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AE MONITORING OF REINFORCED CONCRETE STRUCTURES

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Abstract: In this study, a novel damage evaluation method for concrete structures is introduced, which is based on the rising rate of acoustic emission. This method leverages the fact that when a concrete structure is subjected to stress, acoustic emissions increase, and the rate of this increase can be correlated with the extent of damage. To validate the effectiveness of this proposed method, a seismic damage test was conducted on a frame shear wall structure, which is a common and critical component in many building constructions. The results of the test clearly demonstrated that this method can accurately evaluate the damage status of the structure. More importantly, it has the capability to effectively locate areas where significant damage has occurred. This makes it a potentially valuable tool for post-disaster assessment and structural health monitoring, as it can help engineers and inspectors quickly identify and prioritize areas that require repair or further investigation. Overall, this study presents a promising approach to enhance the safety and reliability of concrete structures in the face of seismic events.
Keywords: Concrete; Acoustic emission; Accumulative time parameter; Seismic damage; Power spectral density

1 INTRODUCTION

Acoustic emission describes the occurrence in which materials emit elastic waves when undergoing fracture. The AE technique is capable of detecting the formation and development of microcracks within a structure. Structural damage is primarily attributed to fracturing processes[1]. Therefore, the AE technology is widely applied in the non-destructive testing and damage assessment of reinforced concrete structures. Currently, many scholars have proposed AE assessment methods specifically for reinforced concrete structures. Ohtsu[2], JI proposed the AE rate theory, which is used to evaluate the compressive strength of actual concrete structures[3]. Based on the Kaiser effect of concrete, the Japanese Society for Non-Destructive Testing (JSNDI) has proposed a NDIS-2421 standard[4], which is used to assess the damage condition of reinforced concrete structures[5]. In addition, there is another method derived from seismology called the b-value theory[6], which is used to predict the entire process from the formation of micro-cracks to the macroscopic expansion of cracks in concrete. Carpinteri extended the b-value theory and proposed a damage assessment method based on the cumulative rate of acoustic emission events[7], which assesses the damage of concrete structures according to the growth rate of acoustic emission events. Liu proposed a new b-value estimation procedure and applied it to the expansion and rupture test[8]. The results confirmed that the b-value depends on the material's in-homogeneity and stress.
Earthquake disasters are often one of the main factors causing damage to concrete structures. The aforementioned method has not yet been applied to the assessment of damage in concrete structures that have been damaged by earthquakes. This paper proposes a method for assessing the damage of concrete structures based on the cumulative growth rate of acoustic emission events, and validates it using an earthquake damage test of a concrete frame-shear structure.

2 THE PRINCIPLE OF CUMULATIVE TIME PARAMETER IN ACOUSTIC EMISSION

In concrete structures, the pulse wave released instantaneously upon the formation of a tiny crack is called an acoustic emission event. The commonly used acoustic emission characteristic parameters include the number of acoustic emission events, the acoustic emission rate, the cumulative acoustic emission energy, the number of acoustic emission oscillations, the duration, and the rise time.
Among the methods for assessing damage in concrete structures using acoustic emission event statistics, the b-value theory is the most representative. The *b*-value theory is proposed based on the following fact: for low-frequency acoustic emission events, their amplitudes are usually relatively high, while for high-frequency acoustic emission events, the amplitudes are generally low. Therefore, Richter calculated the slope of the amplitude distribution, that is, the *b*-value, to statistically analyze the amplitude distribution pattern of acoustic emission events. The *b*-value is shown as following

$$\log_{10} M = a - b(A_{dB}/20) \tag{1}$$

In which, M represents the cumulative number of AE events where the peak amplitude of the signal (measured in dB) is greater than A_{dB}, a is a constant, and the value of b indicates the slope of the distribution of AE events with different amplitudes.

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In the *b*-value theoretical analysis, both parameters *a* and *b* are time-dependent parameters. Therefore, the damage state of the structure is expressed as the rate of increase in the number of AE events at a certain level. Equation (1) is re-expressed in terms of the amplitude A_0 in volts, and a cumulative time parameter β_t for acoustic emission is introduced as follows[8].

$$N(\geq A_0, t) = 10^{a(t)} A_0^{-b(t)} = t^{\beta_t} \tag{2}$$

In the formula, $N(\geq A_0, t)$ represents the cumulative number of AE events with an amplitude greater than A_0. β_t reflects the rate of damage growth. As shown in Figure 1, $\beta_t = 1$ serves as a critical value for damage: when $\beta_t < 1$, the growth rate of *N* is slow; when $\beta_t > 1$, *N* increases sharply, the structural damage becomes severe, the bearing capacity is lost, and the structure is in a state close to collapse. According to reference[7], the value of *b* can be approximately calculated using the number of acoustic emission ringing events N^*, so the time parameter β_t of the amplitude distribution can be approximately calculated using the acoustic emission ringing number.

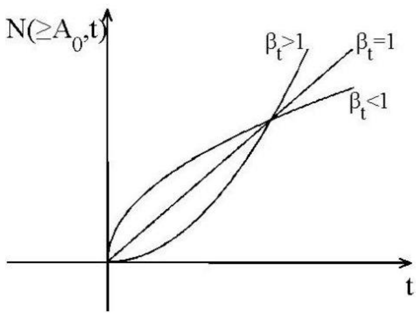

Figure 1 The Illustration of β_t with Three Conditions

3 ACOUSTIC EMISSION MONITORING EXPERIMENT OF CONCRETE STRUCTURES

This paper conducted an AE monitoring test on the seismic damage of a scaled-down reinforced concrete model to verify the feasibility of using the cumulative time parameter of acoustic emission for the assessment of seismic damage in concrete structures. The model was a 1/5-scale two-way double-span three-story reinforced concrete eccentric frame-shear wall structure, as shown in Figure 2. The tensile reinforcement in the model was made of 3mm galvanized iron wire, and 0.9mm galvanized iron wire was used as the stirrups. The reinforcing bars in the shear walls and slabs were double-layer galvanized iron wire mesh with a diameter of 2mm and a spacing of 20mm. The structure was poured with micro-particle concrete. The foundation base was cast with C30 concrete. The cross-sectional dimensions of the columns were 80mm×80mm, the cross-section of the beams was 50mm×100mm, and the thickness of the slabs was 30mm.

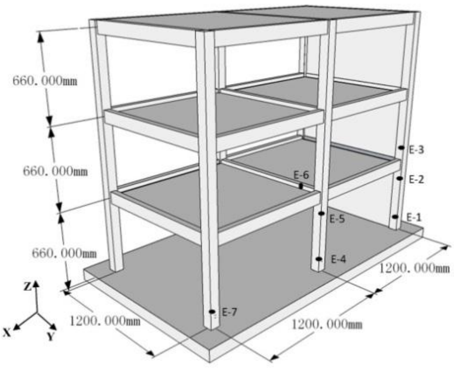

Figure 2 The Dimensions of Model and the Distribution of PZT Sensors

The sensor layout is shown in Figure 2, with numbers E-1 to E-7. The AE sensor signals were collected using the dSPACE system, with a sampling frequency of 10 kHz, and the acceleration in both the horizontal and vertical directions of each layer was simultaneously measured. Figure 3 is a photo of the test model.

Figure 3 The Experimental Photo

Simultaneous excitation in the horizontal direction (Y-axis) and the vertical direction (Z-axis) was carried out. The north-south component and the vertical component of the El-Centro wave in 1940 were used as the seismic input for this experiment. The input seismic wave conditions are shown in Table 1. A total of 13 sets of conditions were input, and each condition had a different amplitude of the seismic wave.

Table 1 The Earthquake Waves List

earthquake wave	EC-1	EC-2	EC-3	EC-4	EC-5	EC-6	EC-8	EC-9	EC-10	EC-11	EC-12	EC-13
peak value（g）	0.16	0.24	0.33	0.4	0.45	0.5	0.58	0.6	0.66	0.7	0.73	0.86

The data of acoustic emission and velocity sensors were simultaneously collected, and the cumulative ringing number of the acoustic emission signal was calculated. The specific method was as follows: set the threshold voltage to 5 mV. When the waveform of the acoustic emission signal passed the threshold voltage during the descending phase, the ringing number was recorded.

The loading time and the cumulative acoustic emission ringing number were normalized, and using equation (2) as the fitting target, the acoustic emission amplitude cumulative time parameter β_t was calculated using the least squares method. Figure 4 shows the normalized t-N* curve during the loading process of EC-11 and the β_t calculated by the least squares method. Among them, R-square is the determination coefficient of the fitting equation.

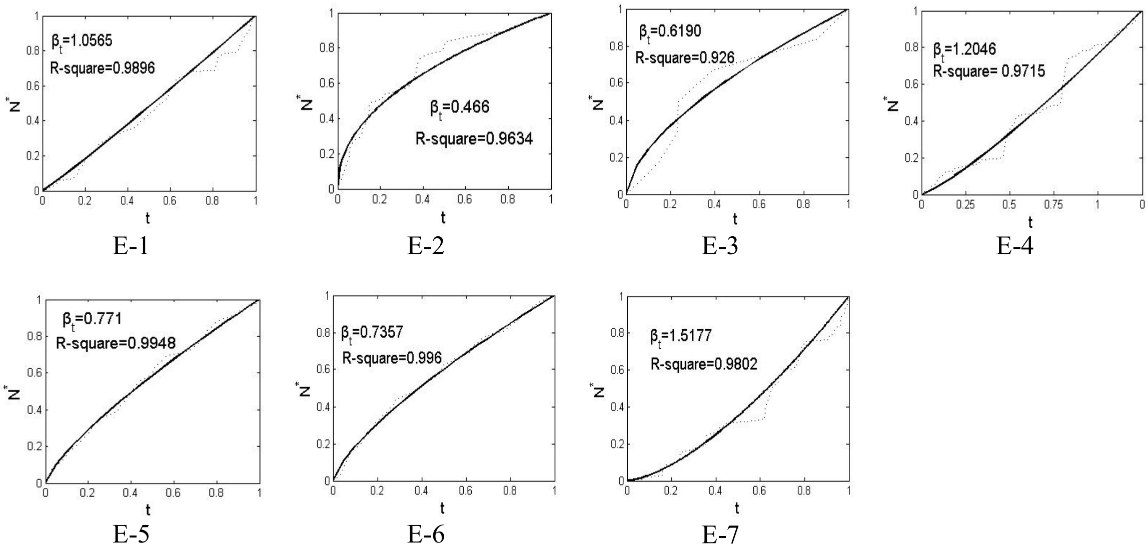

Figure 4 The *t-N** Curve and β_t during EC-11 Loading

It can be seen that the β_t calculated from the acoustic emission signals of E-7, E-4, and E-1 is greater than 1, indicating that during this loading process, the acoustic emission phenomena in the area near these three sensors have increased sharply, and the damage is relatively severe. Figure 5 shows the cumulative ringing numbers of the acoustic emission signals from E-1 to E-7 after all seismic wave loading is completed. Comparing the sensor signals at the bottom of the structure, the cumulative ringing number of E-7 is the highest, followed by E-4, and E-1 has a relatively smaller number of ringings. This is consistent with the results in Figure 4. It indicates that the bottom of the side columns has the most severe damage, followed by the middle columns. In contrast, the bottom of the column connected to the shear wall has less damage. This is because the stiffness distribution along the X direction of the structure is uneven. The stiffness on the shear wall side is larger while that on the side of the side columns is smaller, resulting in the deformation of the side columns being greater than that of the shear wall. Therefore, the damage along the X direction becomes increasingly severe. Figure 6 shows the damage photos near E-1, E-4, and E-7. From the figure, it can also be seen that there are unpenetrating cracks near E-1, penetrating cracks at the bottom of E-4, and more than two penetrating cracks at E-7. The results judged from the photos are consistent with the analysis.

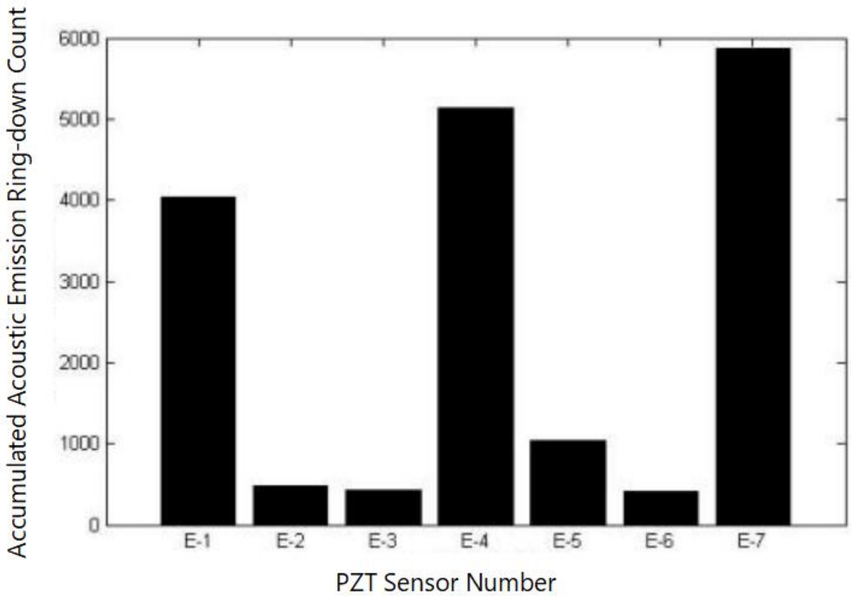

Figure 5 The Total Acoustic Emission Count from E-1to E-7

Near E-1 Near E-4 Near E-7

Figure 6 The Damage Photo Near E-1, E-4 and E-7

4 CONCLUSION

This paper presents a damage assessment method for concrete structures under seismic loads based on the cumulative time parameter of acoustic emission, and the feasibility of the method is verified through an earthquake damage experiment of a concrete frame-shear structure. The results show that this method can effectively evaluate the damage degree of concrete structures, and by using an acoustic emission sensor array, it can effectively detect the damaged areas with larger damage.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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