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Evaluation of cracking damage in freeze-thawed concrete using acoustic emission and X-ray CT image

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HIGHLIGHTS

- To assess the damage of concrete structure subjected to freeze-thawed effects.
- A method to monitor AE activity of core samples under uniaxial compressive loading was investigated.
- The degree of damage was visualized using X-ray CT images.
- Quantification of concrete damage was analyzed relation between AE parameter and spatial statistics of cracks.

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ABSTRACT

The durability of concrete structures decreases easily due to such environmental effects. For effective maintenance of concrete structures, it is necessary to evaluate not only the values of mechanical properties but also the degree of damage. In this study, damage estimation of concrete is proposed to be performed, applying AE and X-ray CT. Testing concrete core samples were taken from reinforced concrete columns of an existing canal, which is strongly affected by freeze and thawed process. Thus, a relation between AE and X-ray CT parameters is correlated, and the damage of concrete is quantitatively estimated using AE and X-ray CT.

1. Introduction

The durability of concrete structures could decrease drastically due to the effects of environmental effects. 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 mechanical concrete properties, such as strength. For effective maintenance and management of concrete structures, it is necessary to evaluate not only the mechanical properties but also the degree of damage (i.e. crack development in concrete). Therefore, to inspect existing structures for maintenance, acoustic emission (AE) techniques draw a great attention. To this end, AE and related NDT (Non-Destructive Testing) by means of elastic-wave methods have been extensively studies. The acoustic emission is one of the most useful methods for damage evaluation of concrete structures [2]. This is because crack nucleation and extension are readily detected and monitored.

The authors propose quantitative damage evaluation of concrete by applying AE [3–7] and X-ray CT [8–10] in the core test. AE activity under unconfined compression is approximated by the rate process theory [3], and the damage parameters derived from the stress-strain behavior using Loland's model [11,12]. Then, it is useful for detection of crack distribution of testing samples using X-ray CT, which is applied to make the proposed method applicable to a limited number of samples taken from an existing structure.

In this study, damage estimation of concrete-core samples are investigated applying AE and X-ray CT. Testing samples were taken from reinforced concrete of an existing canal wall, which has been subjected to the influence of freeze and thaw process. Detection of crack distribution in core concrete was inspected with helical CT scans. After helical CT scan, concrete damage was evaluated by AE in a compression test. The AE behavior is associated with crack volume responsible for damage in concrete. The damage accumulation of concrete could be evaluated by comparing X-ray CT parameters with a damage index. These values are affected by

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the actual cracks. Thus, the decreases in physical properties due to freeze-thaw effect are evaluated by X-ray CT and AE parameters.

2. Analytical procedure

2.1. Quantification of cracking effects in concrete using damage mechanics

The concrete damage is defined as decrease of the effective area in the cross-section [13], which can be detected by X-ray CT test. Quantification of concrete damage is performed using X-ray CT images, which are analyzed by spatial statistics parameters with damage mechanics [9,10]. In this study, estimation of concrete damage defined as high AE generation behavior in low strain level, which is affected by development of crack systems in concrete-core sample. Results of the AE analytical data, damage estimation of concrete is conducted by comparison between the X-ray CT and AE parameters.

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

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

where E is the modulus of elasticity and E^* is the modulus of concrete, which is assumed to be intact and undamaged. Loland assumed that the relationship between damage parameter Ω and strain ε under uniaxial compression is expressed [11],

$$\Omega = \Omega_0 + A_0 \varepsilon^{\lambda}, \tag{2}$$

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. (1) and (2),

$$\sigma = (E_0 - E^* A_0 \varepsilon^{\lambda})\varepsilon. \tag{3}$$

The damage of concrete is evaluated by damage parameter "λ". The equation for λ is expressed (Fig. 1),

$$\lambda = \frac{E_c}{E_0 - E_c}. \tag{4}$$

In this study, accumulation of mechanical concrete damage is evaluated by damage parameter "λ", detected AE and X-ray CT image. The X-ray CT parameters are based on quantification of detected CT numbers, which is obtained in Hounsfield Units (HU) representing the mean X-ray absorption associated with each area on the CT image. The CT numbers vary according to the material properties (i.e. crack concentration of concrete), generally adjusted to 0.0 for water and to −1000 for air. After X-ray CT monitoring, the air void and cracks in concrete are detected by binary treatment of X-ray CT image. These detected void structure is analyzed by roundness parameter C_i and air void ratio.

The roundness parameter C_i is defined as spatial statistics parameter for quantitative evaluation of characteristics of geometric properties [14,15]. The following equation of roundness parameter C_i is introduced to formulate the ratio of the area of cracking damage, A (m^2), and these outer periphery length P (m),

$$C_i = \frac{P^2}{A}. \tag{5}$$

The roundness parameter C_i is calculation from binary images of X-ray CT (threshold level: 73, average max value). The crack detection accuracy is approximately 200 μm in each X-ray CT images. In the case of 'true circle' of air void in non-damaged concrete, analytical result is detected $C_i = 4\pi = 12.56$. On the other hand, in crack developed concrete, the calculated roundness parameter C_i is increased ($C_i > 12.56$).

The air void ratio is calculated from binary image of X-ray CT image. The analysis value is calculated as the ratio of the total void (include cracks) area to the total cross section.

2.2. AE rate-process analysis in core test

The AE activity of a concrete core under compression is associated with the rate process theory, which was introduced [3]. AE behavior of a concrete sample under compression is associated with the generation of micro-cracks. 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 strain from ε to $\varepsilon + d\varepsilon$,

$$f(\varepsilon)d\varepsilon = \frac{dN}{N}, \tag{6}$$

where N is the total number of AE events and $f(\varepsilon)$ is the probability function of AE at strain level ε%. For $f(\varepsilon)$ in Eq. (6), the following exponential function is assumed,

$$f(\varepsilon) = \alpha \cdot \exp(\beta\varepsilon) \tag{7}$$

where α and β are empirical constants. Here, the value β is named the rate (Fig. 2). The probability varies in particular at low strain level, depending on whether rate β is positive or negative. If rate β is negative, the probability of AE events is high at low strain level. This indicates that the tested concrete may be damaged. If the rate is positive, the probability is low at low strain 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 AE generation behavior. In this study, quantitative damage evaluation of freeze-thawed concrete are analyzed by comparison of AE 'β' and X-ray CT 'C_i'.

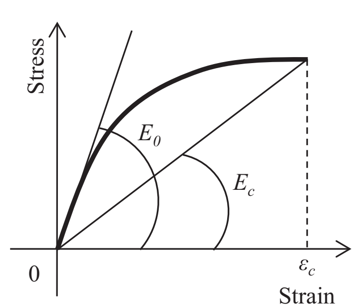

Fig. 1. Stress-strain relation and determination of Young's modulus.

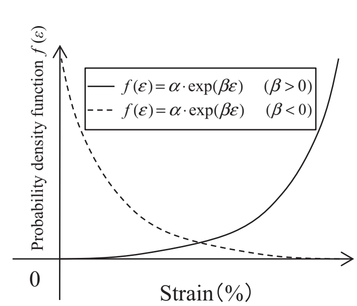

Fig. 2. Two possible relations of probability function $f(\varepsilon)$.