Damage Evaluation of an Historic Concrete Arch Bridge by Acoustic Emission

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Summary

It is widely reported that durability of concrete decreases readily due to such effects, as salt, chemical attack or freezing-thawing process. In existing structures, mechanical damage of concrete has been practically inspected from the strength by a compression test. For effective maintenance of concrete structures, it is necessary to evaluate not only the strength but also the degree of damage. By the authors, quantitative damage evaluation of structural concrete is proposed by applying acoustic emission (AE) technique and damage mechanics. In experiments, core-samples were collected from an arch portion of a reinforced concrete road bridge that had been in service for 87 years. Compressive strengths and Young's moduli were measured during the compression test along with AE monitoring. Dynamic Young's modulus was also calculated from the longitudinal wave velocity. Thus, the relative damages are quantitatively evaluated from static and dynamic Young's moduli and compared with results of AE rate-process analysis.

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Key words : acoustic emission, damage mechanics, dynamic Young's modulus, compression test, non-destructive testing

Damage in concrete grows due to the environmental effects. In recent years, from viewpoint of life cycle cost analysis (LCCA), quantitative damage evaluation in concrete structures has been in great demand. Accordingly, it is necessary to develop a quantitative technique for damage evaluation in concrete. In the case of diagnostic inspection on the concrete structures, mechanical and chemical properties of concrete are normally evaluated by taking core samples. However, physical properties obtained from the compression test are not directly associated with damage evaluation.

Acoustic emission (AE) is known to be promising to evaluate the degree of damage. The authors has proposed that AE generation behavior under compression is formulated by the rate-process analysis (Ohtsu, 1992). Results of samples subjected to freezing-thawing process showed a close relationship between a rate process parameter and pore volume (Suzuki *et al*., 2010). Applying AE rate-process analysis and damage mechanics, the damages of concrete samples cored from existing structures were attempted to be estimated. By calculating an intact modulus of elasticity from the database based on a relation between AE rate and the damage parameter, the degree of damage in a concrete canal was successfully estimated (Suzuki *et al*., 2013). Thus, a procedure to estimate the relative damage of concrete based on the database is implemented as Damage evaluation of Concrete by AE Technique (DeCAT) (Suzuki and Ohtsu, 2014).

In this study, damage estimation of a concrete structure is investigated by correlating AE generation behavior in core test with the scalar damage model. Core samples were collected from an arch potion of a reinforced concrete road-bridge that had been in service for 87 years. By calculating intact moduli of elasticity from the DeCAT analysis, the degree of damage is evaluated as a relative modulus of elasticity which is compared with static and dynamic Young's moduli.

ANALYTICAL PROCEDURE

1. AE parameter analysis for quantification of detected elastic waves

AE behavior of a concrete sample under compression is associated with generation of micro-cracks. These micro-cracks gradually are accumulated until final failure. The number of AE events, which correspond to the generation of these cracks, increases due to the accumulation of micro-cracks. It appears that AE generation behavior is dependent on the number of cracks at a certain stress level and subjected to a stochastic process (Yokohori, 1955). Therefore, the rate process theory is introduced to quantify AE behavior under compression (Ohtsu, 1992). The following equation of the rate process is formulated to represent the number of AE hits dN due to the increment of stress from V to $V+dV$,

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

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 Equation (1), the following hyperbolic function is assumed,

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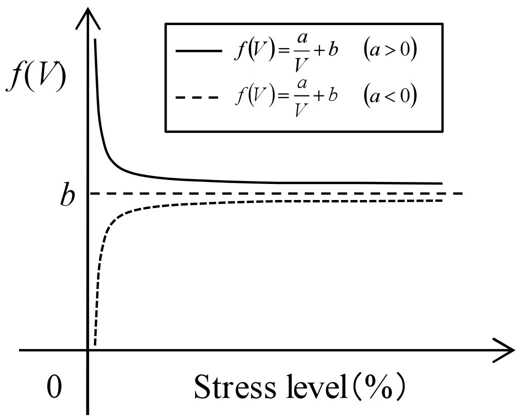


Fig 1. Two possible relations of probability functions *f(V)*.

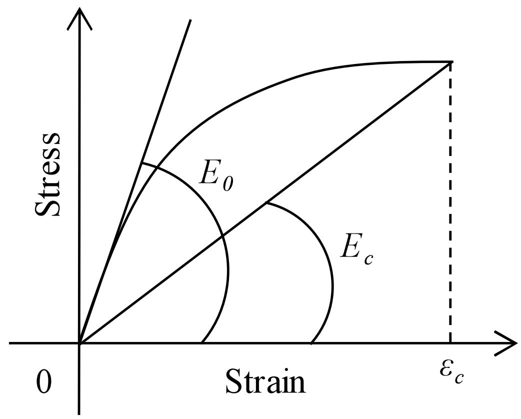


Fig 2. Stress- strain relations in core test and detected E_0 and E_c.

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

where a and b are empirical constants. Here in after, the value '*a*' is called the rate.

In Equation (2), the value of '*a*' reflects AE activity at a designated stress level, such that at a low stress level the probability increases, depending on whether the rate '*a*' is positive or negative. Two possible relations of probability function *f(V)* are shown in Fig. 1. In the case that the rate '*a*' is positive, the probability of AE activity is high at a low stress level, suggesting that concrete is damaged. In the case of the negative rate, the probability is low at a low stress level, revealing that the structure could be in stable condition. Thus, it is possible to quantitatively evaluate the damage in a concrete structure using AE measurement under compression by the rate process theory.

Substituting Equation (2) into Equation (1), a relationship between total number of AE events N and stress level V is represented as the following equation,

$$N = CV^{a}\exp(bV)\ . \qquad (3)$$

Where C is the integration constant.

2. Quantitative damage evaluation of concrete by Loland model

A damage parameter Ω in damage mechanics can be defined from a relative ratio in modulus of elasticity (Loland, 1989),

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

where E is Young's modulus of concrete and E^* is Young's modulus of concrete which is assumed to be intact or undamaged.

Assigning Ω_0 is the initial damage at the onset of the compression test. The following equation is derived,

$$E_0 = E^*(1-\Omega_0)\ . \qquad (5)$$

In the uniaxial compression test of a concrete sample, a relation between stress and strain is typically plotted as shown in Fig. 2. According to Equation 4, the initial Young's modulus E_0 is associated with the current degree of damage Ω_0.

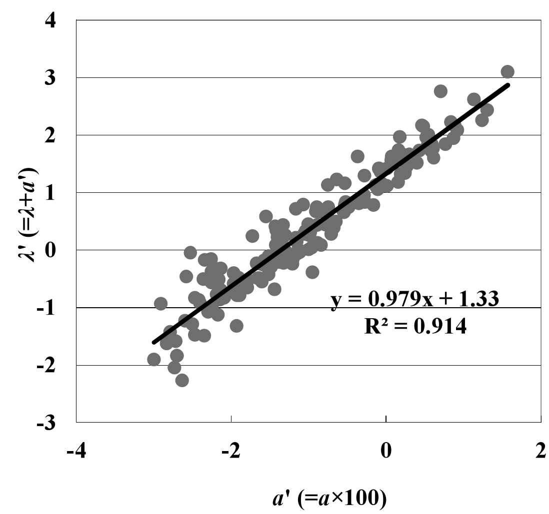


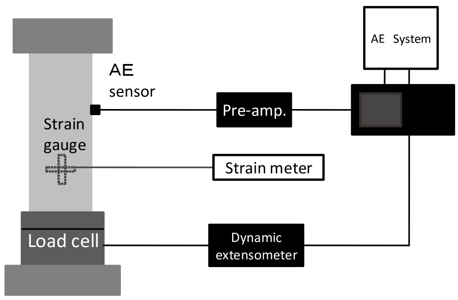
Fig 3. AE database.

Corresponding to the damage Ω_c at the ultimate static ε_c, scant Young's modulus, E_c, is defined. In this study, Young's modulus, E_0, was estimated as a tangential modulus, after appropriating the stress-strain relation by a hyperbolic function.

3. Estimation of Young's modulus of the intact concrete E^* using AE database

As given in Equation (5), the initial damage Ω_0 in damage mechanics represents an index of damage. In Loland's model (Equation (4)), it is fundamental to know Young's modulus of the intact concrete (E^*). Since, it is quite difficult to obtain E^* from an existing structure. Therefore, it is attempted to estimate E^* from AE monitoring in 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. A correlation between the damage parameter 'λ' and the rate 'a' derived from AE rate process analysis is shown in Fig. 3. Good correlation between the 'λ'' and the rate '*a*' 'value is confirmed. Results of all samples damaged due to the freeze-

(a) Arch fragment of concrete bridge.



(b) Test set up for AE monitoring in core test.

Fig 4. Testing concrete and experimental set-up.

thawed process in model experiments are plotted by gray circles. A linear correlation between 'λ'' and the rate 'a'' value is reasonably assumed. The equation of λ' is expressed,

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

$$\lambda + (a \times 100) = (a \times 100)X + Y \quad , \quad \cdots\cdots\cdots\cdots \quad (6)$$

here

$$\lambda = \frac{E_c}{E_0 - E_c} \quad \cdots\cdots\cdots\cdots \quad (7)$$

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,

$$E^* = E_c + \frac{E_c}{Y} \quad \cdots\cdots\cdots\cdots \quad (8)$$

In this study, the concrete damage is evaluated by DeCAT (Suzuki and Ohtsu, 2014).

EXPERIMENTS

1. Specimens and AE monitoring in core test

Cylindrical samples of 10cm in diameter and 20cm in height were core-drilled from a block (3.0m × 3.0m × 0.68m), which was taken from an arch portion of a road bridge in Fig. 4 (a). The bridge was constructed in 1918 and has been located in Kumamoto prefecture, Japan. AE measurement in a compression test was conducted as shown in Fig. 4 (b). 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. 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). The frequency range was from 60 kHz to 1 MHz. For event counting, the dead time was set as 2ms. It should be noted that AE measurement was conducted

Table 1. Mechanical properties.

	f'_c (N/mm^2)	E_0 (GPa)	E_C (GPa)	E_d (GPa)	E^* (GPa)	E_0/E^*	E_d/E^*
Max.	32.4	27.9	13.4	29.7	27.0	1.09	1.16
Min.	20.1	16.8	6.7	14.8	20.2	0.72	0.67
Ave.	25.3	21.2	10.5	22.1	24.1	0.88	0.91

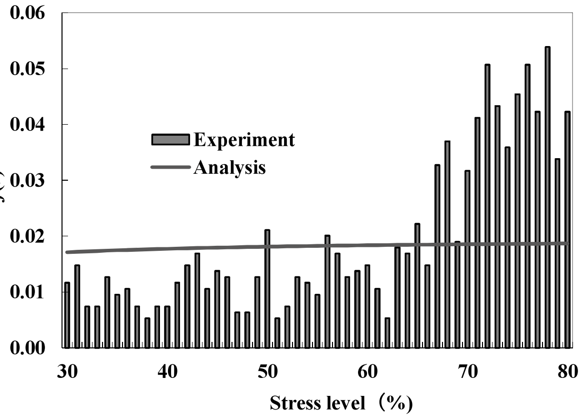


Fig 5. AE generation behavior in maximum strength sample (a=-8.0×10^{-4}).

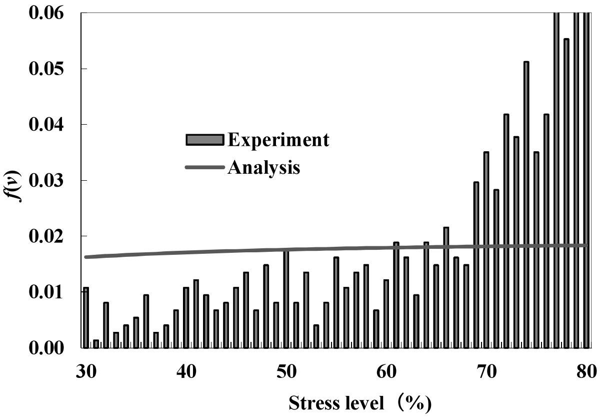


Fig 6. AE generation behavior in minimum strength sample (a=-1.2×10^{-4}).

at two channels as well as the measurement of axial and lateral strains. AE hits and strain of the two channels were averaged as a function of stress level.

2. Non-destructive estimation of dynamic Young's modulus E_d using P wave velocity

The longitudinal wave velocity was measured to estimate dynamic Young's modulus E_d. The arrival times between two end surfaces of the specimen were measured by ultrasonic testing device SIT-021 (manufactured by Tokyo Sanwa Shoukou Co,.LTD). Then dynamic Young's modulus E_d was determined from,

$$E_d = \frac{(1+\nu)(1-2\nu)\rho}{1-\nu} V_p^{\,2} \cdots\cdots\cdots\cdots \quad (9)$$

Here, ρ is the density of concrete specimen and Poisson's ratio is set to 0.2. Vp is the longitudinal wave velocity measured by NDT method.

RESULTS AND DISCUSSION

1. Mechanical properties of concrete-core samples

Compressive strength f'_c of core-samples are summarized in Table 1, with the average, the maximum, and the minimum values of all specimens. 12 samples were collected from concrete block. Compressive strength is 25.3N/mm^2 on the average, 32.4N/mm^2 at the maximum, and 20.1N/mm^2 at the minimum. Initial Young's modulus E_0 is 21.2GPa on the average, 27.9GPa at the maximum, and 16.8GPa at the minimum. Dynamic Young's modulus E_d is calculated from Equation (9). The longitudinal wave velocity of concrete Vp are 3,207m/s on the average, 3,770m/s at the maximum, and 2,600m/s at the minimum. Dynamic Young's modulus E_d is 22.1GPa on average, 29.7GPa at the maximum, and 14.8GPa at the minimum.

2. AE generation behavior under compression process

AE generating behavior of each specimen showed the negative 'a' value in AE rate-process analysis. Results of AE rate process analysis is shown in Figs.5 and 6. Compared to the value (a=-0.0012) for normal concrete with 28 day moisture curing (Suzuki *et al.*, 2004), value obtained in this study are -8.0×10^{-4} for the specimen with the maximum strength (Fig. 5), and -1.2 × 10^{-4} for the specimen with the minimum strength (Fig. 6). This suggests that an increasing trend of 'a' value with the increase in damage.

3. Relative damage evaluation of concrete-core sample

As indicated in Table 1, relative damages of specimens were estimated from the ratio's of initial Young's moduli E_0 to intact E^*, applying DeCAT. Relative damages (E_0/E^*) are compared with compressive strengths (f'_c) in Fig. 7. It is clearly observed that relative damages estimated show a similar trend to the compression strengths. Because the relative damages of all specimens are almost 1.0 or below, it is considered that these samples have been fairly damaged.

4. Comparison of relative damage (E_0/E^*) and dynamic Yong's moduli (E_d/E^*)

In the existing codes or standards, relative damages are normally estimated from relative values of dynamic Young's moduli (i.e. JIS A 1127: 2010). It is reported that dynamic Young's modulus is more than 10% larger than static modulus. Here, static Young's moduli were obtained as initial tangential moduli and dynamic Young's moduli were

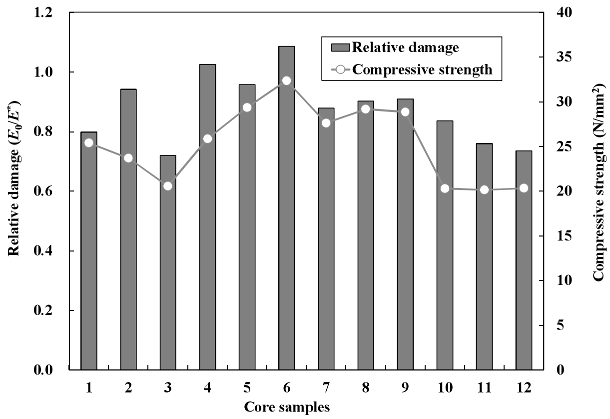


Fig 7. Relation between relative damage and compressive strength.

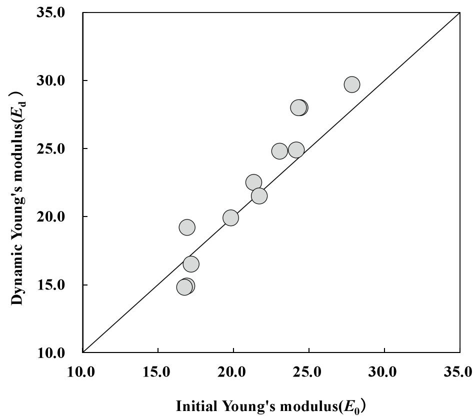


Fig 8. Relation between initial and dynamic Young's moduli.

determined from Equation (9). Consequently, these moduli are compared in Fig. 8. It is obviously observed that the Initial Young's modulus (E_0) and dynamic Young's 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. It is confirmed that the dynamic modulus is physically identical to static modulus in core test.

In the case that initial Young's moduli are not known in service structure, relative damages are not available. But, by applying DeCAT, intact Young's moduli E^* is estimated. Estimated values are directly compared with dynamic Young's moduli E_d. These values are larger than intact moduli E^* in some core samples, of which strengths are larger than 29 N/mm^2. In other samples, the decrease in the moduli from the intact values is suggested. According to Fig. 7, No.4 and No. 6 samples has the relative damage over 1.0, suggesting a non-damaged sample. No. 6 sample has the strength over 30 MPa. It is concluded that concrete where sample No. 6 was core-drilled is sound, but those of other portions are fairly damaged as the relative damages are estimated in the range from 0.6 to 0.9. As a result, the damage degree in the concrete block is quantitatively estimated as the relative value by DeCAT.

CONCLUSION

Quantitative evaluation of damage in concrete is developed, applying AE and damage mechanics. It is well confirmed that damages of concrete-cores can be quantitatively evaluated by DeCAT. Results obtained in this study are summarized below:

1) The relative damage is calculated from AE generation behavior in core test which is applying AE rate-process analysis and damage mechanics. This analytical procedure is named DeCAT (Damage evaluation of Concrete by AE Technique). Core-samples from a concrete block of a bridge were tested, applying DeCAT to estimate the damage.
2) The relative damages estimated show reasonable agreement with the mechanical properties.
3) Comparing the initial Young's moduli with dynamic Young's moduli, it is confirmed that the dynamic modulus is identical to the static modulus. There is little difference between relative dynamic Young's modulus and relative damage. Then, non-damaged part of the concrete is determined, and the damage degree in the other portions are quantitatively estimated.

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AE 法による長期供用した RC アーチ部材の損傷度評価に関する研究

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要　約

コンクリート構造物に関する耐久性の低下は、外部環境の影響による損傷蓄積により進行する。一般的にコンクリート損傷は圧縮強度などにより評価されるが、より効果的な維持管理には強度特性のみではなく損傷度の推定が不可欠である。本報では、AE（Acoustic Emission）法と損傷力学を用いてコンクリートの定量的損傷度評価を試みた結果を報告する。実験的検討では、竣工後87年が経過したコンクリート道路橋アーチ部材を対象とした。供試したコンクリート・コアの力学特性は、AE 計測を導入した圧縮強度試験により評価した。動弾性係数は P 波速度より評価した。検討の結果、破壊試験と非破壊試験により評価した相対損傷度は AE 発生挙動と密接に関連していることが明らかになった。

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