Analysis of failure mechanisms in fatigue test of reinforced concrete beam utilizing acoustic emission

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ABSTRACT
The acoustic emission technique is used for monitoring the fatigue failure mechanisms in reinforced concrete beam under three point bending. The analysis was conducted by using the bathtub curve method plotted from acoustic emission data. In this study, the fatigue behavior was divided into three stages. The first stage is involved with the decreasing failure rate, known as early life failure or burn-in phase, the second stage is characterized by constant failure rate and the third stage is called the burn-out phase which is an increase of failure rate. The three parameters used in analyzing is the fatigue behavior for each stage of failure which are severity, signal strength and the cumulative signal strength. From severity analysis, the range of each stage of failure had been determined while from signal strength analysis, the initiation of distribution of crack had been detected through the fluctuation of signal strength. Cumulative signal strength parameter provides a clearer view of the initiation and distribution of crack.

Keywords: Acoustic emission, Bathtub curve, Fatigue test, Severity analysis

1. INTRODUCTION

The request of non-destructive technique for evaluation of the performance and stability of structure is constantly increasing nowadays. Acoustic emission (AE) technique is one of the non-destructive techniques. AE can be defined as the transient elastic wave generated by the rapid release of energy from a localized source or sources within a material [1].

Acoustic emission (AE) testing is a potentially suitable technique for structural health monitoring applications due to its ability to achieve high sensitivity from a sparse array of sensors [2]. The AE technique is applied to identify defects and damage in RC structures and masonry buildings [3]. This technique permits to estimate the amount of energy released during fracture propagation and to obtain information critically of the ongoing process. AE techniques had been used to detect various types of localized damage such as fatigue cracks growth, corrosion impacts, delamination for many materials and structure.

Fatigue is a process of progressive permanent internal structural change due to repeat loading [4]. The fatigue crack growth in plain concrete beams under three-point loading by utilizing variable amplitude loading with step-wise increase in maximum load had been studied by [4].

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The durability of reinforced masonry walls through fatigue cycles had been studied by [5]. An experimental analysis on two different sets of reinforced masonry walls under fatigue loading had been carried out in their study. The AE data had been analysed by using Fast Fourier Transform (FFT) to evaluate the frequency distribution.

The research done by [6] use AE signal in order to classified the fatigue crack on reinforced concrete beams. The relationship between average frequency and RA value had been used in their research to differentiate fatigue crack developed when cyclic load been applied on specimen tested.

The literature review shown that [7] had derived bathtub curve from severity analysis in order to analyses the fatigue damage of reinforced concrete beam and from the results obtained, the bathtub curve had shown a promising tool to predict the fatigue life of reinforced concrete beam that had been tested in their study.

In fatigue test, few sets of stress ratios are used for investigations. The selection of stress ratio is based on the tested material case study. Study done by [8] had decided to use the stress ratio of 0.93, 0.87, 0.81, 0.76 and 0.70 for upper boundary of cyclic load and selected the stress ratio 0.23 for lower boundary of cyclic load on all notched plain concrete specimens. A set of stress ratio consisting of 0.6, 0.65, 0.7, 0.8 and 0.9 were used for plain concrete specimens while 0.7, 0.8 and 0.9 were used for fibre reinforced concrete by [9] in their study. While study done by [5] had chosen 0.5 stress ratio of the maximum stress to be carried out on brickwork wall specimens.

In this study, failure mechanism in concrete beam under fatigue test with a load ratio of 0.8 in the range of minimum 32kN to maximum of 127kN had been monitored by utilizing AE technique. The AE data is presented in graphical form by using the bathtub curve. Three characteristic parameters which are severity, signal strength and cumulative signal strength of each channel had been compared and discussed in this analysis. Severity can be defined as the average signal strength among the largest numerical values of the signal [10].

2. METHODOLOGY

2.1 PREPARATION OF SAMPLES AND SAMPLE DESCRIPTION

All the beams were designed based on [11]. The concrete grade used in this study is 40 N/mm^2. The concrete was made up from Portland cement, water, river sand as fine aggregate and crushed stone as course aggregate with proportion of 1:0.43:2.16:2.60, respectively. The dimension of test beam is 150mm wide, 150mm deep and 750mm long. The beam is independently reinforced by 2T16, hanger bar of 2R8, spacing of 12R-100mm center to center and 20mm thick cover.

2.2 TESTING SETUP

Throughout the test, the beam was monitored by AE system supplied by Physical Acoustic Corporation (PAC). Four PAC R61 sensors were used in this test. The location of the loading and sensors is shown in Figure 1. Prior to the test, a calibration check was carried out as well as the sensitivity measurement using a Hsu-Nielsen (H-N) technique [12], close to each sensor. H-N technique is used to ensure that the sensor and the specimen are in a good contact to provide an adequate result throughout the test. In this experiment, a pencil with a Nielson shoe was used to break a 0.5mm 2H lead to generate acoustic waves. The major drawback that arose was in the calibration of AE sensors as well as sensitivity checking where the amplitude must be at least within ± 3dB in different [12]. The AE threshold was set 45dB; which allow eliminating the noise in the vicinity of the test area. This permitted to record only the emission produced by cracking of the specimen or the signal received by the sensors came from the stress generated in the material.

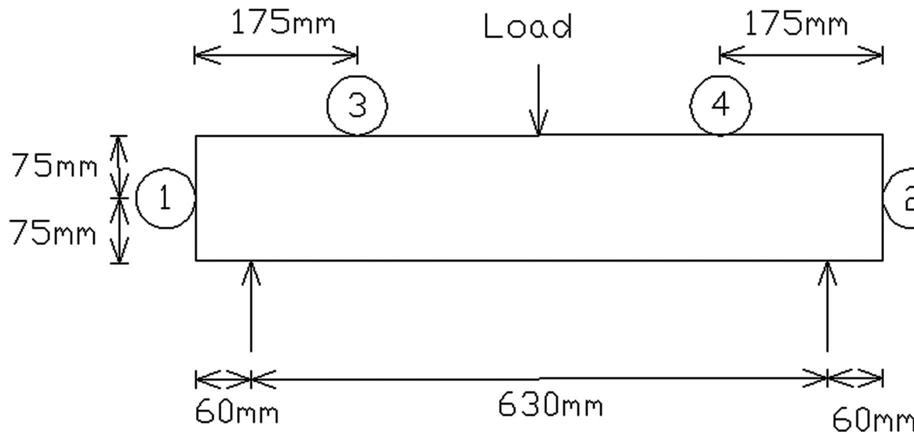

Figure 1: Testing set up

2.3 FATIGUE TEST

The controlled load of fatigue test is a constant-amplitude sine wave loading mode with 0.5Hz frequency until final failure occurs in the beam. The equipment used is 1000kN Universal Testing Machine and the load ratio used is 0.8, at which

$$\text{load ratio, } R = \frac{P_{max}}{P_{ult}} \tag{1}$$

Where:
p_{ult} = maximum load from static test, which is 158.85kN
p_{max} = maximum load for fatigue test, which is 127kN if 0.8 load ratio is used
Minimum load, P_{min} is determined from Equation 2 below:

$$P_{min} = 0.2\ P_{ult} \tag{2}$$

at which p_{ult} = 158.85kN and p_{min} = 32kN. The test was stopped when the beam reached the final failure. Final failure is defined as the moment when strain or displacement radically changes and when fatigue cracks can easily be observed with no other optical tools.

2.4 DATA ANALYSIS USING BATHTUB CURVE

Severity analysis is applied on the AE signal strength data collected by AEWin in software by each sensor. Severity index and historic index is calculated using Equation 3 and Equation 4.

$$H(I) = \frac{N}{N-K} \cdot \left(\frac{\Sigma_{i=K+1}^{N} S_{oi}}{\Sigma_{i=1}^{N} S_{oi}} \right) \tag{3}$$

$$S_r = \frac{1}{j} \cdot \left(\Sigma_{m=1}^{J} S_{om} \right) \tag{4}$$

where H(I) = Historic Index, N = Number of hits up to time t, Soi = Signal strength of the *i*th hit, K = Empirically derived constant based on material, Sr = Severity index, J = Empirically derived constant based on material, Som = signal strength of the *m*th hit where the order of m is based on magnitude of the signal strength. For concrete, K and J values are related to N by the relations: $K = 0$, $N \leq 50$; $K = N - 30$, $51 < N < 200$; $K = 0.85N$, $201 < N < 500$ and $J = 0$, $N < 50$; $J = 50$, $J > 50$.

Bathtub curve approach is used to evaluate the fatigue behavior of the concrete beam throughout this analysis. Three type of graphs are plotted which are severity, signal strength and cumulative signal strength in the function of time.

3. RESULTS AND DISCUSSIONS

3.1 SEVERITY ANALYSIS

The assessment of the severity of the RC beam under fatigue test is presented in graphical form which is known as bathtub curve. The first stage with decreasing failure rate, is known as early life failure or burn-in phase. The second stage characterized as constant failure rate and the third stage is called the burn-out phase which marks an increasing failure rate.

In the first stage, this was the region where early life failure is associated with manufacturing defects, poor installation, poor design or severe overload. Due to the concrete is weak in tensile stress, when load started to be applied on the beam, tensile stress was induced at the bottom of the beam. When the tensile stress is beyond the tensile strength of the concrete, cracking takes place and propagates quickly in a direction to the upper region of the beam, which is crack initiation of the concrete and perpendicular to the maximum tensile stress. But due to the beam steel reinforced, the rebar starts to sustain the tensile stress when the crack propagates towards it and this causes the severity sudden decrease in stage 1 which is known as burn-in. The rebar undergoes elastic behavior which in this situation is recoverable. When the rebar moves to the plastic behavior, the onset of yielding is non-recoverable and the rebar sustains the tensile stress. The onset yielding of the rebar cumulates the fatigue damage and causes a remarkable increase in micro-cracking. The duration of this stage was also small because of the tensile strength of the concrete was weak and the fast crack opening and propagating of the concrete towards the reinforcement bar. Figure 2 shows the portion of concrete severity and the rebar starts to damage at stage 1 of each channel.

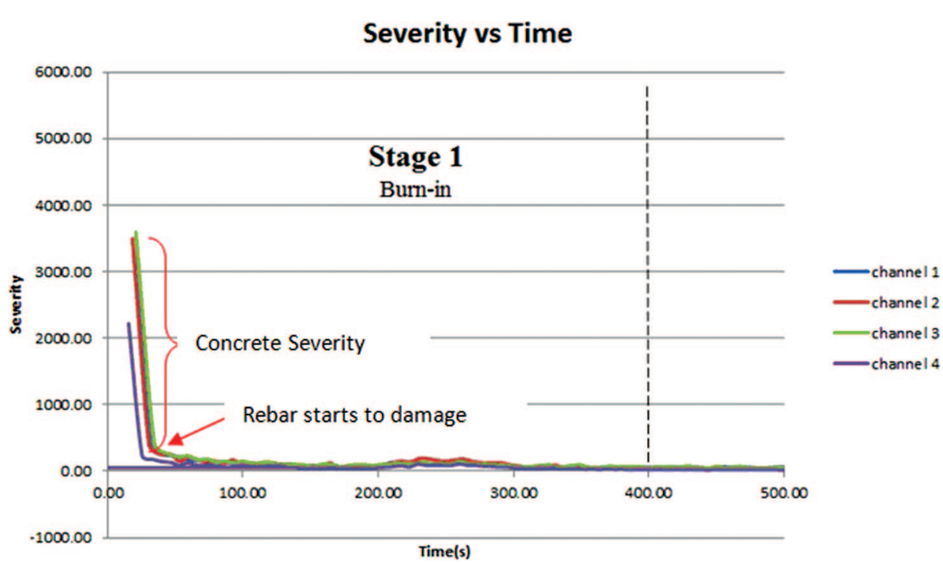

Figure 2: Burn-in of each channel

In stage 2, this region represents in-use phase or constant failure rate. The constant of the severity is due to the distribution of concrete cracking and rebar hardening. The onset of longitudinal cracks was visible along the concrete surface. The duration of this stage was long due to the high tensile strength of the steel reinforcement and the cumulative fatigue damage on the rebar continued until it ultimately led to the final failure which is known as stage 3. Figure 3 shows the portion of distributed crack and rebar hardening of each channel in stage 2.

Lastly, the severity increases rapidly due to concrete splitting and longitudinal macro-crack was visible on the concrete surface until it reaches a peak value which is known as final failure of the beam. When the micro-cracks coalesce to form macro-crack, it induces more AE signal and thus leads to rapid increase of the severity. The concrete and rebar were totally in failure due to stress concentration is beyond its strain limit. The severity decreases after the peak value until zero due to no further new damage and no new AE signal is induced. Figure 4 shows the portion of macro-cracking occurs and the final failure of the beam of each channel. From Figure 4, channel 2 gives relatively small severity as compared to other channels due to channel 2 is located far from the damage occurred on the beam.

3.2 SIGNAL STRENGTH

Signal strength analysis also uses bathtub curve approach to assess the fatigue behavior of the concrete beam throughout the experiment, which can be separated into three stages. From severity analysis, it is known that stage 1 corresponds to the region from 0 to 400s, stage 2 is the region within 400 to 9950s and lastly stage 3 is the region from 9950s towards the end of the test.

Stage 1 shows fluctuations of the signal strength and this indicates that the crack initiation of the concrete and rebar were elongated to yielding phase under cyclic loading.

The seemingly constant value of the signal strength in stage 2 is characterized by the beginning of the distributed of crack of the concrete and rebar hardening which the onset of longitudinal cracks is visible along the concrete surface.

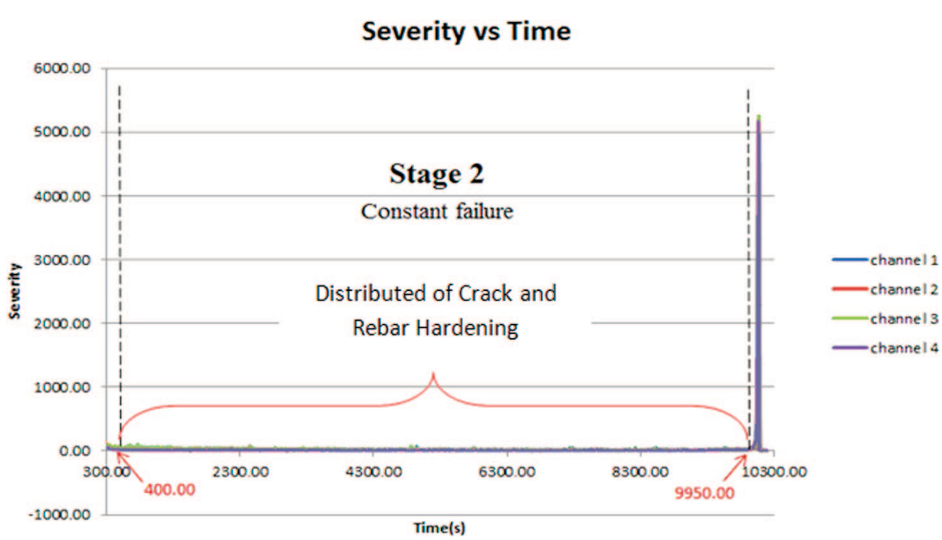

Figure 3: Constant failure of each channel

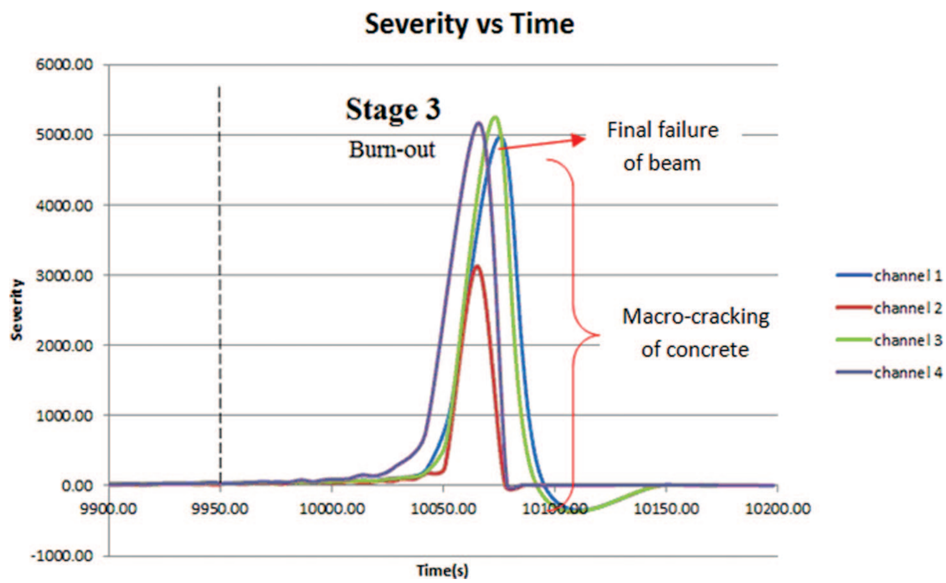

Figure 4: Burn-out of each channel

Finally, when the cumulative fatigue damage on the beam is beyond the tensile strength of the concrete and rebar, final failure of the beam occurs which was stage 3. Stage 3 with increasing signal strength represents propagation of concrete splitting due to the stress concentration in the outer portion of concrete occurred during the rebar's hardening phase.

From Figures 5, 6, 7 and 8, it is noticeable that channel 1 and channel 3 have more signal strength fluctuation at the region between stages 1 and 2, which means that more damage mechanisms occurred at the region near to channels 1 and 3 compared to the region near to channels 2 and 4.

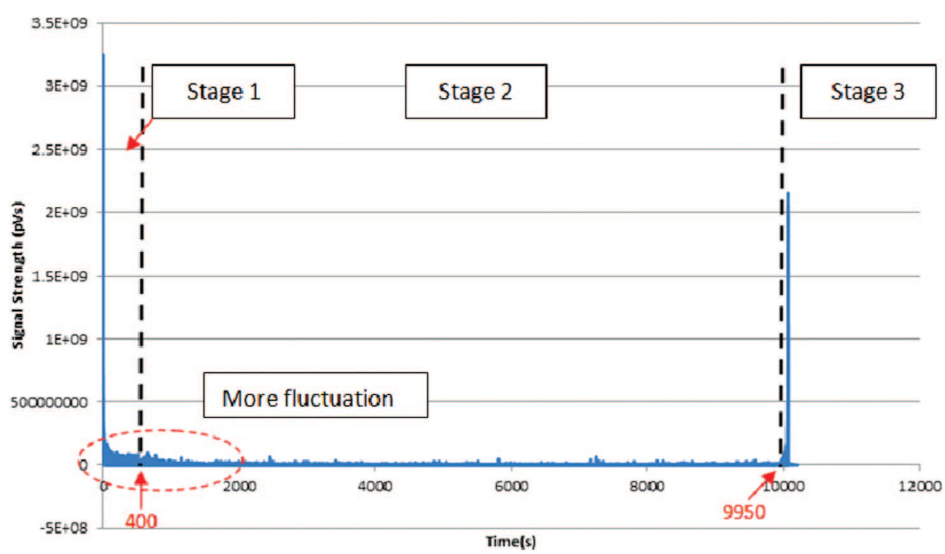

Figure 5: Signal strength versus time for channel 1

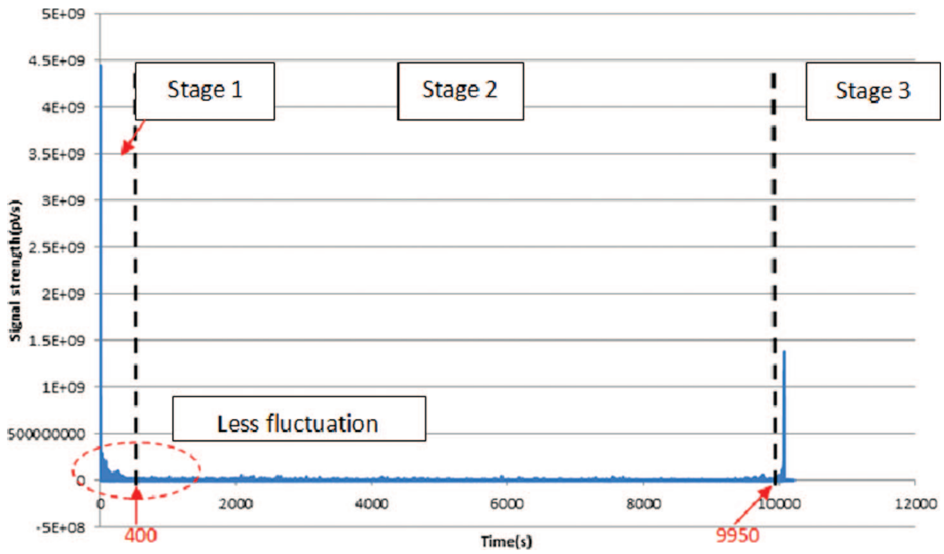

Figure 6: Signal strength versus time for channel 2

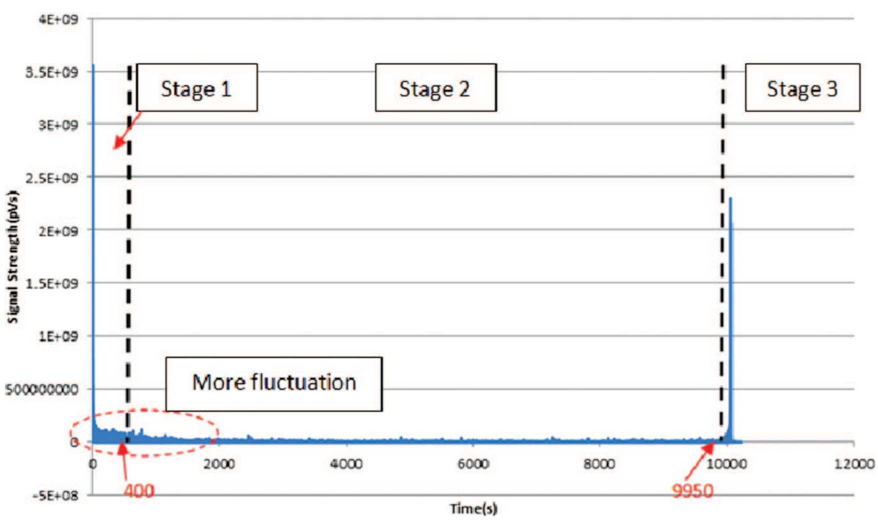

Figure 7: Signal strength versus time for channel 3

3.3 CUMULATIVE SIGNAL STRENGTH

The comparison of the cumulative signal strength for all channels is plotted as shown in Figure 9. From the Figure 9 shown, it is evident that most of the energy is generated at channels 1 and 3, which are located near the area with the most damage concentration after failure. It can be also analyzed using the bathtub curve approach, which is divided into three stages.

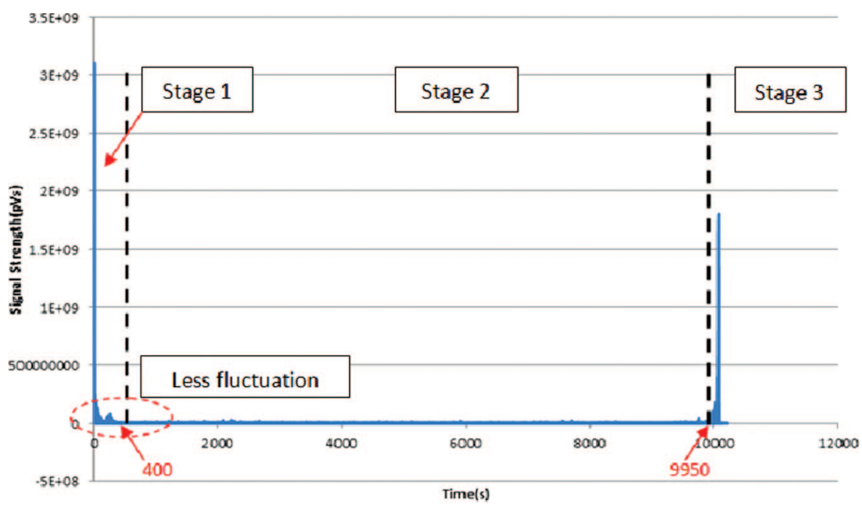

Figure 8: Signal strength versus time for channel 4

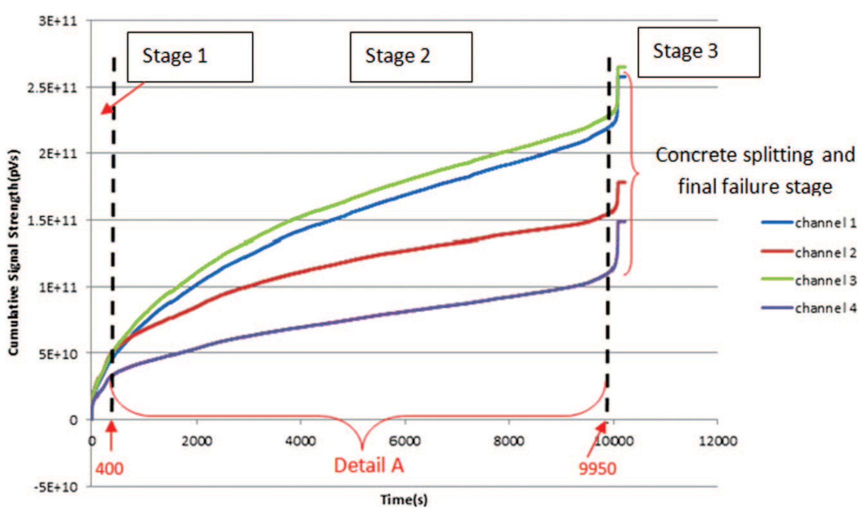

Figure 9: Cumulative signal strength versus time for channel 1 to channel 4

4. CONCLUSIONS

From the results presented in this analysis, the following conclusions can be addressed:

1. Through bathtub curve approach, the damage mechanism of the RC beam of each stage can be easily visualized.
2. The extension or distribution of crack of each channel can be determined by analysis of AE signal strength in the function of time.
3. Cumulative signal strength can be used to provide a clearer view of initiation and distribution of crack of the RC beam by comparing the gradient of graph plotted for each channel.

5. ACKNOWLEDGEMENTS

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