Acoustic Emission Signal Analysis on Corroded Concrete Beam

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Abstract. The steel corrosion of concrete structures has been one of the primary causes of structural degradation. Early identification of the steel corrosion might help minimize the location and the duration of the repair required and the cost associated with restoration work. The acoustic emission (AE) technique is more effective for assessing the corrosion of the steel reinforcement in the concrete structures. The AE technique successfully monitors and analyses energy signals released from the crack of the concrete matrix by the corrosion activity using AE sensors placed on the concrete surfaces. The main objective of this research is to assess the flexural behaviour of the corroded concrete beam specimens under the loading test using the AE technique. Three concrete beams were performed for the evaluation of corroded concrete beam specimens using the AE technique. During the experiments, the corroded beam specimens were flexural loaded together with data acquisition by the AE technique. The data obtained were processed, and AE parametric-based analysis was carried out. The AE technique was successfully conducted for fracture monitoring of the corroded beam specimen under flexure load. The AE parameters include the AE hits, and the \( I_b \)-value of the AE data was successfully introduced to assess the flexure behaviour of the corroded concrete beam specimens. It can be found that fluctuation follows a rising pattern in the \( I_b \)-value and then a declining trend in the \( I_b \) value. The lowest \( I_b \)-value exists at the damage stage IV for all beam specimens except the HC beam specimen. The lowest \( I_b \)-value occurs at the beginning of the damage stage III for the HC beam specimen.

1. Introduction

The RC structures' durability comprises environmental degradation, poor preparation, inaccurate calculation, and bad workmanship caused by steel reinforcement corrosion. In addition, corrosion has a significant effect on the RC structures’s service life and repair costs. It is reported that the costs of repairing and maintaining corroded RC structures approach billions of dollars per year [1]. The costs of repair and maintenance depend on RC structures’ conditions, i.e., the source of the corrosion, level of corrosion, and the impact of corrosion on structural behaviour [2, 3]. Therefore, a reliable method of the assessment (i.e., non-destructive testing (NDT) method) is needed earlier before the structure's integrity is significantly degraded due to the steel reinforcement corrosion. The NDT method is expected to provide the required input for corrosion control, detection, and identification [4].

Several NDT methods for assessing steel reinforcement corrosion in RC structures have been implemented [5-8]. However, the NDT methods have some limitations, such as visual inspection can only provide information regarding to the existence of corrosion damage in an advanced state.
infrared thermography (IRT) and ground-penetrating radar only present the qualitative interpretation to assess the corrosion damage. The fibre Bragg grating (FBG) method only performs localized steel corrosion inspection inside the RC structures. The ultrasonic pulse velocity (UPV) method needs advanced monitoring of the steel reinforcement corrosion in the RC structures. The key application of the impact echo (IE) method is identifying voids and delamination inside the RC structures [9]. On the contrary, due to its ability to detect the steel reinforcement corrosion, the acoustic emission (AE) technique is more efficient for corrosion evaluating steel reinforcement in RC structures.

In order to evaluate and define the steel corrosion phase in the RC structures, the AE parameters include cumulative AE hits, signal strength, and energy, were successfully used [10-13]. And also, in order to differentiate between the failure type, the AE sources have been categorized in RA value and average frequency (AF). In addition, to assess the damage intensity of the RC structures, the AE amplitude distribution in b-value and Ib-value were also proposed [12, 14-16]. The application of the AE technique allows the identification of and detection of micro- and macro-cracking to steel corrosion damage [17-19]. Previous studies have shown the Ib-value of the AE technique for quantifying the corrosion damage of the steel reinforcement in the RC structures. However, limited studies have been attempted the use of Ib-value for quantifying the damage of corroded RC structures under loading test. The researches by Ohtsu et al., and Kawasaki et al. [11-14] only conducted to identify the corrosion process and mechanism of RC structures using the AE technique. In this research, the AE technique is proposed for evaluating the steel corrosion of the corroded RC specimens under flexural loading. The AE parameters, i.e., AE hits and Ib-value, have been performed to characterize the damage of the corroded beam specimens under flexural load.

2. Materials and Method

2.1. Materials

For this research, three beam specimens with the dimension of 1000 x 200 x 150 mm$^3$ and the corrosion level of 0%, 4.55%, and 32.37% were prepared. The cross-section of the beam specimen is 200 x 150 mm$^2$. The beam specimen has been designed for 30 MPa compressive strength at 28 days after casting of concrete in accordance with the BS 8110-1 [20]. The mixture is prepared from Portland cement, sand, limestone with a maximum aggregate size of 20 mm. The concrete is 2430 kg/m$^3$ for dry density. Deformed bars of sizes 12 mm and 16 mm in compliance with BS 4449 [21] were used for steel reinforcements as compression and tension of steel reinforcements, respectively. For shear connections, the stirrup of size 8 mm and spacing of 240 mm was used. Figure 1 show the steel reinforcement. The cover concrete was 36 mm in thickness. The raw materials for the concrete mix include 380 kg/m$^3$ of cement, fine aggregate of 780 kg/m$^3$, coarse aggregate of 1080 kg/m$^3$, water of 190 kg/m$^3$, and water to cement ratio of 0.5.

![Figure 1. The steel reinforcement](image-url)
2.2. Accelerated Corrosion Process

This research works, after the completion of the water curing on 28 days of casting, the beam specimens were subjected to accelerated corrosion process by an impressed current technique. The accelerated corrosion technique was based on ASTM G1-03 [22]. The specimens were partially immersed by volume in a plastic water tank with 5% sodium chloride (NaCl) solution. The steel reinforcements of the beam specimen were corroded after 28th days of concrete casting. In electrolysis of the chemical solution, a direct current (DC) power supply was used, from which the copper wire attached to the beam specimen as the anode (Figure 2). Meanwhile, an aluminum plate as the cathode was attached to the negative terminal. In the corrosion process, a constant current has been applied. The corrosion process was continuously controlled until the steel reinforcement was corroded with needed mass loss. The mass loss was measured using Faraday’s law to convert the current flow. After 28th days of curing, three beam specimens were cast and undergone the corrosion process. Due to the mass loss, low corrosion (LC) and high corrosion are classified.

![Figure 2. Experimental setup of the accelerated corrosion process](image)

2.3. Data acquisitions

Using a universal testing machine (INSTRON Satec Series) with a maximum capacity of 600 kN, all the beam specimens were subjected to a three-point monotonic flexural load. Throughout the load testing, AE monitoring of beam fracture was conducted. The PCI-2 AE system by MITRAS Group, Inc., was connected to six AE SR150M sensors with 150 kHz resonant frequency. And preamplifiers by Soundwel Co., Ltd with 40 dB. These resonant frequency of AE sensors are suitable for concrete monitoring. The AE sensor transforms the electrical signal from the mechanical energy supplied by the elastic wave. Using electron wax as the coupled agent, to mount the sensors onto the concrete surface. The sensor location on the beam specimen is shown in Figure 3. The 6 AE sensors were totally used to detect and capture energy emitted from the cracking of the beam specimens when mechanical loading was ongoing. The position of AE sensors is outside the area of cracks to prevent the sensors from falling down during the loading test due to the beams cracking.

![Figure 3. AE sensor placements](image)
2.4. lb-value
The relation between the magnitude and frequency of earthquakes was established by Gutenberg and Richter with the b-value in seismology [23-25]. In the AE technique, the same concept can be applied to determine the scaling of the amplitude distribution of the AE waves during the fracture process. In terms of the AE technique, the formula was modified by Colombo et al. [24]. However, the formula was improved by Shiotani et al. [26] as an improve b-value (lb-value) to determine the slope failure and fracture phase. For each of the AE amplitude sets, this formulation relies more on statistical analysis like mean and standard deviation. The lb-value is the measure of degradation of the RC specimen. The lb-values become small as cracks occur, indicating nucleation of large AE activities. The micro-cracking is generated at an early stage of damage, there is an increase in lb-value. The lb-value decreases when the RC specimen begins to damage localization [14]. The lb-value is characterized as:

\[ lb = \frac{\log N(\mu - a1\sigma) - \log N(\mu - a2\sigma)}{(a1 + a2)\sigma} \]  

(1)

Where:
\( \sigma \) = standard deviation, \( \mu \) = mean of the amplitude distribution, \( a1 \) = the coefficient related to the smaller amplitude, and \( a2 \) = coefficient related to the fracture level.

3. Results and Discussion

3.1. Mechanical Behaviour
The average of 28th day compressive strength and modulus of elasticity of cylinder are 39.57 MPa and 30.87 GPA, respectively. Figure 4 shows the load against the beam specimen deflection curve. The failure load decreased from about 182.57 kN for the Control beam specimen to less than 150 kN for the LC and HC beam specimens, justifying a decrease in beam stiffness resulting from the corrosion of steel reinforcement. For LC and HC beam specimens, the stiffness decreased from 48.08 (Control beam specimen) to 37.39 and 33.17, respectively. In addition, Figure 4 shows that as load increases, the curve slope of the load-deflection has decreased, which means that as cracks extend at the mid-span, the stiffness of the beam specimens decreases. There was no major difference between their failure loads of the LC and HC beam specimens, i.e., 147.9 kN and 148.8 kN, respectively. Furthermore, there was an almost similar ductility of the LC and HC beam specimens, which were higher.

![Figure 4. Load versus deflection of the beam specimens](image)

In the loading test, Figure 5 shows the progression of the beam fracture. The findings of all three specimens of beams have been defined by macroscopic shear fracture, which is characterized by creating a diagonal crack that penetrated the specimen's height. The amount of visible cracks detected...
before failure was found to be more than the LC and HC beam specimens for the Control beam specimen. The fracture of beam specimens was categorized into four damage stages, i.e., micro-cracking (damage stage I), first visible crack (II), crack distribution (III), and damage localization (IV) to describe the concrete behaviour of the load and deflection to the AE parameters, which were indicated by past studies on flexural behaviour of RC structures using AE technique [27-28].

Figure 5. Progression of the fracture of the beam specimens (a) Control, (b) LC, and (c) HC

3.2. Characteristics of AE parameters

3.2.1. Accumulated AE hits
The AE signals from all the beam specimens were separately divided into four parts according to the damage stages defined above. Figure 6 shows the cumulative AE hits versus load level (%). The accumulated AE hits of the tests decrease in terms of the increase of corrosion level of the beam specimens. All the other specimens show the same trend of accumulated AE hits. Micro-cracking begins to develop at damage stage I, and this is demonstrated by a few AE hits, which increase as the load increases. When the first visible crack is formed, at 25% of load level, an increase of AE hits rate is observed. At the damage stage II, the Control beam has a significant increase in AE hits compare to LC and HC beam. As the loading continues, the cracks propagate in the beam specimens in the damage stage III, and the AE hits increase gradually until damage localization at 75% of load level. A significant increase of AE hits of LC and HC beam at the middle of damage stage III. This phenomenon happens due to the formation of severe crack occurs due to steel corrosion. An increase of AE hits after the damage localization occurs dramatically at early damage IV. The accumulated AE hits of Control beam are higher than LC and HC beam at the damage stage IV. The accumulated AE hits increase more than 60% from around $0.35 \times 10^6$ to around $1 \times 10^6$. 
3.2.2. $I_b$-value

Figure 7 shows the $I_b$-value of the beam specimens. The solid line is a trend line to describe the $I_b$-value trend, however, the $I_b$-value trend cannot be clearly seen. Figure 7(b), on the other hand, gives the $I_b$-value versus load level (%) data, determined by an average of the respective $I_b$-values calculated from the AE data tracked in the current study for each 5% load increase. The fluctuation follows an increasing $I_b$-value trend, and then a decreasing $I_b$-value trend can be clearly observed. Figure 7 (a) shows that the lowest $I_b$-value of the beam specimens were 0.076, 0.064, and 0.067, respectively. Figure 7 (b) and Table 1 show that the lowest $I_b$-value of the beam specimens after modified in each 5% load increase were 0.0988, 0.0934, and 0.1017, respectively. The lowest $I_b$-value occurs at the damage stage IV for all beam specimens except the HC beam specimen. The lowest $I_b$-value occurs at the beginning of the damage stage III for the HC beam specimen. The expansion stress of corroded steel reinforcement influences the lowest $I_b$-value of the HC beam specimen due to the macro-crack generation. The detail of the $I_b$-value is shown in Table 1.

Figure 7. (a) $I_b$-value against load level (%) of the beam specimens and (b) $I_b$-value against load level (%) at each 5% load increase
Table 1. Ib-value of beam specimens

| Load Level (%) | Control  | LC        | HC        |
|----------------|----------|-----------|-----------|
| 5              | 0.12683286 | 0.112377429 | 0.113302245 |
| 10             | 0.134334529 | 0.119495573 | 0.124143532 |
| 15             | 0.135348703 | 0.125435056 | 0.119167759 |
| 20             | 0.136362876 | 0.131374538 | 0.128458075 |
| 25             | 0.138721542 | 0.12417422 | 0.121927142 |
| 30             | 0.129090958 | 0.129598205 | 0.126660774 |
| 35             | 0.129866685 | 0.124909044 | 0.128897665 |
| 40             | 0.131286818 | 0.120219883 | 0.131138757 |
| 45             | 0.122785151 | 0.122795283 | 0.127673658 |
| 50             | 0.1259748   | 0.127161619 | 0.119662505 |
| 55             | 0.125783293 | 0.124704048 | 0.118586593 |
| 60             | 0.126788163 | 0.119912521 | **0.101726991** |
| 65             | 0.126372899 | 0.117972786 | 0.12283178 |
| 70             | 0.122340395 | 0.1157341   | 0.120349976 |
| 75             | 0.119361798 | 0.113081505 | 0.116293039 |
| 80             | 0.115117753 | 0.114198749 | 0.11556107 |
| 85             | 0.112360071 | 0.109035319 | 0.113115205 |
| 90             | 0.108794682 | **0.093368359** | 0.113791694 |
| 95             | **0.098842724** | 0.101932098 | 0.104407883 |
| 100            | 0.108839577 | 0.106070065 | 0.106716889 |

Figure 8 shows the Ib-value of each RC beam specimens. For the Control beam specimen, we can infer that micro-crack formation was dominant in the damage stage I, which shows the increasing trend of Ib-value, as shown in Figure 8(a). Then it began to localize as macro-crack in damage stage II and III with a fluctuation region. After that, the Ib-value started to decrease at the end of the damage stage III to damage stage IV as reinforcement yielding, and macro cracks opening happened. A similar trend also occurs in corroded LC and HC beam specimens, however, at the end of damage stage II, the Ib-value began to decrease earlier. This condition indicated that the macro-crack opening earlier at the tension reinforcement side of the beam specimen. Higher Ib-value reflects small AE events where lower Ib-value implies active nucleation of large AE events [29-31]. Based on Figures 7(b) and 8, results suggest that the 0.12 of the Ib-value is related to reinforcement yielding and macro-crack opening of the beam specimens. This finding is confirmed because the Ib-value of damage stage I-III fluctuated above 0.12 for the Control beam specimen, although no macro-crack was observed visually.
Figure 8. *Ib*-value of beam specimens against load level (%) (a) Control, (b) LC, and (c) HC

4. Conclusions
The conclusions drawn by this study can be summarized as follows based on the AE technique results obtained from the test of the corroded RC beam specimens under flexure loading:

1. The corroded RC beam specimens failed in shear failure based on general observations. The tension side revealed the shear cracks because of the weakening cohesion between steel reinforcements and concrete due to corrosion of steel reinforcement.

2. The damage of the corroded RC beam specimens could be sufficiently characterized by the accumulated AE hits and the *Ib*-value of AE data. These methods are extremely successful in the assessment and monitoring of the corroded RC structures. The experimental result confirmed that the loss of ultimate strength of the specimens was related to the reduction of accumulated AE hits. This trend of accumulated AE hits can be attributed to the stressing and cracking at tension reinforcement, which has already been dissipated by corrosion of steel reinforcement. On the other hand, the *Ib*-value increased during damage stage I, followed by a slight fluctuation of the *Ib*-value during damage stage II, and then decreased in *Ib*-value at the load level of a significant drop of RA value. It is possible to consider a declining trend in *Ib*-value to be a severe damage alert.

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