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Applying *b*-Value Analysis of Acoustic Emission Signals for Assessing Nuclear Power Plant Integrity

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1. Introduction

Acoustic emission (AE) testing is a non-destructive testing technique that detects and monitors the release of elastic waves from localized sources when a material deforms under stress [1]. The AE system is installed within the primary systems of nuclear power plants to monitor leaks and cracks in components such as pipes and joints [2]. The *b*-value analysis is a technique used to assess cracks by utilizing the characteristic of AE signals that sensitively change with material deformation [3], [4]. The *b*-value analysis has been verified in civil engineering and is currently used to evaluate the structural integrity of concrete structures [3], [4]. We assessed the feasibility of applying the *b*-value to nuclear power plant primary systems.

2. Methods and Results

2.1 Mechanical testing

A pair of AE sensors (Nano-30; Physical Acoustics, USA) were affixed to a specimen (Fig. 1). Throughout the testing process, AE signals that surpassed the threshold of 40 dB_{AE} were detected using a digitizer operating at a sampling rate of 10 MHz per sensor (channel). The initiation of the detected signal coincided with the initial healthy state of the specimen and exhibited periodic occurrence until eventual complete material fracture (Figure 2).

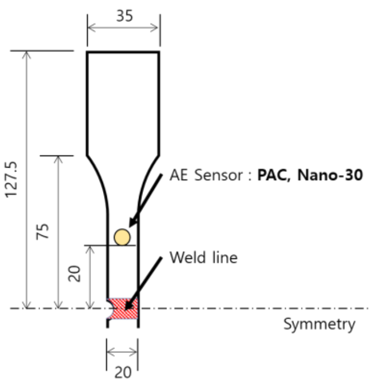

Fig. 1. Schematic illustration of a carbon steel specimen with a single edge showing the location of the acoustic emission (AE) sensor.

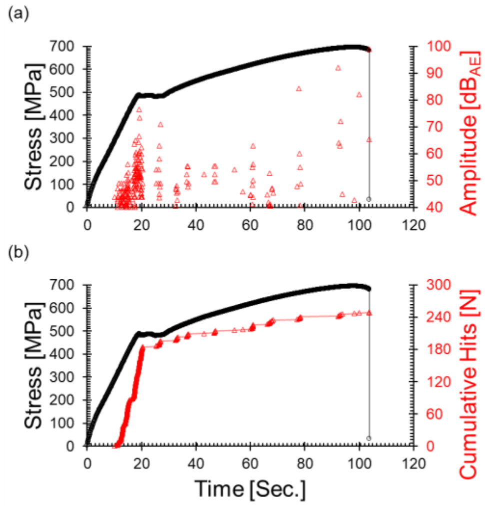

Fig. 2. Conversion of AE signals from tensile testing of carbon steel specimens into AE parameters: (a) amplitude and (b) cumulative hits. Amplitude growth with fracture progression and cumulative hits increase in proportion to crack frequency.

2.2 b-Value analysis

The *b*-value concept originated in seismology through the Gutenberg–Richer formula [5]:

$$\log_{10} N = a - bM \qquad (1)$$

Here, 'N' represents the count of earthquakes exceeding magnitude 'M' in a specific spatiotemporal context, where 'a' is an empirical constant, and 'b' is the well-known *b*-value associated with the linear correlation's slope. This concept was extended to analyze Acoustic Emission (AE) signals in fracturing materials under defined loading and time conditions:

$$A = 20 \cdot \log_{10} \frac{V_1}{V_0} \qquad (2)$$

$$\log_{10} N = a - b(A) \qquad (3)$$

Here, 'A' signifies the AE signal's amplitude in decibels (dB_{AE}, Figure 2(a), while 'N' represents the cumulative count of AE events until amplitude 'A' is reached within the designated timeframe (Figure 2(b)). Amplitude is directly related to fracture scale. The *b*-value, characterized as the collective gradient of the amplitude distribution against cumulative occurrences (Figure 3), is a valuable indicator for understanding fracture initiation and progression during the observation period. An elevated *b*-value signifies the dominance of microscopic fractures (depicted by black circles), whereas a lower *b*-value suggests the occurrence of macro-fractures (represented by a small number of high-amplitude hits, indicated by red triangles). It functions as an encompassing parameter for monitoring, effectively characterizing AE signals arising from stochastic processes like crack propagation.

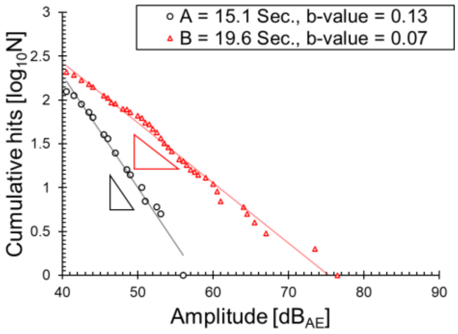

Fig. 3. Re-plotted amplitude and cumulative hits in accordance with Equation 3. The gradient of each line represents the *b*-value. A = 15.1 second and B =19.6 second are indicated alongside Figures 2a, 2b, and 4.

2.3 b-Value analysis

The raw amplitude and AE hit data were processed using Matlab software (MathWorks, USA) for analysis of the *b*-values. The analyzed AE signals were divided into groups of 5 hits, and the amplitude range was divided into 1 dB_{AE} steps from the threshold of each group to 100 dB_{AE}. Logarithmic plots of the amplitude with linear trendlines were calculated using the least-squares curve fitting method.

Figure 4 shows the *b*-values calculated during the tensile loadings. The red symbol (*b*-value) shows increasing trend up to 15.1 second (yield strength), however, the value decreased after 15.1 second. The decrease in this parameter preceding the reduction in load due to crack propagation validates our concept of using a reducing *b*-value as an indicator of incipient cracking.

Finally, the authors suggested the example-standard for structural health based on *b*-value. Table I summarizes the *b*-values determined for experimental composites under tensile loading conditions in the laboratory setting. The AE results corresponded to fracture behavior, and the analysis showed that the *b*-value correlated with the fracture level. The *b*-value results in this study show the utility of AE monitoring for assessing the condition of nuclear power plant primary systems.

3. Conclusions

In conclusion, our investigation delved into the tensile loading behavior of carbon steel through the application of Acoustic Emission (AE) analysis. By subjecting the detected AE signals to amplitude and cumulative hits analysis, we harnessed the derived *b*-value to effectively monitor the progression of crack growth. Notably, the *b*-value demonstrated an ascending trajectory up to the point of yield strength, succeeded by a subsequent decline leading to ultimate fracture. These observations validate the *b*-value's merit as an indicator for evaluating the structural integrity of nuclear power plant primary systems. We explained how to assess structural integrity using the exemplified standard and plan to continue experiments for accurate evaluation criteria.

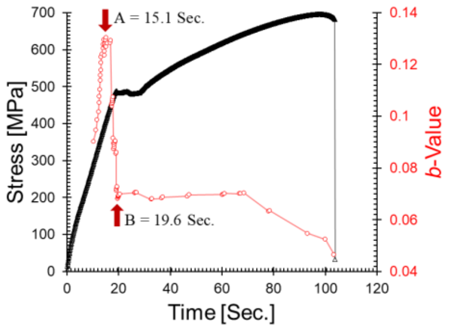

Fig. 4. Changes in stress and *b*-value with increasing strain (5 mm/sec). Time series plot of amplitude-AE hits slope (A = 15.1 seconds, *b*-value: 0.13).

Table I: *b*-value analysis

State	*b*-Value	
I	0.13 – 0.08	Crack initiation
II	0.08 – 0.07	Crack growth
III	0.07 – 0.04	Near to final fracture

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