On-Site Damage Evaluation of Cracked Concrete by Acoustic Emission and Related Non-Destructive Techniques

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Abstract

For detailed inspections of concrete structures, non-destructive tests (NDT) are often conducted and then mechanical properties are compared with detected NDT parameters. In this chapter, damage evaluation of concrete by AE and X-ray computerized tomography (CT) tests are presented. The concrete damage is visualized by X-ray CT. Since nucleation of AE events in damaged concrete is affected by crack distribution, the damage parameter estimated is correlated with the dynamic modulus of elasticity $E_d$ which is calculated from P-wave velocity. The results confirm that the damage of concrete could be estimated by applying AE measurement, damage parameter in damage mechanics, CT images and modulus $E_d$. It is also shown that the static modulus $E_0$ is closely correlated with the dynamic modulus $E_d$. Based on a relation between AE rate and the damage parameters, the damage of concrete is quantitatively estimated.

Keywords: Acoustic Emission, X-ray CT, Concrete damage, Damage mechanics, DeCAT, Dynamic modulus of elasticity

1. Introduction

The durability of concrete structure is found to decrease drastically due to the effects of environmental effects. One particular example is associated with seismic wave-motions (earthquake). Recently, the Great East-Japan Earthquake hit Tohoku area in Japan on March 11, 2011 [1]. As a result, damage evaluation techniques for diagnostic inspection are in great demand in concrete engineering. The degree of damage in concrete structures is, in most cases, evaluated only from the decrease in concrete strength. For effective damage estimation of concrete, it is necessary to evaluate not only the mechanical properties but also directly the degree of damage. We have proposed quantitative damage evaluation of concrete, by applying acoustic emission (AE) and X-ray CT in the core test [2], [3]. The procedure is named DeCAT (Damage Estimation of Concrete by Acoustic Emission Technique), which is based on estimating the intact modulus of elasticity in concrete. To inspect existing structures for maintenance, AE techniques draw a great attention [4]. This is because crack nucleation and extension are readily detected and monitored. In this respect, the measurement of AE
activity in the compression test of core samples is established. By applying DeCAT, the intact modulus of elasticity in concrete is estimated on the basis of damage mechanics. The estimated damage parameter is correlated with the dynamic modulus of elasticity $E_d$ calculated from P-wave velocity [5].

In this research, damage estimation of concrete is investigated applying AE and X-ray CT. Test samples were taken from existing reinforced concrete structures, which were subjected to such environmental effects as freeze-thawed process and earthquakes. Crack distribution in concrete was inspected with helical CT scans, which were performed at one-millimeter intervals. After helical CT scan, concrete damage was evaluated by AE parameters and dynamic modulus of elasticity $E_d$. Thus, the decreases in mechanical properties in service concrete structures are quantitatively evaluated.

2. Experimental and analytical procedure

2.1 Crack evolution in concrete structures in-service using X-ray CT method

The concrete damage is accumulated by development of cracks. Continuous damage mechanics (CDM) describes the influence of accumulation of material damage such as micro-cracks on mechanical response of a solid. The concept of damage mechanics was proposed by Kachanov (1958). Since then, various damage mechanics models have been developed [6]. Loland (1989) developed a scalar damage parameter to describe fracture of concrete under stress-strain condition [7]. The physical meaning of the scalar damage parameter is demonstrated by considering a representative volume element in a material [8], as shown in Figure 1. The element has a gross cross-sectional area $A$, which could results from initial material flaws and load-induced cracks. Here, the net cross-sectional area of the element $A^*$ excludes the area of the defects, which corresponds to $A^* - A$. Thus, the damage parameter $\Omega$ is defined as,
\[ \Omega = \frac{A^* - A}{A^*} = 1 - \frac{A}{A^*} \]  

(1)

Based on the parameter \( \Omega \), Ohtsu (1988) developed an evaluation method for quantification of concrete damage using AE [9]. The AE generation behavior in core test is associated with inner crack development which is evaluated by the parameter \( \Omega \). Suzuki (2010) evaluated the damage degree in freeze-thawed concrete using AE and X-ray CT [2]. Suzuki (2014) found the decrease in CT values in deteriorated concrete samples due to earthquake motion [3]. In this study, cylindrical samples were taken from an existing structure which has been affected by the freezing and thawing effect in Hokkaido prefecture, Japan. The structure was constructed about 40 years ago and was heavily cracked. Core-drilled samples were inspected with a helical CT scan system. CT scans were performed at one-millimeter intervals before the compression test. The measurement conditions are shown in Table 1.

In Figure 2, a heavily cracked core-sample is named “Type A”. A little cracked core-sample is named “Type B”, and a non-cracked sample is named “Type C”. Output images are visualized in gray scale, where air appears as a dark area and the densest portions appear as white. The exact positioning was ensured using a laser positioning device. In this experiment, samples were scanned constantly at 0.5mm pitch overlapping. A total of 200 to 400 two-dimensional (2D) images were obtained from each specimen depending on the specimen length. From results of the CT scans, the probability density function (PDF) of perimeter of pores and cracks was estimated as shown in Figure 3. The perimeters over

<table>
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<th>Table 1. Setting used for helical CT scan</th>
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<td><strong>Helical Pitch</strong></td>
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<td><strong>Slice Thickness</strong></td>
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Figure 2. Characteristics of concrete damage in testing samples

X-ray CT Binarization

Damaged area

Type A

Type B

Type C

X-ray CT Binarization

Damaged area

X-ray CT Binarization

X-ray CT Binarization

X-ray CT Binarization

X-ray CT Binarization

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10mm are compared among Type A, B and C. Large pores and cracks over 20 mm are dominantly observed in Type A, while those of smaller than 10 mm are only observed in Type C. The concentration index I_δ is compared with perimeter of pore and cracks as shown in Figure 4. The concentration index I_δ is defined as,

\[ I_δ = m \sum_{i=1}^{m} x_i (x_i - 1)/ \sum_{i=1}^{m} x_i (\sum_{i=1}^{m} x_i - 1) \]  

(2)

where \( x_i \) is the number of points in the compartment, \( m \) is the number of compartment.

It is considered that the volume of crack is closely associated with deterioration of concrete. These results confirms that the relation between characteristics of X-ray image and crack volume is to be useful for the damage evaluation in concrete.

### 2.2 Evaluation of mechanical properties in cracked concrete by AE

After X-ray CT tests, uniaxial compression tests of core samples were conducted, measuring AE activities along with strains as shown in Figure 5. AE monitoring was carried out by employing AE sensor of 150 kHz resonance (R15α, PAC) which was attached at 6 locations of the specimen. Amplification was 60 dB gains in total. The frequency range was set from 60 kHz to 1 MHz. AE hits were detected at threshold level 42 dB by AE system (SAMOS-AE, PAC).

The averaged compressive strength of Types A and B is 8.5N/mm², as 14.9N/mm² at the maximum, and 4.2N/mm² at the minimum. In Types A and B, particular differences in mechanical properties are not observed. On the other hand, the strength of Type C is 32.9N/mm² on the average, which is 3.87 times higher than Types A and B.
Figure 5. Test setup for AE monitoring system in compression test

Figure 6. AE generation behavior in compression test

Figure 7. Characteristic of detected AE using Weibull analysis
Results of AE tests are shown in Figure 6. In the cracked samples (Type A and B), low amplitude AE events (42-59dB) are observed at the middle height of the specimen. In Type C, in contrast, high amplitude AE events frequently appear. This is because AE generation behaviors in Types A and B are mostly affected by friction of existing cracks. Distributions of AE events detected are analyzed by the Weibull distribution, as shown in Figure 7. It is found an amplitude distribution by PDF is concentrated in low values (40-50dB) in Type A. Therefore, it is found that the strengths may not be explicitly associated with the damages defined by the pore volumes in the case of freezing-thawing damages. Even though the damage is minor, the durability of concrete definitely decreases. These results suggest, in contrast, that AE parameters are quite sensitive to it.

2.3 On-site damage evaluation using DeCAT

Loland (1989) assumed that the relationship between damage parameter $\Omega$ and strain $\varepsilon$ under uniaxial compression as,

$$\Omega = \Omega_0 + A_0 \varepsilon^\lambda$$

where $\Omega_0$ is the initial damage at the onset of the uniaxial compression test, and $A_0$ and $\lambda$ are empirical constants of concrete [7]. The following equation is derived from Eq. 1 and 3,

$$\sigma = (E_0 - E^* A_0 \varepsilon^\lambda)\varepsilon$$

Here,

$$E_{0} = E^* (1 - \Omega_0)$$

$$E_{c} = E_0 - E^* A_0 \varepsilon^\lambda$$

From Eq. 5, to estimate the initial damage $\Omega_0$, it is essential to obtain the modulus of intact concrete $E^*$. However, it is not feasible to determine $E^*$ of concrete in an existing structure. To estimate $E^*$ from AE measurement, the relation between the total number of AE events and the stress level in Eq. 7 is correlated with Loland model [10].
\[ f(V) = \frac{a}{V} + b \]  

(7)

where \( a \) and \( b \) are empirical constants. Here, the value \('a'\) is named the rate.

The static initial modulus of elasticity \( E_0 \) is to be quantitatively determined as a tangential gradient of the stress-strain curve in compression test. From Eq. 4,

\[ \sigma = E_0 \varepsilon - E^* A \varepsilon^{A+1} \]  

(8)

Thus, the static modulus, \( E_0 \), is uniquely determined as a tangential modulus: \( d\sigma/d\varepsilon \) at \( \varepsilon=0 \).

We have found the highest correlation between the damage parameter \('\lambda'\) and the rate \('a'\) (AE database [10]). AE database consists of 200 samples tested in the Kumamoto University from 1988 to 2013. A linear correlation between \('\lambda'\) and the rate \('a'\) value is reasonably assumed. Thus, the equation of \('\lambda'\) is expressed,

\[ \lambda' = a'X + Y \]

\[ \lambda + (a \times 100) = (a \times 100)X + Y \]  

(9)

where

\[ \lambda = \frac{E_0}{E_0 - E_c} \]  

(10)

Here, it is assumed that \( E_0 = E^* \) when \( a = 0.0 \). This allows us to estimate Young's modulus of intact concrete \( E^* \) from AE database as,

\[ E^* = E_c + \frac{E_c}{Y} \]  

(11)

In this procedure, the damage of concrete is evaluated by relative moduli \( E' \) as presented,

\[ E' = \frac{E^*}{E_0} \times 100 \]  

(12)

Here \( E_0 \) is the tangent modulus of elasticity in the compression test. The procedure to estimate the relative moduli \( E' \) is named DeCAT (Damage Estimation of Concrete by Acoustic Emission Technique; Figure 8).

The dynamic modulus of elasticity \( E_d \) is a useful mechanical parameter for damage evaluation of concrete [5]. This parameter is closely related to the relative moduli calculated by DeCAT [5], [11], [12]. Elastic waves are generated and propagate in concrete due to either a dynamic force or crack development. In an isotropic elastic body, the primary wave (P-wave) propagates with the velocity \( V_p \),

\[ V_p = \sqrt{\frac{E_d(1-\nu)}{\rho(1-2\nu)(1+\nu)}} \]  

(13)
where $E_d$ is the dynamic modulus of elasticity, $\nu$ is Poisson’s ratio and $\rho$ is the density of concrete. In concrete engineering, the static modulus of elasticity is normally obtained as a secant modulus in the compression test, while the dynamic modulus of elasticity is determined from the velocity estimated by the ultrasonic test. In the case that the static modulus is determined from a tangential modulus, it is reported that no difference is found between the static and the dynamic modulus [5]. So, relative moduli determined from the dynamic modulus are compared with results of AE rate process analysis [10].

3. Results and discussion

3.1 Damage evaluation of RC arch member in service for 87 years

Core samples were drilled and collected from an arch portion of a reinforced concrete road-bridge that had been in service for 87 years. Using concrete-cores, the damage are estimated by relation between dynamic modulus of elasticity $E_d$ and static modulus of elasticity $E_0$. AE measurement in a compression test was conducted. MISTRAS-AE system (manufactured by PAC) was employed to count AE hits. AE hits were detected by using an AE sensor UT-1000 (resonance frequency: approx. 1MHz).

Results of mechanical properties, compressive strength of core-samples are 25.3N/mm$^2$ on the average, 32.4N/mm$^2$ at the maximum, and 20.1N/mm$^2$ at the minimum. Initial modulus of elasticity $E_0$ is 21.2GPa on the average, 27.9GPa at the maximum, and 16.8GPa at the minimum. Dynamic modulus of elasticity $E_d$ is calculated from Eq. 13. The longitudinal wave velocity of concrete $V_p$ are 3,207m/s on the average, 3,770m/s at the maximum, and 2,600m/s at the minimum. Young’s moduli $E_d$ are 22.1GPa on average, 29.7GPa at the maximum, and 14.8GPa at the minimum. Relative moduli ($E_0/E^*$) are compared with compressive strengths ($f'c$) as shown in Figure 9. It is clearly observed that relative modulis estimated show a

![Figure 9. Comparison of relative moduli and compressive strength](image)

![Figure 10. Comparison of Young’s modulus $E_d$ and $E_0$ in concrete bridge](image)
similar trend to the compression strengths. Because, the relative modulis of all specimens are almost 1.0 or below, it is considered that they have been fairly damaged. In Figure 10, Initial modulus $E_0$ and dynamic modulus $E_d$ are almost identical. It is experimentally confirmed that there exists little difference between initial Young’s modulus and dynamic Young’s modulus. As in the frost damage, relative damages are normally estimated from dynamic Young’s modulus [5]. The dynamic modulus is physically identical to static modulus in core test. Therefore, the dynamic modulus is most useful damage parameter for on-site non-destructive damage evaluation of concrete structure.

### 3.2 Concrete canal structure affected by Earthquake

The testing structure was selected in the Tohoku region, where the damage evaluation was carried out using AE in core test. Core samples of 10 cm in diameter and about 20 cm in height were taken from a concrete open-canal wall in Miyagi prefecture, Japan. The concrete wall of the canal was subjected to the Great East Japan Earthquake which was constructed 8 years ago. Core samples were drilled out from pre- and post- the Great East Japan Earthquake conditions. In addition, the ultrasonic test was conducted in the same canal walls in the conditions of post- earthquake. After longitudinal wave velocity was determined, dynamic modulus of elasticity $E_d$ was calculated from P wave velocity. AE monitoring in core test was conducted same conditions of concrete road bridge. Results of mechanical properties, the compressive strength is 25.0 N/mm$^2$ as the average (max: 30.1 N/mm$^2$, min: 18.5 N/mm$^2$) in the pre-earthquake condition, while that of the post-earthquake condition is 24.8 N/mm$^2$ (max: 31.5 N/mm$^2$, min: 20.5 N/mm$^2$). Thus, the decrease in the mechanical properties is not clearly observed. On the other hand, the CT value and relative damage $E_0/E^*$ are lower than those of pre-earthquake samples [3]. These results indicate that the CT and relative damage are effective for quantitative evaluation of concrete damage. In Figure 11, these dynamic modulus of elasticity $E_d$ are compared with the relative damage $E_0/E^*$ which is defined as damage parameter [2]. It is clearly observed that the relative damages are in reasonable agreement with dynamic modulus of elasticity $E_d$ after the earthquake.

![Figure 11. Comparison of dynamic modulus of elasticity $E_d$ and relative moduli $E_0/E^*$ in concrete canal structure](image)
4. Conclusion

For on-site damage evaluation of concrete, AE and X-ray CT methods were applied to the experiments of core samples. The crack distributions of concrete-core were inspected with X-ray CT method. The damage of concrete due to crack progressive conditions was evaluated by AE parameter in compression test. AE generation behavior is closely associated with the concrete damage, which can be quantitatively evaluated by relation between dynamic modulus of elasticity $E_d$ and static modulus $E_0$. The concrete damage is associated with statistical properties of CT data. Thus, the damage of concrete is quantitatively estimated as damage parameters by AE and X-ray CT.

References