DAMAGE QUANTIFICATION TECHNIQUES IN ACOUSTIC EMISSION MONITORING

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Acoustic emission (AE) analysis is one of the several diagnostic techniques available nowadays for structural health monitoring (SHM) of engineering structures. Some of its advantages over other techniques include high sensitivity to crack growth and capability of monitoring a structure in real time. The phenomenon of rapid release of energy within a material by crack initiation or growth in form of stress waves is known as acoustic emission (AE). In AE technique, these stress waves are recorded by means of suitable sensors placed on the surface of a structure. Recorded signals are subsequently analysed to gather information about the nature of the source. By enabling early detection of crack growth, AE technique helps in planning timely retrofitting or other maintenance jobs or even replacement of the structure if required. In spite of being a promising tool, some challenges do still exist behind the successful application of AE technique. Large amount of data is generated during AE testing, hence effective data analysis is necessary, especially for long term monitoring uses. Appropriate analysis of AE data for quantification of damage level is an area that has received considerable attention. Various approaches available for damage quantification for severity assessment are discussed in this paper, with special focus on civil infrastructure such as bridges. One method called improved b-value analysis is used to analyse data collected from laboratory testing.

Key Words: Acoustic emission, structural health monitoring, damage quantification, b-value analysis

1 INTRODUCTION

Acoustic emission (AE) analysis is one of the several diagnostic techniques available nowadays for structural health monitoring (SHM) of engineering structures. Acoustic emission is the phenomenon of rapid release of energy within a material by crack initiation or growth in form of stress waves. AE monitoring technique involves recording the stress waves by means of suitable sensors placed on the surface of a structure and analysing the recorded signals to gather information about the nature of the source. Some of its advantages over other techniques include high sensitivity to crack growth and capability of monitoring a structure in real time. By enabling early detection of crack growth, AE technique helps in planning timely retrofitting, other maintenance jobs or even replacement of the structure if required.

An area of high importance in AE monitoring technique is appropriate analysis of recorded data for damage quantification and severity assessment [1]. For damage quantification, various methods are available. A brief introduction of parameters of AE signals used during data analysis is presented before discussing some of the commonly used data quantification methods. A local material change giving rise to acoustic emission is known as *event* [2] and if the event signal exceeds a set threshold value it is recorded by the data acquisition system and is known as a *hit*. For analysis purposes the five most commonly used AE signal parameters of a hit are *amplitude*, *counts*, *duration*, *rise time* and *energy* [3]. Amplitude is the highest peak voltage reached by an AE signal waveform. It is expressed in terms of voltage (V) or commonly in terms of dB, calculated as Counts are the number of times an AE signal exceeds the threshold value. Rise time is the time between first threshold crossing and the peak amplitude while duration is the time between first and last threshold crossings. Energy is often measured as area under the signal envelope.

Quantifying damage level has been attempted using the different AE parameters or a combination of these. Various ways to represent data exist, such as, Ledeczi et al. [4] used number of events to measure activity and average amplitudes of the events to measure intensity and developed an index based on these values as shown in Figure 1.

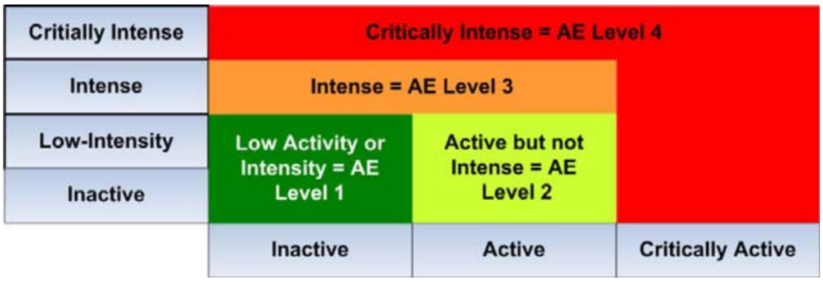


Figure 1. AE classification in terms of intensity (vertical axis) and activity (horizontal axis) [4]

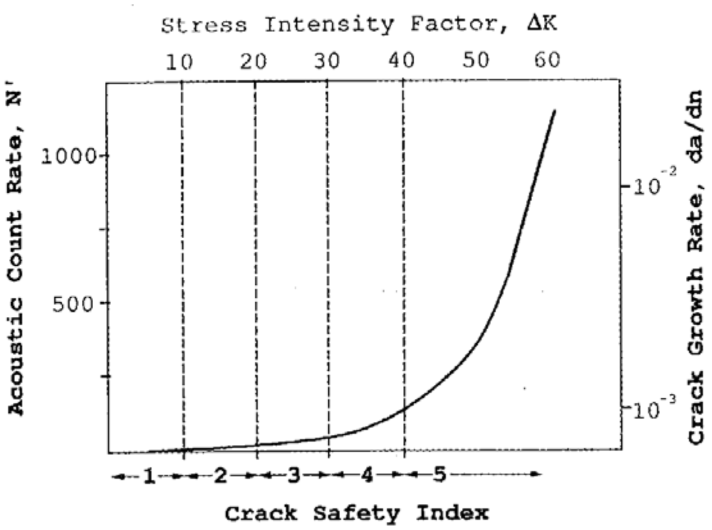
Using the relation between acoustic emission count rate and stress intensity factor range (Equation 1) and results from laboratory tests, Gong et al. [5] devised a way to categorise crack into five different levels, as shown in Figure 2.

$$N' = A(\Delta K)^n \quad (1)$$

where A and n are experimental constants. This is similar to well-known Paris Law of fatigue crack propagation, given as:

$$da / d\eta = C(\Delta K)^m \quad (2)$$

where da/dη is crack growth rate and C and m are experimental constants.



Range of ΔK	Crack Safety Index	Crack Description
$0 < \Delta K < 10$	1	Minor defect
$10 \leq \Delta K < 20$	2	Slow crack growth
$20 \leq \Delta K < 30$	3	Requires repair
$30 \leq \Delta K < 40$	4	Dangerous
$40 \leq \Delta K$	5	Imminent failure

Figure 2. Typical relationships among the crack safety index, crack growth rate, count rate and ΔK for bridge steels [5]

A method, proposed by the Japanese Society of Non-destructive Inspection (NDIS) is dependent on two parameters: load ratio and calm ratio [6,7]. Load ratio (also known as Felicity ratio) is the ratio of the load at the onset of AE activity in subsequent loading to the previous load. Load ratio of greater than 1 indicates good condition while less than 1 indicates damage presence. Similarly, calm ratio is the ratio of the number of cumulative AE activities during the unloading process to the total AE activity during the last loading cycle up to the maximum. Generation of AE during unloading is an indication of structural instability, as no AE is generally recorded in this phase in a structure with good condition [6]. Assessment chart based on the load and calm ratios is shown in Figure 3.

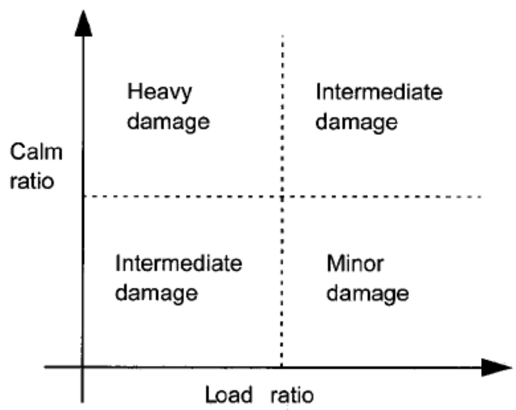


Figure 3. Assessment chart proposed by NDIS [6]

Another common approach for damage quantification is intensity analysis using the historic and severity indices. The historic index is defined as a measure of the change in signal strength throughout the test [8,9]. Historic index is a form of trend analysis with the objective of locating significant changes in the slope of the cumulative signal strength versus time curve [7]. It aims to compare the signal strength of the most recent hits to all the hits, and is calculated as follows [10]:

$$H(I) = \frac{N}{N-K} \cdot \left(\frac{\sum_{i=K+1}^{N} S_{oi}}{\sum_{i=1}^{N} S_{oi}} \right) \tag{3}$$

Similarly, the severity index is the average signal strength for a certain number of events having the largest value of signal strength [10]. It is calculated as follows:

$$S_r = \frac{1}{J} \cdot \left(\sum_{m=1}^{J} S_{om} \right) \tag{4}$$

In equations (3) and (4), $H(I)$ = historic index at time t, N = number of hits up to and including time (t), K, J = empirically derived constant based on material type, S_{oi} = signal strength of the i^{th} event. K values for metals depend on N and are given in [9]. The maximum values of historic index and severity index are then plotted on an intensity chart divided into zones of damage and the location of the point in the chart will indicate the level of damage.

The intensity chart used for analysis of concrete bridges by Golaski et al. [8] is shown in Figure 4, with regions indications as follows: A – minor emission, B – small defect, C – significant defect, further evaluation required; and D,E – major defect, immediate shutdown and follow-up non-destructive examination needed.

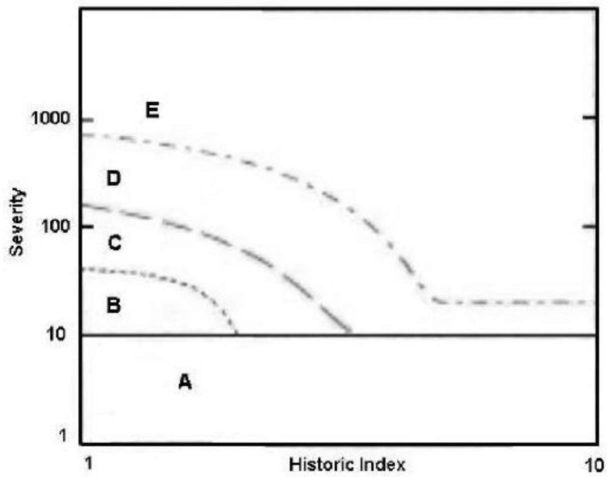


Figure 4. Severity- historic index chart [8]

Another approach for damage quantification that is gaining popularity is the b-value analysis. The b-value analysis takes analogy from seismology, where events of larger magnitude occur less frequently than events of smaller magnitude – the relationship being expressed by Gutenberg-Richter formula as [11,12]:

$$\log_{10} N = a - b\, M_L \tag{5}$$

where M_L = Richter magnitude of the events, N = the number of events with magnitudes in the range $M_L \pm \Delta M/2$, and a and b = empirical constants. The above formula is modified for AE technique and can be written as:

$$\log_{10} N = a - b'\, A_{dB} \tag{6}$$

A_{dB}, the peak amplitude of the AE events in decibels, can be expressed as:

$$A_{dB} = 10 \log_{10} A_{\max}^2 = 20 \log_{10} A_{\max} \tag{7}$$

b value is then expressed as:

$$b = 20b' \tag{8}$$

Thus, b-value is the slope of the log-linear plot of frequency versus amplitude of AE events. It has been found to change during different stages of damage, for example when microcracks occur in the early stages of damage, the b-value is high but becomes low when macrocracks begin to occur [12]. This fact makes the b-value a likely candidate to judge damage progress [13].

The b-value analysis method has been recently modified by using statistical values of amplitude distribution (mean and standard deviation) and the newer method is referred as improved b-value (Ib- value) [14]. It can be expressed as:

$$Ib = \frac{\log_{10} N(\omega_1) - \log_{10} N(\omega_2)}{(\alpha_1 + \alpha_2)\, \sigma} \tag{9}$$

$$\omega_1 = \mu + \alpha_1 \sigma \,, \omega_2 = \mu - \alpha_2 \sigma \tag{10}$$

where μ is the mean amplitude, σ is the standard deviation of amplitude distribution and α_1 and α_2 are constants. Ib value improves calculation by selecting the amplitude limits of the linear range of the cumulative frequency distribution data of AE [15]. Ib-value is usually calculated for a certain number of events (generally ranging from 50 to 100) during the test.

2 EXPERIMENTATION

AE signals from real growing crack were collected from three point bending tests of a rectangular steel specimen - 300 mm long, 25 mm wide and 10 mm thick, with a small through cut notch in the middle to initiate the crack growth, see Figure 5. INSTRON tensile machine with a 50 KN load-cell was used to apply loads to the specimen at a loading rate of 2 mm/min. Four channel micro-disp PAC (Physical Acoustics Corporation) system was used for data acquisition. Two R15α sensors (manufactured by PAC, resonant at 150 KHz) were placed at two ends of the specimen to collect the AE signals. The sensors were coupled to the test specimen using vacuum grease and magnetic holders. Preamplifiers were used along with the sensors with gain set at 40 dB. The signals were bandpass filtered between 20-400 KHz using the software control of the data acquisition system, as most signals were expected in this range. To set the threshold value for recording and ensure sensors were performing correctly, pencil lead breaks (5mm, HB leads) were carried out near the crack tip and recorded signals were observed. The value of 60 dB was decided as this value was found to prevent the recording of lower amplitude reflected signals from the pencil lead break tests.

Due to ductility of the steel specimen, the sample did not fracture but slowly yielded after reaching a peak load value. Loading was stopped after around 16 minutes. The whole process of loading, including crack initiation and growth were recorded using a video camera set on a tripod stand.

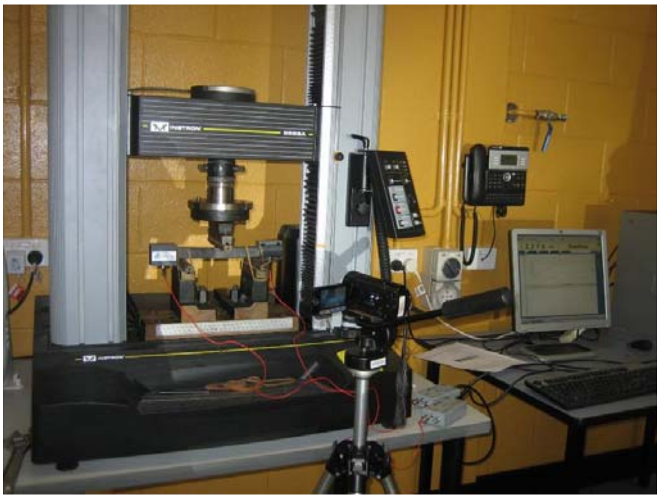


Figure 5. Experimental set up

3 RESULTS AND DISCUSSION

The variation in load with time can be seen in Figure 6. Load first increased linearly up to around 12 KN and then yielding started with the load reaching a peak of around 18 KN. Load then started to decrease nonlinearly till the time the test was stopped. Though the beam did not fracture completely, crack originated at the base of the notch and grew significantly when the test stopped. The number of cumulated hits over time (for one sensor) is also shown in Figure 6. The variation of the peak amplitudes of the hits with time is shown next in Figure 7. The number of hits for each amplitude (cumulative distribution) is also shown in Figure 7.

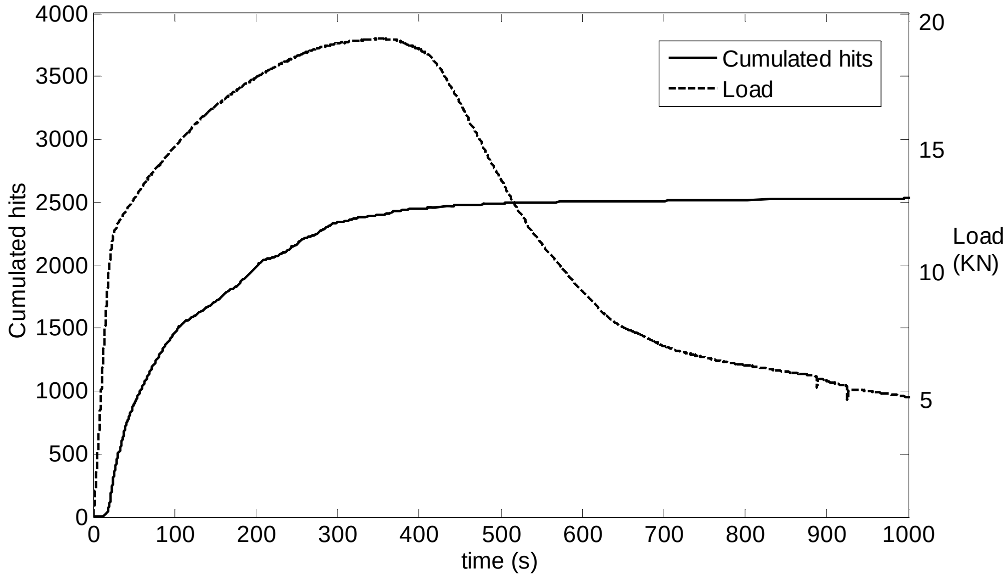
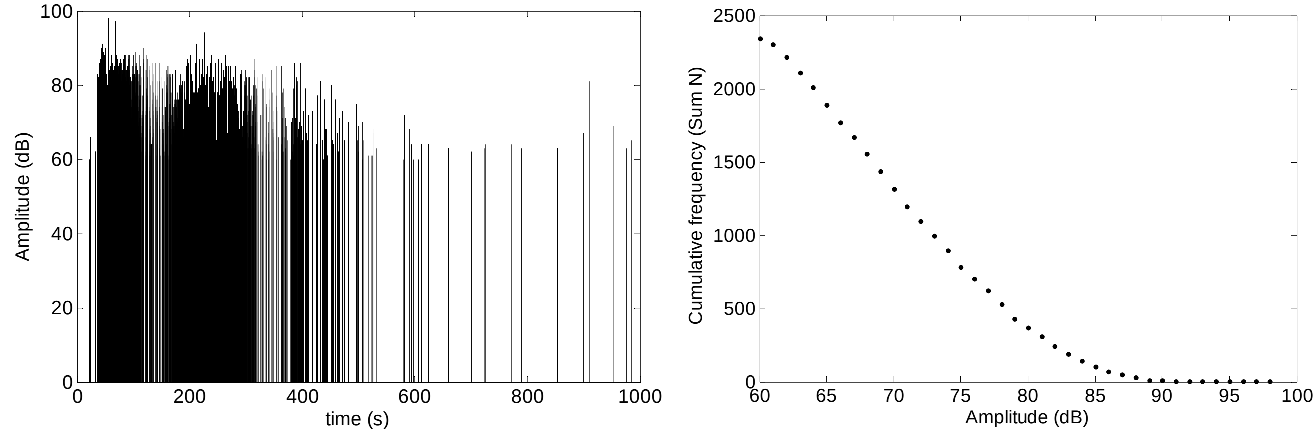


Figure 6. Variation of load and cumulated hits with time



(a) (b)

Figure 7. (a) Amplitude distribution, (b) Cumulative number of events with amplitude

Different stages of crack propagation in selected times are shown in Figure 8. First signs of crack are seen only around 410 s, but most of the acoustic emission hits are already found to occur before that. Once the crack starts, number of AE hits grows very slowly, showing most energy is already generated in the microstructure phases before actual crack growth.

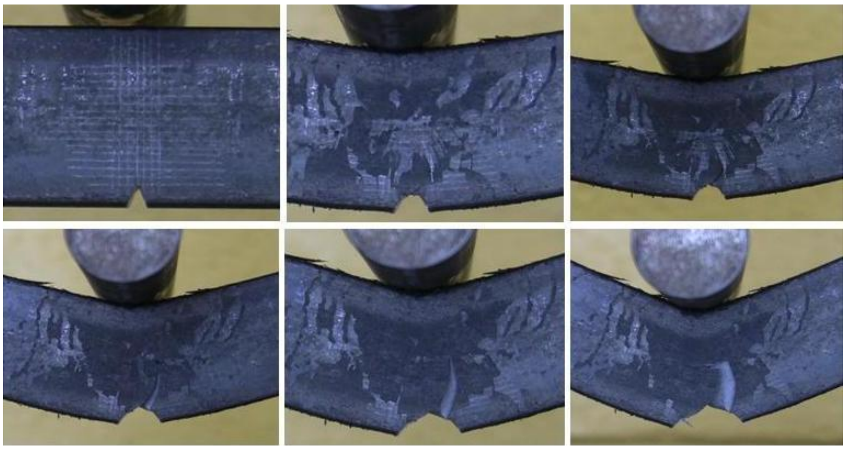
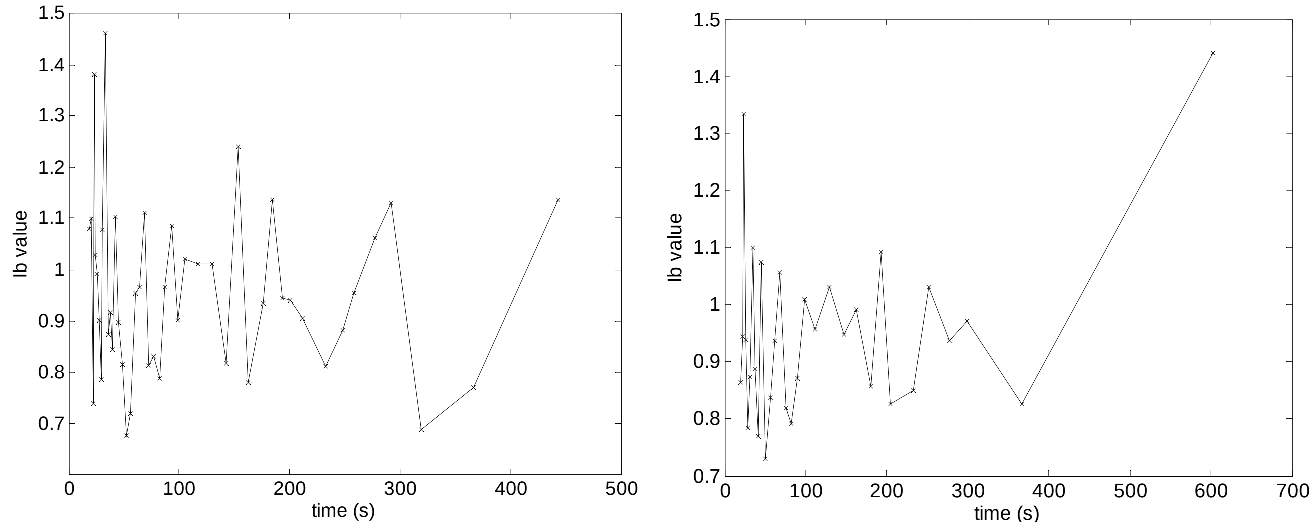


Figure 8. Different stages of crack growth at selected times [0, 410, 500, 615, 720, 935] s

To study how Ib values change during the loading process, first 50 events were taken and calculations were performed to obtain the Ib–value. Ib value was calculated for next 50 events and process repeated till the end of the total time. The Ib values obtained were then plotted against the time (time of the last event in each set). The whole process was then repeated using 75 events. Results are shown in Figure 9. The constants α_1 and α_2 were both taken as 1 for the calculations and Ib values were multiplied by 20 as suggested by [15], in order to enable comparison with seismic b-value.



(a) (b)

Figure 9. Variation of Ib value with time, using (a) 50 events and (b) 75 events

In both cases, lowest value of around 0.7 is seen about the time of 50s. As lower Ib-values indicate more severe damage, it can be implied that most damage occurred in that instant of 50 s. For rock fracture, the Ib value was found to be around 1 [15]; but the value obtained here is lower. To best of our knowledge no values are available for steel in literature; hence no comparison could be made, but it is believed that ductility of steel could be responsible for the lower value. Although it is hard to pinpoint the exact time of damage occurrence, it is believed that study of micro-structural changes of the specimen at different stages using scanning electron microscope may shed further light into this and hence will be carried out in future.

4 CONCLUSIONS

Several methods that have potential in damage quantification for severity assessment in AE monitoring are discussed itn this paper. Preliminary analysis of laboratory experimental data using one of the methods, namely improved b-value analysis, is also presented. Results and analysis are expected to help in increasing effectiveness of AE technique in real life monitoring applications. Improved b-value analysis has been mainly used for brittle materials e.g. concrete and rock so far. Hence, the aim of this study is to check its application for ductile steel materials. In future, with further tests (with different loading rates and loading type) and further analysis (for example, exploring optimal values of α_1 and α_2, or the number of events, or by using sliding window of certain number of events with lag as used in [16]); we hope to gather more information on this interesting field of research.

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