Chapter 6
Acoustic Emission Characteristics for Determining Fatigue Damage Behaviour

N. Md Nor, S. N. Mat Saliah, S. Abdullah, S. S. K. Singh, and N. A. Yahya

Abstract In reality, damage in the reinforced concrete structure under fatigue causes poor performance under service loading. Hence, this study aims to investigate the acoustic emission characteristics of the reinforced concrete beam subjected to fatigue loading at different sensors. Laboratory experiments were performed on the 150 mm × 150 mm × 750 mm reinforced concrete beam under fatigue loading in conjunction with acoustic emission monitoring. Then, the acoustic emission parameters on four sensors such as absolute energy, amplitude and average frequency were analysed. It is found that a good correlation between acoustic emission characteristics and the normalised cycles for all sensors. Hence, the response on the acoustic emission characteristic can be used to predict fatigue damage prognosis of the reinforced concrete beam.

Keywords Acoustic emission · Fatigue · Fatigue damage

6.1 Introduction

Fatigue in a concrete structure is a process of damage accumulation owing to the repetitive application of loads. The repetition of the loads may not produce any effect at an earlier stage. Over several cycles, as the loads continuously applied, the damage generates intrusions and extrusions that resemble a crack, which led to a disaster when the damage becomes larger. It generally occurs on concrete structures such as buildings, bridges and dams. Such a problem led to a recommendation of a proper

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inspection technique so that rational decisions regarding maintenance, repairing, rehabilitation and replacement can be made. Yuyama et al. [1] recommend using acoustic emission technique to inspect fatigue damage of reinforced concrete slab. Wang et al. [2] apply acoustic emission for the investigation of the fatigue damage process of rubberised concrete and plain concrete. Acoustic emission has been used by Md Nor et al. [3] for inspection of fatigue damage behaviour of reinforced concrete beam. Mohammad et al. [4] has applied acoustic emission to predict the fatigue life of SAE 1045 carbon steel. It is also has been used by Md Nor et al. [5] on fatigue damage classification of the precast reinforced concrete beam.

Acoustic emission is defined as the class of phenomena whereby elastic waves are generated by the rapid release of energy from the localised source or sources within a material, or the transient elastic waves generated [6]. The acoustic emission has been generally used for detection of fatigue damage in a concrete structure employing sensors that fixed on the selected positions. From the signal captured by the sensors, it gives information on the condition of the structure, where the increase in acoustic emission characteristic is generally associated with the rise of new structural damage. Investigation of different types of sensors in terms of their frequency, signal and sensitivity has been investigated by Meserkhani et al. [7] and Bhuiyan et al. [8]. Meserkhani et al. [7] found that the general-purpose sensor with the frequency range of 35–100 kHz produced better absorbing acoustic emission energies than the other sensors. Bhuiyan et al. [8] found that all sensors represent a similar pattern of acoustic emission hit. Although types of sensors are essential in acoustic emission monitoring, acoustic emission characteristic at certain sensor positions also needs to be taken into consideration. However, the effect of the sensor's position was not investigated in-depth primarily related to the acoustic emission energy on concrete either absolute energy or signal strength. In the present study, the absolute energy, amplitude and average frequency are highlighted. The absolute energy is true energy which is calculated by squaring the digitised acoustic emission signal and integrating the results during a hit [9]. To develop a comprehensive understanding of the acoustic emission activities, acoustic emission signal collected at different locations of sensors becomes the key that needs to be taken into account. In doing so, the present study investigates the acoustic emission parameters of a reinforced concrete beam subjected to fatigue loading at different sensors.

6.2 Experimental Programme

6.2.1 Preparation of Reinforced Concrete Beam

A total of ten reinforced concrete beams were prepared with the concrete grade of C40. The concrete proportion of 1: 0.43: 2.16: 2.60 was designed for cement: water: fine aggregate: coarse aggregate. To boost the workability of the fresh concrete mix, a retarder with 1% of cement weight was added. The beams are prismatic standard size with an effective length, Le of 630 mm, having an actual length, $L = 750$ mm, width, b = 150 mm and thickness, $h = 150$ mm. The beams were designed as singly reinforced concrete and procured by two high yield steel reinforcements of 16 mm diameter on the tension part. The nominal cover of 20 mm was used for this beam. In order to fix the stirrups, two mild steel reinforcements of 8 mm diameter as hanger bars were set on the compression part. Then, 12 mm diameter of mild steel as stirrups with a spacing of 100 mm centre to the centre were utilised.

In the beam preparation, the reinforcement was submerged in the mould, and the concrete mix was cast. After ±24 h, the beams were demoulded and cured in water for 28 days. The compressive strength of the concrete at the age of 28 days was 44.65 N/mm^2, which found to be greater than the design concrete.

6.2.2 Laboratory Test

A constant-amplitude sine wave load cycle (frequency of 1 Hz) was applied to the beam size 150 mm × 150 mm × 750 mm. Four sensors (CH1 to CH4) were used, and the positions of the sensors on the beam are illustrated in Fig. 6.1.

For fatigue test, maximum load, P_{max} and minimum load, P_{min} were based on the ultimate load, P_{ult} value. The P_{ult} was taken by averaging the ultimate load of five beams under monotonic loading. The average P_{ult} was 158.85 kN. Hence, the P_{max} and the P_{min} were 0.8 P_{ult} and 0.2 P_{ult}, respectively. Wang et al. [2] stated that acoustic emission signals for data analysis obtained from high maximum loading are relatively small. The fatigue test in conjunction with acoustic emission monitoring was performed with this load range until failure, as shown in Fig. 6.2. Four sensors (CH1 to CH4) were used during acoustic emission monitoring. Two sensors were fixed on top of the beam with a distance of 175 mm from the edge of the beam. Meanwhile, the other two sensors were set at the centre of the cross section of the

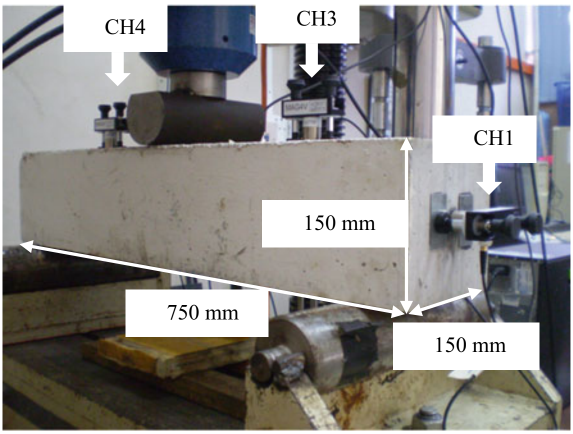

Fig. 6.1 Size of the beam and the location of sensors

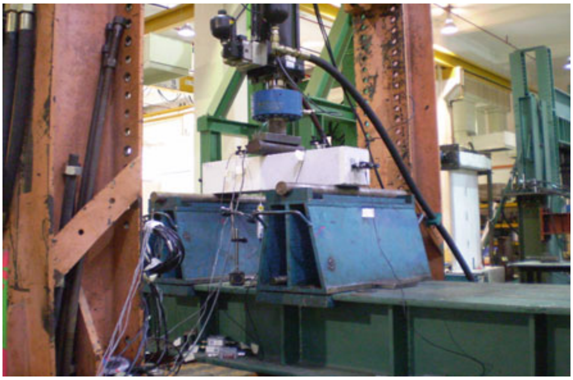

Fig. 6.2 Set up of the beam

beam, as shown in Fig. 6.1. Then, the acoustic emission absolute energy, amplitude and average frequency were analysed and compared for all sensors (CH1, CH2, CH3, and CH4).

6.3 Results and Discussion

6.3.1 Absolute Energy

Figure 6.3 shows the absolute energy, cumulative absolute energy with respect to the normalised cycle (N/Nf) that collected from sensors 1 to 4 and designated as CH1 to CH4, respectively. Generally, the fatigue process in a structure divides into three stages; initiation stage, steady stage (propagation) and final stage (unstable fracture). This process can be seen clearly in CH1, as presented in Fig. 6.3a. CH1, which located at the edge of the beam, received the highest absolute energy at the initiation stage of fatigue damage compared to other sensors. It is because the amplitude of the P_{max} and P_{min} applied to the beam-induced formation of the first fatigue crack, which propagated to the neutral axis of the beam, close to CH1. The process of fatigue damage can be clearly observed through the graph of cumulative absolute energy in Fig. 6.3a. From this graph, it is a fact that high absolute energy is presented in the beginning and the end period of fatigue loading. Xu [10] stated that early microcracks generate a higher signal as the flexural cracks form. The absolute energy was then reduced instantly and almost constant throughout the cycle, produced lower energy in the steady stage. A similar finding has been found by Wang et al. [2] on the fatigue damage process of rubberised concrete and plain concrete.

In the fatigue damage process, high absolute energy at the initiation stage is closely related to the formation of microcrack in the concrete rather than the reinforcement in the beam. Yuyama et al. [1] stated that this is because crack density increases rapidly at the beginning of fatigue life of concrete structure due to formation of

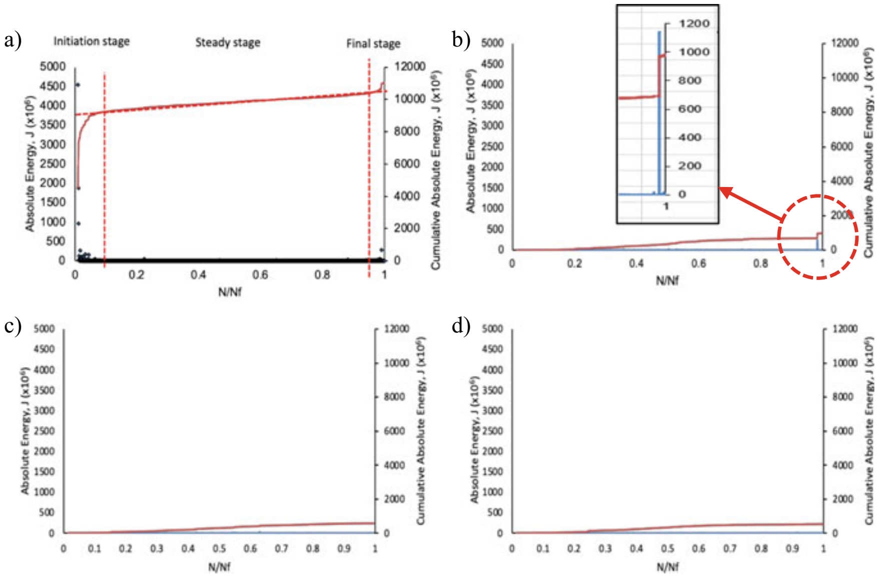

Fig. 6.3 The relationship between absolute energy and cumulative absolute energy and N/Nf for **a** CH1, **b** CH2, **c** CH3 and **d** CH4

microcracking. However, the crack extension starts to slow down after this. As the fatigue loading increases, no significant crack growth can be observed in the steady stage. However, from the experimental work, the other sensors CH2 to CH4 collected lower acoustic emission data and lower absolute energy compared to CH1, as shown in Figs. 6.3b–d. A similar pattern of acoustic emission characteristics can be found for CH2 to CH4 for absolute energy and their accumulation.

Related to high absolute energy, Muhammad Sauki et al. [11] imply that accumulation of damage in the reinforced concrete structure generated high acoustic emission activity. As stated by Abdul Hakeem et al. [12], the cumulative energy is closely related to the formation of crack as the beam subjected to load. However, the appearance of a crack in a structural system depends on the load rate applied during testing [3]. Carpinteri et al. [13] interpreted that the acoustic emission energy correlates to the surplus of elastic energy concerning the dissipated one, which correspondence of unstable behaviours. The more unstable behaviours or instability in the structure, the higher the emitted energy and thus produces higher acoustic emission activities [13].

Although the CH2 represents low absolute energy at the initiation stage and steady stage of fatigue process, high absolute energy can be observed at the final stage as the beam failed, as shown in Fig. 6.3b. Wang et al. [2] imply that the energy of acoustic emission signals also related to the loading and unloading process. Fewer acoustic emission events happen at the unloading stage, and the energy of these acoustic emission signals is much lower when compared with those at reloading stage. The

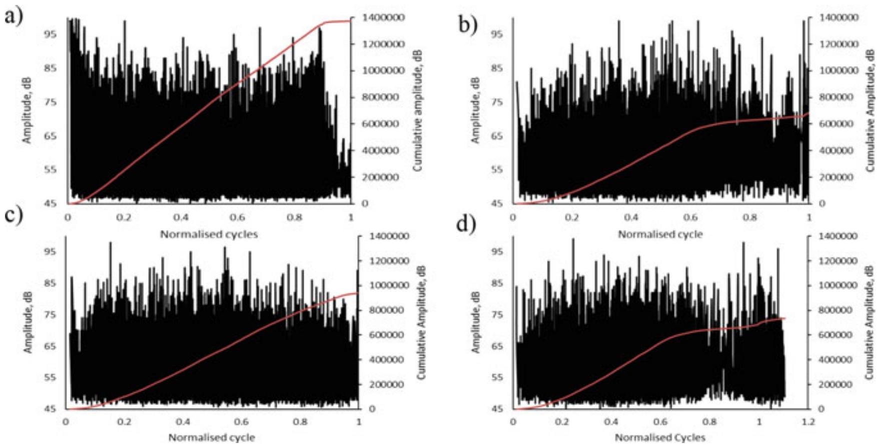

Fig. 6.4 The amplitude and cumulative amplitude for **a** CH1, **b** CH2, **c** CH3 and **d** CH4

peak load generally produces high acoustic emission energy [2]; therefore, acoustic emission in CH2 is.

6.3.2 Amplitude, Cumulative Average Frequency and Cumulative Amplitude

Figure 6.4 shows one of the acoustic emission parameters of amplitude that generally used for evaluation of a structure. CH1 represents a higher amplitude at the beginning of the fatigue process compared to other sensors. This increased amplitude indicates the formation of crack on the concrete as the fatigue load and unloads applied to the beam. The position of the sensors is also played an essential role in collecting the acoustic emission signals. A sensor closer to the acoustic emission source will capture high amplitude than the farther sensor. Since the CH1 is the more relative sensor to the formation of the first crack, it is relatively received the high amplitude at the beginning of the fatigue process. Yuyama et al. [1] added that the microcrack initiation in the beam induces the crack density increases. However, the crack extension starts to slow down after that. However, an almost similar pattern can be observed for CH2 to CH4 when the fatigue process reaches a steady stage. At this stage, the sensors collected high amplitude with the value of more than 95 dB. It pronounces to the progression of crack that occurred in the beam. The amplitude relies on the severity of the fatigue damage during loading and reloading process.

The analysis of the linear correlation between two variables of cumulative average frequency and cumulative amplitude and the normalised cycle is analysed to quantify the damage degree inside the reinforced concrete beam. It also has been performed by Wang et al. [2] to quantify the degree of damage of concrete and rubberised

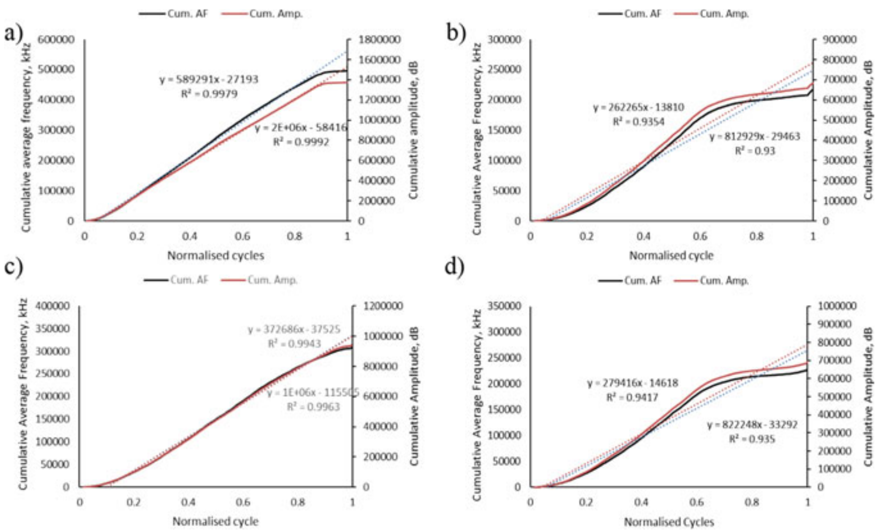

Fig. 6.5 Linear correlation of **a** CH1, **b** CH2, **c** CH3 and **d** CH4

concrete. Figure 6.5 shows the relation between the cumulative average frequency and cumulative amplitude and normalised cycles obtained during the fatigue test. A good linear correlation exhibited between the cumulative average frequency and the cumulative amplitude and the normalised cycle, by presenting the R-squared for all sensors is more than 0.9. Cui et al. [14] stated that a good correlation is indicated if the R-squared value approaches 1.0. Figure 6.5 also presents the equation corresponding to fatigue trendline in terms of the linear-law. From these correlations, the response on the average frequency and amplitude—time series can be used to predict fatigue damage prognosis of the reinforced concrete beam. The fatigue damage prognosis primary aims to predict load-induced fatigue damage to the beam in the future according to the current fatigue damage state of the beam. It can be inferred that the accumulated average frequency and amplitude can be used as a damage variable to quantify damage process of the reinforced concrete beam.

6.4 Conclusions

In a nutshell, acoustic emission characteristics analysed on four sensors of CH1 to CH4 to investigate the fatigue damage of the reinforced concrete beam, which includes the absolute energy, amplitude and average frequency. From the four sensors, the CH1 represents the higher absolute energy compared to other sensors as the sensors located nearer to the acoustic emission source. From the analysis, it is found that high absolute energy was observed at the initiation stage as the microcrack formed and the final stage as the reinforced concrete beam failed. However, the energy is much lower at the steady stage as the crack propagation slows down. Acoustic emission amplitude is higher at the initiation stage of the fatigue process for CH1 compared to other sensors. However, as the fatigue loading increases, high amplitude is noticed at CH2, CH3 and CH4 with the value of more than 95 dB.

From the correlation analysis, a good linear correlation presented for all sensors between the cumulative average frequency and the cumulative amplitude and the normalised cycle with the value of R-squared is more than 0.9. Hence, the response on the average frequency and amplitude related to time series can be used to predict fatigue damage prognosis of the reinforced concrete beam.

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