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Monitoring fracture of steel corroded reinforced concrete members under flexure by acoustic emission technique

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HIGHLIGHTS

- Fracture of the corroded beam specimens using AE technique has been conducted.
- Magnitude of RA value decrease with the increase of corrosion level.
- Index of damage was higher when the corrosion level increased at early stage of damage.
- Weibull damage function was introduced to estimate the remaining flexural capacity of the specimens.
- Tensile fracture became more dominant with an increase in corrosion level.

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ABSTRACT

Acoustic emission (AE) technique is used for monitoring and evaluating the influence of corrosion on the structural behaviour of steel reinforced concrete (RC) beams under three-point flexure test. In this study, steel corrosion was accelerated by electro-chemical method utilising a direct current (DC) power supply and 5% sodium chloride (NaCl) solution. The steel corrosion that was induced into beam specimens casting were estimated at 0%, 4.55% and 32.37%, respectively, according to mass loss of steel reinforcement. Based on observations during static load test, the damage developed in the specimens could be classified into four different stages, namely, micro-cracking, first visible cracks, cracks distribution, as well as damage localization and yielding. Analysis of the AE data reveals distinguishable trends for RA value and average frequency (AF) registered for different corrosion levels, respectively. Moreover, the index of damage (ID) derived from the AE energy parameters obtained during the first stage of damage was found to be useful as an indicator for evaluating the extent of corrosion damage of RC beam specimens at initial loadings. In addition, to provide a practical application of AE toward life span estimation of corroded beam specimen, a Weibull damage function was introduced to estimate the remaining flexural capacity of the beam specimens. Based on analysis as well, it is noted that tensile fracture became more dominant with an increase in corrosion level.

1. Introduction

Corrosion of steel reinforcements in reinforced concrete (RC) structures is a worldwide problem. The corrosion has been recognized as the major deterioration mechanism which affects RC degradation due to the environmental actions [1]. The costs of repair and maintenance of corroded structures worldwide exceed billions of dollars per year [2,3]. Therefore, the effects of steel corrosion in RC structures must be evaluated at early stage detection using effective assessment method before the functionality of RC structures is seriously damaged [4].

Non-destructive testing (NDT) methods provide objective-oriented assessment to different kinds of damages in RC structures, e.g. crack, honeycomb and corrosion. For newly built structures, the principal application of an NDT method is on the quality control, while for structures already in service, the method is expected to provide the needed feedback in monitoring, detection and identification of damage [5,6]. NDT methods are non-intrusive, highly

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repeatable and cost-effective in terms of the execution time and accessibility [7]. Recently, some NDT methods have been implemented for corrosion monitoring of RC structures. They can be classified into six main categories as follows: visual inspection, electrochemical methods (i.e. open circuit potential (OCP), resistivity method, polarization resistance, galvanostatic pulse method (GPM) and electrochemical noise (EN)), elastic wave methods (i.e. ultrasonic pulse velocity (UPV), acoustic emission (AE) and impact echo (IE)), electromagnetic (EM) methods (i.e. ground penetrating radar (GPR)), optical sensing methods (i.e. fibre Bragg grating (FBG)) and infrared thermography (IRT) method [8]. Each of the NDT methods has been used for monitoring, evaluating and assessing of the steel corrosion in RC structures with mixed levels of success. Despite mixed levels of successes by the afore-mentioned methods, there is an increase demand for a reliable technique to be applied in situ that helps evaluate the effect of steel reinforcement corrosion in RC structures from the structural engineering point of view.

The AE technique has also been used to detect steel corrosion in RC structures [9–11]. The elastic wave energies resulted from fracture of concrete matrix by steel corrosion activity can be successfully detected by AE sensors placed on the concrete surface. The use of AE technique also enables localization of corrosion damage in addition to detecting micro- and macro-cracking fractures [12–14]. To the authors' knowledge, the first recorded application of the AE technique for corrosion evaluation in RC structures was by Dunn et al. [15]. By comparing measured AE characteristics, namely counts and amplitude distributions, a relation between the observed damage and the AE was developed. The study illustrated the sensitivity of the AE to the ongoing deterioration process and explores its use as a corrosion damage monitoring technique. In some later studies, AE parameters such as accumulated hits, signal strength and energy were successfully used to identify and characterize the process of steel corrosion in RC structures [11,16–19]. The AE sources were also classified in terms of RA value and average frequency (AF) to distinguish the type of failure. Besides, the *b*-value and *Ib*-value of AE amplitude distribution were also proposed for assessing the damage severity [18,20–22]. However, limited studies have been attempted to evaluate the fracture behavior of corroded RC structures using the AE technique. Kawasaki et al. [10] have carried out the AE technique during a flexure test in RC beam specimens which were corroded by wet and dry cycles. The authors have applied the AE technique to evaluate the seismic capacity of corroded beam specimens. Results showed that the amount of tensile crack was greater than shear crack in the beam specimens with relatively low chloride contents, and vice versa.

In this study, the AE technique is utilized to evaluate the fracture behaviour of corroded beam specimens subjected to static loading. The beam specimens were corroded by the impressed current technique. This technique is able to simulate high level of steel corrosion in concrete within a short time period with easy control on the desired level [3,23]. In order to characterize the fracture of corroded beam specimens subjected to bending, the AE parameters, namely RA value and AF, index of damage (ID) and Weibull damage have been carried out. Furthermore, examination was also conducted on the trend of the monitored AE data for use in determining the corrosion level at early stage of the loading.

2. AE parameters for assessing steel corrosion in RC structures

The parameter-based analysis of AE signal is useful for better characterization of AE source [24–28]. Parametric analysis of the cumulative AE hits, rise time, average frequency (AF), signal strength, energy, *b*-value, *Ib*-value and intensity analysis (IA) are applicable in detecting and assessing the steel corrosion in RC structures. The early number of cumulative AE hits can detect the steel corrosion at early stage [11,20]. The sudden rise in cumulative signal strength (CSS) [29] and absolute energy (ABS) [30] might indicate crack initiation due to steel corrosion. On the other hand, the distribution of RA value and AF also proposed as a means of classifying the onset of steel corrosion and nucleation of cracks in RC structures [20]. In addition, previous researches have indicated that a *b*-value below 1.0 indicates the transition from micro- to macro-cracking [31,32]. The large fluctuations in *Ib*-value imply that these cracks are generally repeated due to expansion of corrosion products [20]. On the other hand, IA uses several criteria to identify the condition in the RC structures (i.e. no corrosion, early corrosion and cracking) [29].

2.1. RA value and average frequency (AF)

The characteristics of AE signals are estimated using two parameters, namely RA value and average frequency (AF) in line with the relevant recommendations [26]. The RA value and AF are defined from the AE parameters, i.e. rise time, peak amplitude, counts and duration [18,19], as given by Eqs. (1) and (2).

$$\text{RA value} = \frac{\text{Rise time}}{\text{Peak Amplitude}} \tag{1}$$

$$\text{AF} = \frac{\text{Counts}}{\text{Duration Time}} \tag{2}$$

A crack type is classified by the relationship between RA value and AF as shown in Fig. 1. A tensile-type crack is referred to as an AE signal with high AF and low RA value. A shear-type crack is identified by low AF and high RA value. This criterion is also used to classify AE data detected from the steel corrosion in the RC structures [11,20].

2.2. Index of damage (ID)

Benavent-Climent et al. [34,35] have proposed a damage evaluation method based on accumulated AE energy with plastic strain energy as index of damage (ID). The authors developed this index during a seismic loading of RC slab using a uniaxial shake table to predict the level of damage based on the AE energy recorded by the AE sensors. On the other hand, Abdelrahman et al. [36] derived another method to obtain ID, which is based on dividing the cumulative AE energy at any instant of the test (E^{AE}) by the cumulative energy registered at the end of loading, in which specimen under investigation experienced the maximum allowable damage ($\mathrm{E}_{\mathrm{D}}^{\mathrm{AE}}$). The ID can be expressed by Eq. (3):

$$ID = \frac{\mathrm{E}^{\mathrm{AE}}}{\mathrm{ED}^{\mathrm{AE}}} \tag{3}$$

2.3. Damage statistical model by mesoscopic element probability function

Reinforced concrete (RC) is a heterogeneous composite material that may be exposed to different types of deteriorations throughout the lifetime of usage, such as fracture, corrosion and surface degradation. The mechanical behaviour of deteriorated RC element with corrosion will become more complex because of stochastic distribution of damages. In addition, deterioration process in corroded RC element is localized and randomly distributed. Consequently, the strength of a corroded RC element can be regarded as a stochastic variable integrating different parameters, such as

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