Review of Research on Damage Identification of Reinforced Concrete Structures Based on Acoustic Emission Technology

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Abstract. This paper summarizes the application of acoustic emission technology in the identification of concrete damage. It reviews the application of acoustic emission technology in the identification of the damage of concrete structure, including the characterization of acoustic emission of concrete structure damage and the application of acoustic emission technology in research of concrete fatigue performance in concrete. Besides, the review of the application of acoustic emission technology on steel corrosion researches is presented, as well as the application of acoustic emission technology in the identification of concrete damage under high temperature and freeze-thaw cycles. The aim of this paper is to provide a systematic reference for relevant researchers.

1. Introduction

When a material or a structure is subjected to stress, there will be localized stress concentration and unstable stress distribution due to the unevenness of its microstructure and the presence of defects. When the strain energy in this unstable state accumulates to a certain degree, the unstable high-energy state must transition to a stable low-energy state. This transition is usually completed in the form of plastic deformation, phase transition cracks, etc. In this process, part of the strain energy is released in the form of stress waves. This phenomenon of releasing strain energy in the form of elastic stress waves is called acoustic emission, also called stress wave emission [1].

When the local deformation of the solid material occurs, volumetric deformation and shear deformation will occur, and the longitudinal wave and transverse wave will be excited. The place where such waves are generated is called an acoustic emission source. This longitudinal wave and transverse wave are generated from the acoustic emission source and propagate to the surroundings in different ways through the material medium. There are three main sources of detection signals: the waves pass the medium directly to the sensor, the waves refracted to the sensor and the surface waves received by the sensor. By detecting, recording, and analyzing these signals, damage assessment and research on materials can be achieved [2]. Figure 1 illustrates the scheme for AE detecting.

The acoustic emission non-destructive testing method has many advantages: 1. It can directly receive the signal from the component, reflecting the change of material or internal defect information; 2. Acoustic emission technology is a dynamic detection method that can detect the crack propagation process; 3. It can reflect the real-time information of defects affected by various factors such as load, time, temperature, etc.; 4. It is convenient to use and not limited by materials or components; 5. The sensitivity of acoustic emission monitoring is high. Based on the above advantages, acoustic emission technology has great advantages on the non-destructive testing of concrete and is widely used on concrete damage detection.

This paper reviews the application of acoustic emission technology in the identification of concrete damage.
structure damage, including the characterization of acoustic emission of concrete structure damage, the application of acoustic emission technology in concrete fatigue performance researches, steel corrosion, and in concrete damage identification under high temperature and freeze-thaw cycles.

2. Application of acoustic emission technology in performance evaluation of concrete structures

2.1. Characterization of acoustic emission of the damage to concrete structures
The application of acoustic emission technology in the field of concrete structures dates back to 1959 when Rusch [3] studied the acoustic emission signals after the concrete was loaded. It is confirmed that in concrete materials, the Kaiser effect does indeed exist in concrete members.

In 1965, Robinson [4] gave the feasibility of acoustic emission detection technology in the field of concrete structures by comparing the acoustic emission signal parameters of concrete and sand body test blocks with different aggregate amounts and different aggregate particle sizes and pointed out the acoustic emission detection has the advantages of real-time, accuracy and no interference.

Mathematical models for evaluating concrete structures based on acoustic emission signals were proposed based on the related test results. In 1997, Dai [5] proposed a mathematical model related to acoustic emission parameters and stress to evaluate material strength and degree of damage based on the relationship between the ringing count and the stress intensity factor of the concrete specimen.

In 2003, Ohtsu [6] used the acoustic emission rate to describe the damage state of concrete, and established the relationship between the acoustic emission behavior and the microstructure change of the concrete material. Also based on the monitoring, established the Empirical relationship between acoustic emission characteristic parameters and concrete stress.

In 2019, Wang Bing [7] based on the multi-angle analysis of acoustic emission, the damage evolution characteristics of concrete beams under three-point bending were analyzed. Through multi-parameter analysis such as acoustic emission event count, ringing count, energy rate and amplitude-frequency extreme value, the damage accumulation process under the three-point bending action of concrete beams was qualitatively studied. Quantitative analysis in the damage amount determination based on the acoustic emission amplitude-frequency extreme value was proposed. Combined with the location of acoustic emission events and the amount of damage, the process of damage accumulation during the loading of concrete beams was quantitatively characterized. The results show that the damage mainly occurs in the plastic stage, gathers in the tension zone, and quickly develops into the compression zone to form a damage zone, which leads to brittle fracture of the specimen. The study provides a basic reference for early warning of the catastrophe damage of concrete beam and engineering design.

2.2. Application of different acoustic emission technical parameters
In 2003, Colombo [8] analyzed the bending failure signals of concrete simply-supported beams based on the b-value analysis method. It is found that the b-value has a strong correlation with the failure process of the concrete beam, micro-cracks initiation or expansion when b-value increases and macro-cracks occur as the b-value decreases. Therefore, the b value of the acoustic emission characteristic
parameter can be used as a new damage variable to indirectly describe the damage behavior of concrete materials. In 2008 and 2009, Grosse [9] used acoustic emission technology to monitor concrete structures. According to the Kessel effect, the researchers introduced "Felicity Ratio" to quantitatively explain the destruction of concrete structures, and believed that when "Felicity Ratio" $\geq 1$, the structure is in a stable state, and when damaged or unstable, "Felicity Ratio" $<1$. The proposed "Felicity Ratio", can be used in damage assessment of concrete structures which provides a theoretical basis for better structural detection in practice.

2.3. Application of acoustic emission technology in the study of fatigue performance of concrete structures

In 2012, Aldahdooh and Bunnori [10] analyzed the AE characteristics of the damage mechanism of reinforced concrete beam with different thicknesses under four-point bending. Studies have shown that as the damage grade of the beam slightly increase, all-acoustic emission characteristic parameters except for the average frequency also increase. Also, AE parameters (including the average frequency) increase with the thickness of the beam, so AE technology can effectively monitor the damage of reinforcement concrete beams of different thicknesses.

In 2013, Noorsuhada and Ibrahim [11], analyzed the relation between the crack mode and the AE signal at a certain concrete structure during the damage process of reinforced concrete beams using acoustic emission technology. Three-point load fatigue tests were conducted according to different fatigue modes, the crack modes loaded at each stage were tensile cracks and shear cracks. The average frequency and RA value of the acoustic emission signal of the corresponding channel were calculated separately, and then the fatigue cracks were classified. The research shows that the crack classification method based on the average frequency of the acoustic emission signal and the RA value can be used in crack monitoring.

In 2016, Yu [12] used the SAEU2S centralized multi-channel USB acoustic emission detector to collect the acoustic emission signals for the damage process of the beam specimen. The related AE characteristic parameter analysis method and improved acoustic emission signal evaluation criteria, combined with pattern recognition technology were used to analyze the damage signal characteristics of beams under different load levels. This research developed a set of methods for structural damage monitoring, safety evaluation, and intelligent identification of damage signals, which provided a theoretical basis for acoustic emission technology in practical use.

3. Research on the reinforcement corrosion using acoustic emission technology

In 1998, Li. et al. [13] pointed out the difference between the behavior of micro-cracks and major crack caused by rebar corrosion, and found that acoustic emission technology can be applied to the detection of micro-cracks.

In 2004, Uddin et al. [14] used acoustic emission-simplified Green's functions to analyze the mechanisms of crack caused by rebar corrosion. The research found that mode-I crack, rather than mixed-mode or mode-II cracks, is the dominant mode due to reinforcement corrosion.

In 2007, Jomdecha [15] studied several types of reinforcement corrosion in concrete, including corrosion caused by irregularities of the rebar surface, pitting corrosion, crack corrosion, and pressure corrosion of the rebar. The research founded that four different types of steel corrosion can be identified using different acoustic emission parameters such as acoustic emission amplitude, energy, and impact. For irregular corrosion of the rebar, the magnitude of the acoustic emission signal is small at the beginning because of the development of passivation film with protective effect, and the magnitude of the signal will increase after the passivation film being destroyed. The acoustic emission behavior from pitting corrosion and fissure corrosion of rebar are the same, and the signals are strong. The magnitude of the acoustic emission signal of the pressure corrosion of rebar is relatively high.

In 2014, Yu [16] conducted online monitoring of the corrosion process for reinforced concrete specimens by acoustic emission technology and studied the relationship between the acoustic emission signal and the corrosion behavior. The comparison shows that the acoustic emission localization result map can reflect the location and distribution of the specimen corrosion, and the number of acoustic emission localization events are in good agreement with the corrosion degree of the specimen under the accelerated corrosion tests. The research suggested that it is feasible to use acoustic emission technology to monitor the entire corrosion
In 2016, Wang et al. [17] conducted a series of acoustic emission tests on the loading and failure process of reinforced concrete beams with different corrosion rates. The comparison between the acoustic emission positioning results and the crack locations of beam specimens are in good agreement for specimens with different corrosion rates, and the increase of the acoustic emission number can be used to indicate the stress stage of the specimens. Therefore, it is feasible to use acoustic emission technology to characterize the defect source. Parameter study showed that the center of the AE signal frequency band of the reinforced concrete beam shifts from low frequency to high frequency as the stress level increases. The number of acoustic emission parts during the failure of reinforced concrete beam reduced when the corrosion rate of the reinforced steel increases, and the total energy released during the failure was reduced.

Ni [18] analyzed the change curve of the acoustic cumulative impact number to predict the development of rebar corrosion. The noise-reduced acoustic emission signals at different development stages of corrosion were analyzed by waveform analysis for reinforced concrete specimens with different strengths, different water-cement ratios, and different protective layer thicknesses. This research suggests that acoustic emission technology can monitor the steel corrosion process under different conditions.

In 2019, Xu [19] used acoustic emission technology to monitor the rebar corrosion process accelerated by the dry-wet cycle for cement-based materials. The results showed that curing process of mortar was accompanied by a large number of acoustic emission signals, and their peak frequencies are mainly distributed in the range of 20-60 kHz and 130-200 kHz; the water absorption swelling and dehydration processes of cement-based material are accompanied by acoustic emission signal, with the peak frequency being about 50 kHz; the peak frequency of the acoustic emission signal for the passivation film is between 100 and 150 kHz, and the peak frequency of the signal for the pitting of the reinforcement is between 20 and 70 kHz.

4. Research on concrete performance under temperature effects based on acoustic emission technology

4.1. The performance of concrete under high temperatures
The damage of concrete structure after high temperature was evaluated mainly based on the appearance, the loss of mass, the deterioration of macroscopic mechanical properties, and the change of fine microstructure [20]. With the development of acoustic emission technology, researches were conducted on the evaluation of concrete damage after high temperature by acoustic emission technology.

In 2009, Huismann [21] studied the acoustic emission signals of concrete during high temperature and after high temperature, and proved that the AE signal can reflect the destruction of concrete under such conditions with good accuracy. The results suggested that AE technology is a useful diagnostic tool in the monitoring of material behavior under high temperatures.

In 2013, Heap et al. [22] analyzed the acoustic emission signals of concrete under high temperature of over 1000 °C and confirmed the existence of Kaiser's "temperature-memory". The fast-acquisition AE monitoring system was also used to study the crack nucleation and growth of microstructure of high-strength concrete after high temperature.

In 2020, Chen [23] conducted uniaxial compression tests and amplitude-amplified cyclic loading and unloading tests on concrete cube blocks at ten temperature levels ranging from 25°C to 900 °C. The acoustic emission of the specimens was monitored during the tests. The test results showed that the test block's appearances, compressive failure morphology, mechanical properties, Kaiser effect and acoustic emission rate process parameters during loading are effective parameters to reflect the damage characterize of concrete under high temperatures.

4.2. The influence of freeze-thaw cycles on concrete
In 2018, Ma [24] used a dynamic and static universal triaxial apparatus to perform the uniaxial cyclic loading and unloading test of the concrete after freeze-thaw cycle. During the test, the acoustic emission device was used to collect acoustic emission data. The relationship between the acoustic emission energy parameters and stress-strain behavior was analyzed, and the characterization of the concrete damage based on acoustic emission results was carried out. The results showed that most of the energy was...
released at the loading stage, while the amount of energy in the unloading stage is very limited. The damage variable of concrete shows a trend of slowly increasing at the beginning, then rapidly increasing, and slowly increasing at the last stage with the increase of cumulative plastic strain.

In 2019, Peng [25] conducted a series of uniaxial and double-axis tests on concrete specimens using a 10 MN large-scale multi-function hydraulic servo static and dynamic universal triaxial apparatus. The real-time acoustic emission data were collected by a new type of dynamic non-destructive testing acoustic emission technology to establish the models between the acoustic emission parameters and the stress of the specimen under different freeze-thaw cycles, and under different loading rates. The process of internal damage of concrete under different loading cases was also analyzed. It was found that there are no acoustic emission energy signals generated at early stage while the energy released rapidly when the stress reaches the peak under dynamic loading. The maximum energy hysteresis effect of the acoustic emission increases under the biaxial state and there is acoustic emission energy generated during the unloading phase.

Ref. [24] and [25] presented similar experiments on the same research problem, while the results for both experiments were almost the opposite. Therefore, more experimental researches are needed in this problem.

5. Conclusions
Acoustic emission technology is an important method for damage assessment of concrete structures. With the development of acoustic emission technology, it has been used in more researches on damage assessment of concrete structures. In this process, more acoustic emission parameters are used for concrete damage evaluation and the accuracy of this method is increasing. The relationship between concrete structure damage and acoustic emission characteristics are studied in-depth. Acoustic emission technology has also been applied to more related studies for concrete structures.

However, there are still issues to be solved. For example, further studies are needed to analyze the acoustic emission characteristics for concrete under the fatigue failure to obtain more clear conclusions. More researches are also needed for the acoustic emission characterization of concrete in the freeze-thaw cycles.

References
[1] Ji H.G. (2004) Material Acoustic Emission Capability and Application. Coal Industry Press, Beijing.
[2] Zhang L.W. (2012) Research on Concrete Damage Detection by using Acoustic Emission Technology, Dalian Maritime University, Dalian (Degree thesis).
[3] H Rusch. (1959) Physical problems in the testing of concrete. Zement-Kalk-Gips, 12(1):1-9.
[4] G S Robinson. (1968) Methods of detecting the formation and propagation of microcracks in concrete. Concrete.
[5] Dai S T, Labuz J F. (1997) Damage and Failure Analysis of Brittle Materials by Acoustic Emission. Journal of Materials in Civil Engineering, 9(4):200-205.
[6] M Ohtsu. (2003) Detection and Identification of Concrete Cracking in Reinforced Concrete by Acoustic Emission. Review of Quantitative Nondestructive Evaluation, 22, 1455-1462.
[7] Wang B., Liu Z. L., Zhuo X. H., et al., (2019) Damage Evolution Characterization of Concrete Beams under Three-Point Bending Based on Acoustic Emission. Bulletin of the Chinese Ceramic Society, 38(11):3663-3669.
[8] S. Colombo, I. G. Main, M. C. Forde. (2003) Assessing damage of reinforced concrete beam using "b-value" analysis of acoustic emission signals. Journal of Materials in Civil Engineering, 15(3):280-286.
[9] Grosse, C.U.; Ohtsu, M. (2008) Acoustic Emission Testing, Basics for Research-Applications in Civil Engineering, Springer – Verlag Berlin Heidelberg.
[10] Aldahdooh M. A. A., Bunnori N. M., Johari M. A. M., (2013) Damage evaluation of reinforced concrete beams with varying thickness using the acoustic emission technique. Construction & Building Materials, 44(44):812-821.
[11] Nor N M, Ibrahim A, Bunnori N M. et al. (2013) Acoustic emission signal for fatigue crack classification on reinforced concrete beam. Construction & Building Material, 49(6): 583-590
[12] Dong Y.K., (2016) Based on the acoustic emission and the BP neural network analysis of the reinforced concrete beam damage evolution. Jiangsu University, Jiangsu.
[13] Li Z, Li F, Zdunek A, et al. (1998) Application of acoustic emission technique to detection of reinforcing steel corrosion in concrete. Aci Materials Journal, 95 (1):68-76.
[14] Uddin A K MF, Numata K, Shimasaki J, et al. (2004) Mechanisms of crack propagation due to corrosion of reinforcement in concrete by AE-SiGMA and BEM. Construction & Building Materials, 18(3): 181-188.
[15] Jomdecha C, Prateepasen A, Kaewtrakulpong P. (2007) Study on source location using an acoustic emission system for various corrosion types[J]. Ndt & E International, 40(8):584-593.
[16] Yu A.P., Zhao Y.L., Wang L., (2014) Acoustic Emission (AE) online monitoring test on corrosion in reinforced concrete. Journal of Building materials, 17(2):291-297.
[17] Wang L., Zhong L. H., Xia H. L., et al. (2016)Acoustic Emission (AE) Characteristics of Corroded Reinforced Concrete Beams in Loading Process. Journal of Building materials, 19 (04) :682-687
[18] Ni X.C., (2018) Monitoring Corrosion of Steel Bar Using Acoustic Emission. Jinan University, Jinan.
[19] Xu G., Zeng Z., Zhang R., et al. (2019) Characteristics of Acoustic Emission Signals from Initial Corrosion of Steel Bar in Cement-Based Materials. Journal of Building materials, 22 (03):385-393.
[20] Zhao D. F., Liu M., (2015) Experimental study on residual strength and nondestructive testing of high strength concrete after high temperature [J]. Journal of Building Structures. 2015, 36(2):365-372.
[21] Huismann S, Weise F, Schneider U. (2009) Influence of preload on the mechanical properties of high strength concrete at high temperatures. Leipzig.
[22] Heap M J, Lavallée Y, Laumann A, et al. (2013) The influence of thermal-stressing (up to 1000 °C) on the physical, mechanical, and chemical properties of siliceous-aggregate, high-strength concrete. Construction and Building Materials, 42(5):248-265.
[23] Chen W.Q., Jing H.W., Gao Y., et al. (2020) AE test study on damage evaluation of concrete after high temperature treatment. Concrete, 2020(03):54-58.
[24] Ma J. B., (2018) Study on Damage Characteristics of Concrete Subjected to Freeze-Thaw Deterioration Based on Acoustic Emission Technology. Yellow River, 40(07):129-133
[25] Peng Z.J., Xiao Y., Wang Q. F., et al. (2019) Experimental study on uniaxial and biaxial dynamic compression test of freeze-thaw damaged concrete based on acoustic emission technology. Water Resources and Power, 37(02):131-134.