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Case study

Damage grading system for severity assessment on concrete structure

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ABSTRACT

Acoustic Emission (AE) is a high frequency stress wave generated by rapid release of energy in solid material due to changes such as crack initiation and growth. High sensitivity to crack growth, the ability to locate the source, its passive nature and the possibility to perform real-time monitoring are some of the attractive features of the AE technique. In spite of these advantages, challenges still exist in using the AE technique for monitoring applications, especially in the analysis of recorded AE data as large volume of data are usually generated during the monitoring process. The need for effective data analysis in a grading system can be linked to the main objective of this research; to develop a new standard grading system for severity assessment. In this research, the cyclic load test (CLT) method is the first method used for this evaluation system. This is a relatively new method that may provide better insights into structural integrity and also collaborates with the AE evaluation system. This study proposed and tested the absolute energy parameter in the evaluation for determining the damage level in Reinforced concrete RC structure. The Intensity Absolute Energy Analysis (IAEA) methods that involved the absolute energy parameter were investigated to determine the damage level in RC structure. This was found to provide encouraging results for the analysis of AE data parameters in determining the damage grading system. By addressing this primary issue, it is believed that this study can help improve the effectiveness of the AE technique for Structural Health Monitoring (SHM) in civil engineering.

1. Introduction

Currently, the acoustic emission (AE) technique has been widely utilized in concrete structures for damage detection and monitoring systems.This technique is unique as it can furnish the internal and external behaviour of material properties and structural conditions under various structural loads [1]. This investigation has been implemented and established by previous research mainly in the evaluation of concrete structure. However, further research is also needed for new evolutions of the AE system in assessing concrete structures. Technically, much remains to be explored about AE. This was proven by previous research which highlighted new developments of the evaluation system [2–6].

The AE damage detection of concrete structures has been analyzed by data parameters in AE signal. The AE signal was produced and recorded from transducers during the testing process. The parameters recorded in the AE win software are

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count, hit, amplitude, frequency, signal strength, absolute energy and energy. Each of them represented the characteristic of AE signal as documented by the Physical Acoustic Corporation (PAC) and the American standard [7].

In the evaluation system, more methods were used to analyze the signal waveforms in concrete structures. The Moment Tensor Analysis (MTA) was used to define the type of cracking process and it involved amplitude and average frequency parameters [8,9]. Parameter based analysis such as calm ratio and load ratio were used to indicate the damage level under hit and load data parameters [3,10]. In addition, the applications of b-Value and RA value analysis were also used to detect and classify the types of cracking such as macro and micro cracking as well as tensile and shear cracking [8–11]. Besides that, intensity analysis (IA) was also used to classify the damage level of concrete structures and the main parameter used in this method is signal strength [12–16]. This research paper emphasizes on the use of IA for damage classification. The main parameter which is used in this method is absolute (ABS) Energy.

ABS energy has been used in the past on concrete structures for damage detection and crack locations [14]. The detailed implementations of this data parameter require more research work, especially in terms of damage grading system. Therefore, this paper focuses on the ABS energy parameter and the IA method to develop damage classifications on concrete structure.

1.1. Absolute energy

According to the Samous AE system user's manual (2005), Absolute energy is a true energy measure of AE hits and it is derived from the integrals of the squared voltage signal over the duration of AE waveforms as seen in Fig. 1. AE hits feature refers to the true energy of the AE hits whilst the time-based feature reports the energy in the time driven data rate. The time driven feature is an excellent parameter for monitoring continuous signals [17]. In Fig. 1, the shaded area in the AE waveform illustrates the true value of the Absolute energy whereas the signal strength features are integral of the rectified voltage signal over the durations of AE waveform packet. The Absolute energy feature is used for damage identification and first crack detection. This was proven by previous researchers [18], in the evaluation of first cracking and corrosion detection in reinforced concrete structure

1.2. Intensity absolute energy analysis (IAEA)

Intensity Absolute Energy Analysis (IAEA) originated from the Intensity Signal Analysis (ISA) method that was developed by Gloski et al., [2] for structural assessments and identification. In this method, absolute energy is considered as the main AE data parameter substituting the previous parameter which is signal strength for the evaluation of damage level systems. The equation and the empirical value for this analysis is equal to the original ISA method. However, minor changes have been made to suit the IAEA method for the evaluation system. The detailed equations are described in Eqs. (1) and (2) [2,18–22]. Evaluation of IAEA involves the use of two indices; historical index (HI) and severity index (Sr). Historical index is used to determine the change of Absolute Energy rate throughout the test. Particularly, it measures the slope change in cumulative Absolute Energy against time by comparing the Absolute Energy of all hits.

$$\mathrm{HI}_{\mathit{Absolute\ Energy}} = \frac{\mathrm{N}}{\mathrm{N}-\mathrm{K}} \cdot \left(\frac{\sum_{i=K+1}^{N} \text{Absolute Energy}_i}{\sum_{i=1}^{N} \text{Abs}_i} \right) \tag{1}$$

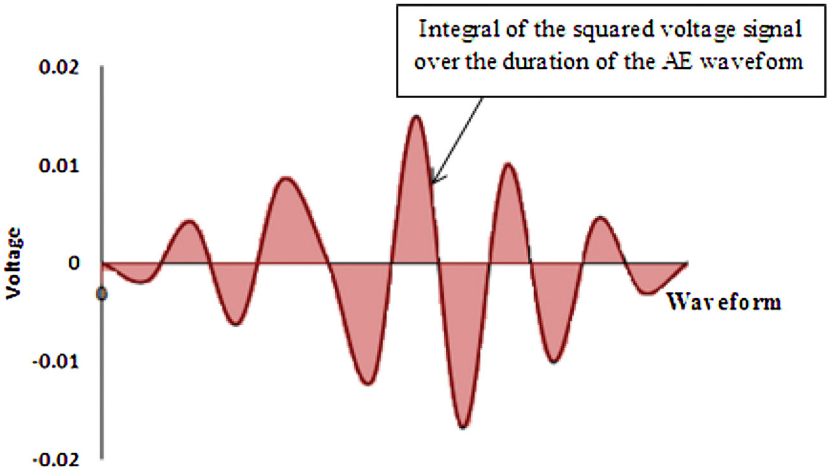


Fig. 1. Absolute energy features.

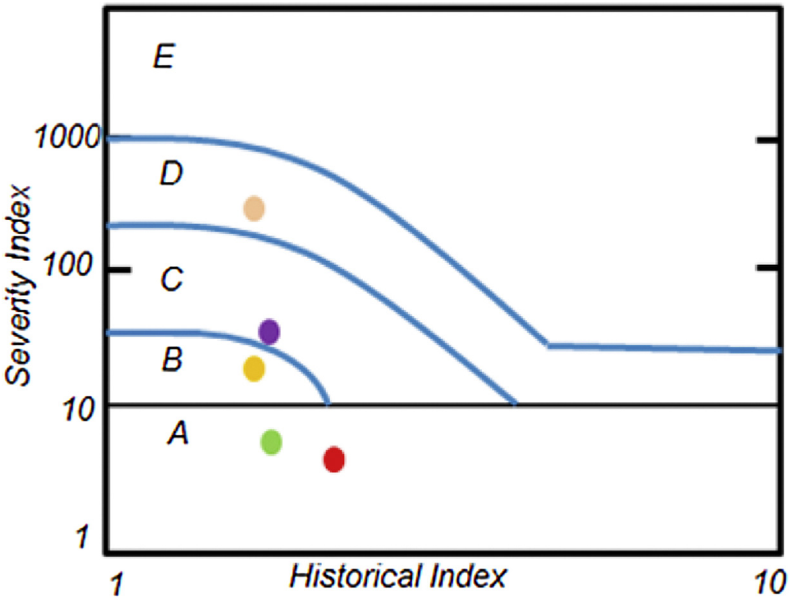


Fig. 2. Example of Intensity Analysis Chart [2].

$$\mathrm{Sr}_{\mathrm{Absolute\ Energy}} = \frac{1}{\mathrm{J}} \cdot \left(\sum\nolimits_{\mathrm{m}=1}^{\mathrm{J}} \mathrm{Absolute\ Energy}_{\mathrm{m}}\right) \quad (2)$$

Where; Sr: Severity index, J: Empirically derived constant based on material, Absolute Energy$_{\mathrm{m}}$: Absolute Energy of the mth hit where the order of m is based on magnitude of the Absolute Energy. For concrete, K and J values are related to N by the relations: $K = 0$, $N \le 50$; $K = N - 30$, $51 \le N \le 200$; $K = 0.85N$, $201 \le N \le 500$; $K = N - 75$, $N \ge 500$; $J = 0$, $N < 50$; $J = 50$, $N \ge 50$.

This method was evaluated from the AE Absolute Energy data parameter which was collected using AE win software. Normally, the previous method is based on the channel basis, but for this research the data was collected and cropped from the critical area of the beams under testing and analyzed by utilizing AE event data. The severity and maximum historical index are plotted on the intensity chart as presented in Fig. 2 where as Table 1 presents the zone description. From the figure, chart is divided into intensity zones which indicate the structural significance of the emission.

2. Experimental work

The reinforced concrete (RC) beam specimens with dimension of 150 mm × 250 mm × 1900 mm were prepared and detailed in Fig. 3. Four-point bending tests under cyclic load test (CLT) were performed on the specimens as illustrated in Fig. 4. The RC beans were designed according to BS 8110: Part 1: 1997. All beams were reinforced by 2T12 and 4T12 longitudinal rebar for compression and tension respectively (Fig. 3). The characteristic strength for concrete (f_{cu}) is 40 Mpa whereas the characteristic strength for reinforcement (f_y) is 460 MPa.

Table 1
Significance of intensity zones edited from [2].

Levels Intensity	Recommended action
A	Insignificant acoustic emission. (No Damage)
B	Note for reference in future tests. Typically minor surface defects such as corrosion, pitting, gouges or crack attachments. (Damage Detected)
C	Defects require follow-up evaluation. Evaluation may be based on further data analysis or complementary non-destructive examination (Minor Damage)
D	Significant defect requires follow-up inspection. It is considered as major damage (Major Damage)
E	Major defect requires immediate shut-down and follow-up inspection. (Severe Damage)

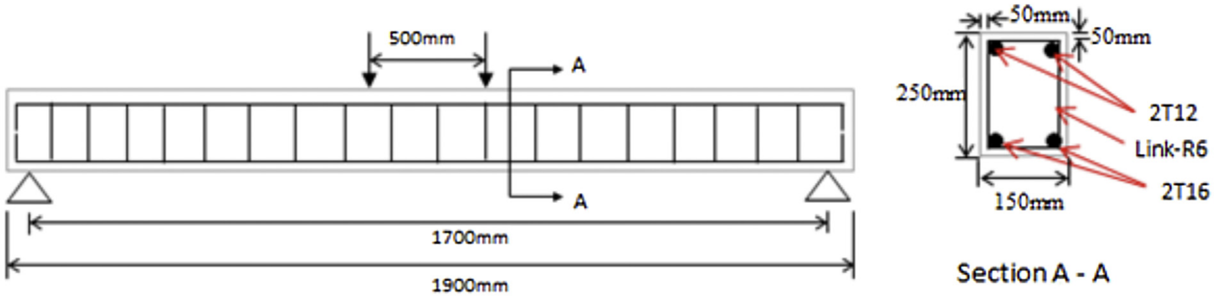


Fig. 3. Detail Reinforcement.

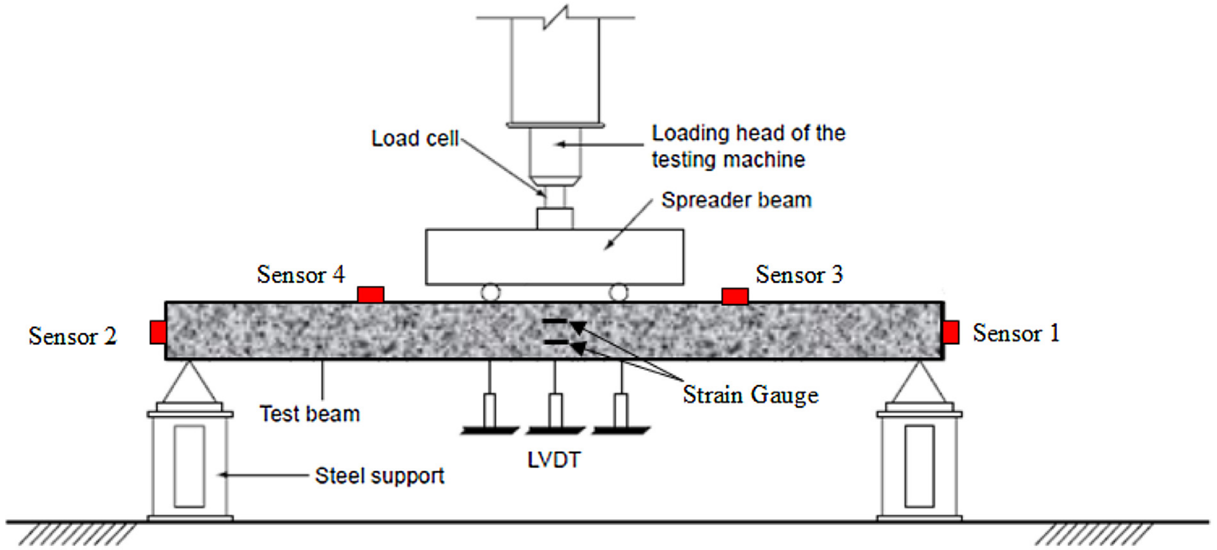


Fig. 4. Testing Method.

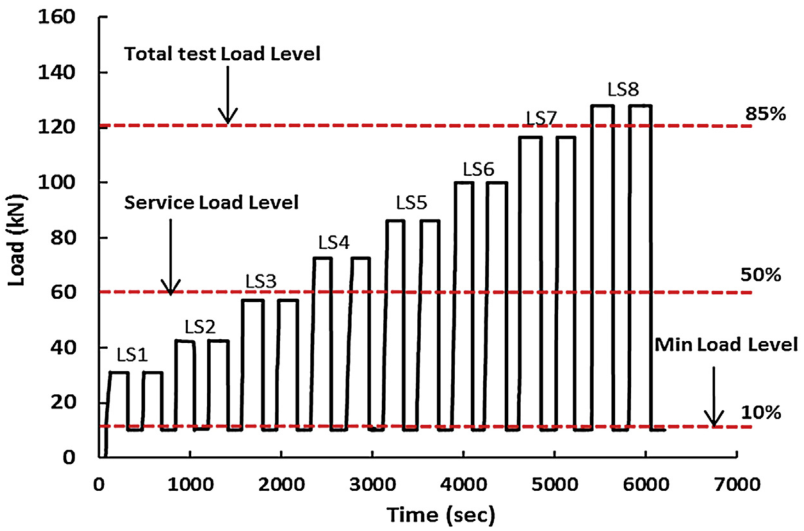
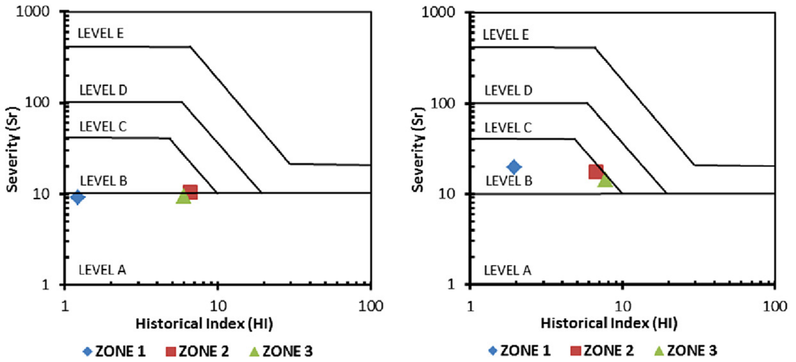
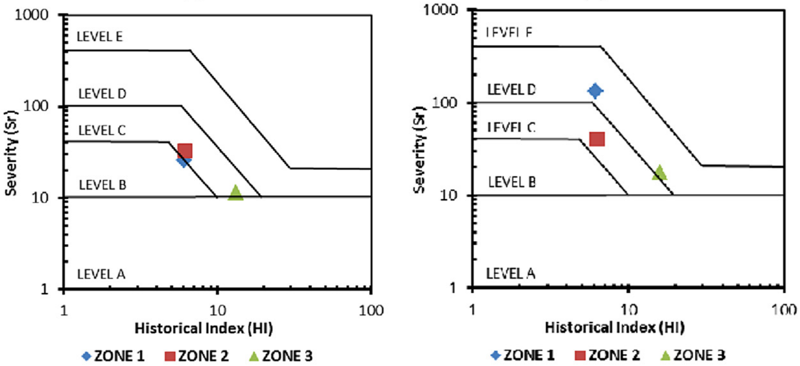


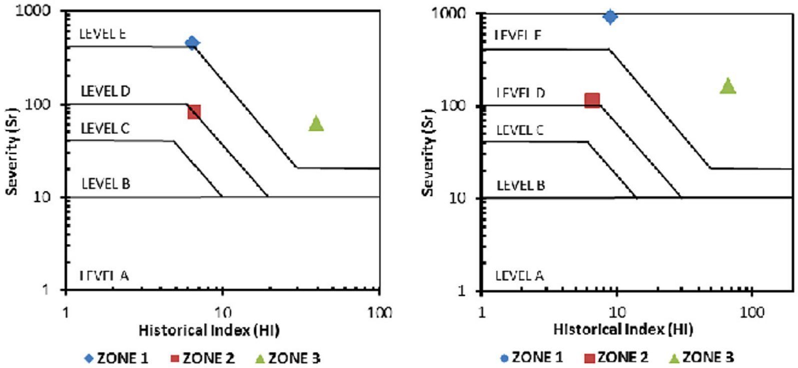
Fig. 5. Cyclic Load Test (CLT) for each load set (LS).



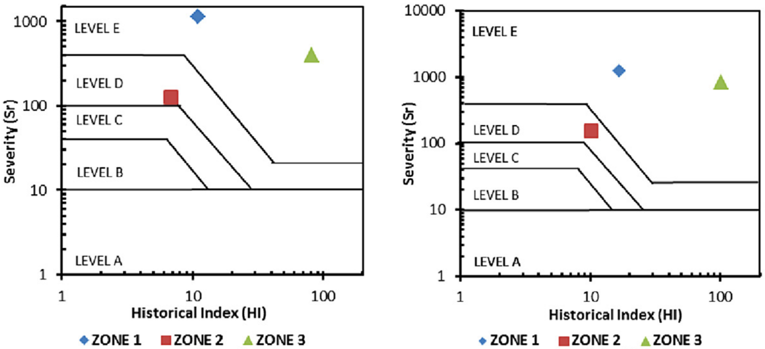
(a) LS 1 (b) LS 2



(c) LS 3 (d) LS 4



(e) LS 5 (f) LS 6



(g) LS 7 (h) LS 8

Fig. 6. Absolute Energy Intensity chart for each load set (LS1-LS8).

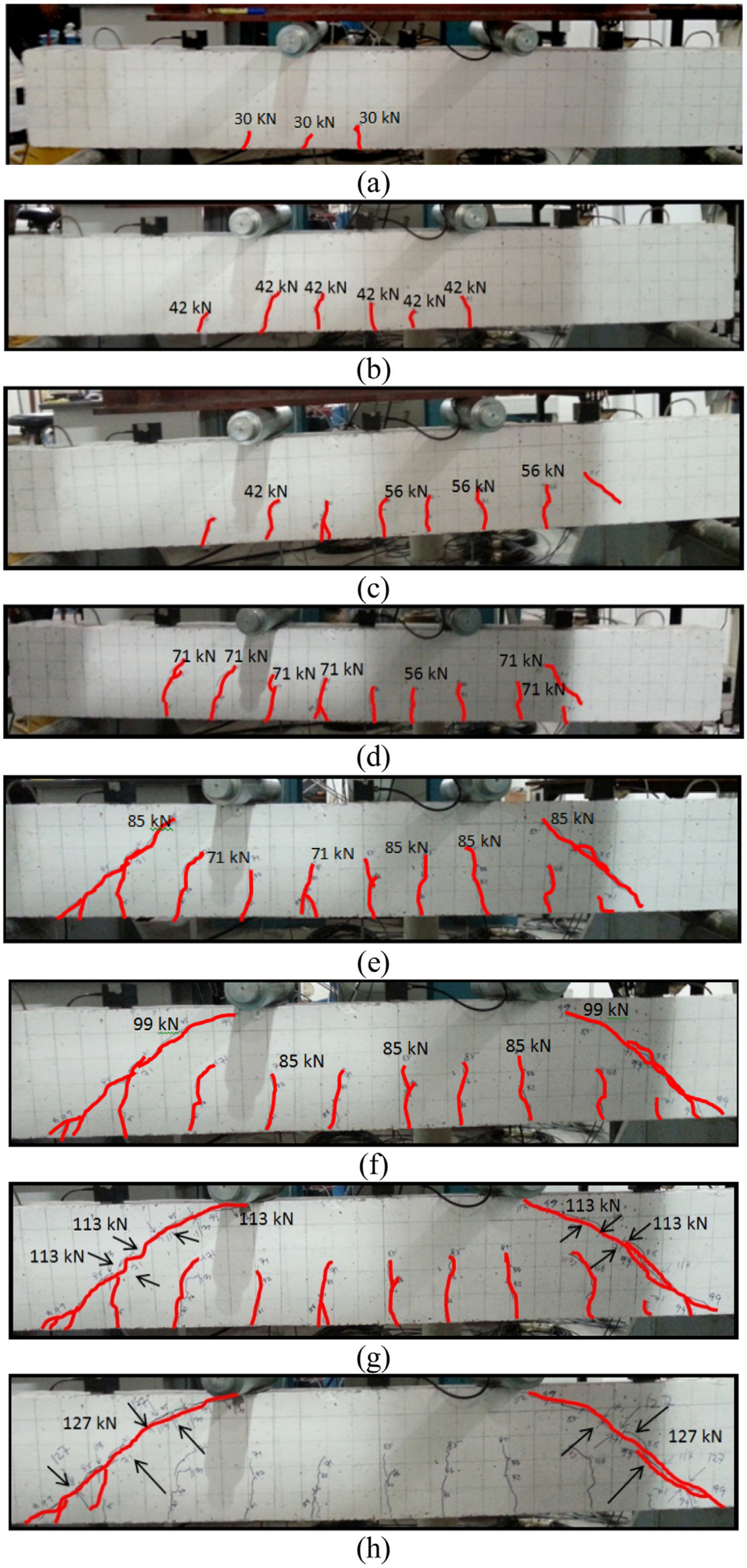


Fig. 7. Photographs of cracks in the RC beam from LS1-LS8.

Tests were divided into two parts; mechanical testing and AE monitoring system. The beam specimens were placed on a steel support with a neoprene pad to reduce the acoustic noise during the test. The beams were loaded and monitored throughout the test using an AE monitoring system (Fig. 4).

The CLT generated the crack growth under different types of cyclic loading conditions. The CLT systems was created from the concentrated load application by using Hjacks. The loading patterns consist of at least three load sets with varying load levels. The maximum test loading is recommended to be at least 85% of the ultimate load. On the other hand, the first loading set should not exceed 50% of the total load test (service load level) and the minimum holding load should also be at least 10% of the total load test [23–25]. The beam specimens were loaded at a rate of 0.5 mm/min using a hydraulic jack system. The CLT system was applied with a starting value of 0.5 kN and the first loading cycle was increased up to 20% of the ultimate load and held for three minutes before releasing it to 10% of the calculated ultimate load. This was held for a further three minutes before the next cycle was applied. These situations were repeated in the second cycle with a similar load level to complete the loading set (LS) as illustrated in Fig. 5. The loading and hold procedure was continued with increasing load until ultimate failure is reached.

3. Result and discussion

All data signals were analyzed during the post-test using IEA method and two values were plotted in the intensity chart to identify the damage level in the concrete beams as presented in Fig. 6. Fig. 6(a)–(h) show the intensity chart for each loading set. For load set 1, LS1, the beam condition for all zones is considered as level A and approaching level B as seen in Fig. 6(a). There is no occurrence of damage observed at this level. On LS2, all zones in the beam were in level B. This indicates that the zones are classified as having minor damage. However, when the loading set increases to LS3 and LS4, the zones moved forward to the next level. Zone 1 and 3 drastically moved to level D from level B whereas Zone 2 moved to level C from level B when the loading set achieved LS4. These situations are shown in Fig. 6(c) and (d). By referring to Table 1, Zone 1 and 3 are classified as having major damage and require a detailed inspection on the monitoring system.

As the loading set increases from LS5 to LS8, all zones again moved to the next level, as can be seen from Fig. 6(e)–(h). Zone 1 and 2 moved to level E from level D during LS4 until LS6. At this stage the zones are considered to be in the failure stage with unsafe conditions., The beams require immediate shut down and detailed inspection using the monitoring system should be considered. For Zone 2, it moved slowly from level C to D as shown in Fig. 6(e)–(h) and this level is classified as having major damage which needs further inspection.

From these figures, it is shown that absolute energy is more efficient in identifying the damage grading level. The application of absolute energy is strongly supported by a study by Muhamad Bunnori et al. [4]. The Absolute Energy Intensity chart also clearly indicated the severe zones for damage localization and the damage process patterns in the concrete structures. The levels of damage conducted in this study are in good agreement with the ISA [1,19]. Previous research considered the use of AE signal strength parameter for identifying the level of damage. Therefore, this study proved that the use of absolute energy in the analysis is able to determine the level of damage in RC beams precisely.

The visual observations are shown in Fig. 7(a)–(h). These figures illustrate the damage level from LS1 to LS8 and the result analysis proved that AE data parameters absolute energy can be a good indicator for real damage mechanism in concrete structures. These evaluation systems are more effective and useable for damage classification. From these figures, the beam specimens obviously indicated the damage progressing by increasing the CLT method. During LS1 to LS3, the beam specimens are classified as having minor damage. When the CLT method increases to service load level, which is LS4–LS5, the beam exhibits intermediate damage. Eventually, the beam is classified as having severe damage when loading is increased up to LS8.The visual observation shows the damage classification on concrete structure using the standard chart in Fig. 6 with the absolute energy parameter. In a nutshell, the figures are more useful and reasonable for determining the damage level in the concrete structure.

4. Conclusion

The AE results for absolute energy parameter clearly indicate the process of damage inside the concrete beam during the initial phase up to the failure phase as presented in the analysis in Fig. 6. In addition, due to the detailed post-test analysis, this parameter value is more effective and promising in identifying the damage outgrowth and localization in concrete beams as seen in the previous analysis of Zone 1 and 3 which are the most severe compared to other zones.

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