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Damage estimation of concrete canal due to earthquake effects by acoustic emission method

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HIGHLIGHTS

- To assess the damage of concrete structure subjected to earthquake effects.
- A method to monitor AE activity of core samples under uniaxial compressive loading was investigated.
- The degree of damage was evaluated using relative moduli 'E/E^*'.
- No difference was physically found between the relative damage E_0/E^* and dynamic moduli E_d/E^*.

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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 due to the 9.0 magnitude earthquake of the Richter-scale. Prior to reconstruction and retrofit of these structures, damage evaluation of in situ concrete structures is now in urgent demand. In this concern, quantitative damage estimation of concrete is proposed to be performed, applying acoustic emission (AE) measurement in a uniaxial compression test of core samples. Generating behavior of AE events in the core test is quantitatively analyzed, based on the rate process theory, because notable discrepancy of AE activity is observed between damaged concrete and undamaged concrete. The damage is quantitatively defined by a scalar damage parameter in damage mechanics. Correlating AE rate with the damage parameter, quantitative estimation of damage is proposed in terms of the relative modulus of elasticity (E_0/E^*). Concrete core samples were taken from reinforced concrete columns of an existing canal in the both periods of pre and post the earthquake. Prior to the compression test, distribution of micro-cracks in a concrete-core sample was inspected by helical X-ray computed tomography (CT), which scans at 1-mm intervals. The results suggest that the damage of concrete could be quantitatively estimated from damage parameter E_0/E^* without knowing the original state of the concrete at construction. The static moduli E_0/E^* and dynamic moduli E_d/E^* is closely correlated. A relation between AE rate and the damage parameters is correlated, and thus the earthquake damage of concrete is quantitatively estimated using AE.

1. Introduction

The durability of concrete structure could decrease drastically due to the effects of earthquakes, in particular, seismic wave-motions. Recently, the Great East-Japan Earthquake hit Tohoku area 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 from the decrease trend of concrete strength. For effective damage estimation of concrete, it is necessary to evaluate not only the mechanical properties but also the degree of damage.

By the authors, quantitative damage evaluation of concrete is proposed by applying acoustic emission (AE) [2] method and damage mechanics [3] in the core test. To inspect existing structures for maintenance, AE techniques draw a great attention. 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 was proposed. The procedure is named DeCAT (Damage Estimation of Concrete by Acoustic Emission Technique) [4–6], which is based on AE rate process

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analysis and is applied to quantitatively estimate the intact modulus of elasticity in concrete based on damage mechanics.

In this study, damage estimation of concrete-core samples is investigated applying AE. Test samples were taken from reinforced concrete of an existing canal wall, which has been subjected to the influence of the Great East-Japan Earthquake. Crack distribution in core concrete was inspected with helical CT scans, which were performed at 1-mm intervals. After helical CT scan, concrete damage was evaluated by the DeCAT system. Thus, the decreases in physical properties due to the earthquake are evaluated by the CT values, mechanical properties and relative damages.

2. Analytical procedure

AE activity of a concrete core under compression is associated with the rate process theory was introduced [7]. AE behavior of a concrete sample under compression is associated with the generation of microcracks. These cracks tend to gradually accumulate until final failure. Since this process could be referred to as stochastic, the following equation of the rate process is introduced to formulate the number of AE events, dN, due to the increment of stress from V to $V + dV$,

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

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,

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

where a and b are empirical constants. Here, the value 'a' is named the rate (Fig. 1). The probability varies in particular at low stress level, depending on whether rate 'a' is positive or negative. If rate 'a' is positive, the probability of AE events is high at low stress level. This indicates that the testing concrete may be damaged. If the rate is negative, probability is low at low stress level and the concrete is in stable condition. Therefore, it is possible to quantitatively evaluate the damage in a concrete using AE under uniaxial compression by the AE rate process analysis.

Substituting Eq. (2) into Eq. (1), a relationship between the total number of AE events N and stress level V is obtained as,

$$N = CV^a \exp(bV), \tag{3}$$

where C is the integration constant.

Damage parameter Ω in continuum damage mechanics is defined as a relative change in the modulus of elasticity, as follows:

$$\Omega = 1 - \frac{E}{E^*}, \tag{4}$$

where E is the modulus of elasticity and E^* is the modulus of concrete which is assumed to be intact and undamaged. Loland [3] assumed that the relationship between damage parameter Ω and strain ε under uniaxial compression is expressed,

$$\Omega = \Omega_0 + A_0\varepsilon^\lambda, \tag{5}$$

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

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

here,

$$E_0 = E^*(1 - \Omega_0), \tag{7}$$

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

To estimate the initial damage Ω_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. (3) is correlated with Loland model.

In the compression test, a relation between stress and strain is observed as shown in Fig. 2. The modulus of elasticity values from E_0 to final E_c. It should be noted that the former is defined as a tangential modulus while the latter is a secant modulus. Following Eq. (5), damage Ω increases from Ω_0 to Ω_c as shown in Fig. 3.

The static initial modulus of elasticity E_0 is to be quantitatively determined as a tangential gradient of the stress–strain curve. From Eq. (6),

$$\sigma = E_0\varepsilon - E^*A_0\varepsilon^{\lambda+1}, \tag{9}$$

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

As shown in Fig. 2, two moduli of elasticity, E_0 and E_c, are determined in the core test. Then, the rate process analysis is conducted in the stress level range from 30% to 80%. This is because AE events, which occur at initial loading below 30% stress due to contact with the loading plate and at an accelerated stage above 80%, have little to do with the damage. We have found the highest correlation between the damage parameter 'λ' (Eq. (11)) and the rate 'a' derived from AE rate process analysis shown in Fig. 1. Good correlation between the parameter 'λ' ' and the rate 'a' 'is confirmed [6]. Results of all samples damaged due to the freeze-thawed process in model experiments are plotted by gray circles (Fig. 4). A linear correlation between 'λ'' and the rate 'a'' value is reasonably assumed. Thus, the equation of λ' is expressed,

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

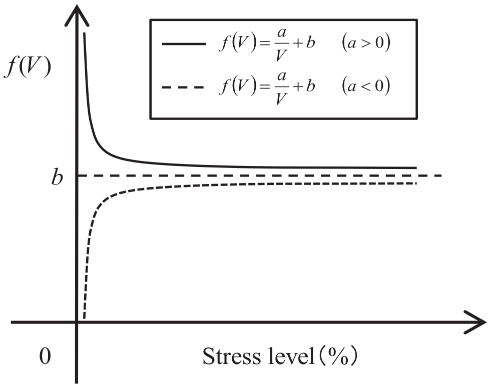

Fig. 1. Two possible relations of probability function $f(V)$.

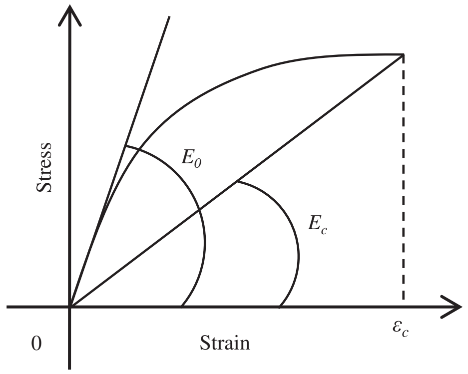

Fig. 2. Stress–strain relation and determination of Young's modulus.

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