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Estimation of the stress level on a cross section of a reinforced concrete beam via Acoustic emission Intensity Distribution (AID) analysis

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HIGHLIGHTS

- AE measurements are used to determine critical stress levels of concrete beams.
- The method exploits a correlation between stress and the relevant AE distributions.
- In tests, the method characterised the stress state with an error of about 5%.
- The idea of the method may work on structures made of concrete or similar materials.

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ABSTRACT

Measuring stress is critical in the Civil Engineering. However, established acoustic emission-based techniques can hardly evaluate the stress level which a structure is experiencing. Accordingly, an idea of 'listening' to Acoustic Emission (AE) to evaluate critical stress states in reinforced concrete (RC) beams is investigated here. Previous work found that the stress diagram of an RC beam cross section strongly correlates with the corresponding AE event intensity distribution pattern. Therefore, the stress level of this type of structures was estimated by utilising the remarkable correlation in this study. First of all, the stress diagrams of a cross section of an RC beam loaded to failure were analysed, revealing features which had close relations with the stress level of the section. Thanks to the correlation, these features were also extracted from the corresponding distribution patterns of the AE event intensity and then used to estimate the stress state. As a result, the AE Intensity Distribution (AID) analysis approach was developed. Data from an experiment conducted on six RC beams with a Digital Image Correlation (DIC) system and an AE device were adopted to verify the approach. Results showed that the indicators of the approach strongly correlated with the stress levels of the specimens; that the approach can characterise the stress states precisely, with an error of about five per cent in critical stages. Besides the approach, more profound significance of this work lies in that it demonstrated the great capability of an innovative strategy, namely characterising structural behaviours accurately via correlating an AE distribution pattern with the corresponding stress diagram.

1. Introduction

Concrete is one of the most extensively applied materials worldwide, especially in such as bridges, dams, and buildings exposed to deterioration or damage in service due to overloading, ageing and environmental impacts, etc. As a result, monitoring the states of concrete structures for better in-service performance & lower maintenance expenditures is a crucial mission of engineers in relevant communities. As a unique, passive Non-Destructive Testing (NDT) approach, Acoustic Emission (AE) technology is capable of accomplishing this kind of tasks [1,2]. Namely, this technology does not permanently alter the article being inspected and is highly valuable. Furthermore, compared with other NDT methods, the techniques have some distinctive advantages, e.g. great ability of detecting active cracks [3], facilitating wide applications in the Civil Engineering [4–6].

The analysis of AE data acquired is essential to different kinds of applications. Two categories of methods have attracted a lot of attention so far. The first category is a quantitative waveform analysis technique known as Moment Tensor Analysis (MTA) [7], and the other is parameter-based [8], e.g. the RA analysis [9], the

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Intensity Signal Analysis (ISA) [2,10] and the b-value methods [11]. These methods are outlined as follows.

The MTA approach is a post-test analysis method employed to identify crack kinematics via AE waveforms [12], and it is well known in seismology [7]. MTA determines the initial P-wave arrival time and amplitude of an AE event from which a second order tensor is computed. After obtaining the eigenvalues of the tensor, every eigenvalue is separated into three components: the shear component, the Compensated Linear Vector Dipole (CLVD) component and the mean component. The AE source can be classified into a tensile crack, a shear crack or a mixed mode according to the ratios of the three components [12]. Meanwhile, the orientation of the crack can be estimated based on the eigenvectors of the tensor [12]. MTA has been applied to concrete structures. For instance, MTA was used in a simulation of crack propagation caused by corrosion of reinforcing steel bars in concrete to distinguish cracking mechanisms [1]. Obviously, structural parameters play no role in MTA.

The analysis of RA and average frequency is one of the simplest methods used to define types of cracks via AE measurements [13]. RA and the average frequency are defined as follows [13]:

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

$$Average\ frequency = \frac{Counts}{Duration} \tag{2}$$

This technique has also been applied to concrete constructions. For example, Shahidan et al. [9] used this technique to determine the movements of cracks on a RC beam. As shown in Eqs. (1) and (2), it is very clear that no structural response or property is present in this evaluating model.

The Intensity Signal Analysis (ISA) is adopted to identify damage via AE data analysis. Two indices, the historical index (HI) and the severity index (S_r), play crucial roles in ISA [9]. They are calculated according to the following expressions [9,14]:

$$HI = \frac{N}{N-K}\left(\frac{\sum_{i=K+1}^{N} S_{oi}}{\sum_{i=1}^{N} S_{oi}}\right) \tag{3}$$

$$S_r = \frac{1}{J}\left(\sum_{k=1}^{j} S_{ok}\right) \tag{4}$$

where N is the number of hits; S_{ok} is the signal strength of the kth hit where the order of k is based on the magnitude of the signal strength. Both K and J are empirically derived constants relevant to the material under test, and for concrete, their values are related to N by relations specified in literature [10,14]. It is also clear that structural responses are not involved directly in the method.

The b-value methods [15] have been employed to analyse post-test AE signals for years. Conventionally, the AE-based b-value is calculated according to the Gutenberg–Richter relation (Eq. (5)) used in seismology widely [16].

$$log_{10}N = a - b\frac{A_{dB}}{20} \tag{5}$$

where A_{dB} is the peak amplitude of AE hits in decibels, N is the number of AE hits with amplitude greater than A_{dB}, a is an empirical constant, and b is the AE-based b-value. Many researchers have applied the methods to concrete structures [17]. For example, Sagar et al., employed the methods to analyse fracture processes in RC beams [16]. Obviously, no structural quantity is involved here yet.

Meanwhile, estimating stress via AE measurements has been extensively studied by fully using the Kaiser effect [18]. Fu et al. [19], studied the Kaiser effect in marble under tensile stress, and concluded that it is possible to measure the pre-existing tensile stress in the marble using the Kaiser effect-based method. Tuncay and Obara [20] compared stress values obtained with AE and Compact Conical-Ended Borehole Overcoring stress measurement techniques, respectively, applied to limestone samples, and the results showed that, in some cases, the Kaiser effect-based method may produce two or three times greater values. Moreover, the Kaiser effect-based method depends on many factors, some of which are considerably subtle. Lehtonen et al. [21], explored important factors involved in in-situ rock stress estimations using the Kaiser effect, and found that the Kaiser effect-based method heavily relied on key geological information and procedures. Hsieh et al. [22], investigated the effect in specimens being uniaxially compressed at much lower stress-to-strength levels; they found that free particles (e.g. dusts) staying on the ends of the samples provided a source of AE signals. This phenomenon is very easy to be wrongly regarded as occurrence of the Kaiser effect and then used to determine the stress levels of specimens. In another article, Hsieh et al. [23], concluded that researchers should firstly identify a stress range in which the Kaiser effect can be detected; otherwise, acoustic bursting caused by the damage accumulation may imitate the effect and mislead analysis. In brief, it is very clear that these methods can provide information on stress history that a sample experienced and relevant research deserves more work.

The above analyses on typical AE data processing techniques have shown that few correlations between AE and structure responses are concerned in most AE data processing methods. However, at least two reasons highlight the necessity of developing structural response-related AE signal processing approaches. Firstly, both acoustic emissions and common structural responses, such as strain, are different forms of outputs from structures being loaded. Secondly, more importantly, these responses are simultaneously developed during the same loading procedure; therefore, they are inherently related to each other. So, it is inevitable to deal with AE data according to intrinsic connections among these quantities. In fact, as demonstrated in this paper, combining two categories of measurements, i.e. acoustic emissions and stresses, is of great potential to establish new models of processing AE data with high efficiency and effectiveness.

Accordingly, this study was conducted. Its fundamental innovation lies in that AE event (parameter) intensity distributing patterns over the compressive zone of an RC beam cross section are used to estimate its real-time stress level. Technically, the approach introduced here is generally applicable to concrete structures of different types. Furthermore, the key idea of the study, correlating an AE signal pattern with a structural response diagram to investigate the behaviour of structures, deserves attention from other fields. The rest of the paper is structured as follows. In Section 2, the foundation of the proposed approach and some basic concepts involved subsequently are detailed. In Section 3, a new approach—the AID analysis is introduced to estimate stress levels of concrete structures. In Section 4, the specimen design, instrumentation and loading schemes of the experiment are summarized. In Section 5, data obtained from the experiment are analysed to verify the AID analysis approach. In Section 6, main conclusions are presented.

2. The fundamental idea and concepts

In this Section, the basic knowledge of the proposed approach is detailed. Firstly, the foundation of the approach is outlined, linking AE to one of the most important structural responses, namely stress. Secondly, a counterpart concept of stress, i.e. the AE parameter intensity, is defined, offering a primary quantity for the approach. Finally, the idea behind the approach is discussed, revealing the essence of the approach.