Intensity crack zones of reinforced concrete beam under monotonic loading

S N Mat Saliah1,2*, N Md Nor1, K N Kamaruzzaman1, M A Mohd Mesron1, and N Abd Rahman2

1Faculty of Civil Engineering, Universiti Teknologi MARA, Cawangan Pulau Pinang, 13500 Permatang Pauh, Pulau Pinang, Malaysia
2School of Civil Engineering, Universiti Sains Malaysia, Engineering Campus, Universiti Sains Malaysia (USM), Seri Ampangan, Seberang Perai Selatan, 14300 Nibong Tebal, Pulau Pinang, Malaysia

* soffi581@uitm.edu.my

Abstract. This paper presents the intensity crack zones of reinforced concrete (RC) beam under monotonic loading in conjunction with acoustic emission (AE) monitoring. Five RC beam size 200 mm x 300 mm x 1500 mm were prepared and tested. Due to similar pattern in term of the crack pattern and the analysis, only one beam was presented in this paper. The intensity crack zones were performed by mean of historic and severity indices at sensor 6 (CH6) and sensor 7 (CH7). The plot in the intensity crack zone was based on the crack mode performed during testing. As a result, the progression of the crack was well-matched with the plots in the intensity crack zones. In a nutshell, the data obtained from the AE signal and analyse using intensity analysis, it can be used to classify damage in the RC beam.

1. Introduction
Reinforced concrete (RC) structure is mainly used in civil engineering construction industry. It has been applied for various utilizations such as buildings and infrastructures. The RC structure can deteriorate as a result of increasing loading and aging of the structure. Owing to increasing loading, it induces the formation of cracks in the structure and assessment of the cracks is required in order to maintain the integrity of the structure. Acoustic emission (AE) technique has been used widely in the world to assess, to detect and to locate the occurrence crack in the structure. Md Nor [1] stated that the AE can be used as a structural health monitoring technique to monitor the integrity of the RC structure. For crack development in the RC structure, AE has been used to assess the development of tensile crack and shear crack in the RC beam subjected to increasing fatigue loading [2]. AE has also been used to determine the start of crack when subjected to dynamic loading [3]. The effect of loading rate due to the occurrence of fracture in the RC structure has been identified using AE analysis [4]. From the review, found that the crack assessment of RC structure is significantly important especially the development of crack in the structure. As the structure in service, cracks developed slowly in the structures at initiation stage towards to the failure stage. The assessment is required in order to detect the development of cracks in the structure before it is getting worse and becoming dangerous. This assessment can also be done by classifying the crack into intensity crack zones and AE is the best technique can be adopted. In the intensity crack zone, it involves the plot of log historic index, \( H_I \) and...
log severity index, $S_r$. The crack can be classified either it is in the Zone A – no significant crack, Zone B – Minor crack, Zone C – Intermediate crack, Zone D – the crack needs for the follow up and Zone E – Major crack. The intensity zone has been firstly utilised by Fowler et al. [5] and after that drastically utilised by many other researchers for various applications [6–10]. From the intensity crack zone, the quantification and evaluation of damage severity can be adopted [9]. It is also qualitative information for development of damage in a structure [10]. In the present study, the intensity crack zones for two sensors CH6 and CH7 were identified for each crack mode when the RC beam subjected to monotonic loading to failure. The plots for both sensors were then compared.

2. Experimental Programme

2.1. Preparation of RC Beams

RC beam size 200 mm x 300 mm x 1500 mm was prepared and designated as S1C. The beam was designed with concrete grade C40 with high yield steel bars at tension and compression parts. The concrete mix was designed with different proportions by weight of water, cement, fine aggregate and coarse aggregate and it was 0.43, 1.00, 1.73, 2.70, respectively. 0.45% superplastisizer and 0.3% retarder were mixed into the fresh concrete. The maximum size of coarse aggregate was 20 mm. It was found that the compressive strength of the hardened concrete at 7 and 28 days was 50.27 MPa and 56.87 MPa, respectively. For the preparation of steel reinforcement, the tension part of the RC beam was two number of bars with the diameter of 16 mm (2T16). Meanwhile, for the compression part of the RC beam was two number of bars with the diameter of 10 mm (2T10). The spacing of the stirrups were 175 mm centre to centre with the diameter of 8 mm (R8 – 175 mm c/c).

2.2. Test Set-up and AE Monitoring

For loading application, a constant load rate of 0.02 kN/s of three-point loading was applied to the beam in conjunction with AE monitoring as shown in Figure 1. The Universal Testing Machine (UTM) was used throughout the testing. It was applied to the beam to failure. For the AE monitoring, four sensors were used and applied to the selected positions on the beam as illustrated in Figure 2. The sensors type VS275-V was designated as CH5, CH6, CH7 and CH8. In this paper, data obtained from two sensors were analysed and discussed. The sensors were CH6 and CH7. The selection of the sensors for the analysis was based on the highest AE hits and highest AE activities during testing. The sensors were firstly calibrated to ensure their sensitivity with the beam surface. The same technique as presented by Md Nor [6] and Mat Saliah and Md Nor [11] has been applied for this study. For the analyses, crack modes, load and signal strength were analysed and discussed. From the AE signal strength, it was transformed into historical index and severity index to determine the crack zone for each crack mode.

2.3. AE Analysis of Severity Index – Historical Index

From the intensity analysis (severity index – historic index plot), the classification of crack can be identified. The plot of severity index – historical index was based on the AE signal collected at each identified crack mode. All data collected from CH6 and CH7 were analysed. The severity and historic index were based on the two equations as following [12]:

$$HI = \frac{N}{N-K} \left( \frac{\sum_{i=1}^{N-K} S_{ni}}{\sum_{i=1}^{N} S_{ni}} \right)$$

(1)

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

(2)

where N is the number of hits up to time t; $S_{ni}$ is signal strength of the $i^{th}$ event, K and J is empirical derived constant based on material; and $S_{om}$ is signal strength of the $m^{th}$ hit, where order of m is based on signal strength amplitude. The K and J used for reinforced concrete structures are: $N \leq 50$, $K = 0$;
51 \leq N \leq 200, K = N - 30; 201 \leq N \leq 500, K = 0.85N; and N \geq 501, K = N - 75 as well as J values for N < 50, J = 0 and N \geq 50, J = 50 [13].

Figure 1. The beam setup concurrent with AE monitoring

Figure 2. Illustration of the beam set up and location of sensors (dimension in mm)

3. Results and Discussion

3.1. Identification of Crack Modes - AE Signal Strength and Load with respect to Time

Figure 3 shows the relationship between signal strength, load with respect to time for beam S1C. Meanwhile, Figure 4 shows the illustration of the crack mapped on the beam when subjected to monotonic load to failure. It was found that the maximum load of beam S1C is 185.20 kN. When the beam subjected to load, five crack modes were identified namely CM1, CM2, CM3, CM4 and CM5. CM1 is the nucleation of crack, in which the crack is unable to be seen visually. The identification of CM1 was based on the Degala [14], that the high spike of signal strength is used. CM2 is the first crack that appeared on the beam's surface when subjected to load. CM3 is the flexural crack localized, where the crack sometimes propagated below and beyond the neutral axis of the beam. CM4 is the development of the shear crack in the beam. CM5 is failure of the beam. The identification of the crack modes was based on the crack observation and the AE signal strength analysis during the beam subjected to monotonic loading to failure.

When the load reached 37.00 kN, no crack appears on the beam surface so called as CM1 as depicted in Figure 4a. It indicates that the crack nucleated when it reaches 20% of the maximum loading for Beam S1C. As stated previously, the nucleation of crack is only detected by the AE
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...technique and unable to be seen visually. The load of 37.00 kN induced the formation of signal strength with the value of 2760 nVs at time 147 s. The high signal strength for this crack mode was captured by CH7. The nucleation of crack was based on the spike of signal strength shown in the AE visual during testing prior to the first crack appeared on the beam surface as depicted in Figure 3. The same concept was previously utilised by Md Nor and Mat Saliah [15] for evaluation of RC beam subjected to fatigue loading. High signal strength at this crack mode is also due to high stress concentration which tends to the formation of crack.

As the load on the beam increases to 73.81 kN, the first two hairline cracks, CM2 coincidently appeared on the beam surface as shown in Figure 4b at time 246 s. It was generated of about 40% of the maximum load. The first and second cracks were measured of 625 mm and 888 mm from left edge of the beam. A spike of signal strength of 15600 nVs was noticed few seconds earlier prior to the first crack, CM2 from CH7 which appeared on the beam’s surface when subjected to this load. This spike of signal strength seemingly gives earlier notification on the occurrence of the first crack in the beam. Chotickai [16] stated that the signal strength is normally associated with the occurrence of damage in the specimen. It is due to the signal strength is related to the amount of energy released by the specimen [17].

More flexural cracks, CM3 were generated on the beam as depicted in Figure 4c. It was occurred at time 347 s when the load reached 52% (96.89 kN) of the maximum load. This load produced lower signal strength of 4580 nVs at time 347 s compared to the first crack mode. As shear crack, CM4 was visually observed; signal strength of 3990 nVs was produced at load 82 % of the maximum load or 158.12 kN. It was occurred at time 781 s. The CM4 cracks can be seen in Figure 4d. When the shear crack occurs, it produced the low signal strength compared to the flexural crack. Similar findings have been found by Muhamad Bunnori [18] that shear crack produced lower AE energy compared to other types of crack. It was enhanced by Md Nor et al. [2, 19] on the study of damage evaluation of RC beam subjected to increasing fatigue loading.

The failure, CM5 was occurred at time 4729 s when the load reached 146.68 kN (79 % of the maximum load) as shown in Figure 4(e). At this stage, it produced extremely high sound with the highest signal strength of 40200 nVs (4729 s). Similar finding has been shared by Budano et al. [20] where the higher AE energy is closely related to brittle fracture, which is accompanied by an audible noise. Meanwhile, the lower AE energy is closely related to the stable ductile crack propagation. This has been supported by Nayak et al. [21] when the author explains that the flexural failure occurred due to complete yielding of the longitudinal reinforcement in the RC structure. Figure 4f, shows the crack mapped onto the beam at failure when subjected to monotonic load.

![Figure 3. Signal strength and load with respect to time for beam S1C](Image)
3.2. Intensity Zones of Beam S1C for each Crack Mode

The intensity plots which were collected from CH6 and CH7 for beam S1C subjected to monotonic loading of all crack modes are shown in Figure 5. The plots of intensity zones for both sensors can be used to predict future performance of the beam. From Figure 5a, the intensity zone for nucleation of crack at both sensors falls in the Zone A. It implied that no significant crack emission occurred in the beam.

CH6 indicated the CM2 was in intensity Zone B (minor damage) which reflects to the formation of the first crack in the beam as shown in Figure 5b. However, CH7 was in Zone C implied that two cracks which are appeared from the bottom of the beam at tension part were in intermediate damage. Although the sensors were located at the same position, on top of the beam 300 mm from the point load, they presented different intensity zones. It is close related to the AE waveform captured by the sensors. As stated by Md Nor et al. [22], the AE waveform travels to the sensor plays important role in the collection of the energy released from the source. It is also related to the time of arrival (TOA) of the wave and distance of the crack to the sensor [22]. It is because the AE signal strength is the main parameter used in the determination of historic index and severity index, the CH7 received more AE activities compared to CH6, which induced the formation of intensity zone. At the same time, the propagation of the crack is also effect to the result of the signal strength.
When the tensile crack localised, CM3, the intensity zone for CH6 indicate the beam was in Zone B showing the beam was in minor damage as shown in Figure 5c. Meanwhile, the CH7 indicated the beam was in the middle of Zones C and D. It implied that the beam was in the transition between intermediate damage to follow up, which recommended for significant defect requiring follow up inspection [8]. The intensity zones are well matched with the crack pattern as illustrated in Figure 4c where smaller crack occurred under CH6 compared to CH7. Under CH6, most of the cracks were propagated below neutral axis. Meanwhile, one crack which closes to CH7 was propagated beyond neutral axis, which is induced development of high AE activities.

As the shear crack developed, CM4, the plot for CH6 indicates the beam was in the Zone D where requiring follow up inspection (Figure 5d). However, it is different for CH7 where the plot was in between Zone D and Zone E, indicates the transition between follow up to major damage. As stated by Buyukozturk et al. [23], the shear failure occurs if the shear capacity of the beam cannot accommodate the increase in the flexural capacity. The plots are well matched with the crack pattern as the CM4 developed. All plots on both sensors were indicated the beam was in the major damage as depicted in Figure 5e as the beam was failure, CM5.

**Figure 5.** The intensity zones obtained from CH6 and CH7 for a) CM1, b) CM2 c) CM3 d) CM4 and e) CM5

Figure 6 shows the summary of the plots of intensity zones at CH6 and CH7. As the load increases which tend to the progression of the crack modes in the beam, the plots in the intensity zones at each crack mode progressed from Zone A to Zone E. It indicates the progression of the crack is well-matched with the plots in the intensity zones.
Figure 6. The intensity zone for beam S1C taken at a) CH6 b) CH7

4. Conclusion
In the present study, intensity crack zone at CH6 and CH7 form beam S1C subjected to monotonic loading to failure was investigated. Five crack modes were identified namely the nucleation of crack (CM1), the first crack (CM2), the flexural crack localized (CM3), the development of the shear crack (CM4) and the failure (CM5) of the beam. It is found that the intensity plots are well matched to the crack mode identified. As the load increases, the plots in the intensity zones at each crack mode progressed from Zone A to Zone E. It indicates the progression of the crack is well-matched with the plots in the intensity crack zones for both sensors.

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