

A review of the application Acoustic Emission (AE) incorporating mechanical approach to monitor Reinforced concrete (RC) strengthened with Fiber Reinforced Polymer (FRP) properties under fracture

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Abstract. Concrete durability may be affected by so many factors such as chemical attack and weathering action that reduce the performance and the service life of concrete structures. Low durability Reinforced concrete (RC) can be greatly improved by using Fiber Reinforce Polymer (FRP). FRP is a commonly used composite material for repairing and strengthening RC structures. A review on application of Acoustic Emission (AE) techniques of real time monitoring for various mechanical tests for RC strengthened with FRP involving four-point bending, three-point bending and cyclic loading was carried out and discussed in this paper. Correlations between each AE analyses namely b-value, sentry and intensity analysis on damage characterization also been critically reviewed. From the review, AE monitoring involving RC strengthened with FRP using b-value, sentry and intensity analysis are proven to be successful and efficient method in determining damage characterization. However, application of AE analysis using sentry analysis is still limited compared to b-value and intensity analysis in characterizing damages especially for RC strengthened with FRP specimen.

1. Introduction

Fiber Reinforced Polymer (FRP) strengthening system was first developed in Europe since 1980 as a replacement for steel strengthening. This technique was widely used to upgrade many bridges and other structures around the world. Nowadays, FRP material shows an increased number of application in the construction industry and it is successfully being used in strengthening deficient concrete structures [1]. FRP is more effective as it provides a better solution in terms of properties and application. These materials are lightweight, noncorrosive, and exhibit high tensile strength [2-3]. FRP strengthening systems can be used to rehabilitate or restore the strength of the deteriorated structural member, retrofit or strengthen the sound structural member to resist increased loads due to change in the use of structure, or address design or construction errors found in a structure [4]. These FRP materials are readily available in several forms such as plates, rods and sheets. Application of a Non-Destructive Technique (NDT) is reliable and robust to provide real time information and important to monitor and assess the condition of buildings. There are many types of NDT testing and one of the promising methods of NDT testing commonly used to monitor the damage or deterioration in structures is known as AE technique [5]. AE technique method was first introduced by a German



scientist, Kaiser in year 1950 [6]. Meanwhile in civil engineering, AE application has started since the late 1970s with an investigation on concrete material response towards AE carried out by Fetis and Cabe [7]. AE has the ability for real time process monitoring applications. It can monitor the occurring defects in concrete structure such as concrete fracture starting from the initial micro crack to macro crack formation and finally, structural failure [8]. Nowadays, many researchers are motivated to improve the use of AE instrumentation, AE source localization and work extensively in the AE signal processing system [6]. In this paper, an overview of the application of AE for RC strengthened with FRP under mechanical tests such as bending test (four-point bending and three-point bending) and cyclic loading test are discussed. Numerical method and statistical method from AE are usually performed to evaluate b-value, sentry and intensity analysis to study the effect of loading rate on variation, understand the behavior of the material, and quantify and evaluate the damage severity on samples. Studies on AE monitoring of application of AE for FRP in the form of sheets laminated onto RC specimen being put under mechanical tests have been reported in extensive literatures. The formation of cracks in FRP laminated onto RC structures within fracture process can be noticed by recording AE signals during the process and data obtained from such studies could be used to assess the amplitude (stress-strain), delamination (crack initiation and its internal microevents) and level of deterioration (quantification).

2. Acoustic emission based on b-values

B-value method was historically introduced by Gutenberg and Richer in year 1949 [9]. This method can be used to evaluate structural damage [10]. The b-value is functioning in the form of log-linear slope representing the cumulative amplitude distribution of AE. Previously, study of b-value on RC structures has proved that it is useful in providing details of early crack formation up to the failure fracture with the support of quantitative b-value ranges and damage levels descriptions as shown in table 1 [10].

2.1. Formulation of b-value

B-values may change systematically due to the different stages of fracture growth [10]. The most commonly used equation is known as Gutenberg-Richter formula presented in equation (1).

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

According to equation (1), M is the peak amplitude of AE hit in decibel unit obtained from AE, N is number of AE hits with magnitude greater than M while a is an empirical constant. The cumulative frequency distributions of the linear gradient descend, b is taken as AE b-values. Value of M can be determined by calculating the magnitude of waveform using equation (2) while conversely, the coefficient of 20 can also be divided with the slope to obtain the b-values [11-14].

$$\log_{10} N = a - b \left(\frac{M}{20} \right) \quad (2)$$

The b-value is known as the log-linear slope of the frequency-magnitude distribution of AE. From this formula, Colombo et., al. [10] found that larger b-values are obtained when the distributed micro crack are occurring in an early stage of damage, meanwhile b-value is low when the macro cracks begin to localize. The b-value is one of the AE functions which experienced continuous improvement accordance to findings from case studies. To date, the function of b-value is improved with Ib-value to evaluate the slope failure and process of fracture [9-12]. The calculation of Ib-value is based on the slope of the amplitude distribution from AE signal. The Ib-value formula is shown in equation (3) below:

$$Ib = \frac{\log N(\mu - \alpha_1\sigma) - \log N(\mu - \alpha_2\sigma)}{(\alpha_1 + \alpha_2)\sigma} \quad (3)$$

Where σ is a standard deviation, μ is the mean value of amplitude distribution; α_1 and α_2 are the coefficients related to the smaller amplitude and fracture level, respectively. This formula varies

depending on the damage level. The function of the I_b -value is to evaluate the fracture process in concrete.

2.2. Applications of b -value

There are numerous studies on damage characterization using b -value contributing deeper information for damage descriptions. Therefore, marks b -value analysis as one of the most promising method to be used for quantitative damage classification. In the four-bending test, AE monitoring of b -value has been reported by Guzman *et al.* [13]. In the study, AE event represented by accumulated frequency of the AE and maximum amplitude was characterized in a form of semi-logarithmic scale and lineal correlation scale. The b -value ranges were characterized based on the four-bending test final load to define severity of damages as two stages as shown in table 1. The minimum and maximum b -values were considered for each cycle load failure phase. All the cycles and channels were plotted to expose the value variation and the development of micro and macro cracks. The maximum b -value shows the trend of the micro crack growth and the minimum b -value shows the trend of the formation of macro cracks as shown in figure 1(a). Table 1 shows the quantitative b -value. Previously, Colombo *et al.* [10] has established quantitative results for b -value. The research showed that the b -value is very useful for understanding the data obtained from all the monitoring work of concrete structure. To date, classification of damage particular for concrete specimens strengthened with FRP was reported in Ma and Li [15]. The characteristics of damage level were made based on the distribution of AE hits during the test and the observed damage states of the FRP-strengthened column of AE hits can be related to four different damage levels of the FRP-strengthened column qualitatively as shown in table 2. Therefore, it can be concluded that the crack process of FRP-strengthened columns can be monitored by AE techniques and the damage levels can also be determined qualitatively and conveniently based on the distribution of AE hits. In the study, AE event represented by accumulated frequency of the AE and maximum amplitude was characterized in a form of semi-logarithmic scale and lineal correlation scale. Figure 1(b) indicates the inhomogeneous mechanical properties of concrete, the crack process of the concrete in the plastic region was essentially non-uniform, resulting in that the entire b -value curve along the time axis was not smooth.

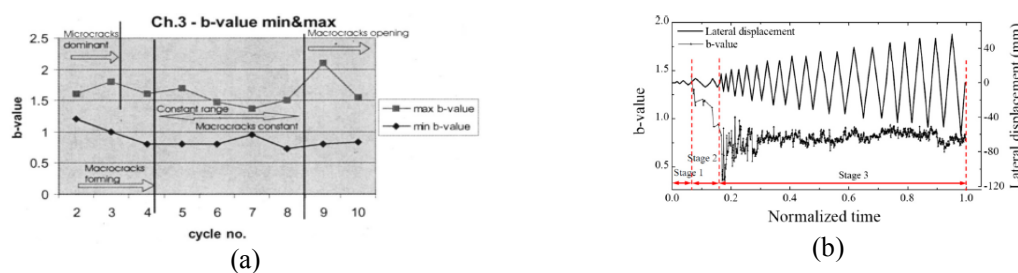


Figure 1. (a) b -value analysis pattern for RC structure [10], (b) b -values correlative to the number of AE hits in a certain range of time for RC structure strengthened with FRP [15].

Investigations for the assessment of signal characteristics for RC members strengthened with Carbon Fiber Reinforced Polymer (CFRP) sheets have only begun [16]. In three-point bending test conducted by Do Hyun *et al.* [16], AE monitoring based on b -value is correlated to the fracture process of the RC beams bonded with CFRP sheets and the degree of localization of damage. The evolution of acoustic activity caused by micro-fractures within concrete is often quantified using the concise framework originated by Gutenberg and Richter in their analysis of earthquake magnitudes, which is a reflection of the view that large-scale (geological) and small-scale (micro-fracture) acoustic events share a common origin in cascades of strain energy release events. Choi and Yun [14] claim the AE cumulative amplitude distribution emitted was used as a statistical data to look at parametric AE data. The b -value formula indicated three ranges of damage levels or fracture levels as shown in table

3. In the development stage of micro cracking, the b-values show a value higher than 1.25. The b-value range in the crack propagation and crack widening stage is between 1.25 and 1.15. At the micro crack level, the b-value varies between 1.15 and 0.08.

Table 1. Quantitative damage progressions by Colombo *et al.* [10].

B-value ranges	Types of damage progressions
$1.0 < b\text{-value} < 1.2$	Indicates that the channel is in the closest position towards a large crack such as macrocracks forming
$1.2 < b\text{-value} < 1.7$	Cracking is uniformly distributed suchlike the macrocracks are constant
$b\text{-value} > 1.7$	Microcracks are prevailing or macrocracks are opening

Table 2. Quantitative damage levels based on the distribution of AE hits by Ma and Li [15].

Damage levels	AE hits stage	Damage states FRP-strengthened column
Slight	Stage 1	No crack
Minor	Stage 2	No crack
Moderate	Early part of stage 3	Some horizontal cracks above FRP sheets, cracks between column and pedestal
Severe	Latter part of stage 3	Horizontal cracks on FRP sheets, interface failure between column and pedestal.

Table 3. B-value for damage level by Choi and Yun [14].

B value ranges	Damage description
$b\text{-values} > 1.25$	Formation of micro-cracks
$1.25 > b\text{-values} > 1.15$	Propagation of micro-cracks and crack-widening
$1.15 > b\text{-values} > 0.80$	Formation of macro-cracks, de-bonding of CFRP, rupture

The most recent study conducted by Ma and Li [15] involving AE monitoring and damage assessment of FRP strengthened reinforced concrete columns. Analysis of b-value reported that the accumulative AE energy exhibited a good correlation with the accumulative hysteretic energy dissipated during the cyclic test for the FRP-strengthened column. By rule of thumb, high b-value density represented a large number of AE hits (high degree of crack activity) meanwhile low b-value density meant a small number of AE hits (low degree of crack activity).

3. Acoustic emission based on sentry function

Sentry method was first discovered and introduced by Minak [17]. By definition, sentry method is known as combination of mechanical and acoustic energy information in AE parameters [16]. The sentry values are calculated by combining the logarithm ratio of Strain Energy (E_s) and the acoustic energy (E_{AE}) using particular formula. This method has been extensively used in the study of composite material and steel [16]. The rule of thumb for sentry method, f is divided into four levels demonstrating increasing of sentry function $f(x)$. The four levels were labelled from PI(x) until PIV(x). Figure 2 illustrate the schematic diagram of PI(x), PII(x), PIII(x) and PIV(x) which used to describe the whole function of sentry.

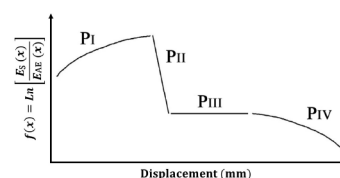


Figure 2. Schematic diagram of sentry function (f) [18].

Table 4. Standard sentry function sentry function (f) behaviors [14,18].

Type	Symbols	Descriptions
Type I	PI(x)	An increasing trend, which represents the strain energy storing phases
Type II	PII(x)	Illustrated by the sudden drops of the function f, which may be related to a significant internal material failure occurrence
Type III	PIII(x)	There is an equilibrium state between the mechanical and AE energy
Type IV	PIV(x)	The decreasing behavior of f, related to the fact that the AE activity is greater than the material strain energy storing capability and the damage has reached a maximum

3.1. Formulation of sentry function

Sentry function requires vital combinations of both mechanical and acoustic energy information to perform deeper quantitative analysis of damages occurs in structure members. The formulation of sentry function is represented in the equation (4):

$$f(x) = \ln \left[\frac{E_s(x)}{E_{AE}(x)} \right] \quad (4)$$

According to equation (4), E_s is expressed as the strain energy, E_{AE} refers to AE energy while x is the test driving variable (displacement or strain).

3.2. Applications of sentry function

Application of sentry method was widely used for composite material and steel. Previously, sentry method was used to detect important events conforming to sudden drops and occurrences of delamination for various specimens such as glass fiber or epoxy composite materials [17], glass fiber reinforced plastics (GFRP), CFRP composite laminate, polyester resin reinforced with glass fiber [18] and many more. However, for specimen involving RC strengthened with FRP, the number of study is still limited. Selman *et al.* [19] conducted a study on a RC beam strengthened with CFRP undergoing a cyclic load test. The damage characterization was made by calculating sentry function. AE parameters such as cumulative acoustic emission energy and acoustic emission signals analysis was taken into account to further study the fracture progression in the specimen. Outcomes was summarized and test driving ($x=1$) was chosen to be presented in table 5.

Table 5. Damage characterization based on sentry function (f) behaviors [19].

Type	Symbols	Sentry value (f)	Damage characterization
Type I	PI	$12.5 \leq f \leq 12.3$	No significant event detected
Type II	PII	$12.8 \leq f \leq 12.4$	Sudden released of elastic waves. Initial flexural crack developed at CFRP joint and grew rapidly. Flexural crack started to propagate towards RC sub-layer. Shear cracking occurs at CFRP joint. Drop of stiffness in both flexure and shear.
Type III	PIII	13.9	Specimen is in equilibrium state
Type IV	PIV	$13.8 \leq f \leq 13.7$	Opening of shear crack increased and peeling of CFRP. Rebars yields. Shear damaged.

By considering both acoustic emission and strain energy simultaneously using sentry function, the trends variation of sentry can be accurately presents the phenomenon occurred whilst loading. Therefore, the researcher concluded that the sentry function is an effective tool which can be used to investigate the fracture mechanism of CFRP strengthening reinforce concrete. It also clearly demonstrates the damage progression.

4. Acoustic emission based on intensity analysis

One of the AE analyses used to categorize the level of damage is known as intensity analysis [11]. The intensity analysis also known as a graphical method to assess structural performance using AE. The origin of this analysis is found in the structural evaluation of FRP structures by Fowler since year 1989 [20]. This intensity analysis technique had already been successfully applied to FRP and metal piping system evaluations [21]. Figure 3 illustrates a typical chart on which maximum values of historic

index and severity are plotted to determine the intensity of a source. Based on figure 3, the established intensity chart by Gostautas [22] was classified in five zones and written more detailed as shown in table 6. This typical intensity chart has been widely used for miscellaneous systems.

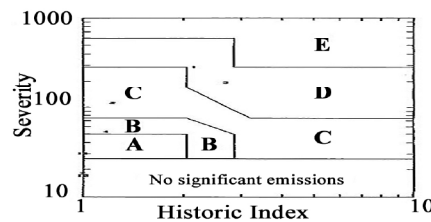


Figure 3. Representative intensity chart of FRP material [21].

Table 6. The general intensity zone [22].

Zone Intensity	Recommended Action
Zone A – Insignificant	Nonsignificant of AE
Zone B – Minor	Note for reference in future tests. Normally represents minor surface defects for example corrosion, pitting, gouges or crack by weld attachment
Zone C - Intermediate	Defects considering follow-up evaluation. Evaluation may be made based on further data analysis or complementary non-destructive analysis
Zone D – Follow up	Significant defect considering supplementary follow up or inspection task
Zone E - Major	Major defects require immediate closure and supplementary inspection task to be carried out

4.1. Formulation of intensity analysis

Intensity analysis is well known as a statistical approach that calculates two values which are historical index (HI) and severity (Sr) [11,12]. The HI is an analytical quantity that traces the slope change of the cumulative signal strength parameter measured during a test. Meanwhile Sr is the value is obtained by averaging the strongest signal strength values and helps normalize the collected AE data making it independent of the location of the AE source. The equation of the Historical Index (HI) and Severity (Sr) [11,20-22] are shown below as equation (5) and (6) respectively:

$$H(I) = \frac{N}{N-K} \left(\frac{\sum_{i=K+1}^N S_{oi}}{\sum_{i=1}^N S_{oi}} \right) \quad (5)$$

According to equation (5), H (I) is indicates as historical index, N is the number of hits up to time t and S_{oi} is the signal strength of the i th hit. K is a parameter that depends on the number of AE hits and the types of material. K value for concrete: K = 0, $N \leq 50$; K = N – 30, $51 \leq N \leq 200$ and K = 0.85N, $201 \leq N \leq 500$.

$$S_r = \frac{1}{J} \left(\sum_{m=1}^J S_{om} \right) \quad (6)$$

Based on equation (6), S_r indicates as the Severity index; J is an empirically derived constant based on material type. J value for concrete material: J = 0, $N < 50$ and J = 50, $J \geq 50$, S_{om} is the signal strength of the m th hit where the m is based on the magnitude of the signal strength.

4.2. Applications of intensity analysis

Damage characterization using intensity analysis approach involving correlations between the properties of the AE such amplitude, duration and signal strength. Degala *et al.* [23] presented an Acoustic Emission (AE) study performed during a four-point bending test on concrete slab specimens strengthened with CFRP strips. The findings for all slabs on parametric analysis reported that flexural cracks near the laminates and debonding create AE activities much higher in terms of signal amplitude and frequency range than eventual shear cracking was shown in figure 4. The peak value of HI was associated with the variation in slope. The specimen experienced lost in energy and generates a significant increase in the slope of the severity line. The significant increase in slope notifying

presence of CFRP strip debonding. The maximum values of HI and severity indicated that specimen experienced CFRP debonding together with shear failure. Thus, the correlation between HI and Sr are able to demonstrate the progression of the intensity values moving from lower-left of the chart to the upper-right can be used in real-time to flag combinations of HI and Sr which enter an intensity zone associated with severe damage.

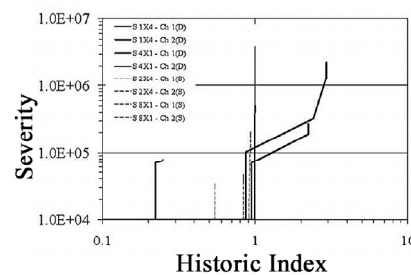


Figure 4. The intensity charts for all slabs strengthened with CFRP strips [23].

5. Conclusion

In a nutshell, these three types of AE analyses are available for identifying cracks and detecting the damage mechanism level of FRP concrete structures. This is because both of the AE analyses have their own advantages where the best application of the significant AE analysis can provide the damage mechanism and details of the fracture failure in concrete structures. To sum up, by utilizing the b-value, sentry and intensity analysis as parameter analysis, all AE analyses are able to deliver the damage progression and classification of damage in structures as their final output values.

6. References

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Acknowledgement

This work was supported by the Faculty of Civil and Environmental Engineering, University Tun Hussein Onn Malaysia, Center for Graduate Studies, UTHM and the Research Acculturation Grant Scheme (RAGS) Vot. 053.