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ACOUSTIC EMISSION MONITORING OF FATIGUE CRACKS IN BRIDGE COMPONENTS

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Summary

A laboratory investigation into the effectiveness of acoustic-emission (AE) monitoring as a non-destructive evaluation technique to detect and monitor fatigue cracks in steel bridges indicates some AE instrumentation can readily detect initiation and growth of these cracks in a very noisy test environment. In these tests a strong positive correlation existed between the degree of acoustic activity and the rate of crack growth. Based on initial data analysis, the following preliminary conclusions may be made:

- Fatigue testing of specimens taken from cracked girders of the Mason Creek Bridge on the Canadian National Railway (CN) was successfully conducted. The loading regime of combined four-point bending with lateral-web displacement resulted in reinitiation of existing cracks as well as growth of new cracks.
- Three types of AE monitoring systems were used. Of these, the new modal analysis system readily detected the initiation and effectively monitored the growth of fatigue cracks in the bridge specimen. This system was able to effectively reject background noise without the extensive data analysis required for other AE systems. (Correlation of results from all three types of AE monitoring will be presented in the final report).
- A strong positive correlation existed between the growth rate of the crack and the degree of acoustic activity; i.e., the rate of growth of fatigue cracks is closely related to the emission of acoustic energy. The AE technique can be an effective method for finding fatigue cracks in critical bridge members and for determining the relative activity of these cracks.

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INTRODUCTION AND CONCLUSIONS

Laboratory fatigue tests were conducted on bridge specimens removed from Canadian National Railway's (CN) Mason Creek Bridge. Before replacement, the bridge had been field tested using AE monitoring to determine the performance of this technology as an evaluation technique to assess the condition of structural members of the bridge. The preliminary test results indicate that AE monitoring is a reliable method for finding active fatigue cracks and for assessing their activity (rate of growth). Information about activity of fatigue cracks assists bridge engineers in determining the severity of a developing problem and enables planning and scheduling the necessary action to repair the damage and maintain safe train operation.

The usual method of assessing the condition of a bridge is by visual inspection. Unfortunately it does not always provide sufficient information about the condition of fracture critical members such as internal flaws, fatigue cracks, fabrication quality and stability. Other evaluation techniques that complement visual inspection are required to fully assess the condition of railway bridges. Acoustic emission monitoring is one potential technique that can be used to characterize the condition of bridge structures.

The purpose of this test, performed at the Federal Railroad Administration's Transportation Technology Center (TTC) as a collaborative effort between the Transportation Technology Center, Inc. (TTCI), and DNL Infrastructure Technologies, Inc. (DNL), was to evaluate the correlation between AE field-test results and laboratory results using accelerated laboratory fatigue testing.

AE monitoring is a passive inspection technique that measures the stress waves generated at the tip of a fatigue crack as the crack propagates. The occurrence of these elastic waves (called AE events) is monitored during normal cyclic loading, such as during the passage of several trains over a bridge. The collection of AE events from a crack in a monitored bridge component indicates that a crack is active. The degree of crack activity is established based on parameters such as the number of collected events or the AE count rate, with the higher activities associated with increased crack-growth rates.

MASON CREEK BRIDGE

The Mason Creek Bridge is located at mile 82.8 of the former Grande Cache Subdivision of the CN in Alberta, Canada. It was constructed in 1967 and consists of 16

welded deck-plate-girder (DPG) spans with an overall length of 1,122 feet (342 m). The traffic on the bridge consists of southbound unit-coal trains and northbound empty-car trains. Annual traffic is about 9 million gross tons. Despite its low traffic volume and relatively young age, the bridge has been experiencing fatigue problems primarily at the intersections of the girder webs, welded stiffeners, cross frames, and lateral braces.

To evaluate activity of fatigue cracks at critical areas of the bridge, CN had arranged for AE tests to be performed on the structure. Based in part on AE tests done in 1993 and 1996, spans 5 and 7 were replaced in 1995 and spans 1 and 15 in were replaced in 1997. Representatives of CN, DNL, and TTCI selected test specimens from spans 1 and 15. After their removal, specimens were taken from the top flange and the web at the cross frames and lateral braces.

AE THEORY

When a bridge is subjected to repeated load cycles, fatigue cracks may be initiated due to discontinuities and material imperfections in critical load-bearing members. The rate of crack growth depends on a number of factors including both the load magnitude and the current crack length.

Controlled laboratory fatigue tests, as demonstrated in Exhibit 1, have shown that for a specific load amplitude, these factors are exponentially related as follows:

$$da/dn = b(K)^m$$

In this equation, a is the crack length, b and m are constants depending on the material and load conditions, and K indicates the current state of crack activity and is known as the stress intensity factor. K varies from 0 to about 50, with a value of 0 indicating no crack activity and a value of about 50 occurring at specimen failure. The exponent ' m ' has a value of 3.15 for steel.

This relationship may even be used to predict the remaining life of fatigue-test specimens. However, in-service field conditions may present many complications when predicting crack propagation on bridges, due to complex structural geometry, random loading conditions, and unknown previous load history. As a result, the above relationship can be used only in a general sense to estimate current fatigue-crack activity. DNL in its AE bridge-testing program rates fatigue cracks on a scale of 1 to 5. This rating considers not only the crack activity as determined by AE monitoring, but

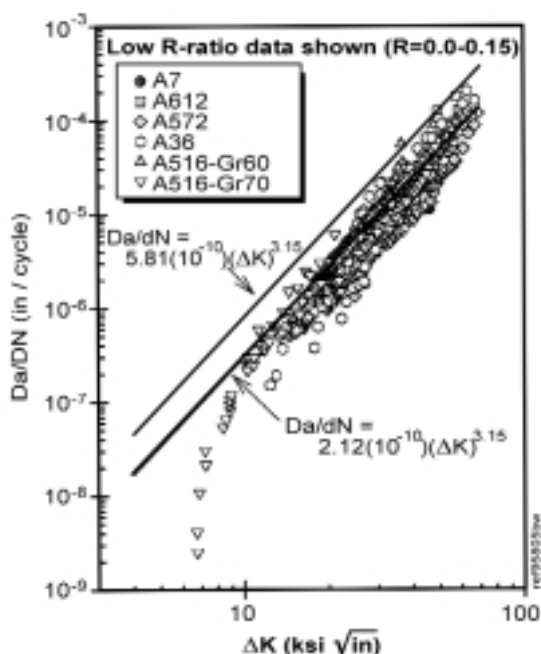


Exhibit 1. Crack Growth Rate as a Function of the Stress Intensity Factor

also other factors as determined from visual inspection or other techniques in the general vicinity of the crack.

When a fatigue crack propagates in a member, it emits an acoustic signal known as an “event.” The number of events emitted, the acoustic-count rate, the rise time, amplitude, and duration are key features common to the time-domain analysis of AE signals. As cracks grow in welds or in the parent steel, these parameters change, signaling transitions in crack activity from initiation to slow growth and to rapid growth. As a further complication, on a complex structure, crack activity may increase with increased crack length, or conversely a crack may progress to a certain length to relieve stress sufficiently to reduce further crack activity. Being able to assess current crack activity is one of the benefits of AE monitoring.

AE monitoring systems use dynamic pattern recognition techniques to interpret signals. Since AE can also be detected from sources such as fretting, corrosion, and loose fasteners, these techniques are employed to separate crack growth AE event signals from erroneous signals. Three different types of AE systems were used in the specimen tests at TTC, an analog system that uses time-domain signal analysis, a digital system that uses frequency-domain signal analysis and a new modal-analysis system that uses a signal-comparison technique to eliminate noise.

LABORATORY TEST PROGRAM

A laboratory evaluation of the AE monitoring techniques was conducted on a 24 x 48-inch (610 x 1,220 mm) bridge specimen which contained a 0.6-inch (15 mm) crack in the stiffener weld extending to the edge of the web metal. Accelerated laboratory fatigue tests were conducted in TTC’s 660-kip (2,900 kN) MTS servo-hydraulic fatigue machine while loading the bridge specimen in four-point bending as shown in Exhibit 2. The maximum cyclic loads during testing ranged from +20 to +135 kip (+89 to + 600 kN). To determine the required test parameters prior to testing, the mechanical properties, chemistry, and cleanliness of the bridge steel were thoroughly evaluated.

Chemical and metallurgical analyses of the bridge specimens revealed typical structural steel (0.14 percent C) with a grain size of ASTM No. 8 or finer. The steel contains numerous alumina inclusions due to the 0.41 percent aluminum content, which could encourage fatigue-crack initiation and propagation. The alloy content of the steel is consistent with CSA G 40.8 which is comparable to ASTM A36. Tensile properties of the bridge steel are as follows: ultimate tensile strength = 75.1 ksi (518 Mpa); yield = 51.0 ksi (352 Mpa); elongation = 31.0 percent, and reduction of area = 63.2 percent. The fatigue characteristics of the steel were also determined using compact tension specimens per ASTM E647. This provided information to determine appropriate settings for the MTS machine that would result in crack reinitiation during the AE evaluation.

Before testing, the specimen was visually inspected using dye penetrant and magnetic particle techniques to characterize its initial condition. This inspection was repeated at nine different times throughout the test.

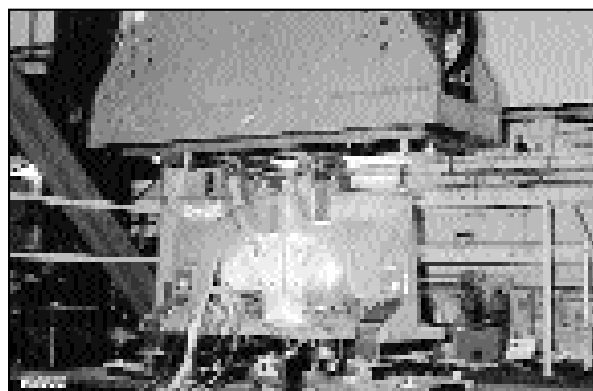


Exhibit 2. Test Setup Showing Fixtured Bridge Specimen

The fatigue-test fixtures used damping assemblies consisting of alternating steel and aluminum plates installed at each of the four load points in specially designed grips in an attempt to minimize the transmission of hydraulic noise from the MTS machine to the specimen. The MTS head block, which is operated by two parallel actuators, was not restrained from movement in the lateral specimen direction, which allowed the generation of some lateral web flexure. This complex loading may have more closely duplicated the field loading of a DPG under traffic.

AE transducers were attached to the web in three different configurations depending on the type of instrumentation. All were configured to monitor the activity of the existing crack(s). Two strain rosettes were mounted on the specimen near the crack tip to enable strain measurements and calculation of the principal stresses in the vicinity of the crack. Two Brunson optical telescopes were also used to visually determine the crack length with a precision of 0.0001 inch (0.0025 mm).

RESULTS

Preliminary findings indicated that some of the AE instrumentation used in the test readily detected fatigue-crack initiation and growth in a very noisy test environment. As the crack grew longer, it grew faster with each successive loading cycle. Because each later cycle broke a large area of metal, more acoustic energy was released. Therefore, as the crack grew longer, more acoustic bursts were emitted and measured. Thus the equipment used, accurately measured the actual dependence of acoustic emission and crack growth, as shown in Exhibit 3. Based on the initial data analysis from this laboratory investigation, the following preliminary conclusions are made:

- Fatigue testing of specimens taken from cracked girders of the CN Mason Creek Bridge indicate the loading regime of combined four-point bending with lateral web displacement resulted in reinitiation of existing cracks and growth of new cracks.

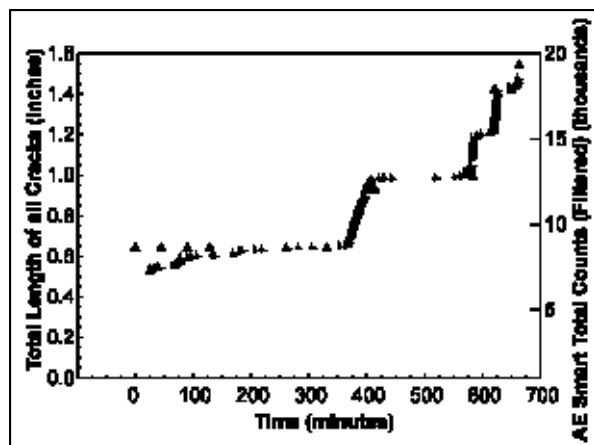


Exhibit 3. Crack Length and Number of Counts vs. Time

- Three types of AE monitoring systems were used. Of these, the new modal analysis system readily detected the initiation and effectively monitored the growth of fatigue cracks in the test specimen. This system was able to effectively reject background noise without the extensive data analysis required for other AE systems.
- A strong positive correlation existed between the crack-growth rate and the degree of acoustic activity. This means that the rate of growth of fatigue crack is closely related to the emission of acoustic energy. The AE technique can be an effective method for finding fatigue cracks in critical bridge members and for determining their relative activity.

FUTURE WORK

Further investigation should be carried out to determine if AE techniques could effectively be used to monitor the initiation and growth of cracks in concrete and timber railroad bridges.

REFERENCE

Hudak, S. J., Burnside, O. H., and Chan, K. S., "Analysis of Corrosion Fatigue Crack Growth in Welded Tubular Joints," *Trans. ASME*, Vol. 114, February, 1992.

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