DAMAGE AND FAILURE ANALYSIS OF BRITTLE MATERIALS BY ACOUSTIC EMISSION

By S. T. Dai,1 Associate Member, ASCE, and J. F. Labuz,2 Member, ASCE

ABSTRACT: Application of stress or changes in environmental conditions can cause a material such as concrete or rock to become damaged, thereby affecting the performance of the structure. Because damage processes produce microseismic events called acoustic emission (AE), the growth of damage and the onset of failure can be identified by monitoring AE. In particular, a probability density function of acoustic emission events was used to describe the development of damage. It was observed that more porous or cracked materials displayed a higher AE rate than less porous or cracked materials at the same percentage of the maximum stress prior to failure. This suggests that the AE technique may be applied to diagnose the level of damage in a brittle material and may be useful to select materials for certain applications. Also, the experimental results indicated that the average root-mean-square value from a number of AE signals could be used as a real-time monitoring tool to predict the onset of failure.

INTRODUCTION

Acoustic emission (AE) is concerned with the detection of elastic waves generated by what might generically be termed damage processes in stressed solids. AE has the potential to characterize crack nucleation and growth (Scruby et al. 1985; Shah and Labuz 1995). Evaluating deterioration in brittle materials such as concrete and rock is of importance because these materials exhibit softening behavior, such that a further increase in displacement (beyond peak load) is associated with a decrease in load. Therefore, the development of a diagnostic method would be helpful in assessing the service life of a structure composed of a brittle material.

AE as a monitoring technique has been widely used to assess degradation of materials and assure safety of various systems. Kaiser (1950) first observed that during loading and unloading of certain metals, no AE occurred until the previous maximum load had been exceeded; this phenomena is known as the Kaiser effect. AE may also be an indicator of prior stress conditions and has been studied in the context of estimating the in-situ stress state in rock (Holcomb 1993). It should be noted that the Kaiser effect does not reliably occur in brittle materials. Sondereg and Estey (1981) conducted cyclic uniaxial loading of Westerly granite specimens and found that AE commenced well below the peak stress attained in earlier stress cycles.

Ohtsu (1987) and Ohtsu et al. (1993) used AE to diagnose damage of concrete. A probability density function was defined to relate AE activity to material damage. Ohtsu et al. (1993) concluded that the AE activity becomes high when the concrete contains many microcracks and this tendency can be quantitatively evaluated on the basis of rate process theory. Landis and Shah (1993) conducted beam tests on mortar and concluded that the inversion of AE data is a unique method of monitoring the dynamic processes of damage evolution and crack growth. AE event rate and locations have been used to study fractures. Re (1986) conducted fracture tests on a steel alloy and claimed that AE is a suitable method to measure the fracture toughness. Cumulative AE counts have been found to be related to the fracture toughness of concrete (Reymond et al. 1983).

The AE technique has been applied to field monitoring as well. In structural engineering it has been used to detect and locate fatigue cracks in steel bridges (Ghorbanpoor and Rentmeester 1993). It has also been widely used in geotechnical engineering. For example, in tunnel, slope modification, and stabilization and mine roof support it is important to have the capability of evaluating the current state of mechanical stability. AE techniques are suitable to provide such real-time data. Review given by Hardy (1989) on AE applications to the geotechnical field provides an overview on the applications.

Furthermore, durability of concrete pavements is important for highway engineering. Deterioration of concrete from freeze-thaw cycles is a major form of distress in cold weather climates. Thus, to design a better pavement in these regions assessing the degradation of concrete due to freeze-thaw cycles becomes a necessary task. On the other hand, the ability to detect subsurface flaws in rigid pavements is also a concern in pavement management.

The objectives of this paper are to evaluate the effectiveness and suitability of the AE technique as a tool to (1) assess the increase of damage in brittle materials; (2) detect preexisting defects in brittle materials; and (3) predict the onset of failure in structures composed of brittle materials. Since many problems in civil engineering are approximated as two dimensional, plane-stress (three- and four-point bending) and plane-strain (biaxial compression) tests were conducted on different size specimens of rock-like materials, and the AE technique was used to monitor the failure process. A probability density function of AE activity was used to quantitatively evaluate damage of the material. In particular, the value of the function corresponding to the same percentage of maximum stress was compared for different materials. In addition, a feature that indicates the onset of failure in structures from AE energy was observed.

Damage Analysis

In general, as stress applied to a brittle material increases beyond a certain level, internal damage in the form of microcracking will occur in the material. These microcracks correspond to a generation of acoustic emission. To quantify the AE activity during the application of stress, a probability density function \( f(V) \) of AE occurrence is defined as

\[
f(V)dV = \frac{dN}{N_v}
\]

\[ f(V)dV = \frac{dN}{N_v} \quad (1) \]
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$$f(V)dV = \frac{dN}{N_o}$$

(1)
where \( V \) = stress ratio, which is a measure of the external loading

\[
V = \frac{\sigma}{[\sigma]}
\]

where \([\sigma]\) = ultimate strength of the material; \(\sigma\) = stress corresponding to the \(N\)th AE event number; and \(N\) = total number of AE events up to \(V = 1\) or \(\sigma = [\sigma]\). Physically, the function \(f(V)\) describes the rate of microcracking within the material during an increment of the applied stress \(dV\).

The relationship between \(V\) and \(N\) can be established from experimental data. Typically it has the form

\[
V = aN + c\ln(1 + qN)
\]

Substituting (3) into (1) and solving for the probability density function \(f(V)\), the following equation is obtained:

\[
f(V) = \frac{1}{N} \left( \frac{1 + qN}{a + cq + aqN} \right)
\]

where \(a, c,\) and \(q\) are coefficients that can be found from experimental data for a particular experiment. In addition, \(f(V)\) satisfies the condition

\[
\int_0^1 f(V) \, dV = 1
\]

which simply states that the area under the curve of \(f(V)\) versus \(V\) is 1. Thus, \(f(V)\) provides a method to choose materials for an application based on the AE response: a larger value of \(f(V)\) for a given stress ratio \(V\) indicates a greater rate of AE, which means the material has experienced more stress-induced microcracking.

**Failure Prediction**

The acquired AE waveform is a time history that, in some sense, reflects the energy released from the source. A rigorous approach to determine the energy requires the quantitative AE technique. This involves a comprehensive sensor calibration and source characterization using the seismic moment tensor (Shah and Labuz 1995). For practical purposes, however, the magnitude of an AE event can be related to the root-mean-square (RMS) value, which can be obtained by taking the actual voltage \(g(t)\) at each point along the AE waveform and averaging the square of \(g(t)\) over the time period \(T\). The square root of the average value gives the RMS value. The value of a time-dependent signal \(g(t)\) is given by

\[
\text{RMS} = \sqrt{\frac{1}{T} \int_0^T [g(t)]^2 \, dt}
\]

The hardness of brittle materials has been correlated to the RMS value (Jung et al. 1994). Because RMS is associated with energy released by damage within the material, it may be possible to use RMS to predict the onset of failure.

A signal recorded at only one sensor cannot be used to estimate energy released due to geometric attenuation of the signal. One event occurring near a sensor can have a greater RMS than another event of greater magnitude but farther away from the sensor. However, for a large number of sensors with sufficient spacing, an average RMS value from all the sensors will be representative of the energy released, as the effect of sensor position relative to the event will be cancelled. The actual value of the RMS, which is dependent on the instrumentation and the material, is not critical; rather, the relative change during application of stress is of importance for the prediction of failure.

**EXPERIMENTAL SETUP**

**AE System**

The data acquisition system for AE consisted of four, two-channel LeCroy 6840 digitizers with a sampling rate of 20,000,000 samples per second per channel (50 nanoseconds between two consecutive samples) and a LeCroy 6010 controller. A block diagram of the system is shown in Fig. 1. The digitizers were equipped with an internal trigger that was activated whenever an AE signal exceeded the preset value (7 mV). This threshold of amplitude must be set so that environmental noise does not trigger the system; but the threshold should not be set too high as to exclude signals of low amplitude. The trigger-out signal of the first digitizer was connected to the other three digitizers for the acquisition to begin simultaneously at all the digitizers. One of the trigger-out signals was also sent to the load-displacement data acquisition system to correlate AE with the loading history.

The LeCroy 6010 controller has a Motorola 68020, 10 MHz microprocessor with 512 kilobytes of RAM. This allows the 6010 to locally execute programs. A segmentation code provided by LeCroy was customized and downloaded into the 6010 to permit data acquisition until the memory (128 kilobytes per channel) of each digitizer was filled, and then the data were transferred to the host computer. The code was set to acquire 2,048 data points for each event (a time of about 100

![FIG. 1. Block Diagram of Acoustic Emission System](image)
μs), with half of the points being the pretrigger. This meant that the system can record up to 64 events almost continuously.

The acoustic emission signals were captured using Physical Acoustic (model S9225) piezoelectric transducers attached to the specimen surface, and preamplified before recording. The sensors have a reasonably flat frequency response from 0.1 to 1 MHz and a sensor diameter of about 3 mm. They were mounted directly to the material with a methyl-cyanoacrylate glue and catalyst. Preamps (40 dB gain) and filters (bandpass from 0.1 to 1.2 MHz) were chosen to maximize amplification, minimize noise, and assure matched frequency response.

Continuous recording was not possible because of the type of transducer used. The major element of an AE sensor for laboratory applications is a piezoceramic mounted with little backing. The response is underdamped, and the sensors resonate after detecting particle motion on the surface. It was found that when the recording of an event was complete, ringing of the transducers sometimes triggered the system. A sleep time of 9 milliseconds between two consecutive events was prescribed during which the system could not be triggered.

This meant that one event could be captured every 9 milliseconds until the digitizer’s memory was filled. The transfer was done using direct memory access, which allows the transfer rate of 600 kilobytes/s. The total transfer time for 64 events, including the storage time on the computer, was found to be 4 s.

Once the system was armed it could acquire 64 events in 0.573 s, which includes the recording time and the sleep time of 9 milliseconds between any two consecutive events. The load-displacement data acquisition system was not able to store load and displacement for each event at such a high rate. Instead the segmentation code was modified to store the time of each event using the clock of the 6010. The load-displacement system also has a clock and it stored data every 1 s. The time difference between the two clocks was determined prior to the experiments and used to obtain load and displacement for every AE event.

**Bliaxial (Plane Stress and Strain) Testing**

A plane-strain compression apparatus (Fig. 2) was developed at the University of Minnesota (Labuz et al. 1996a). The apparatus is unique because it allows the failure plane to develop and propagate in an unrestricted manner by attaching the upper platen on a low friction linear bearing referred to as the sled. Plane-strain deformation is enforced by a stiff frame, whereby the specimen is wedged against a thick-walled steel ring. Prismatic specimens were used, with the size range from 75 to 100 mm in height, 30 to 40 mm in thickness, and 100 mm in width. The two surfaces of the specimen exposed to confining pressure were sealed by a polyurethane coating. The four surfaces in contact with polished-steel platens were covered with a stearic acid lubricant to reduce the friction between

![Elevation view](image)

**FIG. 2. Plane-Strain Apparatus**

![Plan view](image)

**FIG. 3. Bending Tests: (a) Three-Point; (b) Four-Point**
the platen and the specimen (Labuz and Bridell 1993).

Beam experiments (Fig. 3) consisted of specimens with rectangular cross sections supported by steel rollers at each end. For three-point bending (3PB) load was applied at the middle of the beam through a steel roller. For four-point bending (4PB) loads were symmetrically applied at the outer quarter points of the specimen (the distance between the two loading points was half the span of the support) through two steel rollers, achieving pure bending in that portion.

Material and Specimen Descriptions

Four different materials were selected for study: three rocks of low, medium, and high strengths and Portland cement concrete (high strength). A total of four plane-strain (PS) experiments were conducted on the low- and medium-strength rocks. One specimen fabricated from the medium-strength rock had a hole (12 mm diameter) in the center along the plane-strain direction. The hole was made to create a defect within the specimen. Porosities of the low- and medium-strength rocks were about 26% and 14%, while the porosity of the high-strength rock was less than 1%. The strong and medium rocks and the concrete were used for beam tests. Two concrete beam specimens were tested under 3PB. One concrete beam was damaged by freeze-thaw cycles: the specimen was placed in an environmental chamber for a period of 30 d under a temperature change of −18°C to 5°C. The time of each temperature cycle was about 3 h. The other concrete beam was an intact specimen to serve as a reference. The material properties and specimen dimensions are listed in Table 1.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Material</th>
<th>Size (mm)</th>
<th>Young's modulus (GPa)</th>
<th>Uniaxial strength (MPa)</th>
<th>Test type</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Original concrete</td>
<td>400 x 100 x 70</td>
<td>36</td>
<td>60</td>
<td>3PB</td>
</tr>
<tr>
<td>B</td>
<td>Damaged concrete</td>
<td>400 x 100 x 70</td>
<td>19</td>
<td>20</td>
<td>3PB</td>
</tr>
<tr>
<td>C</td>
<td>Medium rock</td>
<td>254 x 76 x 38</td>
<td>16</td>
<td>40</td>
<td>4PB</td>
</tr>
<tr>
<td>D</td>
<td>Strong rock</td>
<td>890 x 104 x 32</td>
<td>60</td>
<td>200</td>
<td>4PB</td>
</tr>
<tr>
<td>E</td>
<td>Weak rock</td>
<td>100 x 100 x 40</td>
<td>4</td>
<td>10</td>
<td>PS</td>
</tr>
<tr>
<td>F</td>
<td>Medium rock</td>
<td>100 x 75 x 24</td>
<td>16</td>
<td>40</td>
<td>PS</td>
</tr>
<tr>
<td>G</td>
<td>Medium rock</td>
<td>100 x 100 x 30</td>
<td>16</td>
<td>40</td>
<td>PS</td>
</tr>
<tr>
<td>H</td>
<td>Medium rock</td>
<td>100 x 100 x 40</td>
<td>16</td>
<td>40</td>
<td>PS</td>
</tr>
</tbody>
</table>

EXPERIMENTAL RESULTS

Kaiser Effect

Loading-unloading cycles were applied during a plane-strain experiment on the medium rock (specimen F) prior to peak load. As mentioned previously, the trigger time of each AE event and the time of the corresponding load and displacement were recorded. Therefore, the load and displacement at each event were known. Fig. 4 shows the loading history corresponding to the AE events from the test. A, C, and G in the figure indicate the beginning of AE activity during each load cycle. In the first cycle (OABE) the AE events started at point A, while the maximum load for this cycle was at point B (about 120 kN). Also, note that no events occurred on the unloading part (BE). In the second loading cycle (CDEF) it was observed that AE events did not occur until point C, close to the maximum load from the previous cycle (120 kN). A similar situation was observed in the third loading cycle (DFG), although microseismic activity was generated slightly before (about 10% of) the previous maximum load. The peak load of the test was about 340 kN (not shown in Fig. 4), while the load at point D was about 240 kN. This observation means that the Kaiser effect does not develop over the complete range of loading under plane-strain compression, as it seems to depend on stress level. For example, it may not be applicable to brittle materials stressed above 75% of their strength (Lockner 1993).

Damage Analysis

Since the load corresponding to each event is known, the stress ratio V of a material during the application of stress can be calculated using (2). Fig. 5 is a typical curve of N versus ...

![FIG. 4. Acoustic Emission from Medium-Strength Rock under Plane-Strain Compression](image)

![FIG. 5. Typical Curve of Stress Ratio versus Event Number](image)

![FIG. 6. Probability Density Functions of Damaged and Original Concrete Beams in Three-Point Bending](image)
$V$ for the materials tested up to peak load. It shows that as the load increased, the AE event rate increased, which is indicated by the tangent to the curve becoming flatter. Furthermore, this curve can be well described by (3), and the coefficients ($a$, $c$, and $q$) can be obtained through a nonlinear curve fitting regression (Fig. 5). Having obtained the coefficients in (3) for each experiment, the probability function $f(V)$ can be found from (4).

Fig. 6 illustrates the comparison of $f(V)$ between the damaged and the original concrete loaded under 3PB. The damaged material shows a higher $f(V)$ value than the original one at the same level of $V$ before about 98% of peak stress, which corresponded to the start of localization. However, after this point, the original concrete exhibits a higher $f(V)$ value than the damaged one. Furthermore, a similar feature was observed from the tests on the medium and strong rocks (Fig. 7). Again, the medium rock, which has a higher porosity, exhibited a higher $f(V)$ than the strong rock before about 98% of peak stress.

In addition, two specimens (G and H) made of the medium rock were tested under the plane-strain condition. Specimen H had a hole (12 mm diameter) in the center of the specimen, while specimen G was intact. The hole can be viewed as a preexisting defect in the material. Fig. 8 presents the $f(V)$ comparison of the two tests. Once again, the specimen with the hole shows a higher $f(V)$ value before about 95% of peak stress, while the reference specimen demonstrates a higher $f(V)$ near the peak.

The above results indicate that more porous and cracked materials show a higher damage level prior to localization (before 95–98% of peak stress), while a large amount of damage for the less porous and cracked materials is from a portion where the load is close to the peak. The point (about 95% of the maximum stress) may be an indicator of intense microcracking and development of a localized fracture. Similar features, with regard to localization, were also reported by Labuz et al. (1996b) from source locations of experiments on different rocks in compression and bending.

**Onset of Failure**

As already mentioned, the average RMS value (from the eight AE sensors) is related to the energy released from localized sources during the application of stress. Furthermore, the sum of the RMS values, the so-called cumulative RMS, is a measure of the amount of stress-induced damage. In the laboratory experiments, the specimen dimensions are several hundreds of millimeters. The reflected waves from boundaries may also be captured by the transducers if the source location was close to the boundaries and the transducers. Considering this boundary effect on the signal, only the first 50 points (2.5 μs) after the arrival have been used to calculate the RMS value for each event. This ensures that reflected waves from the

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**FIG. 7.** Probability Density Functions of Medium and Strong Rocks in Four-Point Bending

**FIG. 8.** Probability Density Functions of Medium Rock with and without a Defect

**FIG. 9.** Cumulative RMS for Weak Rock in Plane-Strain Compression

**FIG. 10.** Event Locations of Weak Rock in Plane-Strain Compression: (a) before 95% of peak; (b) 95% of peak to peak
The average root-mean-square (RMS) value is associated with the energy released from internal damage in a brittle material. The cumulative RMS value shows a sudden increase when the applied stress approaches the material strength for different types of loading (biaxial compression, pure bending) and different materials (weak, medium, and strong rock). This observation indicates that the cumulative RMS value could be used to predict the onset of failure in real time.

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APPENDIX. REFERENCES


