at the visible crack tip and three others were placed in a triangular array surrounding the crack tip. The AE data was recorded and analyzed post test. Any signal originating at the crack will reach the crack mounted sensor first. AE signals arriving from outside the array will be received at a guard sensor first. An additional sensor was mounted at the tip of the vertical stiffener to catch any AE generated by fretting from the end of the stiffener on the bottom flange. Post test analysis showed this precaution to be unnecessary for all but the third test in which a large portion of the 12,233 events came from the vertical stiffener fretting. A summary of the AE results is shown below in Table 3.

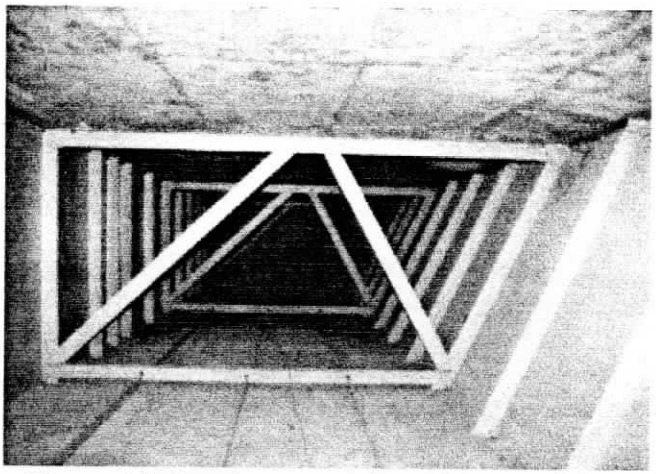
Figure 4 Internal construction of Trapezoidal Box

Location	Total Events	Crack Related Events
SP19;Girder 2;XF3	2117	434
SP19;Girder 2;XF1	1821	193
SP29;Girder1;XF5	12233	335

Table 3 AE Summary for Bryte Bend Bridge

loading during the tests included many large and obviously heavy loads. A wide range of environmental conditions were encountered including high gusty winds and temperatures ranging from 37 degrees F. to 80 degrees F. Test results are summarized in Table 1 below. These results show no detectable crack activity at any of the test sites and very low live strains. These test results imply that some other mechanism besides fatigue is responsible for the visible cracks.

TABLE 1 I-43 (B-5-158)

Site	Condition	Strain Gage	AE
NG4W	No Visible Cracks	30 to 50 µin./in.	No Flaw Ind.
NG4E	Visible Cracks	30 to 50 µin./in.	No Flaw Ind.
NG6W	No Visible Cracks	30 to 50 µin./in.	No Flaw Ind.
SG4E	Visible Cracks	30 to 50 µin./in.	No Flaw Ind.
SG4W	No Visible Cracks	30 to 50 µin./in.	No Flaw Ind.
SG6E	No Visible Cracks	30 to 50 µin./in.	No Flaw Ind.

Caltrans Structure B-28-153, Benicia Martinez, CA

California Department of Transportation structure B-28-153 carries Interstate Highway 680 traffic across the Sacramento River at the east end of Carquinez Strait thirty miles northeast of San Francisco, California. This 1.2 mile long, high-level structure consists of ten steel deck-truss spans ranging in length from 330 to 528 feet. The bridge was designed by CALTRANS in the late 1950's and has been in continuous service since it was opened in 1963. An overall view of the structure is shown in Figure 2.

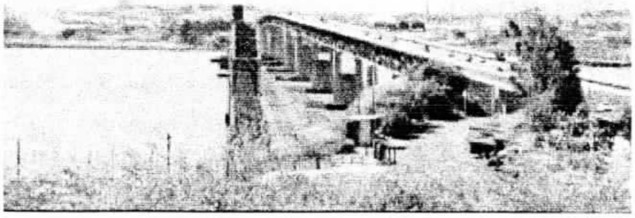

Figure 2 The I-680 Bridge

The design uses built-up steel H-sections for the truss members and bolted connections. The steel H-sections were fabricated using T-1 and ASTM A242 plates. Stay plates were welded to the flanges of the H-sections at the joints of the truss members. Cracks have been detected in these welds. Subsequent retrofit was performed on these details that included removal of the ends of the cracked plates by coring and adding bolted doubler plates. A typical crack site is shown below in Figure 3.

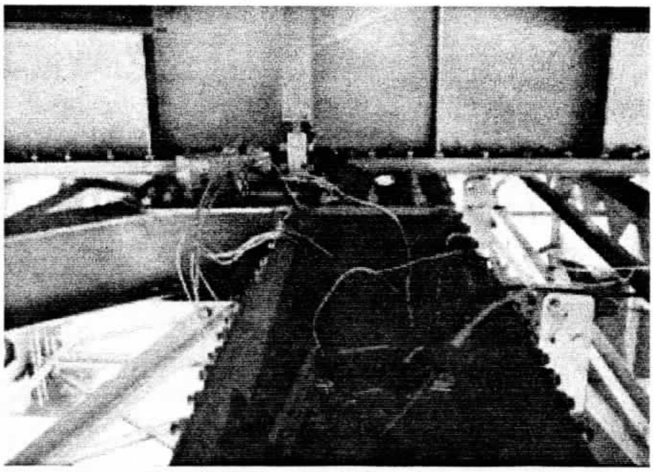

Figure 3 Typical Crack Site

We applied AE and strain gage monitoring to two of these crack sites. The first site was located in span 7 of the west truss at location L11, bottom plate. This crack was approximately 1/2 inch long. The second test site was located in span 5 of the west truss at

Strain gages were mounted on the web of the girder near the crack site. Two gages were mounted at each test site and data was recorded in the rainflow mode. In the relatively short period of time taken for these tests significant live strains were recorded with ranges of 200 microstrain and higher. The conclusion reached from the combined AE and strain gage tests were that the cracks were growing under fatigue loading. Discussions with Caltrans engineers subsequently led us to apply strain gages over longer time periods to obtain more statistically significant live strain histograms. This additional work was performed in June of 1994. An analysis of the strain gage data further confirmed the fatigue findings. A summary of these tests is shown below in Table 4. Channel 1 was mounted on the horizontal stiffener transverse to the bridge axis. Channels 3 and 4 were mounted on the vertical web with 3 horizontal and 4 vertical. The counts to date are based on the life of the bridge assuming uniform traffic volume.

Total Counts	4831	577	1389
Counts/hour	39.72	4.74	11.42
Counts/day	953.27	113.86	274.08
Total Counts to-date	8,002,687	955,817	2,300,918
	Ch 1	Ch 3	Ch 4

Table 4 June 1994 Strain Gage Results (Range > 100 micro-strain)

Wisconsin DOT Structure B-47-40, Prescott, WI

Wisconsin DOT structure B-47-40 carries east and westbound traffic on U.S. highway 10 over the St. Croix River in the town of Prescott in Pierce County, Wisconsin. The bridge consists of 5 spans and has an overall length of 682.7 feet. The center span (span 3) is a two leaf, rolling bascule lift bridge with an overall length of 205.5 feet. The bridge deck is 66 feet in width and has four lanes of vehicular traffic and a pedestrian sidewalk.

The three piece segmental castings that the bridge rolls on are attached to the bascule girders with high strength friction bolts. This is a relatively recent design modification (8 to 10 years ago) and replaces the traditional turned bolts or rivets that were commonly used in this application. This design change is basically a cost cutting measure. Wisconsin DOT bridge inspectors have observed cases of bolt failure and casting slippage on similarly constructed bridges. These occurrences can lead to dangerous operating conditions or structural failure.

Prior to this test, concerns for safe bridge operation by Wisconsin DOT bridge inspection personnel led them to call upon BIRL engineers to apply advanced NDE technology to the Tayco Street lift bridge (WI-DOT structure B70-97-93) in Menasha, WI in September of 1993. This bridge utilized the same design modification as the Prescott bridge. Bridge operation and inspection personnel had observed loud audible impact noises during bridge operation. BIRL engineers applied acoustic emission monitoring techniques to determine that the source of the impact noises was the high strength bolts. Strain gages were applied to the casting/girder interface and large permanent displacements of the casting with respect to the girder were observed.

The loud impact noises that were observed on the Tayco Street bridge were not observed during operation of the Prescott bridge. However, continuing concerns on the part of WI-DOT inspection personnel over the performance of the friction bolts led to an agreement with BIRL to perform the type of testing on this structure that was previously applied to the Tayco St. bridge.

Tests utilizing acoustic emission and strain gage monitoring were performed. Additional experiments were performed using a displacement sensor based on laser triangulation. The tests were completed on November 8 and 9, 1994.

Acoustic Emission Testing

AE testing was performed on each of the four casting assemblies using a field portable AE monitoring system. The test procedure was developed during a series of experiments performed on a similar bridge in Menasha Wisconsin during September of 1993. AE sensors were attached to each of the three casting segments. An additional sensor was attached in the vicinity of the pinion gear on the upper part of the bascule girder. The sensors were 175 kHz resonant piezoelectric devices. Silicone grease was used for acoustic couplant and magnetic hold downs were used to clamp the sensors to the structure. Unity gain line driving pre-amplifiers were used in each signal line to eliminate cable loading effects on the sensors. AE system gain was set at 40 db on each channel and was checked using an electronic pulser and AE transducer as a simulated AE source. AE data was recorded on disk files using a portable PC attached to the AE monitor via an RS232C serial port. The recorded data was analyzed post test. The casting mounted sensors were used to detect any impact or fretting events related to the casting attachments. The pinion mounted sensor was utilized to intercept drive gear and deck related AE signals and to act as a guard for the casting mounted sensors. The AE parameters of interest for these tests are hits and average relative energy. A hit is defined as the receipt by one sensor of an AE burst. The sensor that first receives the burst is the one most closely located to the AE source. The arrangement of sensors for these tests insures that any signal that hits sensor #1 first (#1 is mounted on casting segment #1) has to originate in that casting segment. The same holds true for the remaining two casting mounted sensors. Bursts that arrive at the sensor mounted near the pinion gear first, originate either in the drive gear, or the upper bridge structure.

Examination of the three casting mounted sensor's hits and energy shows that the Prescott bridge had both lower hit counts and much lower energy. The difference in AE test data between the two bridges is even more apparent if we look at the product of event counts and their average energy which is a relative measure of the total detected AE activity resulting from a complete bridge operating cycle. Table 5 shows this result for the two bridges. Clearly, the Prescott bridge has less overall AE activity.

AE Sensor	Tayco St.	Prescott NE	Prescott NW	Prescott SE	Prescott SW
1	0	2,325	646	53	417
2	111,544	178	544	504	0
3	0	4,734	0	0	4,730
4	1,776	0	136	8,640	5,150

Table 5 Summary of AE Activity

Strain Gage Testing

A Measurements Group quarter bridge type CEA-06-W250A-350 weldable foil strain gage was mounted diagonally across the center casting to bascule girder mating surface on both the north and south corners at the east end of the bridge. This application is a non-standard approach to using strain gages. The purpose is to attempt to observe displacements between the casting segment and the girder flange. The observations are more qualitative than quantitative because the gage is not subjected to a uniform strain field across the gage width. This mounting approach was developed during experiments performed on the Tayco St. Bridge in Menasha, WI.

Strain gage data was recorded using a Somat model S2000 field computer in the time history mode. The S2000's programmable digital low pass filter was set at 15 Hz cut-off to eliminate electrical noise. The strain gage signals were sampled at a 100 Hz rate with 8 bit resolution.

The strain gage data taken on the Prescott bridge showed three significant departures from similar tests on the Tayco St. bridge. The peak strain on Prescott was 50 to 75 micro-inches per inch while Tayco St. was 600 to 1200 micro-inches per inch. Secondly, the Prescott strain gage data showed even symmetry and good repeatability on the strain wave forms recorded during raising and lowering while poor odd symmetry and no repeatability was observed in the Tayco St. data. The Prescott strain gages returned to their original zero within the quantization error of the monitoring system (approx. 10 micro-inches per inch) while the Tayco St. strain data was offset by as much as 150 micro-inches per inch following a complete bridge cycle.

Laser Displacement Gage Testing

The laser displacement gage (Aeromat LM300) had source and target mounted on opposite sides of the casting to girder interface and aligned parallel to this interface. It allowed us to observe the elastic deformation of the casting under dynamic loading conditions during bridge open and closure and was easily capable of detecting slippage of the casting. The shape and symmetry of both the laser gage and the strain gage data agreed well and the laser gage showed no appreciable slippage between the girder flange and the casting following a complete bridge operating cycle. A typical laser gage plot is shown in Figure 5. The laser gage typically showed some offset when the bridge was at the maximum opening point (mid-range). The gage was mounted on the center casting in all tests. We believe the offset observed at the bridge up position is the result of load sharing between the castings that is fostered by the wedges applied between castings. These test results indicate that under current operating conditions the segmental casting attachments on the Prescott bridge (B-47-40) exhibit no abnormal behavior as evidenced by AE, strain gage, and laser displacement testing. However, future re-testing would be prudent based on past experience with this design.

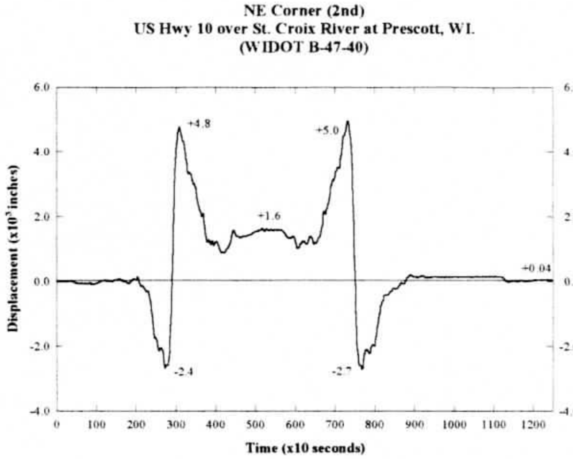

Figure 5 Typical Laser Gage Plot

Summary and Conclusions

The four tests discussed in this paper are examples of the useful information that application of AE, strain, and optical sensors can provide to the bridge owner. The I-43 Green Bay bridge had both visible as well as suspected flaws. AE and strain gage tests clearly showed that the visible cracks were not of fatigue origin. The lack of crack related AE coupled with low live stresses indicate that the cracks were most likely an example of early failure of a weld flaw. AE further confirmed that there were no active cracks in the stiffener to web welds. The tests performed on the Benicia Martinez on the other hand clearly confirmed that one of the visible cracks is being driven by fatigue. Similarly, the AE and strain measurements on the Bryte Bend bridge clearly showed that the cracks are active fatigue cracks being driven by significant live strains.

The Menasha and Prescott lift bridges are examples of an application of this sensor technology that is quite different from the usual crack characterization. In this example, these sensors were used to diagnose a problem in a new structure that was simply a case of poor mechanical design. In one case the AE was able to clearly pinpoint the source of the loud impact noises while strain gage monitoring confirmed that the castings were moving tangentially with respect to the bascule flange. This diagnosis was made early enough to allow corrective action to be taken before bolt failure and potential jamming of a casting which would render the bridge in-operable. In the other case, the sensor technology showed that at least for the present, the attachments are performing properly.

Acknowledgments

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