Quantification of Fatigue Cracking in CT Specimens with Passive and Active Piezoelectric Sensing

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ABSTRACT

Monitoring of fatigue cracks in steel bridges is of interest to bridge owners and agencies. Monitoring of fatigue cracks has been attempted with acoustic emission using either resonant or broadband sensors. One drawback of passive sensing is that the data is limited to that caused by growing cracks. In this work, passive emission was complemented with active sensing (piezoelectric wafer active sensors) for enhanced detection capabilities. Passive and active sensing methods were described for fatigue crack monitoring on specialized compact tension specimens. The characteristics of acoustic emission were obtained to understand the correlation of acoustic emission behavior and crack growth. Crack and noise induced signals were interpreted through Swansong II Filter and waveform-based approaches, which are appropriate for data interpretation of field tests. Upon detection of crack extension, active sensing was activated to measure the crack size. Model updating techniques were employed to minimize the difference between the numerical results and experimental data. The long term objective of this research is to develop an in-service prognostic system to monitor structural health and to assess the remaining fatigue life.

Keywords: acoustic emission, bridge health monitoring, diagnosis, fatigue crack, prognosis, piezoelectric wafer active sensors, PWAS

1. INTRODUCTION

Acoustic emission monitoring has been shown to be able to detect crack growth in metals\textsuperscript{[1-10]} and assess the integrity of structures such as bridges and aircraft\textsuperscript{[11-14]}. The method has the notable advantage that the precise location of cracking does not need to be known for evaluation purposes. Rather, the sensors together with appropriate algorithms are capable of locating and quantifying active crack activity. It has been reported that acoustic emission techniques are so sensitive that fatigue cracks can be detected successfully even though the crack length may be less than 10 µm\textsuperscript{[3, 5]}. There are four major causes that contribute to acoustic emission when structures are subjected to cyclic loading: plastic flow ahead of the crack tip, crack growth, grating from fracture surfaces, and extraneous noise. The sources of acoustic emission in tension load cycles are shown in Figure 1. The numbers in the load versus time diagram correspond to the numbers in the cyclic stress-strain curve (hysteresis loop). Acoustic emissions are generated by crack opening, yielding and crack extension during the loading procedure 1→2, and then from crack closure and reversed yielding during unloading procedure 2→3. Similar emissions will be generated during subsequent procedures such as 3→4 and 4→5. The grating exists in the crack closing and opening procedures. The extraneous noise mainly comes from the hydraulics, machine start and stop, slippage and abrasion of load train in laboratory testing. Extraneous noise can become more complicated in field testing such as bridge monitoring\textsuperscript{[11, 13]}. However, experience has also shown that extraneous noise can be minimized for certain field applications and should therefore be addressed on a case-by-case basis.

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One of the challenges in passive monitoring is the discrimination of crack signals from noise signals. Acoustic emission from grating can be minimized by collecting and analyzing signals just around the peak load \[^1, 8\]. The spatial filtering techniques based on the source location, guard transducers \[^4, 16\] and time of arrival \[^4, 17\] can be employed to separate extraneous noise from crack bursts in laboratory testing to understand the mechanism of acoustic emission associated with crack growth behavior, based on the prediction that the crack initiates ahead of the notch tip and grows along the notch plane. The techniques used to minimize extraneous noise in laboratory testing may not be entirely applicable for acoustic emission bridge-monitoring because the crack location, the environmental noise and loading amplitudes can be less predictable in the field. The waveform-based acoustic emission approaches \[^12, 15, 18, 19\] have therefore been proposed to interpret signals. In the work described here, the characteristics of waveforms induced by cracking (including grating) and noise were first analyzed then defined to determine the characteristics of acoustic emission caused by crack growth behavior.

Passive sensing does well in collecting transient signals from crack growth behavior, but it does not generally allow an estimate of the size of defects. Active sensing provides an alternate means of detection, not simply listening, but interrogating the structure by exciting a propagating wave in the structure and sensing the response. By analyzing the structural response, information regarding the structural integrity, damage location, and damage size can be estimated.

One of the primary challenges for health monitoring and the related field of prognostics lies in relating the sensed data to the remaining strength or fatigue life of a component or system. Numerical analysis usually depends on several material constants, with values found experimentally \[^2, 20\]. However, the constants may not meet some conditions that are specific for the specimen used in the study. Model updating is an efficient technique in minimizing an objective function that represents the difference between the numerical results and experimental data \[^21, 22\].

In this paper, the application of both passive and active piezoelectric based sensing is described for cyclically loaded steel compact tension test specimens. The specimens are representative of steel bridge construction and were specially designed and fabricated for this purpose. The acoustic emission characteristics associated with the crack growth behavior of the material used for in-service bridges were collected through conventional fatigue crack testing and acoustic emission techniques. Tests for collecting acoustic emission from grating and extraneous noise were also performed. Signals were interpreted through a combined approach involving Swansong II Filters and investigation of waveforms. The model updating approach is also described for assessment of the fatigue behavior. The results of the testing described will be used in part for the development of a specialized prognostic system for bridge-monitoring.

### 2. EXPERIMENTAL PROCEDURES

Compact Tension (CT) specimens, made of structural steel A572 Grade 50, were used in this study. The geometry of the specimens is displayed in Figure 2. The effective width as defined in ASTM E647 \[^23\] is 241.3 mm. The thickness and notch length are 12.7 mm and 82.55 mm, respectively. Custom fixtures were designed and fabricated to mount the CT specimens. The cyclic tension loads of minimum 1 kN and maximum 50 kN as shown in Figure 1 were applied to the specimen using a servo-hydraulic mechanical testing machine (810 Material Test System). Fatigue tests were conducted under load-controlled mode with frequency of 1 Hz. A clip gage was employed to measure the crack mouth opening displacement (CMOD) to clarify crack opening and closure and to determine the magnitude of the CMOD. The surface cracks were also monitored optically with a high resolution recording microscope.

Instruments manufactured by Mistras Group (formerly known as Physical Acoustic Corporation (PAC)) were employed to monitor the fatigue cracks. Standard resonant transducers of type R15I-AST with integral 40 dB preamplification were utilized to detect the pulses from crack initiation and propagation. The layout of five transducers is shown in Figure 2. Transducers were attached to the specimen with vacuum grease, and doubly fixed in place with duct tape and clamps. Acoustic emission data was processed and displayed through a 16-channel Sensor Highway II-Remote Asset Integrity Monitor system. The time driven rate was set at 100 μsec, which permitted 10 data points to be collected in a load cycle for parametrics such as strain, load and CMOD. The fixed threshold (trigger point) of each acoustic emission channel was 45 dB. Band pass of the analogue filter was from 100 kHz to 1 MHz. Five waveform samples could be recorded each μsec. Pencil lead break tests were performed before and after each loading test in order to check the performance of the transducers and to obtain reference waveforms.

The extraneous noise could not be completely eliminated although pins were wrapped with cloth and gaps were filled with plastic shims. The acoustic emission data caused by grating of crack surfaces and extraneous noise are referred to as ‘friction emission’ in this paper. Verification tests were performed to determine the intensities of the friction emission.
In these tests, the maximum load in the cycles was decreased to a lower level after the crack propagated to a length of 40 mm. The lower peak load was selected so as to be insufficient to produce crack growth. All of the acoustic emission events at this lower peak load were therefore assumed to be due to friction emission. Emission having the characteristics of friction emission was then filtered.

To compare with conventional AE transducers, dual use piezoelectric wafer active sensors (PWAS) were also installed on the CT specimen as AE sensors on the opposite side of the specimen (Figure 2 dashed line). The PWAS are made of APC-850 piezoceramic, 0.2-mm thick and 7-mm round (APC Inc.). They are installed on the specimen following the usual strain gauge procedure using M-200 bonding adhesive curing at room temperature. To improve the signal-to-noise ratio, PAC 2-4-6 preamplifier were used providing 40 dB amplifying factor. Data collection was conducted by the Sensor Highway system as well using a four-channel digital oscilloscope.

Additional PWAS were installed on the CT specimen for ultrasonic guided wave active sensing (Figure 2). The active sensing takes data at predetermined loading stages when crack growth is observed via AE detection. During the sensing, one PWAS serves as the transmitter sending out interrogating guided waves to propagate in the specimen in all directions; other PWAS serve as receivers picking up the structural responses at different locations. By comparing structural responses at different stages and performing signal analysis, information regarding the crack existence, location, and growth may be obtained. The active sensing data analysis algorithms include damage index definition and sparse array imaging.

3. NUMERICAL PROCEDURES

The formula to calculate number of load cycles \(N\) can be found from the Paris Law as

\[
N = \int_{a_i}^{a_f} \frac{da}{C \Delta K^m}
\]

where \(a_i\) and \(a_f\) are the initial and final crack length, \(\Delta K\), is the range of stress intensity factor, \(C\), and \(m\), are material constants for fatigue crack growth.

A probability distribution was used to model the uncertainty on the updating parameters. The Bayes’ theorem [21] was employed to update a probability density function of the crack length obtained from experimental data. The crack length measured at different numbers of load cycles was utilized as identified parameter to update the model. Genetic algorithms were then used for finding the regions of highest probability which represent the most likely parameter values.

Let, \(M\), represent a chosen model (e.g. finite element model from a real structure or Paris Law), which is a function of the material parameters \(D\), and some experimental information obtained from the structure \(\Theta\) (i.e. crack length). The Bayes’ theorem can be written as

\[
P(\Theta|D,M) \propto P(D|\Theta,M)P(\Theta|M)
\]

where, \(P(\Theta|D,M)\) corresponds to the probability density function (PDF) of the material parameters \(\Theta\) for the chosen model \(M\) after being updated with the observation \(D(\text{crack length})\), or posterior PDF. \(P(\Theta|M)\) is the PDF of the parameters \(\Theta\) for the chosen model \(M\) before updating, or prior PDF, and \(P(D|\Theta,M)\) is the likelihood of occurrence of the measurement \(D\) given the vector of parameters \(\Theta\) and the model \(M\). Model updating requires the comparison of experimental and analytical data. Therefore, features from the data records that are easily calculated with a numerical model are commonly used for updating. For example, in structural dynamics the natural frequencies and mode shapes of the structure are commonly used for model updating. Modal parameters can be obtained from field measurements and can be easily calculated from numerical models. In this example the crack length measured at different numbers of cycles for a fixed minimum load applied was chosen as the identified parameter to update the model. The model is updated using measured crack lengths of up to 40 mm. The parameters \(C\), and \(m\) were chosen as updating parameters, and the value of \(\Delta K\) was calculated based on theoretical functions [24].

Assuming that no prior information about the crack length is known, the prior PDF would correspond to a uniform distribution. The likelihood PDF for a function which is proportional to a Gaussian distribution of the difference between the numerical model and the measured data, the posterior probability can be calculated as
where, $n$ is the number of length of crack measured (in this case eight), $u_j^{id}$ is the $j$-th measured crack length, $u_j^{fe}(\Theta)$ is the $j$-th crack length to be updated, $\sigma_j^h$ is the standard deviation of the error in the $j$-th length of the crack, $\Theta_l$ and $\Theta_u$ are the lower and upper bounds of the updating parameters ($C$ and $m$). This equation is proportional to the probability of the structural parameters $\Theta$ given a set of experimental modal parameters $D$ and could have one or several local maxima. Eq.(3) is used to calculate the probability of the numerical model as the parameters $\Theta$ vary. Furthermore, an optimization of Eq.(3) will result in the values of the parameters $\Theta$ that best represent the model. For this particular example the identified standard deviation of the error was assumed to be 10 % of the length of the crack used to update the model.

Numerical models are updated on a Bayesian approach by finding the values of the parameters $\Theta$ that maximizes Eq.(3). Numerical methods such as Hill Climbing algorithms and Genetic Algorithms are common approaches to calculate the values of high probability of the posterior PDF. Genetic algorithms are used in this paper. Constraints were used to ensure that the updating parameter values were within reasonable limits according to different values reported in the literature for different steel types. Table 1 shows the constraint values used to update the model.

<table>
<thead>
<tr>
<th>Material constants</th>
<th>Lower bound</th>
<th>Upper bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C$</td>
<td>1e-18</td>
<td>1e-10</td>
</tr>
<tr>
<td>$m$</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

The updated model is verified by estimating the crack length after a determined number of cycles. In this particular case 3 points were used to update the model and the 3 subsequent points validate the model. In this study only the values of $c$ and $m$ that maximized the probability were used to calculate the crack length of subsequent loads.

### 4. RESULTS AND DISCUSSION

#### 4.1 Passive sensing

Friction emission tests at 40mm crack length were carried out with maximum loads from 5 kN to 30 kN. To obtain a high threshold of friction emission and a conservative evaluation of the crack growth detection, the maximum emission in each sample rate was collected and is shown in Figure 3. The fracture surfaces were the most uneven at the beginning of the friction test. Leaving the specimen overnight at zero load caused the crack to close completely. In addition, the fracture surfaces mostly were in close contact when the peak load was 5 kN. The friction emission was highest therefore during the first 1000 load cycles. In subsequent tests where the peak load was 10 kN (1,000 cycles), 15 kN (1,000 cycles), 20 kN (1,000 cycles), 25 kN (1,000 cycles) and 30 kN (1,500 cycles), almost all the amplitudes of the friction emissions were below 60dB and this was therefore used as a threshold to minimize friction emission from the dataset. The waveforms of representative hits are also demonstrated in Figure 3. The dominant frequency of each waveform is nearly the same due to the resonant sensors that were used in the tests. The waveforms from the friction emission have long rise time with poorly defined peak amplitudes. The interface between the axial and flexural modes becomes ambiguous in a friction emission waveform as shown in Figure 3.

The amplitude of each channel and representative waveform from the pencil lead break test are displayed in Figure 4. Each channel recorded a hit with amplitude of approximately 97 dB due to a pencil lead break in the vicinity of the crack tip. This indicates that, each transducer has the integrity and ability to detect simulated AE signals with approximately the same sensitivity level. The characteristics of the waveform from pencil lead breakage are also shown in Figure 4. The wave first rapidly attains the peak amplitude, and then fades gradually. The higher peak amplitude associated with shorter rise time is indicative of genuine AE, as is the clean front-end of the waveform. The waveforms collected during
friction emission and pencil lead break testing provided an approximate point of reference to distinguish the friction emission from the emission caused by crack growth.

The amplitude vs. duration plot of the hits recorded during the fatigue test is shown in Figure 5 (with AE below 60 dB filtered). The hits recorded in fatigue and fracture testing should concentrate in a band region where in general the low-amplitude emission has short duration and high-amplitude emission has longer duration [25]. The data was then filtered again based on the technique of the Swansong II Filter [26]. The filtered plot of amplitude vs. duration is also shown in Figure 5. The waveforms of the hits numbered in Figure 5 are displayed in Figure 6. It can be seen by comparing numbered waveforms with the references from friction emission and pencil lead breakage that most of the hits are from crack extension in the filtered dataset as shown in Figure 6-(1-4). Some visual inspection of the waveforms remained necessary.

To associate acoustic emission with crack growth behavior, the plots of energy/amplitude vs. time during the entire fatigue test and classic curve of crack growth rate da/dN vs. stress intensity range ∆K are shown in Figure 7a and 7b, respectively. There are three significant clusters of acoustic emission activity that are indicative of three stages of crack growth as shown in Figure 7a. The transducers were triggered firstly at crack initiation. Intensities of the events were medium in this stage. The fatigue crack came into the stage of relatively stable propagation after crack initiation, which made the emission rate become lower. The energy release rate became higher with crack extension, and catastrophic fracture finally occurred. The intensity and rate of acoustic emission increased most significantly in the third stage. There are three regions of crack development from initiation to catastrophic failure, such as low crack growth rate, linear region and high crack growth rate, as shown in Figure 7b. Since the notched specimens were used in the tests, the magnitude of energy release in the region of low crack growth rate was more than that in the linear region (because notch tip was blunter than crack tip, and more energy needed to be released to initiate crack), but less than that in the region of high crack growth rate. The collected signals of acoustic emission are in reasonable agreement with the energy release in crack development.

4.2 Active sensing

In the active mode, PWAS can excite guided wave modes at different frequency as a broadband transducer [27]. To achieve good signal-to-noise ratios (SNR) yielding usable information, three frequencies have been identified through the tuning technique, 60 kHz, 102 kHz, and 159 kHz. Sample signals collected at pristine specimen condition (baseline signals) from PWAS 1 to 12 are given in Figure 8. Due to the specimen thickness (12.7 mm) and the low frequencies used, the signals are not very strong. A voltage amplifier will be included in the future test to increase the SNR for reliable signal analysis.

4.3 Numerical analysis

The model updating procedure previously described was implemented in Matlab using a population of 1,000 individuals for the genetic algorithm. Values of 2.93×10⁻¹⁶ and 3.29 were obtained for C and m, respectively. Three values of crack length (16 mm, 20 mm, 25 mm) were used in model updating to estimate crack length from 16 mm to 40 mm. Figure 9 shows the number of load cycles vs. crack length from the updated model and experiments. Results from the updated model could better match experimental results if all available data were used to update the model.

5. CONCLUSIONS

Passive and active sensing techniques were utilized to monitor the fatigue cracking in CT specimens that were designed and fabricated to be representative of steel bridge construction. A model updating approach was also employed to assess the fatigue damage and confirm the test results. For passive sensing (acoustic emission), reference tests such as friction emission and pencil lead breakage were performed to obtain reference waveforms from noise and cracking. A Swansong II filter was used to minimize noise in the dataset. Based on this study, the following conclusions can be drawn:

1. Friction emission testing can provide reference waveforms to aid in the differentiation of noise from cracking, but cannot provide all-inclusive reference parameters to filter data. This is, because the loads are decreased to keep the crack length constant during the friction emission testing.

2. The combination of a Swansong II filter with a waveform-based approach is appropriate for data processing and interpretation. This combined method holds promise not only in the laboratory studies but also in field testing. It is very important to define the waveforms associated with background noise and crack growth if this method is to be used.
3. Acoustic emission can characterize and reflect crack growth phenomena such as crack initiation, stable propagation, and catastrophic failure.

4. For active sensing, due to the low frequencies excited and large specimen thickness, low SNR signals were detected. Further improvements will be made to have an amplifier deployed for data acquisition to obtain stronger signals for reliable analysis.

5. A probabilistic model updating framework that included the Paris law to model crack growth, Bayesian inference to model uncertainty in the data, and Genetic algorithms to maximize the probability of the updating parameters was proposed and implemented. Results from updated model show a fair agreement with those from tests, even though sparse data was used in the model updating process.

This study is a step in the development of a prognostic system for monitoring of in-service bridges. Associating the parameters in crack growth behavior with the corresponding parameters in acoustic emission through sparse data sets, as well as efforts on active sensing estimating crack length and model updating assessing remaining fatigue life, will be addressed in future studies.

ACKNOWLEDGEMENT

This work is performed under the support of the U.S. Department of Commerce, National Institute of Standards and Technology, Technology Innovation Program, Cooperative Agreement Number 70NANB9H9007. The authors wish to acknowledge those involved at Mistras Group, especially Didem Ozevin, Valery Godinez, and Richard Gostautas; and joint venture partners University of Miami (Antonio Nanni) and Virginia Tech (Dan Inman).

We also thank DRPA, Virginia DOT, South Carolina DOT and Florida DOT for providing access to bridges and related information for this project.

REFERENCES


Fig. 1 Sources of acoustic emission in tension load cycles

Fig. 2 Geometry of CT specimen and arrangement of transducers
Fig. 3 Friction emissions at 40 mm crack with peak load from 5 kN to 30 kN, and representative waveforms

Fig. 4 Amplitude of each channel and representative waveform in pencil lead break test
Fig. 5 Amplitude (dB) vs. Duration (µs) before and after Swansong II filter

Fig. 6 Waveforms from numbered hits in cleaned data (see Fig.5).
a. Energy/amplitude vs. time in crack growth behavior

Fig. 7 Acoustic emission and crack growth behavior

b. Crack growth behavior

Fig. 8 PWAS active sensing on CT specimen: signal collected on clean plate from PWAS #1 to #12 at 60 kHz, 102 kHz and 159 kHz.
Fig. 9 Comparison between updated model and experimental results

![Comparison between updated model and experimental results](image)

- **Updated model**
- **Experimental results**

Fig. 9 Comparison between updated model and experimental results