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DAMAGE EVALUATION OF CRACKED CONCRETE BY DECAT

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Abstract: The Great East Japan Earthquake hit Tohoku Area in Japan on March 11, 2011. A large number of concrete structures were damaged by the 9.0 magnitude earthquake in Richter-scale. Prior to reconstruction and retrofit of these structures, damage evaluation of in-situ concrete is now in urgent demand. In this concern, quantitative estimation of damaged concrete is going to be performed, applying acoustic emission (AE) measurement in the compression test of core samples. The procedure is named DeCAT (**D**amage **E**stimation of **C**oncrete by **A**coustic Emission **T**echnique), which is based on estimating an intact modulus of elasticity in concrete. Distribution of micro-cracks in a concrete-core sample is inspected by helical X-ray computer tomography (CT) scans at one-millimeter intervals. Then, damaged samples are evaluated based on AE generating behaviors due to fracturing under compression. It is demonstrated that the decrease in physical properties could be evaluated by comparing an average CT number with a rate of AE generation, which is analyzed by the AE rate process. A relation between AE rate and damage parameters is correlated. Thus, by calculating initial Young's modulus from the DeCAT system, the damage of concrete is quantitatively estimated.

1 INTRODUCTION

The durability of a concrete structure could decrease drastically due to earthquakes, in particular, seismic wave-motions. The degree of damage in concrete structures is, in most cases, evaluated from mechanical properties. For effective damage estimation of concrete structures, it is necessary to evaluate not only the mechanical properties but also the degree of damage. Quantitative damage evaluation of concrete is proposed by applying acoustic emission (AE) method [1] and damage mechanics [2]. The procedure is named DeCAT (**D**amage **E**stimation of **C**oncrete by **A**coustic Emission **T**echnique) [3-4].

In this study, core samples were drill out from a damaged water-canal of concrete, which has been subjected to the influence of the Great East Japan Earthquake. Core samples were taken out both before and after the earthquake in the same structure. Crack distribution in core concrete was inspected with helical CT scans, which were made at one-millimeter intervals. After helical CT scan, concrete damage was evaluated, based on fracturing behavior under compression with AE measurement. The decreases in physical properties due to the earthquake are evaluated by the CT values, mechanical properties and relative damages. Thus, it is shown that concrete structures in service damaged due to the earthquakes could be quantitatively evaluated by AE.

2 ANALITICAL PROCEDURE

2.1 AE rate-process analysis

AE behavior of a concrete sample under unconfined compression is associated with the generation of micro-cracks. These micro-cracks are gradually accumulated until final fracture. The number of AE events, which correspond to the generation of these cracks, increases accelerated by the accumulation of micro-cracks. This process is dependent on the number of cracks at a certain stress level and the progress rate of the fracture stage, and thus could be subjected to a stochastic process. Therefore, the rate process theory is introduced to quantify AE behavior under unconfined compression [5]. The following equation is derived to formulate AE occurrence dN due to the increment of stress from V to $V+dV$,

$$f(V)dV = \frac{dN}{N}, \qquad (1)$$

where N is the total number of AE events and $f(V)$ is the probability function of AE at stress level V(%). For $f(V)$ in **Eq.1**, the following hyperbolic function is assumed,

$$f(V) = \frac{a}{V} + b, \qquad (2)$$

where a and b are empirical constants. Here, the value 'a' is named the rate, which reflects AE activity at a designated stress level. This is because at low stress level the probability varies, depending on whether the rate 'a' is positive or negative. In the case that the rate 'a' is positive, the probability of AE activity is high at low stress level, indicating that the structure is damaged. In the case of the negative rate, the probability is low at low stress level, revealing that the structure is in stable condition. Therefore, it is possible to quantitatively evaluate the damage in a concrete structure using AE under unconfined compression by the rate process analysis.

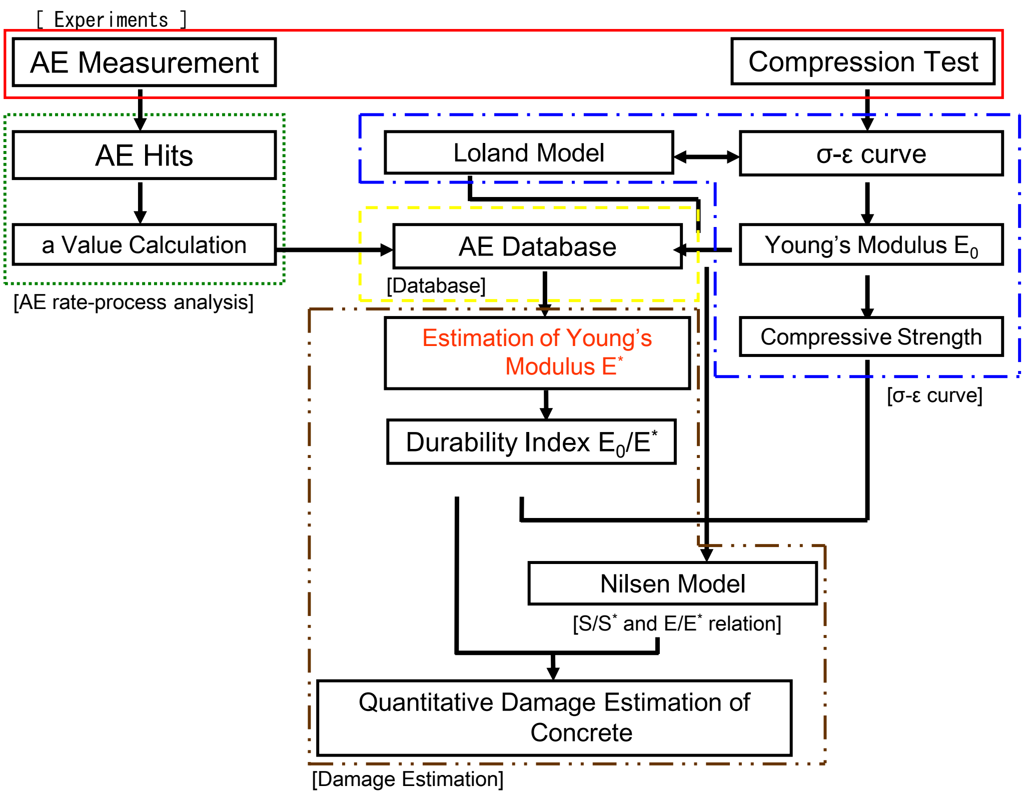


Figure 1: Analytical flow of DeCAT system.

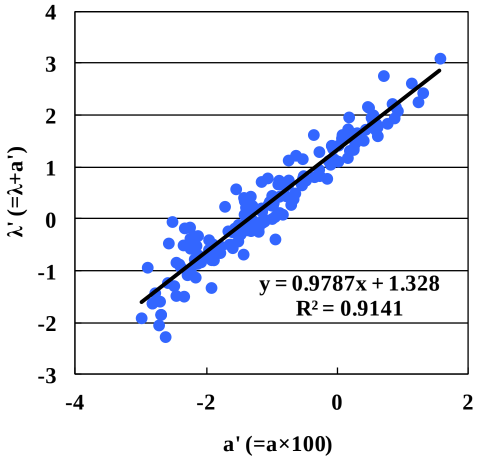


Figure 2: AE database of DeCAT.

Based on **Eqs.1** and **2**, the relationship between total number of AE events N and stress level V is represented as the following equation,

$$N = CV^a \exp(bV), \quad (3)$$

where C is the integration constant.

2.2 Scholar damage model

A scholar damage parameter Ω in damage mechanics can be defined as a relative change in modulus of elasticity, as follows,

$$\Omega = 1 - \frac{E}{E^*}, \quad (4)$$

where E is the modulus of elasticity of concrete and E^* is the modulus of elasticity of concrete which is assumed to be intact and undamaged.

Loland assumed that the relationship between damage parameter Ω and strain ε under unconfined compression is expressed [6],

$$\Omega = \Omega_0 + A_0 \varepsilon^{\lambda}, \quad (5)$$

where Ω_0 is the initial damage at the onset of the unconfined compression test, and A_0 and λ are empirical constants of the concrete. The following equation is derived from **Eqs.4** and **5**,

$$\sigma = (E_0 - E^* A_0 \varepsilon^{\lambda})\varepsilon, \quad (6)$$

here

$$E_0 = E^*(1 - \Omega_0), \quad (7)$$

$$E_c = E_0 - E^* A_0 \varepsilon_c^{\lambda}. \quad (8)$$

2.3 Estimation of intact Young's modulus

As given in **Eq.5**, the initial damage Ω_0 in damage mechanics represents an index of damage. In Loland's model (**Eq.4**), it is fundamental to know Young's modulus of the intact concrete (E^*). However, it is not easy to obtain E^* of concrete in situ. Therefore, it is attempted to estimate E^* from AE monitoring in the compression test. Two relations between total number of AE events and stress level and between stress and strain are taken into account. Based on a correlation between these two relationships, a procedure is developed to evaluate the intact modulus from AE analysis. This process is named "DeCAT" as summarized in **Fig.1**. A correlation between the damage parameter 'λ' and the rate 'a' derived from AE rate process analysis is given in **Fig.2**. Good correlation between the 'λ' ' and the rate 'a' 'value is confirmed. Here results of all samples damaged due to the freeze-thawed process in model experiments are plotted by gray circles. A linear correlation between 'λ' ' and the rate 'a' ' value is reasonably assumed, and the equation of λ' is expressed,

$$\lambda' = a'X + Y$$

$$\lambda + (a \times 100) = (a \times 100)X + Y, \quad (9)$$

where

$$\lambda = \frac{E_c}{E_0 - E_c}. \quad (10)$$

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 rate process analysis as,

$$E^* = E_c + \frac{E_c}{Y}. \quad (11)$$

In the DeCAT system, a relative damage of concrete core is estimated from the ratio E_0/E^*, where E_0 is the initial tangential modulus of elasticity in the compression test of concrete. By applying **Eq.11**, the intact modulus of elasticity, E^*, is estimated from AE database. AE database consists of 200 samples tested in

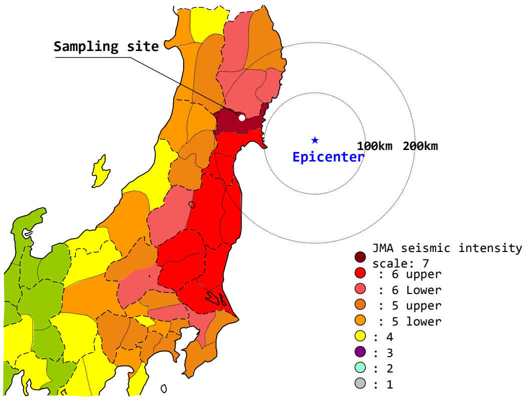


Figure 3: Location of sampling site.

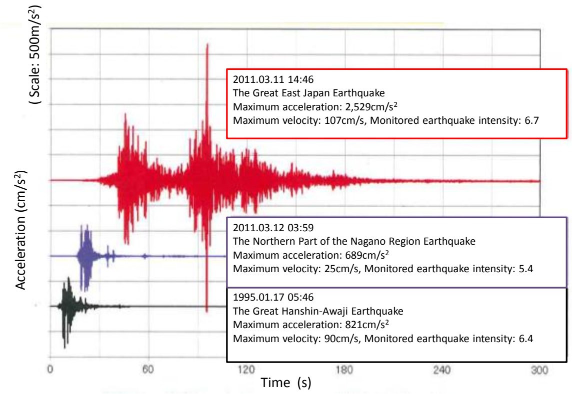


Figure 4: Detected earthquake waves in Japan.

Table 1: Setting used for helical CT scan.

Helical Pitch	15.0
Slice Thickness	0.5mm
Speed	7.5mm/rotation
Exposure	120kV and 300mA
Recon Matrix	512×512
Field of View	100-200mm

the Kumamoto University from 1988 to 2012.

3 EXPERIMENTAL PROCEDURE

3.1 Core concrete

Core samples of 10cm in diameter and about 20cm 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 (**Fig.3**). Typical seismic-waves detected are shown in **Fig.4,** compared with one of the Great Hanshin-Awaji Earthquake. The structure was constructed 7 years ago, and is not severely damage as observed.

Core samples are classified into two types of Type A and Type B. Type A samples are not subjected to the effects of the earthquake. This is because these samples were drilled out in October, 2009 surely before the Great-East Japan Earthquake hit Tohoku area. Type B samples were drilled out of the concrete canal at close locations to cores of Type A in January, 2012 after the Great East Japan Earthquake. In addition, the ultrasonic testing was conducted in the same canal walls before and after the earthquake.

3.2 Visual observation of concrete damage using X-ray computed tomography

Prior to the compression tests, core samples were inspected with helical CT scans at the Animal Medical Center, Nihon University. The helical CT scan was undertaken at one-millimeter intervals. The measurement conditions are summarized in **Table 1**. The output images are visualized in gray scale, where air appears as dark area and the densest areas appear as white in the image. The exact positioning was ensured using a laser positioning device. Experimental samples were scanned constantly at 0.5mm pitch overlapping. A total of 400 2D-images were obtained from each specimen depending on the specimen length. These 2D images can be assembled to provide 3D representation of core specimens. The CT scanning system operates, collecting X-ray absorption values. The values of the absorption coefficients are transformed into CT numbers using the international Hounsfield scale.

3.3 AE monitoring in compression test

A uniaxial compression test of the sample was conducted as illustrated in **Fig.5**. Silicon grease was pasted on the top and the bottom of the specimen, and a Teflon sheet was inserted to reduce AE events generated by friction between the loading plate and the specimen. SAMOS-AE system (manufactured by PAC) was employed as the measuring device. AE signals were detected by using AE sensor

Table 2: Mechanical properties of core samples.

Samples	Numbers	Compressive * Strength(N/mm^2)	Vp * (m/sec)
Pre-earthquake samples (Type A, October, 2009)	15	18.5-30.1 (25.0)	1,503-3,748 (3,020)
Post-earthquake samples (Type B, January, 2012)	12	20.5-31.5 (24.8)	1,899-4,571 (3,055)

*Minimum-Maximum (Average)

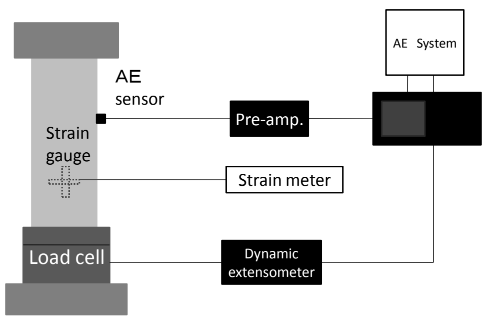


Figure 5: Test setup for AE monitoring in core test.

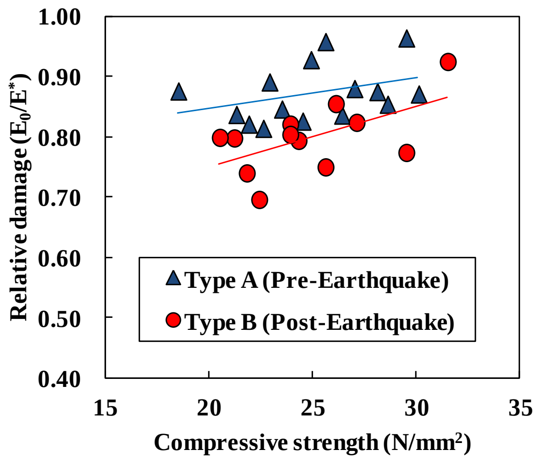


Figure 6: Relations between relative damages E_0/E^* and compressive strengths in pre- and post-earthquake conditions.

(R15α: resonance frequency: approx. 150 kHz). To count the number of AE hits, the threshold level was set to 60dB with 40dB gain in a pre-amplifier and 20dB gain in a main amplifier. For event counting, the dead time was set to as 2ms. It should be noted that AE measurement was conducted with two channels as the same as the measurement of axial and lateral strains.

4 RESULTS AND DISSUCUSSION

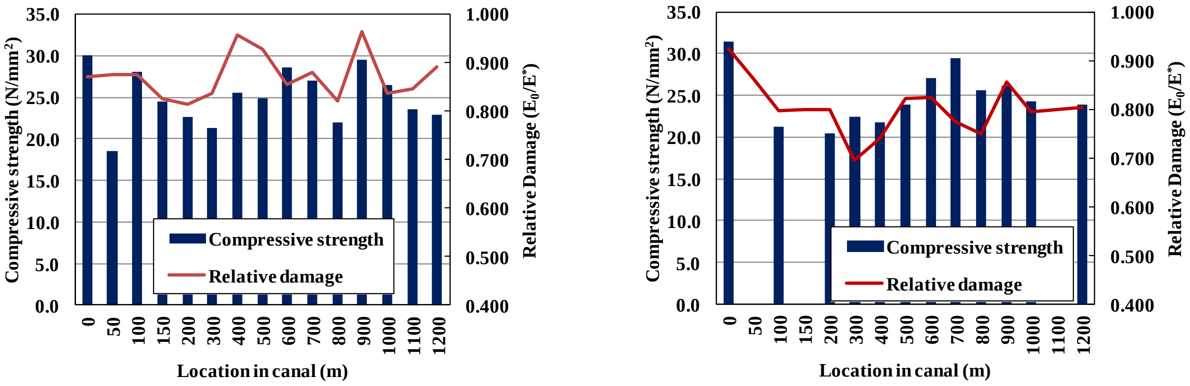
4.1 Mechanical properties

Compressive strengths and longitudinal-wave velocities, Vp, obtained are summarized in **Table 2**, with the maximum and the minimum values of all specimens. The longitudinal-wave velocity is 3,250m/s as the mode value in the pre-earthquake condition, while that of the post-earthquake condition is 3,000m/s. Thus, the decrease in the velocity is clearly observed, suggesting the damage evolution due to earthquake. At the damaged joint parts, the longitudinal wave-velocities vary from 3,440m/s at the maximum to 2,360m/s at the minimum as the average of 2,830 m/s. These values are lower than those of non-damaged areas.

4.2 X-ray observation of damaged concrete subjected to the Great East Japan Earthquake

The crack distributions of core samples were measured by the helical CT scanner with test conditions in **Table 1**. The CT number obtained in Hounsfield Units (HU) represents the mean X-ray absorption associated with each area on the CT image. The CT numbers vary according to the material properties, generally adjusted to 0.0 for water and to -1,000 for air.

In this experiment, it was found the CT numbers were +130 to +1,780 for pores and +2,000 over for aggregate. At cross-sections of Type A sample (pre-earthquake condition), the average CT numbers varied between +1,542 and +1,833. In contrast, in Type B sample (post-earthquake condition), at the regions where small cracks were observed, the average CT numbers varied between +143 and +1,054, showing the decrease in the CT values. Suzuki et al. [7] carried out experiments to compare the CT values in cracked and non



(Type A; Pre-Earthquake condition) (Type B; Post-Earthquake condition)

Figure 7: Spatial properties of concrete mechanical values and relative damages in monitoring canal.

cracked concrete-core. It is demonstrated that the decrease in the CT values are definitely observed in damaged parts. As a result, damage evolution is surely confirmed in the concrete sample subjected to the earthquake.

4.3 Quantitative damage evaluation of concrete by estimated intact Young's modulus E^*

A relative damage is estimated from the ratios of initial Young's moduli E_0 to intact E^*. The intact modulus E^* is estimated by AE database (**Fig.2**). The compressive strength and the relative damage were determined as the damage index. Results of these parameters are summarized in **Fig.6**. A relationship between the compressive strengths and the relative damage in Type A is similar to that of Type B, although the relative damages are definitely lower in Type B than in Type A. This confirms that the effect of the earthquake results remarkably in the decrease in the relative damage. These results suggest that the strength may not be a key factor for the durability, while the relative damage (E_0/E^*) is really sensitive to it.

Along the canal wall of 1.2 km, the longitudinal-wave velocities were measured before and the after the earthquake with 100 m interval. The modulus of elasticity, E, was estimated from the velocity, and the relative damage at the location of the velocity measurement is estimated as E/E^*, where the modulus E^* of the core sample closest to the location was applied. In **Fig.7**, these relative values in the canal are compared with the compressive strengths determined at their locations. It is clearly observed that the relative damages estimated are in reasonable agreement with the compressive strengths. In Type B (post-earthquake) samples, the relative damages E_0/E^* vary from 0.696 to 0.925 and are estimated as below 1.0 which implies the damaged condition. Comparing results of Type A with those of Type B, it is quantitatively observed that the relative damages estimated in Type B (post-earthquake samples) are clearly lower than those in Type A. This demonstrates that the open canal has been damaged due to the effect of Great East-Japan earthquake.

5 CONCLUSION

For quantitative estimation of damage in concrete, AE monitoring is applied to the uniaxial compression test of concrete samples. The procedure is named DeCAT (**D**amage **E**stimation of **C**oncrete by **A**coustic Emission **T**echnique), which is based on estimating the intact modulus of elasticity in concrete. The DeCAT system is applied to concrete-core samples taken from a concrete water-canal which is affected by the Great East Japan Earthquake. It is quantitatively demonstrated that concrete of the canal is damaged. In addition, applying the velocity measurement, spatial distribution of the damage in the canal is readily determined. Reasonable agreement with spatial distribution of the relative damages is confirmed by the results of AE generation behavior in the core test.

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