Crack intensity of the damaged RC beam repaired with epoxy injection using acoustic emission technique

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Abstract. This paper presents the intensity crack zones of a damaged reinforced concrete (RC) beam with the size of 200 mm x 300 mm x 1500 mm repaired with an epoxy injection under monotonic loading. The acoustic emission (AE) technique concurrent with three-point loading was used to monitor the behaviour of the beam. The intensity analysis based on AE signal strength was carried out on CH6 and CH7 at each crack mode. It was found that the intensity plots are well matched with the progression of the crack in the beam. It is inferred that the intensity zones can be utilised to characterise the damage in the beam.

1. Introduction

RC has been popularly used as a composite material in civil engineering construction industries in the world and mainly used for buildings, bridges and dams [1]. It is well-known truth that the structure would deteriorate such as crack after several years of service. The deterioration would alter the performance and appearance of the structure, which induce the reduction of structural integrity [2]. Hence, the deterioration becomes a significant concern on maintaining structural performance. Most deterioration starts with nucleation of crack and growth as the load increases or overloading.

As mentioned by many researchers such as Jumaat et al. [3] and Matthew [4], overload is one of the causes of deterioration mechanism in the RC structures, which tend to fail the structure, especially in extreme cases. Hence, the prediction of the progression of the deterioration is required through continuous monitoring during its service life. Since the overloading causes the crack formation; action should be taken into account, especially when the crack appeared on the beam surface. Most often the deterioration may cause severe damages to the structure, and unable to be repaired. However, The Concrete Society [5] exclaimed that a suitable repairing technique of severe damage structures can prolong the service life of the structure by several years. Hence, suitable repairing should be taken into account following the inspection and assessment of the repaired structures.

There are several types of repairing that can be done, depending on the purpose and the type of the crack, either minor, intermediate or severe cracks. Some of the researchers have been using CFRP to repair damaged structures [6 – 8], epoxy injection [9 – 10] and a combination of epoxy injection and CFRP [11]. In the present study, a repairing technique using epoxy injection was investigated to...
understand the behaviour of the beam when such repairing technique is utilised. Since the crack would exit to the RC structure when it is under service, the assessment of the crack needs to be carried out. The assessment can be done using the non-destructive testing (NDT) technique such as acoustic emission (AE). The assessment of the crack progression may help to maintain the structural performance. From the AE technique, the occurrence of cracks in the structure can be detected and located. Meanwhile, from the AE analysis, the crack progression can be classified into suitable intensity zones. The quantification and damage severity evaluation can be adopted [12]. Hence, in the present study, the assessment of the damaged RC beam repaired with epoxy injection using an AE signal of intensity analysis was performed. The intensity analysis was carried on the AE data obtained from two sensors, and the results were then compared.

2. Experimental programme

2.1. Preparation of RC beams and damaged beams

A total of five RC beams were prepared. The concrete grade of C40, high yield steel bars and mild yield steel bars were used in the construction of the beams. The concrete proportions by the weight of cement; water: fine aggregate: coarse aggregate of 0.43: 1.73: 2.70 was used. The fresh concrete was mixed with 0.45 % superplasticizer and 0.3 % retarder. The compressive strength of the cubes at 28 days was 50.57 MPa, which was higher than the required strength. The beams were reinforced with 2T16 at the tension part and 2T10 at the compression part with link of R8 – 175 mm centre to centre.

The beams were intentionally pre-damaged with the crack width up to 1 mm using the three-point loading in a constant load rate of 0.02 kN/s. The crack width was based on the RILEM [13] and JKR [14]. RILEM [13] stated that severe damage is when the crack width falls in the range of 1 mm to 3 mm. JKR [14] classified the crack is severe if the crack width range of 0.3 mm to 1 mm. The beam was then unloaded after the required crack achieved. The cracks were cleaned, and the packers were mounted close to the crack on the required angle. The American Concrete Institute, ACI [15] was referred for the repairing process using epoxy injection. The epoxy was injected to the crack using mechanical pressure injection so the low viscosity injection – liquid able to penetrate the cracks. The beams were designated as S4B.

2.2. Set up for testing and AE monitoring

A constant load rate of 0.02 kN/s was set during three-point loading application on the beam; monotonically loaded to failure. Figure 1a indicates that the beam was set-up with a linear vertical displacement transducer (LVDT) and equipment for AE. Four sensors of type VS275 –V was used and designated as CH4, CH6, CH7 and CH8. Figure 1b shows the illustration of the AE sensors set on the beam to determine the behaviour of damaged RC beam repaired with epoxy injection. In this study, only AE data collected from CH6 and CH7 were analysed and discussed. The AE hardware and the AE procedures were based on previous researchers [2, 7]. The crack modes, AE signal strength and intensity analysis were analysed and discussed. The intensity analysis was based on the relationship between historic index and severity index. Equations 1 and equation 2 represent the formula for both historical index and severity index. Both indexes were performed at each identified crack mode.

\[
HI = \frac{N}{N-K} \left( \frac{\sum_{i=K+1}^{N} S_{oi}}{\sum_{i=1}^{K} S_{oi}} \right)
\]

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

Where; \(N\) is the number of hits up to time \(t\); \(S_{oi}\) is the signal strength of the \(i^{th}\) event, \(K\) and \(J\) are empirically and constantly derived based on the material; and \(S_{om}\) is the signal strength of the \(m^{th}\) hit, where the 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 ≥ 50, J = 50 [16]. In the present study, the plot for intensity crack zone was based on Noorsuhada [2].

Figure 1. a) The beam and instrumentation setup b) Illustration of the beam set up and location of sensors (dimension in mm).

3. Results and discussion

3.1. AE signal strength, load and identification of the crack modes

The AE signal strength characteristic of damaged beam repaired with epoxy injection (S4B) is presented in figure 2. Five crack modes were identified namely nucleation of crack (CM1), first crack (CM2), flexural crack (CM3), shear crack (CM4) and failure (CM5). Figure 3 shows the illustration of the crack mapped on the beam S4B when subjected to monotonic load to failure. Maximum loading of this beam is 212.74 kN.

The nucleation of crack, CM1 occurred when load 28.68 kN was applied onto the beam. The nucleation of crack was noticed at the time of 226 s on the AE visual during a flexural test in conjunction with AE monitoring. This high signal was captured by CH6 with the signal strength of 1700 nVs. The nucleation of the crack is generated earlier as indicated in the AE visual in figure 2.

As the load on the beam increases, the first hairline crack, CM2 as illustrated in figure 3b occurred. The crack was generated at about 30 % of the maximum load or 64.34 kN with the signal strength of 13700 nVs at 287 s. The crack formed on the beam was located at 25 mm, offset from the repaired crack location. It is due to the epoxy injection helped to restore initial pre-cracked stiffness of the beam [11]. It indicates that the use of epoxy injection can bridge and restore the damaged RC beam. Issa and Debs [10] have extended the study and found that the use of epoxy either using gravity filling method or epoxy injection is sufficient to restore the structural integrity of the concrete. Grosskurth and Perbix [17] stated that if epoxy injection has been used for repairing, the resin may able to penetrate the microcrack and pores in the crack. It generates good bonding strength between resin and concrete. Hence in this study, it was found that the first crack occurred at a new location. The occurrence of new crack on the beam was located at 844 mm from the left edge of the beam. Most of the cracks start to propagate from tensile part of the beam.

When the load reached 44 % of the maximum load (93.53 kN), more flexural cracks, CM3 was generated and localized as shown in figure 3c. It produced signal strength of 9040 nVs (at time 409 s). Meanwhile, the shear cracks developed, CM4 when the load reached 88 % of the maximum load (188.05 kN). The CM4 cracks can be seen in figure 3d and signal strength of 9590 nVs. At the maximum load of 212.74 kN, more cracks developed and generated the highest spike of signal strength of 18200 nVs at 5732 s.
The failure, CM5 takes places when the load reached 175.33 kN (82 % of the maximum load) as illustrated in figure 3e. 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. [18] where the higher AE energy is closely related to brittle fracture, which is accompanied by audible noise. Meanwhile, the lower AE energy is closely related to stable ductile crack propagation. Thus, it is found that the epoxy injection on the damaged RC beam is able to bridge the crack and improves the integrity of the damaged RC beam. Figure 4 shows the crack mapped onto the beam at failure when subjected to monotonic load.

![Figure 2. Relationship between the signal strength and load and time for a damaged beam repaired with epoxy injections.](image)

![Figure 3. Illustration of crack mapped on the beam S1C experiences a) CM1, b) CM2 c) CM3 d) CM4 and e) CM5.](image)
3.2. Plots of intensity analysis of the beam for each crack mode

Figure 5 shows the intensity plots at CH6 and CH7 for CM1 to CM5. From figures 5a and figure 5b, the intensity zone for CM1 and CM2 at both sensors was in Zone A. It implies that no significant crack emission occurred in the beam. Although the first crack appeared on the beam surface close to CH7, the intensity zone is still in Zone A. However, as the crack was increased to CM3, the CH6 and CH7 are at the intensity Zone C and Zone D, respectively as shown in figure 5c. As the CH6 was in intensity Zone C or intermediate crack, the crack requires a follow-up evaluation in term of further data analysis or complementary non-destructive examination. The intensity plot for CH7 was in the intensity Zone D; where the beam requires a significant follow-up evaluation.

More cracks were observed when the load increases and CM4 developed. The new cracks progressively occurred and the cracks extended from the previous crack to a slightly higher than the mid-depth of the beam. This crack mode matched with the intensity plot, and it falls under Zone D as shown in figure 5d. In the following load, the intensity plot was in the intensity Zone E (Major defect) as shown in figure 5e, well matched to the condition of the beam as it was a failure. Hence, it is confirmed that the intensity plot in the previous crack mode can be used to predict the condition of the beam if the next crack mode would occur. The plots are more reasonable and well matched with the actual condition of the beam.

Figure 6 shows a summary of the plots of intensity zones for the beam. 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 5. The intensity zones obtained from CH6 and CH7 for a) CM1, b) CM2 c) CM3 d) CM4 and e) CM5.
4. Conclusion

In the present study, the crack pattern for each crack mode was illustrated. The identification of the crack mode was based on the visual observation and the AE signal strength obtained from CH6 and CH7. The intensity zone at each crack mode of damaged beam repaired with epoxy injection subjected to monotonic loading to failure was then identified. From the plot on intensity chart, it is learned that the CH7 predict the earlier forthcoming crack in the beam compared to CH6. The intensity plot for each crack mode of the beam is well matched with the crack pattern that was visually occurred on the beam surface. From the summary on intensity chart, the progression of the crack can be identified.

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