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RELATIONSHIP BETWEEN AE SIGNAL STRENGTH AND ABSOLUTE ENERGY IN DETERMINING DAMAGE CLASSIFICATION OF CONCRETE STRUCTURES

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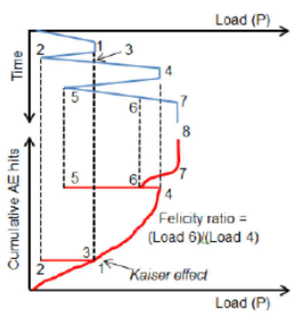
Graphical abstract



Abstract

The most efficient tools in real monitoring system is acoustic emission (AE). This technique can be used to identify the damage classifications in RC structure. This research paper will mainly focus on the utilization of signal strength and Absolute energy (AE signal) in determining on the damage quantification for RC beam subjected to cyclic load test. The beam specimens size (150 X 250 X 1900) mm were prepared in the laboratory and tested with the four point bending test using cyclic loading together with acoustic emission monitoring system. The results showed that the analysis of AE data parameters is capable of determining the damage classification in concrete structures and the data corresponded to the visual observations during the increased loading cycle.

Keywords: Acoustic emission, felicity ratio, calm ratio, reinforced concrete

Abstrak

Salah satu alat yang paling berkesan dalam pemantauan kesihatan struktur (SHM) di dalam sistem pemantauan sebenar adalah teknik pancaran akustik (AE). Teknik ini boleh digunakan untuk mengenal pasti klasifikasi kerosakan dalam struktur konkrit bertetulang. Kajian ini lebih tertumpu kepada penggunaan kekuatan isyarat dan tenaga mutlak (isyarat AE) dalam menentukan tahap kerosakan rasuk bertetulang berdasarkan ujian beban kitaran. Saiz spesimen rasuk (150 X 250 X 1900) mm telah digunakan di dalam kerja-kerja makmal dan diuji dengan ujian empat titik lentur menggunakan beban kitaran bersama dengan sistem pemantauan pancaran akustik. Keputusan telah menunjukkan bahawa analisis data parameter AE mampu menentukan klasifikasi kerosakan dalam struktur konkrit dan ianya selari dengan pemerhatian ketika beban kitaran meningkat.

Kata kunci: Pancaran akuastik, nisbah Felicity, nisbah Calm, konkrit bertetulang

1.0 INTRODUCTION

Reinforced concrete structures have been facing many types of damage mechanisms and deterioration during their life time. Factors such as frost damage, excessive loading due to the increase in traffic flow on the bridge and severe environmental exposure can cause concrete cracking, scaling and spalling [1-4].Due to that matter, it reduces the load carrying capacity of the structure. Therefore, the process of damage mechanism in concrete structure will induce the interaction of duration between long term services and short term services [5-9]. However, these interaction times of the process affect the structural conditions and structure integrity.

In order to ensure that the structure is safe, the importance of early damage detection is required before appropriate maintenance can be carried out. This can be done by conducting visual inspection called traditional monitoring method by trained inspectors but it might not be able to detect early stages of damage on the concrete structures [10, 11]. Hence, more efficient and reliable techniques are often required for better results in the evaluation system.

One of the most efficient tools in real time monitoring system is Acoustic Emission (AE). This technique is a powerful tool for evaluation of any system without disturbing the condition of the structures [12-16]. It enables early crack detections and is also highly sensitive in assessing crack growth. The technique is based on the phenomenon whereby high frequency waves are generated from rapid release of energy inside a material such as from initiating and growing cracks [15, 17-19]. Therefore, this research focuses on AE technique for the evaluation of damage mechanism on concrete structure.

This investigation considers the development of cyclic loading testing (CLT) method with the evaluation using AE parameter analysis method for determining the level of damage mechanism. These methods have been extensively for numerous applications but there is little research on the relationships between absolute energy and signal strength parameter for the level of damage mechanisms in concrete structure. The significance of this evaluation is key for structural integrity and performance. In addition, the combination of the existing and new development methods will provide more confidence as a benchmark for evaluation systems in reinforced concrete (RC) structures.

2.0 AE ANALYSIS

2.1 Parameter Analysis

A Parameter-based Analysis (PA) is a powerful and sophisticated method for AE analysis data parameter to evaluate and assess the material. This analysis method has been applied over the last few decades and it is currently known as the classical approach method of AE analysis [9, 20]. This method is defined to identify the AE wave for the particular parameters. Basically, AE wave parameters are indispensable to describe the feature fracture phenomena with the occurrence rate or accumulated trend in the time domain [10, 21, 22].

This paper focus on the result analysis involving Kaiser Effect to assess the structure under two condition; loading and unloading. Kaiser Effect was first investigated by Joseph Kaiser in 1950. The characteristic of the Kaiser effect is the material under load is known to emit the acoustic wave only after the primary load level is exceeded. The effects of Kaiser are along points 1, 2, 3 as shown in Figure 1 while the composite has led to the use of felicity ratio.

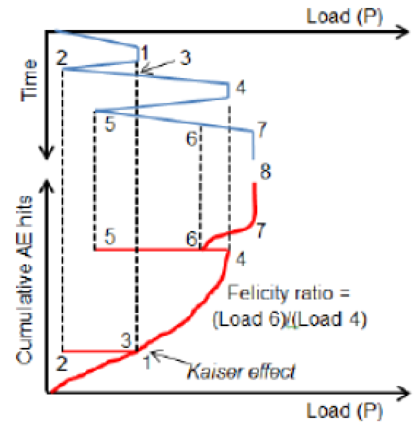


Figure 1 Kaiser Effects [11]

2.1.1 Felicity Ratio

The felicity ratio is defined as:

$$FR = \frac{P_{AE}}{P_{1st}} \quad (1)$$

Where P_{AE} is stress at which AE activity start to generate (load at onset of significant AE during reloading) P_{1st} is the maximum stress (maximum loading during the previous loading history).

According to the felicity ratio value, the Kaiser effect is strongly present when the value is equal or greater than 1.0 while the structure is stable and it becomes unstable when the value is less than 1.0 [12,21-23]. The value of Felicity Ratio is changeable depending on the structure condition, but most studies used 0.5 as the level for damage identification in RC columns [14, 18, 24].

2.1.2 Clam Ratio

This ratio was proposed by [15] and it is based on the total number of AE activities during loading and unloading. This is a very important parameter in concrete structure to characterize the damage progression and damage state. The ratio is defined as the total hits during unloading over total hits during loading [15, 16]. However, it was found that this ratio was not effective to detect the damage progression due to the hits characteristic [14]. In addition, further investigation was carried out on the cumulative signal strength parameter in calm ratio and the result is promising by including damage identifications in the analysis [14]. Therefore, this study has selected absolute energy parameter and substituted it into calm ratio analysis method.

Furthermore, damage classification based on AE activity can also be determined by using the calm and felicity ratio. These two ratio are recommended by the previous researches to determine the collaboration between failure mechanism and AE hit signal [11, 18]. Figure 2 presents the damage quantification with a combination of Calm and Felicity ratio. This standard chart was presented by [15] to classify the damage mechanism into 3 levels; minor, intermediate and heavy damage.

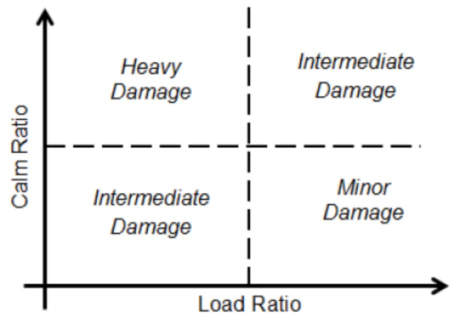


Figure 2 Damage quantification Calm and Felicity ratio by [15]

3.0 EXPERIMENTAL WORK

3.1 Specimen Preparation

Reinforced concrete beams were design according to British Standard (BS 8110) with cross section of 150x 250x1900mm as shown in Figure 3. The beam was reinforced with high tensile strength steel bar.

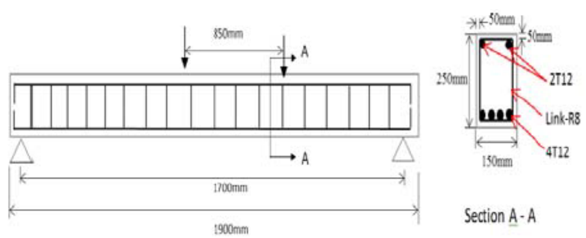


Figure 3 Beam cross section and detail reinforcement

Along with the RC beam specimen, three cubes specimen size of 150x150x150mm were also cast to assess the target compressive strength of 40MPa. The beam specimens were cured for 28 days in order to gain uniform strength.

3.2 Experimental Setup

The beam specimens were placed on a steel support with a neoprene pad to reduce the acoustic noise while testing, the beam were loaded under cyclic load test system (CLT) and were monitored throughout the test using an AE monitoring system as shown in Figure 4. Figure 5 shows the real observation on the setting up of the RC beam in the laboratory work. The setting up of AEwin software must be performed after the installation of AE sensor and before testing.

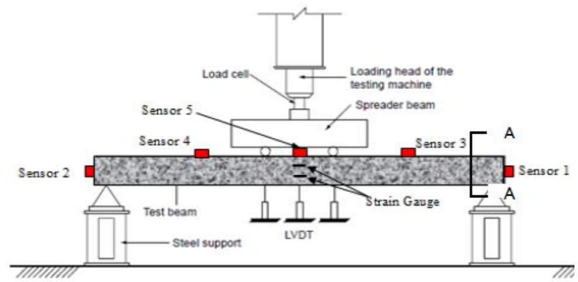


Figure 4 Experimental set up

Figure 5 Real testing observation

The CLT systems are based on the concentrated load application by hydraulic. The pattern of the loading is compressed at least three load sets with the various load levels. The maximum test loading is recommended to be at least 85% of ultimate load. Whereas, the first loading set should not exceed 50% of the total load test (service load level) and the minimum holding load also should be at least 10 % of total load test [14] (ACI 437 & 318). The loading profile for CLT is presented in Figure 6.

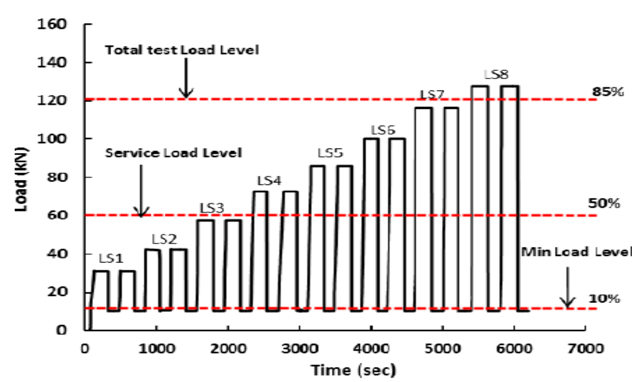


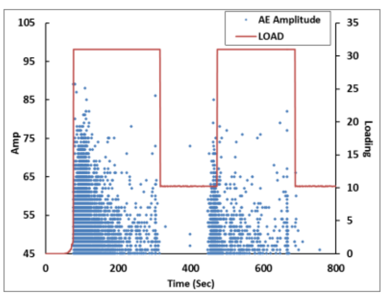
Figure 6 Loading Profile of CLT

The beam specimens were loaded at a rate of 0.5mm/min using a hydraulic jack system. The CLT system was applied with a starting load value 0.5kN and the first loading cycle was increased up to 20% of ultimate load and held for three minutes before releasing 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 the similar load level to complete the loading set (LS) as seen in Figure 6. This loading and hold procedure was continued with increasing load until the beam failed. The specimens were monitored using a Physical Acoustic Corporation (PAC) system, and AEwin software. The AE sensor type of R6I (40-100kHz) was mounted at the location using viscous coupling agent. The sensitivity of the AE sensor installation was verified using the Hsu-Nielsen source method and the threshold setting is 45dB to prevent the system detecting any noise from the surrounding area [19-23].

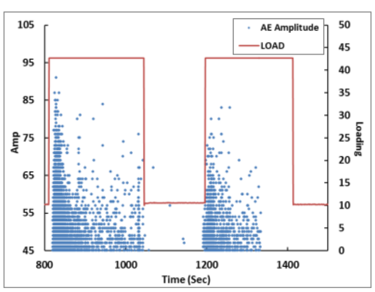
4.0 RESULT AND DISCUSSION

4.1 Mechanical Responses in RC Beam

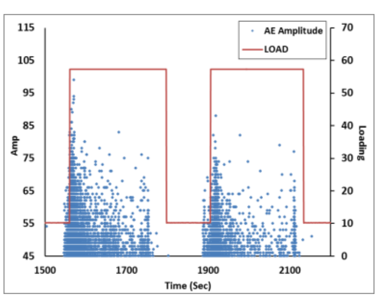
Figure 7 presents the general view of AE activity response to each load set system (LS1 to LS8) by plotting AE amplitude over time with the superposition of load set variation. These two plots calibrated each other and the primary features show that; AE activities increased when the load sets increased especially during the first cycle as compared to the second cycle. Besides that, at the lower load set (hold time), there is lesser AE activity recorded since the increase in the load level as shown in Figure 7.



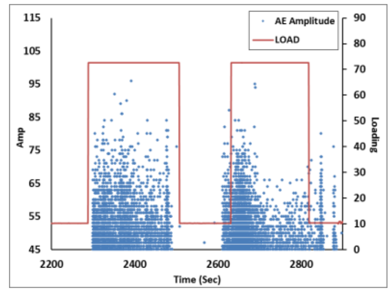
(a) LS1



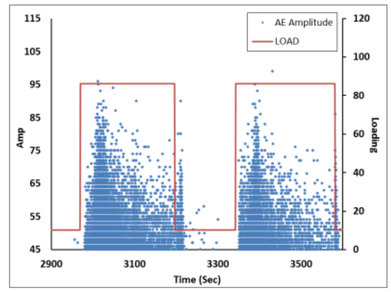
(b) LS2



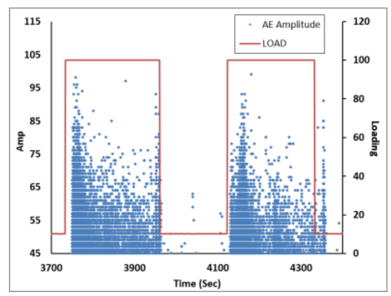
(c) LS3



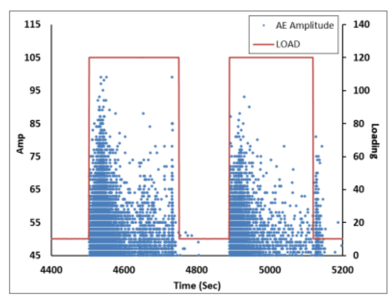
(d) LS4



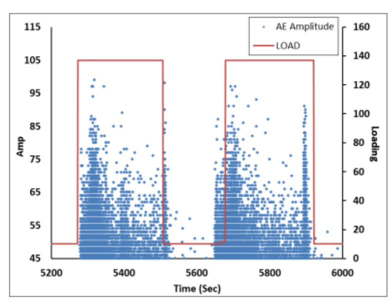
(e) LS5



(f) LS6



(g) LS7



(h) LS8

Figure 7 Typical AE activity responses to CLT from LS1 to LS8

These correlations between AE activities with the CLT method are good indicators for the damage level from the initial load set until the final load set point. Nevertheless, the calibrations between loading and unloading condition for CLT method can be quantified by AE parameter analysis. Detailed analysis on this method will be further explained in the next section.

4.2 Felicity Ratio

Figure 8 illustrates the solution for the determination on the Felicity ratio by 10% of loading hits for LS1. The procedure defines that the accumulation of a straight percentage of the total hits that occurs during the loading portion of load cycle and it was found that the practical percentage is more effective and recommended by previous researches [20]. Similar procedure is used to calculate remaining load set (LS2 – LS8).

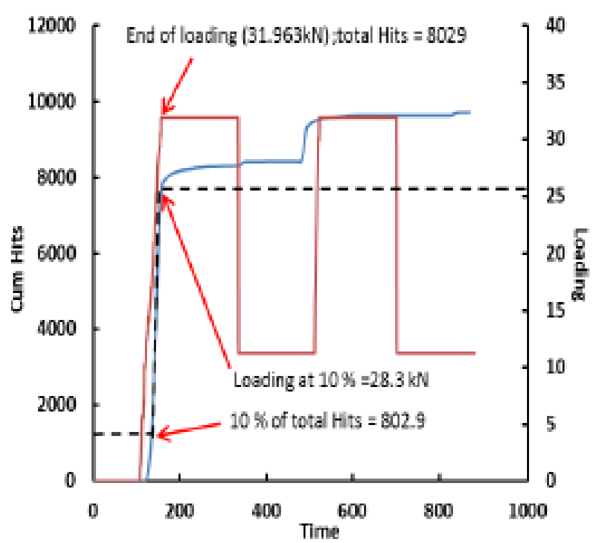


Figure 8 Example solutions for felicity ratio

Figure 9 shows the relationship between Felicity ratio and loading set for RC beam. The graph clearly indicates that as the damage increases in the concrete structure, the Felicity ratio values slightly descend when the loading reaches the service load level at LS 4. The Felicity ratio range value is from 0.80 of up to 0.99 at the LS1 and the rate decreased to 0.1 during the final stage of LS8. It is clear that the Felicity ratio decreases with the increase in load set number by hyperbolic trend instead of linearity. At this time, the cracks are initiated during the higher rate at lower load levels and the rate decreases to 0.1 when the cracks continue to develop until the specimen fails.

From Figure 9, the result of Felicity ratio criteria can be determined and concluded as follows; the value greater than 0.5 is considered as a minor damage, whereas the range value between 0.3-0.49 is classified as an intermediate damage and for the rate value less than 0.29 is considered as severe damage.

The results obtained in this analysis correspond to the result found in Liu, 2007[14] The Felicity ratio rate is very high during the initial load level and the rate decreases when the load set or damage level increases.

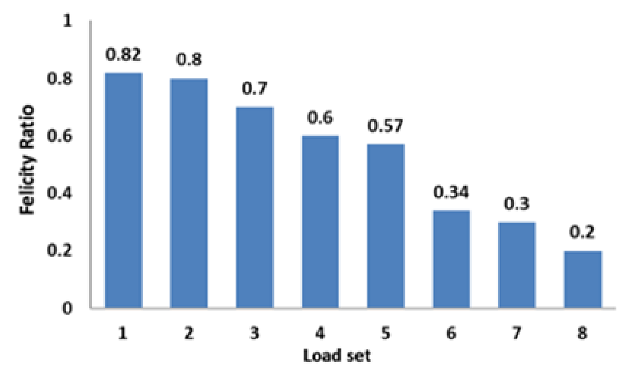


Figure 9 Felicity Ratio Result

4.3 Calm Ratio

An absolute energy and signal strength are the two parameters related to the amplitude and duration components of AE signal. Therefore, it is more reasonable for quantifying the damage in concrete structure. This ratio was calculated by using Equation 2 and 3 for repeated cycle of loading set.

Figure 10 shows the result analysis of Calm ratio for RC beam specimen with signal strength and absolute energy parameters. The results for calm ratio absolute energy were compared with the existing method from calm ratio signal strength [14]. The figure illustrates that generally the Calm ratio value for absolute energy parameter (red color) is higher than signal strength parameter especially on the final load set (LS8) with the rate of 1.27 compared to 1.04 for calm ratio signal strength. This rate is reasonable for the damage identification in concrete structure.

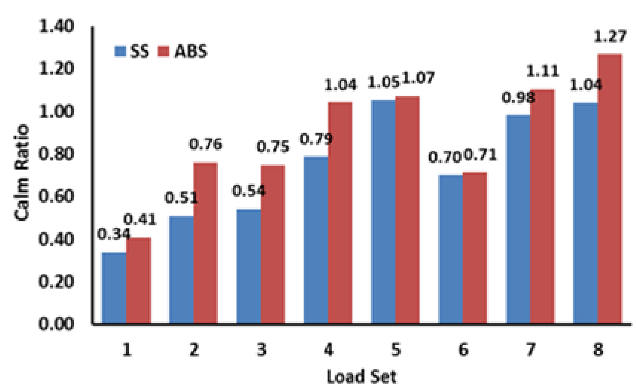


Figure 10 Calm ratio results for signal strength and absolute energy

The lower rate values continue to slowly increase from LS1 to LS4. At this time, it is considered as before yielding, then the value decreases during LS5 although some specimens show a decrease on LS6. This level is classified as the yielding process and eventually the rate values dramatically increases up to failure stage. The evaluation rate criterion for Calm ratio can be defined as 1.0. This evaluation rate corresponds to the previous research from Liu, 2007 [14]. If the Calm ratio is greater than 1.0, this is an indication that the structures have been seriously damaged. This criterion is more effective and serves as good indicator of the level of damage in concrete structure.

4.4 Standard Chart

The combination of two ratios parameter (absolute energy and signal strength) provides more information to access the condition on RC structure. These evaluation criteria were developed by Japanese Society of Nondestructive Inspection (JSNDI) [16, 23-27].

By this standard, the loading effects are characterized by Felicity ratio and unloading effects by Calm ratio to develop the damage classification as seen in Figure 2. This standard is generally acknowledged as the most mature AE assessment method for RC structure.

Figure 11 and Figure 12 are the standard charts for damage classification on concrete structure. This evaluation is based on the load set with three types of classification; minor damage, intermediate damage and severe damage. In this chart, it is very important to define the appropriate threshold setting for Felicity and Calm ratio. The common threshold setting is 1.0 for Calm ratio and 0.5 for Felicity ratio. Based on the previous researches, these ratios are selected according to the material and type of structure [22, 24, 25].

The positions of load set into a damage classification chart are also shown in similar figures (Figure 11 and 12). These two charts calibrate with signal strength (Figure 11) and absolute energy (Figure 12) parameters. From the general observation, these two charts are useable to designate the level of damage from LS1 to LS8. From the chart in Figure 11, LS1, LS2, LS3 and LS4 are classified as minor damage and LS5-LS6 are categorized as intermediate damage and the rest are classified as heavy damage. The chart patterns in Figure 12 are insignificantly different compared with Figure 11. The differences are encountered in LS4 and LS7, where LS4 is classified as intermediate damage and heavy damage for LS7. From this analysis, it is proven that, the intermediate damage started at the service load level, LS4 while for the heavy damages is LS7. Hence, due to the safety conditions and structural integrity in concrete structure, these changes are acceptable and more efficient in determining the level of damage in concrete structure and this result analysis is compatible with the visual observation as presented in the next section.

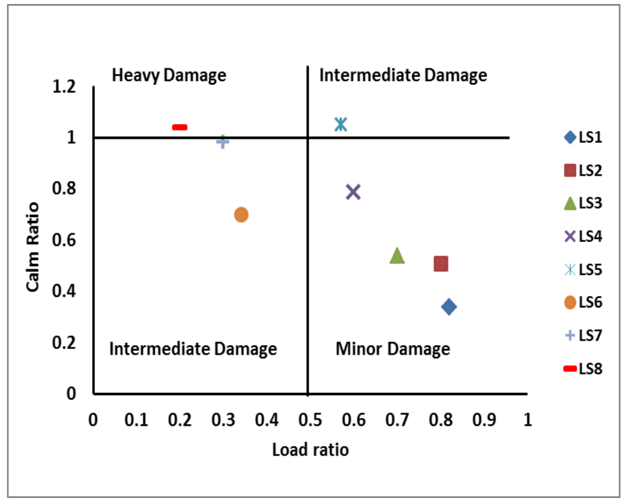


Figure 11 Standard Chart for signal strength

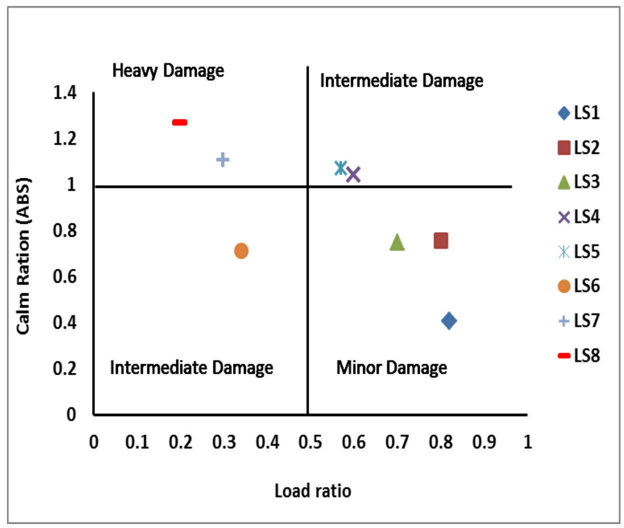


Figure 12 Standard Chart absolute energy

4.5 Visual Observation

The visual observations on the RC beams during testing at various load state (LS1-LS8) are shown in Figure 13 (a) - (h). From the visual observation on the test specimen and the result analysis proved that AE data parameters signal strength and absolute energy are good indicator for real damage mechanism in concrete structure. These evaluation systems are more effective and useable for damage classification.

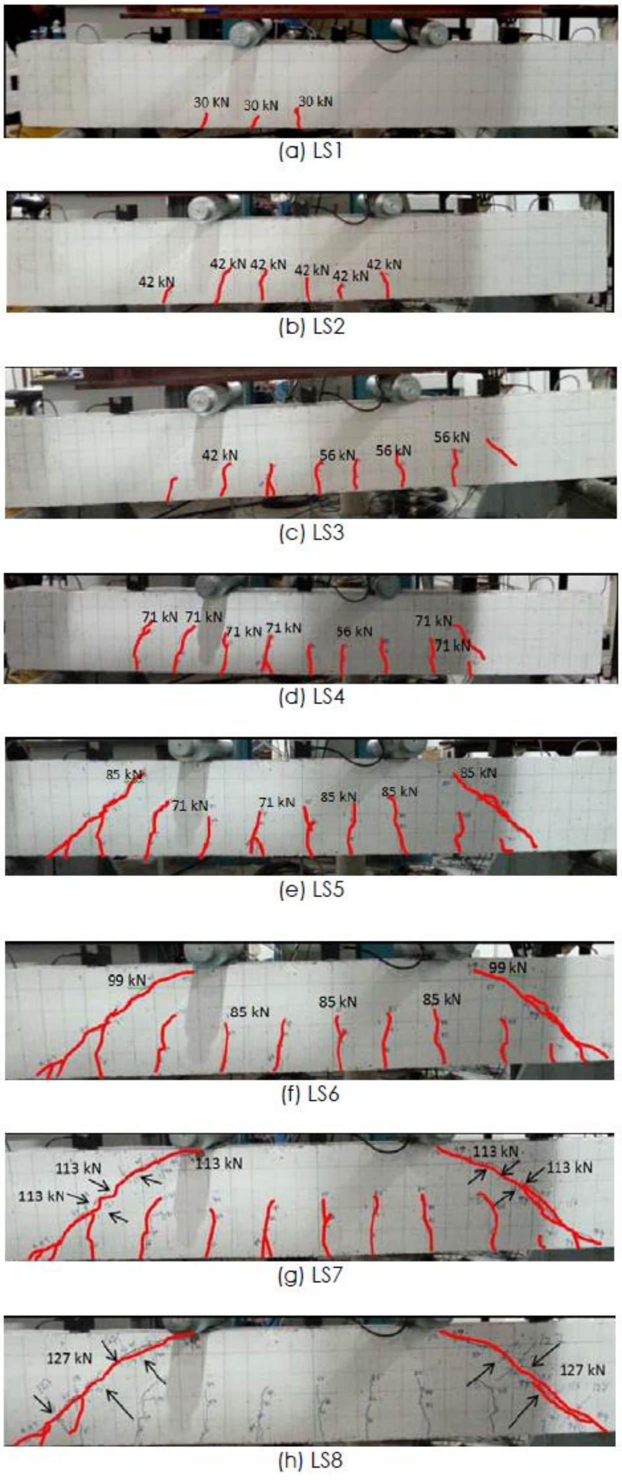


Figure 13 Visual observation in the laboratory work from LS1 to LS8

The damage process with increased CLT methods in the beams is clearly shown in the Figure 13. During LS1 to LS3, the beam specimens are classified as a minor damage where number of flexural cracks is minimal when the CLT method increases to service load level (LS4–LS5), the beam exhibits the intermediate damage and it is shown the existing crack are growth slightly. The cracks predominately located at the mid span and propagate further to the upper face of the beam. At this level also, the shear cracks start to develop. Eventually, when the load is increased of up to LS8, the cracks on the beam is becoming significant and the beam is classified as severe damage. The visual observation shows the damage classification on concrete structure by using the standard chart in Figure 11 and Figure 12 with two parameters which are signal strength and absolute energy. In a nutshell, visual observations are more useful and reasonable to determine damage level in the concrete structure.

5.0 CONCLUSION

This study has assessed the ability of AE to monitor the damage level of RC beam in the laboratory. The following points summarize the most significant conclusions:

- The evaluation systems on the condition of RC beam are essential to maintain the structural integrity against damage.. In this study, two methods have been presented for evaluations systems which are CLT method and AE evaluation method. These two methods are generally effective and efficient in assessing the damage process and classification of RC beam.
- The existing AE evaluation methods such as Felicity and Calm ratio were established by previous researches. However, these methods require improvement for precise result analysis. The application of AE data parameter absolute energy were promising for determining the level of damage beginning from LS1 up to final point. The levels of damage were classified into minor, intermediate and heavy damage as described in the standard chart.

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References

[1] Md Nor, N., A. Ibrahim, N. Muhamad Bunnori, H. M. Saman, S. N. Mat Saliah and S. Shahidan. Diagnostic of Fatigue Damage Severity On Reinforced Concrete Beam Using Acoustic Emission Technique. Engineering Failure Analysis (In Press Corrected Proof).

[2] Shahidan, S., R. Pulin, N. Muhamad Bunnori and K. M. Holford. 2013. Damage Classification In Reinforced Concrete Beam By Acoustic Emission Signal Analysis. *Construction and Building Materials*. 45(0): 78-86.

[3] Shahidan, S., R. Pullin, K. M. Holford, B. N. Muhamad and N. Nor. 2013. Quantitative Evaluation Of The Relationship

Between Tensile Crack And Shear Movement In Concrete Beams. *Advance Material Research Journal.* 626: 355-359.

[4] Shahidan, S., N. M. Bunnori, N. Md Nor and S. R. Basri. 2012. Health Index Evaluation On Acoustic Emission Signal For Concrete Structure By Intensity Analysis Method. 403-408: 3729-3733.

[5] Aldahdooh, M. A. A., N. M. Bunnori and M. A. Megat Johari. 2013. Damage Evaluation Of Reinforced Concrete Beams With Varying Thickness Using The Acoustic Emission Technique. *Construction and Building Materials.*

[6] Nair, A. and C. S. Cai. 2009. Damage Detection Of Concrete Structures Using Acoustic Emission. *Key Engineering Materials*. 400-402: 101-106.

[7] Kaphle, M. R., A. C. C. Tan, D. P. Thambiratnam and T. H. T. Chan. 2011. Review: Acoustic Emission Technique - Opportunities, Challenges And Current Work At Out. *The First International Postgraduate Conference on Engineering, Designing and Developing the Built Enviroment for Sustainable Wellbeing (eddBE 2011).* Queensland University of technology, Brisbane.

[8] Ohtsu, M. 1996. The History And Development Of Acoustic Emission In Concrete Engineering. *Magazine of Concrete Research.* 48(177): 321-330.

[9] Proverbio, E. 2011. Evaluation Of Deterioration In Reinforced Concrete Structures By AE Technique. *Materials and Corrosion.* 62(2): 161-169.

[10] Grosse, C., M. Ohtsu and T. Shiotani. 2008. *Parameter Analysis. Acoustic Emission Testing*. Springer Berlin Heidelberg. 41-51.

[11] Kocur, G. K. and T. Vogel. 2010. Classification Of The Damage Condition Of Preloaded Reinforced Concrete Slabs Using Parameter-Based Acoustic Emission Analysis. *Construction and Building Materials*. 24(12): 2332-2338.

[12] Grandt, A. F. 2003. *Fundamentals of Structural Integrity: Damage Tolerant Design and Nondestructive Evaluation*. John Wiley and Sons Ltd. 1 - 426 9780471214595.

[13] Miller, R. K. and E. v. K. Hill. 2005. *Nondestructive Testing Handbook "Acoustic Emission Testing*. Vol 6: 3rd Edition. American society for Nondestructive Testing 450ISBN1-57117-106-1.

[14] Liu, Z. 2007. Evaluation of Reinforced Concrete Beams Using Cyclic Load Test, Acoustic Emission and Acousto-Ultrasonics. Department Of Civil Engineering. South Carolina, university of South Carolina. Doctor of Philosphy. 1-220.

[15] S. Shahidan, N. M. Bunnori, N. Md Nor, and S. R. Basri. 2011. Damage Severity Evaluation On Reinforced Concrete Beam By Means Of Acoustic Emission Signal And Intensity Analysis. In *2011 IEEE Symposium on Industrial Electronics and Applications*. 337-341.

[16] Ohtsu, M. 2008. Source Mechanisms of AE. Acoustic Emission Testing. C. Grosse and M. Ohtsu, Springer Berlin Heidelberg. 149-174.

[17] Liu, Z. and P. Ziehl. 2009. Evaluation of Reinforced Concrete Beam Specimens with Acoustic Emission and Cyclic Load Test Methods. *ACI Structural Journal*. 106(3): 288.

[18] Tomoda, Y., Y. Sakata, H. Matsusita, M. Murata and M. Ohtsu. 2000. In Situ Monitoring and Daignosis of Reinforced Concrete Member In an Exposure Test Against Salt Attack. JSNDI NDIS-2421.

[19] ASTM-E976. 2011. E976-11. Standard Guide for Determining the Reproducibility of Acoustic Emission Sensor Response. United State, American Society of Testing Material.

[20] Lovejoy, S. C. 2006. Development Of Acoustic Emissions Testing Procedures Applicable To Conventionally Reinforced Concrete Deck Girder Bridges.

[21] Ohtsu, M., T. Okamoto and S. Yuyama. 1998. Moment Tensor Analysis of Acoustic Emission for Cracking Mechanisms in Concrete. *ACI Structural Journal.* 95(2): 87-93.

[22] Ohno, K. and M. Ohtsu. 2010. Crack Classification In Concrete Based On Acoustic Emission. *Construction and Building Materials.* 24(12): 2339-2346.

[23] S. R. Basri, N. M. Bunnori, S. A. Kudus, S. Shahidan, M. N. Jamil, and N. Noor. 2013. Applications of Acoustic Emission Technique Associated with the Fracture Process Zone in Concrete Beam – A review. 626: 147-151.

[24] S. Shahidan, N. M. Bunnori, S. Mohd, N. Nor, and M. A. M. Johari. 2012. Analysis of the AE Signals Parameter At The Critical Area On The Concrete Beam. 386-391.

[25] N. Md Nor, N. M. Bunnori, A. Ibrahim, S. Shahidan, and S. N. Mat Saliah. 2011 Relationship Between Acoustic Emission Signal Strength And Damage Evaluation Of Reinforced Concrete Structure: Case Studies. In 2011 IEEE Symposium on Industrial Electronics and Applications. 308-313.

[26] S. Shahidan, Noorshuhada Md Nor, and N. M. Bunnori. 2011. Overview Of Moment Tensor Analysis Of Acoustic Emission Signal In Evaluation Concrete Structure. *2011 IEEE 7th Int. Colloq. Signal Process. Its Appl*. APRIL: 15-18.

[27] Ohtsu, M., M. Uchida, T. Okamoto and S. Yuyama. 2002. Damage Assessment Of Reinforced Concrete Beam Qualified By Acoustic Emission. *ACI Structural Journal.* 99(4): 411-417.