Paper Title: **FIELD MONITORING OF FATIGUE CRACK ON HIGHWAY STEEL I-GIRDER BRIDGE**

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ABSTRACT

This paper presents a field test program for fatigue crack growth monitoring on a highway steel I-girder bridge. Acoustic emission (AE) monitoring of an existing fatigue crack on a diaphragm connection plate was performed using piezoelectric film AE sensors. Laser sensors were also used to continuously measure the differential deflection between two adjacent girders. The AE events identified by the piezoelectric film AE sensors are considered to be induced by fatigue crack growth activities based on preliminary analysis.

INTRODUCTION

Fatigue-induced cracking may occur in steel bridges reaching their original design life. These aged structures have experienced increasing traffic volume and weight, deteriorating components, as well as a large number of stress cycles. A number of cases have been reported recently that involve fatigue damages in highway steel bridges. For example, fatigue cracks resulting from the typical web gap distortion near the bottom flange of welded plate girders were reported in a multi-girder steel bridge *(1)*. The distortion induced stresses initiated horizontal cracks in the web-to-flange welds and some propagated into vertical cracks at the end of the web-to-connection plate welds. On March 14, 2003, two large cracks were discovered in the webs of two welded plate girders on a multi-girder steel bridge*(2)*. The fracture was believed to have originated at the top of the web-to-stiffener weld. One crack propagated downward and diagonally fractured the full height of the 90-inch web plate.

Many nondestructive evaluation (NDE) techniques have been used for fatigue crack detection, including eddy current, magnetic particle inspection, radiography, thermography, acoustic emission (AE) and ultrasonic testing. In particular, AE techniques have been receiving growing popularity in use for fatigue crack monitoring on bridges (e.g., *(3), (4), (5)*). AE is the elastic wave generated by sudden energy releases within a material; it provides real-time information on damage progression in a structure. Since many AE sources are damage-related, AE monitoring can be effectively used to diagnose impending structural material failure. Different from ultrasonic test, which excites elastic waves into a solid, AE sensor passively listens to the signals generated by crack initiation and progression within the monitored structure.

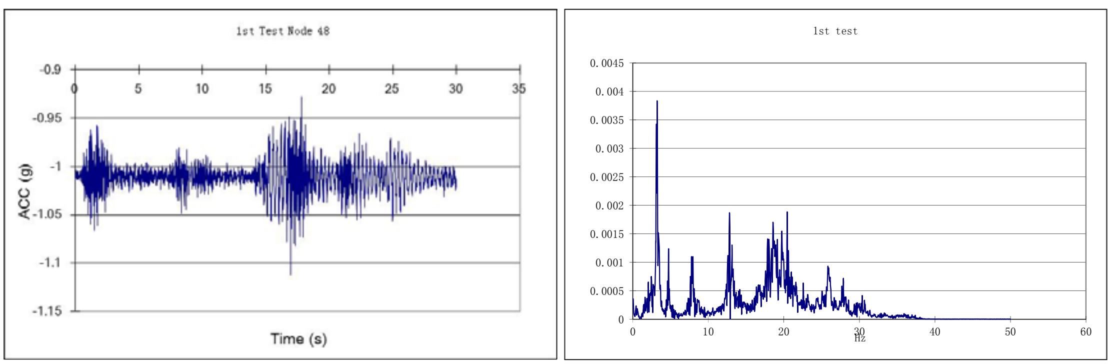
Piezoelectric materials have been used as surface-mounted sensors to measure surface acoustic waves or dynamic strains by directly bonding or embedding piezoelectric film onto the structure (e.g., *(6), (7), (8)*). In conjunction with close-range AE monitoring technique (*(9), (10)*), piezoelectric film AE sensor could provide additional AE source information, such as source location and crack mode. The advantages of piezoelectric film AE sensor include low profile, wide frequency bandwidth enabling high fidelity signal collection and inverse analysis for source information, and conformability to curved surfaces. In this paper, preliminary results from a field test of the piezoelectric film AE sensor for fatigue crack monitoring on a steel I-girder bridge are discussed.

BRIDGE DESCRIPTION AND FIELD TEST PROGRAM

Field test was conducted on a multiple steel I-girders bridge in Maryland. The bridge is a single-span structure of a span length of 46.76 m (140 ft.), as shown in Figure 1. The bridge was built in 1980's and fatigue cracks were identified in some of the diaphragm connection welds. Types of sensors used in the field test include piezoelectric film AE sensors, wireless accelerometers, laser distance sensors and strain transducers. A total of five piezoelectric film AE sensors including three piezoelectric paint AE sensors were installed to monitor the growth of existing fatigue cracks in the connection weld. Here, the piezoelectric paint AE sensor is a type of piezoelectric film AE sensor (*(9)*) The sensors are connected to preamplifiers and a PXI high speed data acquisition system for long-term AE signal collection and fatigue crack growth monitoring. Also, to measure the differential deflections between two adjacent girders (which is believed to be the cause for the fatigue cracking), a laser distance sensor was used to measure the differential deflection between Girders #2 and #3. The details of these two types of sensors and data will be discussed in the next two sections.

FIGURE 1 Field test on a steel I-girder bridge in Maryland.

In addition, a total of four wireless accelerometers - Imote2 from MEMSIC were used to monitor the vibration responses of the bridge. One accelerometer was installed on each of the girders (Girder 2 to 5) and acceleration data was acquired at a 100 Hz sampling rate synchronically. The acceleration data was used to provide modal frequency information (Figure 2-b) that can be used to calibrate the finite element model of the bridge as well as a side-by-side comparison with laser distance data for accuracy cross-check. The fundamental frequency identified from the measured acceleration data was 3.22 Hz.



(a) **(b)**

FIGURE 2 Acceleration data measured by wireless sensor: (a) Acceleration time history; (b) Frequency spectrum (horizontal axis: frequency (Hz); vertical axis: FFT amplitude).

NON-CONACT MONITORING OF BRIDGE DEFLECTION

A major cause for the fatigue crack is believed to be live load induced stresses in the diaphragm connection welds resulting from differential deflections between adjacent girders. A laser system was used to monitor the differential deflections between two adjacent girders. The system includes a laser distance sensor mounted on one girder, two reflective mirrors on the ground, and a reflective target on the other girder, as shown in Figure 3.

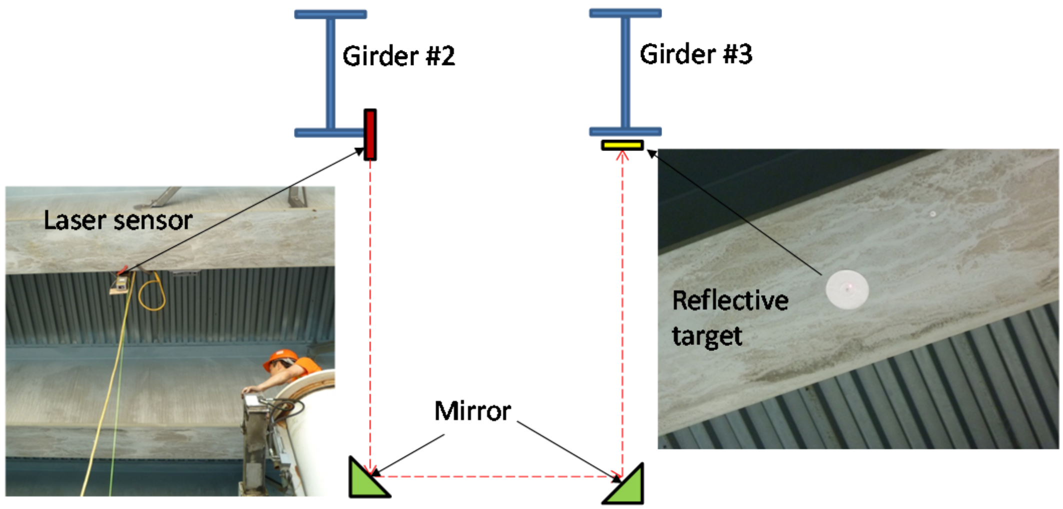
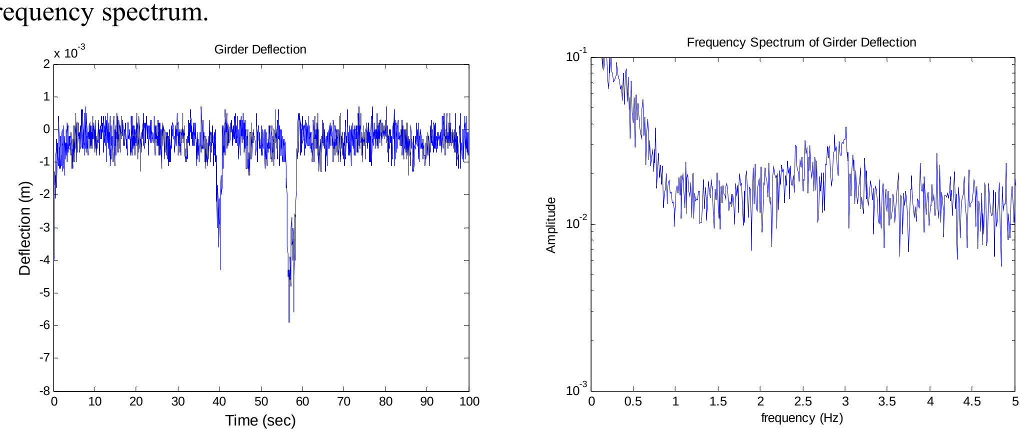


FIGURE 3 Laser system for measuring differential deflections between two adjacent girders (not to scale).

A Model FLS-C series laser distance sensor made by Dimetix was used for this field test. The measurement principle of this laser distance sensor is based on comparative phase measurements, which uses a laser diode as its source to send out a laser beam and the amount of phase shift is reflected back to determine the distance. Under normal operation condition with good reflective target, an accuracy of 1 mm can be achieved with a sampling rate up to 10 Hz. But higher sampling rate up to 100 Hz can be used at the price of reduced accuracy. The laser distance sensor was calibrated with both a static and moving target in the lab before the field test. Single girder deflections were first measured by pointing the laser sensor to the natural road surface without a reflective target at a sampling rate of 20 Hz. Although there were noises in the frequency spectrum (two causes for the noise: sampling rate higher than 10 Hz and natural road surface without the use of a reflective target), the fundamental natural frequency of the bridge can still be identified around 3 Hz. This 3 Hz natural frequency was also verified by other laser sensor data and the frequency identified using acceleration data (i.e., Figure 2). A sample time history of girder deflection is shown in Figure 4(a) along with its frequency spectrum.



(a) **(b)**

FIGURE 4 Measured girder deflections: (a) sample time series; (b) FFT spectrum (average of four time series)

Figure 5 shows the differential deflection time series between Girders #2 and #3 measured during this field test. This data was collected at a sampling rate of 10 Hz using the set up described in Figure 3.

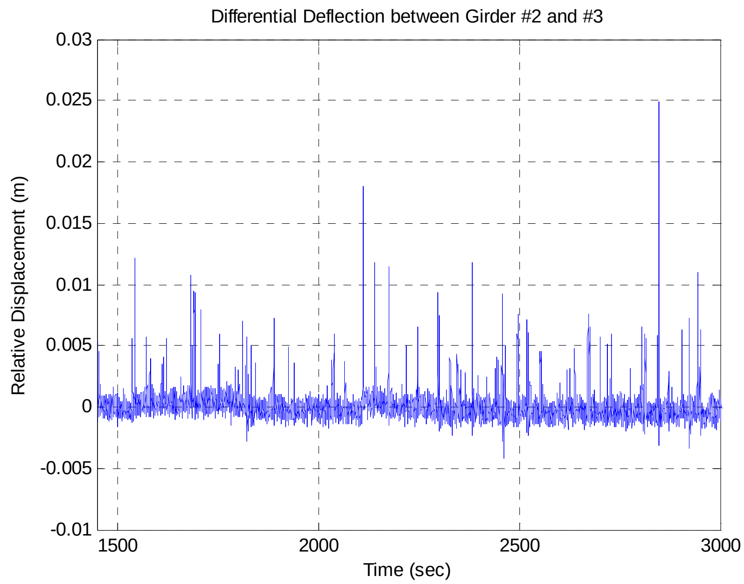
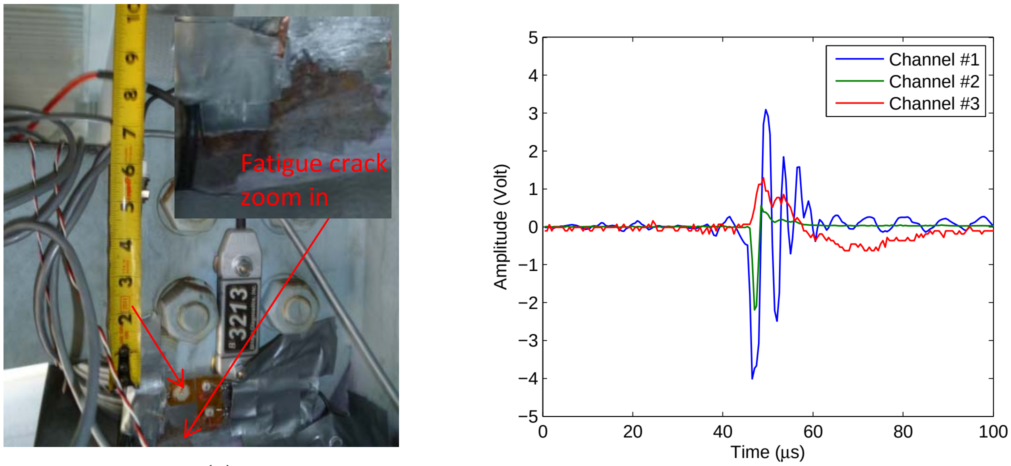


FIGURE 5 Differential deflections between Girders #3 and #2 measured by laser distance sensor.

ACOUSTIC EMISSION MONITORING OF FATIGUE CRACK

A remote acoustic emission monitoring system was installed to the steel I-girder bridge in June 2012 and its long-term performance in the field was studied in the context of fatigue crack monitoring. This remote monitoring system is comprised of three major components: sensors with signal conditioning circuits, data acquisition system and remote access. The AE events due to fatigue crack growth are monitored with piezoelectric film AE sensors with a 40-dB pre-amplifier and a band-pass filter which filters low frequency noises (< 5 kHz) induced by bridge vibration. The 5 kHz low cutoff frequency was assigned since fatigue crack induced AE signals are usually on the order of 100 kHz. The output from the signal conditioning unit is passed to a PXI-based data acquisition system made by National Instruments. A Labview-based software program was developed and installed on the PXI system for data logging and processing. For this test, the sampling frequency was set at 2 MHz for all four channels.

In this field test, four piezoelectric film AE sensors were used. Three were placed near the fatigue crack tip. Figure 6 shows the test set up as well as sample AE signals measured by the three piezoelectric film AE sensors. Two of these three piezoelectric film AE sensors (channel #1 and #2) are made using PZT-5A discs and thus have a higher sensitivity (about 30 times higher) than the other sensor (channel #3, made of piezoelectric paint). This signal is triggered by channel 3. Note that in order to make visual inspection of the waveform easy, the signal from channel #3 is scaled up by ten times since piezoelectric paint AE sensors have lower sensitivities compared with the PZT-5A AE sensors. Close examination of these three signals reveals that some phase shift occurs between the signals, suggesting this AE event must be induced by near-field source.



(a) **(b)**

FIGURE 6 (a) Three piezoelectric film AE sensor near fatigue crack tip on the connection plate; (b) Typical AE event measured by the three piezoelectric AE sensors.

Figure 7 shows the average frequency spectra of the triggered AE signals from these three piezoelectric film AE sensors. Ninety-two AE events similar to that shown in Figure 6(b) were used for this averaging so that ambient noise effect could be canceled out. It is seen that there is an attenuation of 7 dB from the channel #1 signal to the channel #2 signal. This is consistent with the $r^{-1/2}$ Rayleigh wave attenuation relationship reported by Mooney (*11*), where r is the distance from AE source. It is calculated that from r_1 = 0.98 inches to r_2 = 1.67 inches, the attenuation is about -5.4 dB. The actual attenuation of -7 dB from field test data is close to this $r^{-1/2}$ Rayleigh wave attenuation relationship, especially considering the fact additional attenuation might be caused by inherent material damping (which is not accounted for by the $r^{-1/2}$ Rayleigh wave attenuation). This attenuation relationship verifies that the triggered signal is not due to far field traffic induced noise (e.g., friction between tire and bridge deck) since for far field signal the attenuation between these two signals (channel #1 and #2) would be much smaller based on the dimensions of this bridge and sensor location, the attenuation would be around -0.47 dB. Also, since Channel #3 and Channel #2 are at similar distance to the crack tip, the attenuation (-27 dB in Figure 7) is close to the value (-30 dB) due to sensor sensitivity difference (note that this calculation is based on original data, not the one presented in Figure 6 which has been scaled up ten times for ease of waveform identification). Considering this attenuation relationship reflected in the measured AE signals, it is very likely that the AE event in Figure 6(b) was triggered by AE activities associated with fatigue crack growth.

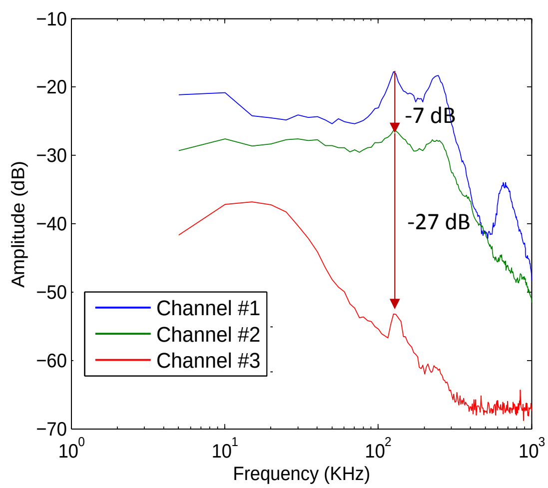
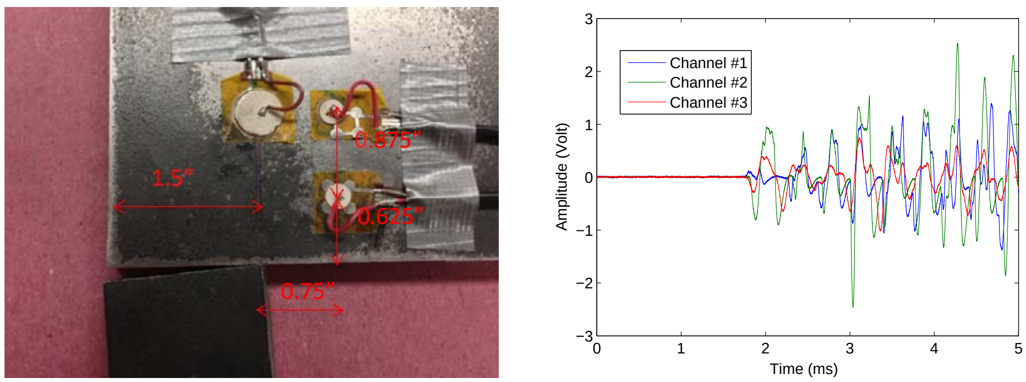


FIGURE 7 Average frequency spectrum of triggered AE signals by three piezoelectric film AE sensors.

In order to eliminate possibilities of signals due to friction or impact of the cracked surface, a laboratory simulation was carried out with similar configurations on a 7/16″-thick steel plate. The detailed setup is shown in Figure 8 (a). It can be seen that the test results presented in Figure 8 (b) are considerably different from the AE signals obtained from the field test on the field test bridge, in both waveform characteristics and frequency contents. Therefore the AE signals collected in field are unlikely to be caused by the opening and closing of the fatigue crack. This further verifies the judgment that those AE events were very likely to be associated with fatigue crack growth.



(a) (b)

FIGURE 8 (a) Experimental set up for lab test; (b) Typical AE event due to surface impact measured by the three piezoelectric AE sensors.

CONCLUSION

A remote acoustic emission monitoring system was installed on a steel I-girder bridge in Maryland to monitor possible fatigue crack growth. Sensors used in the field test include piezoelectric film AE sensors, wireless accelerometers, laser sensor, laser distance sensors and strain transducers. A total of seven piezoelectric film AE sensors including two piezo paint AE sensors were installed to monitor the growth of existing fatigue cracks on a connection plate of the steel I-girder bridges. To monitor the differential deflection between two adjacent girders, a laser system consisting of a laser distance sensor, two reflective mirrors and one reflective target was installed on the two girders. The laser system continuously recorded the differential deflections between girders #2 and #3 at a sampling rate of 10 Hz during the field test. The feasibility of using thin-film sensors for long term fatigue cracking AE signal sensing is confirmed by the field test results. Considering the attenuation relationship reflected in the measured AE signals, it is very likely that the AE signals were triggered by AE activities associated with fatigue crack.

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