Analysis of Low-Temperature Damage of Reinforced Concrete Beams Using Acoustic Emission Parameters

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Abstract. Reinforced concrete (RC) beams will be affected by various external environmental in the service process, of which low-temperature is a representative factor. This paper presents a study on using the low-temperature damage test on damage and fracture of RC beams, and an acoustic emission (AE) system is used to monitor the whole process of testing. In the low-temperature damage test, AE hits are used to characterize the damage of each cooling step, and the low-temperature damage of the beam is divided into three processes: initial damage, extended damage and attenuated damage. A damage parameter ($D_{TEM}$) based on the accumulated energy of AE is used to analyze the whole process of low-temperature damage of the beam, and the percentage of low-temperature damage in each cooling step is obtained. The environment chamber is used to simulate the extreme low-temperature environment, and the damage of RC beam after the sudden temperature drop (process I) and the end of cooling (process II) is obtained. These two processes have important reference value for the damage degree analysis and damage warning of RC beams in the actual extreme low-temperature environment.

Keywords. Acoustic emission, reinforced concrete beam, damage process, low-temperature damage parameter.

1. Introduction
Reinforced concrete (RC) materials are good in tensile strength, compressive strength, durability, and economy, and are widely used in various civil structures, such as highway bridges, buildings, and underground facilities [1-3]. In these structures, RC beams play an important role in structure safety and stability. RC beams are vulnerable to damage and fracture due to their material properties and external factors such as load, vibration, temperature, and corrosion. Therefore, it is necessary to test RC beams under different service conditions. Acoustic emission (AE) method is an important and effective nondestructive testing method [4]. The AE method is to use professional AE instruments to collect and analyze the whole process of AE signals of material components under various loading and external environmental conditions, so as to realize the service performance evaluation and failure trend prediction of the components [5].
RC beams will be damaged and fractured under loading. At present, the damage of RC beams based on AE technology are mainly studied from two aspects: damage degree analysis and damage
classification. Nor et al [6] comprehensive analysis of AE parameters and load values, and six damage modes of RC beams under bending were observed. Aldahdooh et al [7] analyzed the damage degree of variable thickness RC beams based on AE parameters.

The accumulation and development of damage will cause cracks and eventually fracture of beams, which will seriously affect the safety of structures and buildings. AE technology is a very effective detection method, which is used to study the generation, development and classification of cracks in RC beams. Goszczynska et al [8] used the AE method to analyze the generation and development of cracks in RC beams, and established a damage criterion considering structural durability. In the process of fracture, RC beams will produce a large number of different types of cracks. Through the classification of cracks, the cracking process and failure form of beams can be better understood. Different AE parameters can be used to classify the cracks of RC beams. The tensile crack, shear crack and flexible crack of beams were obtained by the average frequency of AE [9, 10]. Sagar et al [11] studied the influence of loading rate on crack development and AE parameters [12], and proposed a method to determine the yield point and crack type of RC beams based on AE parameters [13].

The corrosion of reinforcement will seriously affect its normal use function and safe service life, and the corrosion of prestressed reinforced concrete directly affects its prestressed strength and working capacity. The accelerated corrosion method is helpful to obtain the corrosion damage of RC beams more quickly, which is suitable for laboratory test. Di et al [14, 15] proposed a monitoring method of RC beams combining accelerated corrosion and AE monitoring, and based on this method, the corrosion damage of beams was analyzed. Abouhussien et al [16, 17] drew a damage classification diagram based on AE parameters to quantify the damage and deterioration degree of RC beams caused by corrosion of reinforcement.

The above research mainly focuses on the analysis of damage and fracture characteristics of RC beams under corrosion and CFRP reinforcement, and the fracture mechanism and damage degree of RC beams were evaluated by AE technology. However, environment is an important factor affecting the service performance of RC beams, especially under extreme weather conditions (such as abrupt temperature drop, cold wave, snowstorm, etc.), RC beams will be damaged and destroyed at low-temperature, which will seriously affect the safety and service life of the structure. Therefore, it is of great significance to analyze the low-temperature damage of RC beams. In this study, through temperature control, AE equipment is used to monitor the whole damage process of RC beams under different low-temperatures. Through the analysis and calculation of AE parameters, the low-temperature damage parameter \( D_{TEM} \) is obtained. The whole process of low-temperature damage analysis of RC beams is realized.

2. Test Method

2.1. Specimen Parameters
According to ASTMC293/C293M-16 standards [18] and considering the environmental chamber size (length × width × height: 1300 mm × 600 mm × 750 mm), the beam section size of RC beam designed in this test is: \( b \times h = 100 \text{ mm} \times 120 \text{ mm} \), length: \( L = 1200 \text{ mm} \), and the design grade of concrete is C40. The type of tensile reinforcement and erection reinforcement is HRB400. The type of stirrup is HPB235. Figure 1 shows the section size and reinforcement of the beam.

![Figure 1. Section size and reinforcement of the RC beam.](image)
2.2. AE System Parameters
A PCI-2 AE acquisition system produced by American Physical Acoustics Company (PAC) is used in this experiment. The fixed threshold of the system is 45 dB and the sampling rate is 1Msps. The correct setting of peak definition time (PDT) will ensure that the system can accurately identify the rise time and amplitude of signal peak. The correct setting of the hit definition time (HDT) will ensure that an AE signal in the specimen is unique to the system. The correct setting of hit lockout time (HLT) can avoid the false signal when the signal attenuates, and can improve the data acquisition speed. According to the recommended values for composite materials in AE-win software manual, PDT, HDT and HLT are set as 50 μs, 200 μs and 300 μs respectively [19]. The type of AE sensor is R15a; its working temperature is -65 °C to 170 °C; its working frequency range is 50-400 kHz; and its center frequency is 150 kHz. The gain of the pre-amplifier is 40 dB. A high vacuum grease is selected as coupling agent for good contact between sensor and specimen surface (figure 2).

![Figure 2. AE acquisition system and coupling agent.](image)

2.3. Test Process
In this research, low-temperature damage test is carried out for RC beams. In the low-temperature damage test, the AE monitoring of the whole cooling process of RC beams is carried out by using the environment chamber and the AE acquisition system.

The RC beam is put into the environment chamber, and AE sensors are symmetrically arranged on the beam surface with coupling agent. The noise reduction lines of AE sensors are connected with a pre-amplifier and the AE acquisition system through the reserved hole of environment chamber. Liquid nitrogen is used as refrigerant to connect to the environmental chamber. The initial temperature of the environmental chamber is set at 20 °C for AE monitoring of the following three cooling steps (table 1). The test time of each cooling step is 30 minutes. AE signal acquisition and cooling start and end simultaneously. Figure 3 shows the process of low-temperature damage test.

| Cooling step | Cooling temperature (°C) | Cooling rate (°C/min) | Test time (min) |
|--------------|--------------------------|-----------------------|-----------------|
| Step 1       | 20°C to 0°C              |                       | 30min (The cooling process is 2 min and the holding process is 28 min) |
| Step 2       | 0°C to -20°C             | 10                    |                 |
| Step 3       | -20°C to -40°C           |                       |                 |

![Table 1. Cooling temperature and test time of each step.](table1)
Figure 3. Low-temperature damage test.

3. Low-Temperature Damage Analysis
AE hit refers to number of cycles of AE signals that exceed the threshold value and a certain channel is used to collect the AE signal. AE hit reflects the total amount and frequency of AE, which is often used to evaluate the activity of AE. Figure 4 shows the relationship between AE hit and time obtained from low-temperature damage test of each cooling step. It can be seen from figure 4 that AE hit tends to zero in step 1, indicating that there is no damage to the RC beam in this step. In step 2, AE hit appears obviously, which indicates that the RC beam has low-temperature damage. In this case, 0℃ is taken as the initial temperature of low-temperature damage of RC beams. The AE hit of step 3 is larger than that of step 2, which indicates that the damage of RC beam in step 3 is more serious at lower temperature. Since the cooling rate of the test environment chamber is 10 ℃/min, the time for each cooling step is 120 s. However, it can be seen from figure 4 that after the cooling is completed (120 s), there is still a large AE hit, which lasts until about 600 s.

Figure 4. The relationship between AE hit and time in each cooling step.

It can be seen from figure 4 that AE hit tends to zero after 600s, so AE hit of 0-600 s is selected to characterize the low-temperature damage of RC beam. Figure 5 shows the AE hit distribution of each cooling step in the 0-600 s period. By analyzing the AE hit distribution of each cooling step, the low-temperature damage of RC beam can be divide into three processes: initial damage, extended damage and attenuated damage. Initial damage (process I) is the low-temperature damage of RC beam during cooling, and the duration is 0-120 s. During this process, AE hit increases with time, and the AE hit reaches the peak at different cooling steps, which indicates that the low-temperature damage of RC beam gradually increases and reaches the maximum damage degree. Extended damage (process II)
and attenuated damage (process III) are low-temperature damage of RC beams after cooling, with the duration of 120-235 s and 235-600 s, respectively. During process II, AE hit still shows a high value, but the AE hit of each cooling step gradually decreases with time, indicating that although the cooling has ended, the low-temperature damage of RC beam still continues. Although AE hit still occurs in process III, it is generally small compared with these in processes I and II, which indicates that the low-temperature damage of RC beam in process III is decaying.

Figure 5. AE hit distribution of each cooling step.

The cooling rate of the test environment chamber is 10°C/min, which can effectively simulate the extreme low-temperature environment (such as abrupt temperature drop, cold wave, snowstorm, etc.). A large number of AE hits occurred in process I and reached the peak value, indicating that extreme low-temperature will cause serious damage to RC beams and affect the service and safety of the structure. Although the cooling in process III has ended, there is still a large AE hit in the process, which indicates that RC beams will still suffer from low-temperature damage. Therefore, process I and II have important reference value for the damage degree analysis and damage warning of RC beams in the actual extreme low-temperature environment.

As an important index of AE parameters, AE energy is often used to measure the activity and intensity of AE. AE energy is the area of time-domain waveform envelope diagram of signal crossing threshold (figure 6), which can be calculated by the following equation [20, 21]:

\[
E_i = \int_0^{t_{AE}} V_i^2(t) dt
\]

where \(E_i\) is the AE energy collected by sensor \(i\); \(V_i\) is the instantaneous voltage value collected by sensor \(i\); \(t_{AE}\) is the duration of AE events collected by sensor \(i\).

Figure 6. Time-domain waveform of AE energy.
The relationship between AE accumulated energy and time in each cooling step is shown in figure 7. It can be seen from the figure that AE energy is not released during the cooling step 1, which indicates that the RC beam has no low-temperature damage in this step. A large amount of AE energy is released in step 2 and step 3 during and after the cooling, which indicates that the RC beam has low-temperature damage in these two cooling steps. This is consistent with the analysis results based on AE hit.

![Figure 7. The relationship between AE accumulated energy and time in each cooling step.](image)

The AE energy is used as an index to measure the damage parameter, and the following equation is used to calculate the damage parameter [22]:

$$D_{TEM} = \frac{\Omega_E}{\Omega_{TE}}$$  \hspace{1cm} (2)

where $D_{TEM}$ is the damage parameter; $\Omega_E$ is AE cumulative energy of each cooling step; $\Omega_{TE}$ is the AE accumulated energy in the whole cooling process.

According to the AE hit analysis, the effective low-temperature damage time of RC beams is 0-600 s. Therefore, AE cumulative energy during 0-600 s in each cooling step is selected for the calculation of the damage parameter, and three cooling steps are put on the same time axis to analyze the low-temperature damage of the whole cooling process (figure 8).

![Figure 8. Change curve of damage parameter with time in the whole cooling process.](image)
Figure 8 shows the relationship between the damage parameter and time during the whole cooling process. It can be seen from the figure that the \( D_{TEM} \) of cooling step 1 approaches to zero, which proves that the RC beam has no damage in this step. The \( D_{TEM} \) peak value of step 2 is 0.37, which proves that the RC beam is damaged by low-temperature. The peak value of \( D_{TEM} \) in step 3 is 0.63, which proves that the low-temperature damage of RC beam in this step is more serious.

4. Conclusion
Low-temperature damage test is carried out for RC beams, and AE system is used to monitor the whole process of beams. Through the analysis of AE parameters, the following conclusions are obtained:

(1) The lower the temperature, the more serious the damage of RC beam. 0 °C is the initial temperature of low-temperature damage of RC beam.

(2) Low-temperature damage of RC beam is divided into three processes: initial damage (process I), extended damage (process II) and attenuated damage (process III). Process I is the low-temperature damage of RC beam during cooling, Process II and III are the low-temperature damage of RC beams after cooling.

(3) The damage parameter (\( D_{TEM} \)) of RC beam with different cooling steps is different. The RC beam in cooling step 1 has no low-temperature damage. In the cooling step 2 and 3, the low-temperature damage of the beam accounted for 36% and 73% of the total low-temperature damage, respectively.

The low-temperature damage and fracture of civil engineering materials caused by extreme low-temperature conditions (such as abrupt temperature drop, cold wave, snowstorm, etc.) should be concerned. In this experiment, the environment chamber is used to simulate the extreme low temperature environment, and the damage of RC beam after the sudden temperature drop (process I) and the end of cooling (process II) is obtained. These two processes have important reference value for the damage degree analysis and damage warning of RC beams in the actual extreme low temperature environment.

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