Diagnosis of Concrete Structures by AE

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1. Scope

Acoustic emission (AE) techniques are extensively studied in concrete engineering and are recently going to be applied to practical use. In particular, the increase of aging structures and the disastrous damage due to earthquakes substantially demand for the maintenance of reinforced concrete (RC) structures in service. It results in the need for the development of advanced and effective inspection techniques. Accordingly, AE techniques draw an attention for diagnostic applications to RC structures. By several authorities in Japan, activities for the standardization of AE testing procedure are in progress.

The concrete structures have their particular functions in service, which may deteriorate due to heavy traffic loads, fatigue, chemical reactions, and other disasters. To perform their functions properly, repair and rehabilitation of the structures are eventually necessary. In this case, an inspection on the current state is necessary. Consequently, to estimate the degree of the damage or structural integrity of the existing concrete structures, in situ monitoring techniques by AE are going to be standardized. Some fundamental results associated with these actions are reviewed.

2. Measurement

According to extensive research on AE in concrete (Ohtsu, 1987), the following conditions are reported to properly detect AE signals.

(1) AE device for concrete usually requires total amplification around 60 dB to 90 dB. To decrease the effect of noises on site, 1 MHz low-pass filter is desirable, as well as a high-pass filter over several kHz. The noise should be lower than 20 mV as input.

(2) A monitoring system can measure at least some of the following parameters: count, hit, event, maximum amplitude, energy, rise time, duration, energy-moment, RMS voltage, frequency spectrum, and arrival-time difference.

(3) Elimination of the noises shall be performed by setting the threshold level, filtering and post-analysis of the data. In any cases, the averaged amplitude of the noise should be managed to be lower than 10 mV as input.

(4) Inspection of the operating system shall be carried out routinely, checking that the variation of sensitivities in the channels is within 3 dB. Sensor array shall be determined from the attenuation properties of AE waves, setting the distance where attenuation of travel is less than 30 dB. Then, the frequency range from 20 kHz to 100 kHz is recommended for in situ monitoring.
3. Monitoring

For AE monitoring of existing concrete structures, it is essential to confirm that any AE signals responsible for the damage are not observed under service conditions. In the case that AE signals not of noises but due to deterioration process are detected, the monitoring and the analyses shall be conducted. The monitoring shall be performed continuously or routinely, and sometimes temporarily after the disasters.

Due to the sudden increase of AE activity, the deterioration process and in many cases the impending failure can be estimated. There is a report on AE activity under freezing and thawing process (Murakami et al., 1991), where AE counts rapidly increase prior to the volumetric expansion associated with microcracking and scaling in concrete. Another result on continuous monitoring under corrosion of the reinforcement in RC beams is given in Fig. 1. By visual observation prior to the test, the beam at channel 5 was found to be sound without any cracks, while one surface crack running vertical to the reinforcement axis was observed at that of channel 6. These beams were exposed on shore for three months. Due to rainfall, some AE activities were observed simultaneously at both the beams as seen in the figure. At the beam of channel 5, AE activity always ceased right after the rain. In contrast, after heavy rain at 50 days elapsed and 60 days AE counts were periodically observed following the activities due to the rain. This was considered to be an evidence for corrosion of the reinforcement. Water of the rainfall permeated into the concrete along the existing crack and probably corroded the reinforcement, which could generate microcracks and AE signals in concrete around the rebars. In the test, the corrosion in the beam at channel 6 was confirmed after removing rebars. These findings confirm an applicability of AE monitoring to estimate nucleation of microcracks in concrete structures.

4. Trend Analysis

From a relation between any AE parameters and other physical parameters, its trend can be analyzed and applied to the diagnosis. For example, the change of AE activity could be related with the rate of
the deterioration process. The rate-process analysis was introduced to evaluate quantitatively the change of the activity. When concrete contains a number of critical microcracks, active AE occurrence is expected under compression due to crack propagation from existing defects or microcracks. In contrast, AE activity in sound concrete is known to be stable and low prior to final failure. Thus, to formulate AE activity under loading, the rate process theory is introduced. Probability function of AE occurrence from stress level $V(\%)$ to $V+ dV(\%)$ is formulated as a hyperbolic function. Eventually, a relationship between the number of total AE events $N$ and stress level $V(\%)$ is obtained as,

$$N = C V^a \exp(bV).$$  \hspace{1cm} (1)

Here $a$ and $b$ are empirical coefficients and $C$ is the integration constant.

From previous research, the rate $a$ is, in particular, known to be sensitive to the damage degree. Core samples were taken from an aqueduct of a nuclear power plant. To drill core samples, three sites were selected: at the gate (Site A), 20 m inland (Site B), and 30 m inland from the gate (Site C). Then, a uniaxial compression test of the sample was conducted. Three samples at each site were tested. The uniaxial compressive strength and the rate $a$ were determined as the averaged value of the three. In order to quantify microscopic damage, distribution of pore radii was also measured by the mercury intrusion method from concrete fragments at the three sites. After determining the pore distribution, the volume of pore radii over 0.5 mm was determined, because microvoids over 0.5 mm are predominantly responsible for deterioration of concrete. Results of the pore volumes over 0.5 mm radius, the rate $a$, and the compressive strength are summarized in Fig. 2. From Site A to Site C, the pore volume over 0.5 mm radius decreases with the increase of the distance from the sea. This implies that the heaviest damage was introduced in concrete at the gate (Site A), where concrete was frequently deteriorated by seawater. Apart from the seaside, it is expected that the damage of concrete decreases. In accordance

![Fig. 2](image)

Fig. 2  Relation among the pore volume, compressive strength and the rate $a$. 

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with the increase of the pore volume over 0.5 mm radius, the rates a increase from Site C to Site A. Thus, the increase of the pore volume over 0.5 mm radius corresponds remarkably to the increase of the rate a. It suggests that with the increase in the rate a, the volume of the microvoids responsible for damage increases. Consequently, the trend analysis of AE occurrence could give us information on the deteriorated degree of concrete.

5. Distribution Analysis

Distribution of AE parameters is analyzed in relation to the occurrence of AE counts, hits, and events. The purpose of the analysis is variation of such AE parameters as RMS, energy, amplitude distribution and so forth. Concerning the variation of AE parameter during the deterioration process, it is found that the change of amplitude distribution is useful. In Fig. 3, amplitude distributions observed in RC beams under bending are shown. RC beams were damaged by cyclic loading of prescribed level. After particular loading cycles, the beam was statically loaded up to the service-load limit, and AE was measured. In Fig. 3(a), RC beam was repeatedly loaded at 85% static load-bearing capacity until final failure. After several cycles of loading, amplitude distributions of AE signals were measured under monotonous loading. With the increase of loading cycles, amplitude distributions shift to the distribution where AE signals of the larger amplitudes are dominant. In contrast, there exist no change of the amplitude distribution in RC beam (Fig. 3(b)) which was repeatedly loaded at only 75% until 2,500,000 cycles. The beam was not broken in the test. This implies that amplitude distribution can be applied to routinely inspection, investigating the variation of the distribution. The distribution is also quantitatively estimated from the gradient of the slope, which is called the b value (Shiotani et al. 1999).

![AE amplitude distribution during the fatigue test.](image)

6. Clustering Analysis

From the arrival time differences, AE sources are located one-dimensionally, two-dimensionally, or three-dimensionally. By applying AE location procedure, a relation between the location of AE cluster and existing defects is readily obtained. In Fig. 4, AE locations observed in a retaining wall are shown (Matsuyama et al., 1993). According to the two-dimensional locations of the raw data, wide scattering of
AE locations is observed. Eliminating the noises and compensating the effect of the existing surface cracks, AE locations are calibrated as shown in Fig. 4(b). All signals are mainly observed along the existing cracks. This implies that AE events are mostly nucleated due to fretting of the existing cracks. Thus, repair of the wall was carried out, just sealing the surface cracks. In addition to AE location, the moment tensor analysis is developed to classify the source into the tensile crack and the shear crack, and to determine crack orientations.

7. Estimation Based on Kaiser Effect

Concerning AE activity under repeated loading, the Kaiser effect is well known. In RC beams, the relation between crack opening and the presence of the Kaiser effect was reported (Yuyama et al., 1996). In order to apply the Kaiser effect, further, to evaluate the damage of concrete structures, the following two parameters are proposed.

(a) Ratio of load at the onset of AE activity to previous load:

Load ratio = load at the onset of AE activity under the repeated loading / previous load.

(b) Ratio of cumulative AE activity under unloading to that of previous maximum loading cycle:

Calm ratio = the number of cumulative AE activity during unloading / total AE activity at the previous maximum loading cycle.

One result on the relation between these ratios and crack-mouth opening displacements (CMOD) observed in RC beams tested is given in Fig. 5. Based on the ratios, one criterion the damaged degree is presented in the figure. Agreement between the damage estimated from the maximum CMOD observed in the beams after the tests and the zone of the criterion is remarkable. This implies that the deterioration
process and the current conditions of the concrete structure could be estimated under repeated loading or traffic loading from this kind of criterion.

![Graph showing the relation between CMOD and the ratios in RC beams tested.](image)

**Fig. 5** Relation between CMOD and the ratios in RC beams tested.

**REFERENCES**


