Invited paper

Nondestructive Evaluation of Damaged Concrete due to Freezing and Thawing by Elastic-Wave Method

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Abstract

The damage of concrete subjected to freezing and thawing is normally evaluated with the resonance method, which estimates the elastic properties of concrete. This method is one of several nondestructive evaluation (NDE) techniques that use elastic-wave methods. The damage is evaluated based on resonant frequencies, which are related to the dynamic properties of concrete. Because resonance is closely associated with wave motions, the ultrasonic test (UT), which measures the velocity of wave propagation, is also available for NDE of damaged concrete. Another NDE technique using elastic-wave methods that can be applied to evaluate the damage of concrete is acoustic emission (AE) measurement.

These three techniques are investigated and discussed for NDE of damaged concrete due to freezing and thawing. To theoretically clarify the dynamic behaviors of concrete specimens in the tests, numerical analysis of the three-dimensional boundary element method (BEM) were conducted.

No difference between the dynamic modulus of elasticity and the static modulus was found to exist. Compared with UT and AE, the heaviest damage was estimated by the resonance method in the freeze-thaw process. These results have to be carefully taken into account for NDE of damaged concrete.

1. Introduction

According to JIS A 1148 (2001), the resonance method (JIS A 1127, 2001) is standardized to evaluate the damage of concrete subjected to freezing and thawing. The resonant frequencies of bending-vibration modes are determined, the relative dynamic moduli of elasticity are calculated therefrom and are applied to estimate the damage and the durability of concrete.

As nondestructive evaluation (NDE), a dynamic modulus of elasticity is calculated from the resonant frequency of a particular vibration mode. It is reported that estimated dynamic moduli of elasticity are more than 10% greater than static moduli. The author considers that this result may be related to the facts that Poisson’s ratio was neglected for computation of the dynamic modulus based on one-dimensional vibration, and that the static modulus of elasticity was estimated as a secant modulus. In order to clarify the former fact, the vibration modes of the resonance method were analyzed with the three-dimensional boundary element method (BEM). Concerning the latter, the procedure to estimate the static modulus of elasticity as a tangential modulus was applied. Thus, the difference between the dynamic modulus of elasticity and the static modulus is discussed.

Recently, a RILEM recommendation (2004) was published to determine the frost resistance of concrete to internal damage due to frost action. For NDE of internal damage, two alternative methods, A and B, are standardized. Alternative method B is the same as the resonance method of the bending vibration. In alternative method A, the wave velocity (ultrasonic transit time) of concrete is measured. This technique is known as an ultrasonic test (UT). Since the resonance method is theoretically based on a relationship between travel distance and transit time (time-of-flight), wave velocities are also responsible for mechanical changes due to damages. Accordingly, the applicability of UT to the freezing and thawing test was studied.

Another NDE technique of the elastic-wave methods that is available for evaluation of the damage in concrete is acoustic emission (AE) measurement. We proposed damage evaluation of concrete using a compression test, applying AE rate process analysis (Ohtsu and Watanabe, 2001). This procedure requires the measurement of the static modulus of elasticity. Applying the AE method, the static moduli of elasticity are obtained for comparison with the dynamic moduli.

Employing concrete specimens subjected to freezing and thawing, the resonance method, UT and AE were examined for NDE of damaged concrete.

2. Mechanical properties

2.1 Dynamic modulus of elasticity

Elastic waves are generated and propagate in concrete due to either a dynamic force (UT) or cracking (AE). In an isotropic elastic body, the primary wave (P wave) propagates with the velocity \( v_p \).

\[
v_p = \left[ \frac{E(1 - \nu)}{\rho(1 - 2\nu)(1 + \nu)} \right]^{1/2}
\]  

(1)

\( E \) - Modulus of Elasticity

\( \rho \) - Mass Density
where $E$ is the modulus of elasticity, $\nu$ is Poisson’s ratio and $\rho$ is the density of concrete.

In JIS A 1127 code (2001), the P wave is assumed to propagate in an infinite bar. As a result, Poisson’s ratio is set to be equal to zero as one-dimensional wave propagation. Thus Eq. (1) becomes,

$$v = \frac{|E/\rho|^{1/2}}{(1 - 2\nu)(1 + \nu)/(1 - \nu)}$$

(2)

if the dynamic modulus of elasticity, $E_d$, is determined from Eq. (1),

$$E_d = \rho f^2$$(1 - 2\nu)(1 + \nu)/(1 - \nu)$$

(3)

when we assume Poisson’s ratio $\nu = 0.2$ in concrete, the coefficient $\{(1 - 2\nu)(1 + \nu)/(1 - \nu)\} = 0.9$. The 10% difference in the dynamic modulus of elasticity between $\rho f^2$ obtained from Eq. (2) and $E_d$ is already derived. Thus, the difference could actually result from a formula to calculate the modulus. Measuring the velocity of the P wave in UT, the dynamic modulus of elasticity $E_d$ is readily estimated from Eq. (3).

In the resonance method, the resonant frequency, $f$, is determined. In the case of the longitudinal vibration, a relationship between the wavelength $\lambda$ and the wave velocity $v$ is derived as,

$$\lambda = \frac{v}{f}$$

(4)

the first mode of longitudinal resonance leads to a relation where the characteristic length $L$ is equal to half the wavelength as $\lambda = 2L$, and thus we have,

$$v = 2Lf$$

(5)

the dynamic modulus of elasticity, $E_{dp}$, is obtained by combining Eq. (5) with Eq. (2),

$$E_{dp} = \rho (2Lf)^2$$

(6)

Comparing Eq. (3) and Eq. (6), the dynamic modulus of elasticity, $E_d$, is obtained from the velocity, whereas the modulus, $E_{dp}$, is derived from the resonant frequency.

### 2.2 AE rate process analysis and static modulus of elasticity

To model AE generating behavior under compression, the rate process theory was introduced (Ohtsu and Suzuki, 2005). 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 $V + dV$,

$$dN/N = f(V) dV$$

(7)

where $N$ is the total number of AE events and $f(V)$ is the probability function of AE at stress level $V$. Then, a hyperbolic function $f(V)$ is introduced,

$$f(V) = a/V + b$$

(8)

where $a$ and $b$ are empirical constants. Hereinafter, value ‘$a$’ is called the rate. 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 activity is high at a low stress level. This indicates that the concrete may be damaged. If the rate is negative, the probability is low at a low stress level and the concrete is referred to as sound in this case.

Substituting Eq. (8) into Eq. (7), a relationship between the total number of AE events $N$ and stress level $V$ is obtained as,

$$N = C1^a \exp(bV)$$

(9)

where $C$ is the integration constant.

Damage parameter $\Omega$ in continuum damage mechanics is defined as a relative change in the modulus of elasticity, as follows,

$$\Omega = 1 - E/E^*$$

(10)

where $E$ is the modulus of elasticity and $E^*$ is the modulus of concrete that is assumed to be intact and undamaged. Loland (1989) introduced a relationship between damage parameter $\Omega$ and strain $\varepsilon$ under compression,

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

(11)

where $\Omega_0$ is the initial damage at onset of the compression test, and $A_0$ and $k$ are empirical constants. From Eqs. (10) and (11), the following relations are derived,

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

(12)

and

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

(13)

To estimate the initial damage, $\Omega_0$, it is essential to obtain the modulus of intact concrete $E^*$. Yet, 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. (9) is correlated with Loland’s model.

In the compression test, a relation between stress and strain is obtained as shown in Fig. 1(a). The modulus of elasticity varies from initial $E_0$ to final $Ec$. It should be noted that the former is defined as a tangential modulus while the latter is a secant modulus.

Following Eq. (11), damage $\Omega$ increases from $\Omega_0$ to $\Omega$ as shown in Fig. 1(b). The static (initial) modulus of elasticity $E_0$ is to be quantitatively determined as a tangential gradient of the stress-strain curve. To this end, a stress-strain relation is approximated as a hyperbolic function as,

$$\sigma = a_1 \varepsilon + a_2 \varepsilon^2$$

(14)

where $a_1$ and $a_2$ are empirical constants. Then, the static modulus, $E_0$, is uniquely determined as a tangential modulus: $d\sigma/d\varepsilon$ at $\varepsilon = 0$. 

As shown in Fig. 1(a), two moduli of elasticity, $E_0$ and $E_c$, are determined in the test. Then, 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% strength due to contact with the loading plate and at an accelerated stage above 80%, have little to do with the damage. We have found (Ohtsu and Watanabe, 2001) that the highest correlation is between the increase in the damage ($\Delta E$) and rate $'a'$. According to Loland’s model, the increase in the damage corresponds to the decrease in the moduli, $E_0 - E_c$, as follows,

$$E_0 - E_c = E^*(1 - \Omega_0) - E^*(1 - \Omega_c) = E^*(\Omega_c - \Omega_0)$$

(15)

thus, a linear correlation between loge($E_0 - E_c$) and the rate $'a'$ is proposed,

$$\log_e(E_0 - E_c) = \log_e[E^*(\Omega_c - \Omega_0)] = Da + c.$$  

Assuming that $E_0 = E^*$ when $a = 0$, the modulus of elasticity $E^*$ of intact concrete is obtained from,

$$E^* = E_c + \exp(c).$$

(16)

In order to estimate $E^*$ for a few samples, a linear correlation database has already been constructed (Ohtsu and Suzuki, 2005). Accordingly, a relative modulus, $E_0/E^*$, is estimated in each specimen by AE rate process analysis without knowing the modulus of the intact state or initial state right after construction.

3. Experiment

3.1 Specimens
The mixture proportions and mechanical properties of concrete are given in Table 1. The compressive strength of concrete was determined as the averaged value of three cylindrical samples of 100 mm diameter and 200 mm height after 28-day standard curing. For a freezing-and-thawing test, prismatic specimens of dimensions 100 mm x 100 mm x 200 mm were prepared. After 28-day standard curing, eight specimens were deteriorated through freeze-thaw cycles. During each cycle, the temperature was varied from -18°C Celsius to 5°C Celsius for three to four hours. Pairs of two specimens, respectively damaged through 50 cycles, 100 cycles, 150 cycles and 200 cycles, were prepared. Additionally, a pair of 0-cycle specimens was also stored in the standard room until the test.

3.2 Elastic-wave methods
The damaged specimens were tested by employing a device designed for the resonance method (Model MIN-011-8, Marui Co.). The test setups for longitudinal vibration and bending vibration are illustrated in Fig. 2. By employing a sweep-mode drive (auto-scanning), the resonant frequencies were determined from the spectral responses of the specimens. The responses were calibrated by compensating the system response, which was measured by the face-to-face of the input and output sensors.

The wave velocity was also measured by using a UT device (SIT-021, Sanwa Co.). As shown in Fig. 3, a through-transmission technique was applied to measure the transit time (time-of-flight).

3.3 Compression test
After the elastic-wave tests of the resonance method and UT, each specimen was cut into two prismatic specimens of dimensions 100 mm x 100 mm x 200 mm. The compression test was then performed, measuring AE activities. Two strain gauges were pasted in the axial direction to measure axial strains. AE measurement was conducted by employing two AE sensors of 1 MHz resonance (UT-1000, PAC), which were attached at the middle height of the specimen. Amplification was 60 dB gain in total. The frequency range was set from 60 kHz to 1 MHz. AE hits were detected and recorded at the threshold level of 42 dB by an AE analyzer (MISTRAS-AE System, PAC).

A relation between stress and strain was determined from the averaged value of two strain gauges, and similarly the relation between AE hits and stress was obtained.

4. BEM analysis
Two three-dimensional models that were analyzed are shown in Fig. 4. An analysis was performed in the frequency domain. Deformations were analyzed under a particular frequency with 1 N force at the input point. Corresponding to Fig. 2 (a) and (b), input and output points were arranged for longitudinal and the bending
The size of the boundary mesh was 50 mm x 50 mm for longitudinal vibrations, and 20 mm x 20 mm for bending vibrations because of the supporting conditions.

In order to construct a frequency spectrum, which was detected at the output point, 100 Hz frequency increment from 0 to 20 kHz were used. The moduli of elasticity for computation were estimated from Eq. (3) after freeze-thaw cycling, measuring velocities P wave velocity and density. These values are summarized in Table 2. Poisson’s ratio was always set to be equal to 0.2, not taking dynamic Poisson’s ratio into consideration.

5. Results and discussion

5.1 Spectral responses in the resonance method

The spectral responses observed in the test of longitudinal vibration are shown in Fig. 5. The resonant frequencies for determining the dynamic moduli are identified as the maximum amplitudes of the spectral density in the graphs. As can be seen in these graphs, the resonant frequency is observed as the lowest (first) peak-frequency around 5000 Hz and decreases with the increase in the number of freeze-thaw cycles from 5600 Hz to 5200 Hz.

Table 1 Mixture proportions and mechanical properties of concrete.

<table>
<thead>
<tr>
<th></th>
<th>Maximum gravel size (mm)</th>
<th>Water-to-cement ratio (%)</th>
<th>Volume ratio of fine aggregate (%)</th>
<th>Slump value (cm)</th>
<th>Air content (%)</th>
<th>Weight per unit volume of concrete (kg/m³)</th>
<th>Compressive strength at 28 days (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20</td>
<td>55</td>
<td>42.7</td>
<td>1.5</td>
<td>2.2</td>
<td>175</td>
<td>318</td>
</tr>
</tbody>
</table>

Table 2 Mechanical properties for BEM analysis.

<table>
<thead>
<tr>
<th></th>
<th>Cycles</th>
<th>Density: ρ (kg/m³)</th>
<th>Velocity: v_p (m/s)</th>
<th>Modulus: Ed (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>2595</td>
<td>4010</td>
<td>37.2</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>2573</td>
<td>3910</td>
<td>35.4</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>2553</td>
<td>3800</td>
<td>33.2</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>2549</td>
<td>3710</td>
<td>31.6</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>2545</td>
<td>3660</td>
<td>30.7</td>
</tr>
</tbody>
</table>

The amplitudes of the second and the third peaks decrease gradually following the first peak. Spectral responses for the bending vibration are shown in Fig. 6. The lowest (first) peak-frequency is 2350 Hz at 0 freeze-thaw cycles, and then decreases up to 1960 Hz at 200 freeze-thaw cycles.

In the case of longitudinal vibration, velocities v_p were estimated from Eq. (5) by employing the first peak-frequencies. These are compared with the velocity measured by UT in Fig. 7. It can be clearly seen that the velocities decrease with the increase in the number of freeze-thaw cycles. The velocities, v, determined from the resonance frequencies are always 400 to 500 m/s.
faster than the measured velocities, \( v_p \). This implies that the velocity estimated from the resonance might be not identical to the velocity of wave propagation.

### 5.2 Analytical results

The analytical spectra in the case of longitudinal vibration are given in Fig. 8. Displacements observed at the output point are plotted against frequencies in the abscissa. Amplitudes are relative because 1 N force is applied at the input location. Several peak frequencies can be observed besides the first peak-frequencies in Fig. 5.

The nearest peak-frequencies corresponding to the peak-frequencies in the test at 5600 Hz (50 cycles), 5400 Hz (100 cycles), 5300 Hz (150 cycles) and 5200 Hz (200 cycles) are 5600 Hz, 5400 Hz, 5400 Hz and 5300 Hz, respectively. Thus, slightly higher frequencies are obtained in the analysis. In particular, two other peak-frequencies not actually observed in Fig. 5 can be seen around 3000 Hz and 7000 Hz. These differences may be due to the fact that the boundary meshes are not properly divided to be identical to deformations in the test, as well as the fact that the supporting conditions are different from those of the test. Globally, analytical responses increase with increases in frequency, whereas they decrease in Fig. 5. It seems that the frequency response of the device for the resonance method is fairly low over 10 kHz, although the sensor response was calibrated by compensating the face-to-face response.

The analytical spectra for the bending vibration are shown in Fig. 9. The first peak-frequencies observed are
2300 Hz at 0 cycles, 2200 Hz at 50 cycles, 2200 Hz at 100 cycles and 2100 Hz at 200 cycles. Compared with those in Fig. 6, again slightly higher frequencies are obtained. Several peak-frequencies are also observed over 10 KHz in the analysis, while no particular peak-frequencies are found in Fig. 6.

In the analysis, the peak-frequencies observed with the resonance method are found at frequencies close to them, although agreement is not complete. The purpose of the analysis was the applicability of Eq. (5) to estimate P wave velocity from longitudinal vibration. Therefore, vibration modes at the peak-frequencies were thus determined. Elevation views in longitudinal vibration at the first resonance are illustrated in Fig. 10. Displacements were magnified to allow visualization of the vibration modes. If Eq. (5) were applicable to the estimation of wave velocity, longitudinal vibration should be simply observed as one-dimensional motion. Unfortunately, this is not the case as bending vibrations are combined with longitudinal vibrations. This suggests that estimation of the wave velocity from the resonance vibration is not rational, because the vibration modes are not properly longitudinal. This may be one reason why the wave velocities estimated by Eq. (5) are always higher than those by UT as observed in Fig. 7.

5.3 Modulus of elasticity
The modulus of elasticity estimated by the resonance method is suggested to be identical neither to the theoretical modulus obtained by Eq. (3) nor to the static modulus. Although the wave velocity estimated in the resonance method is based on one-dimensional motion as formulated in Eq. (5), there exist not only longitudinal vibration but also bending vibration as shown in Fig. 10. As a result, the wave velocity estimated from the resonance method could become higher than the values actually measured by UT. This could lead to the fact that the dynamic modulus obtained from the resonance method is normally larger than that by UT.

Another difference between the dynamic modulus and the static modulus of elasticity results from the secant modulus to be estimated in the compression test. Consequently, the static modulus of elasticity, $E_0$, was obtained...
from Eq. (14) as a tangential modulus in the compression test. Then, the dynamic modulus of elasticity was determined by Eq. (3) based on UT results. Figure 11 shows a comparison between the static and the dynamic moduli. The static moduli of elasticity are in reasonable agreement with the dynamic moduli. These results show that there are no differences between the static (tangential) modulus of elasticity in the compression test and the dynamic modulus based on wave velocity.
5.4 Damage evaluation

In the JIS A 1148 code (2001) and alternative method B of the RILEM recommendation (2004), damage due to freezing and thawing is estimated as a relative modulus, which is estimated from the decrease in the peak frequency in bending vibration,

\[ P_n = \left( \frac{f_n}{f_0} \right)^2 \times 100 \]  

where \( f_n \) is the peak-frequency in bending vibration at \( n \) freeze-thaw cycles and \( f_0 \) is the peak-frequency at 0 cycles. In principle, the relative modulus defined by Eq. (17) is equivalent to that in longitudinal vibration. Consequently, similar parameters \( P_{ln} \) to \( P_n \) are taken into account,

\[ P_{ln} = \left( \frac{f_{ln}}{f_{l0}} \right)^2 \times 100 \]  

where \( f_{ln} \) is the first peak-frequency in longitudinal vibration at \( n \) freeze-thaw cycles and \( f_{l0} \) is the first peak-frequency at 0 cycles.

From Eqs. (5) and (6), it is found that the relative modulus is equivalently obtained from the velocity of the P wave. Thus, the other parameter is estimated as,

\[ V_n = \left( \frac{v_{pn}}{v_{p0}} \right)^2 \times 100 \]  

where \( v_{pn} \) is the velocity of the P wave in UT after \( n \) freeze-thaw cycles, and \( v_{p0} \) is the velocity at 0 cycles.

Because the above-mentioned parameters in Eqs. (17), (18), and (19) are relative moduli, they are directly estimated as the ratio of moduli,

\[ E_n = \frac{E_{0n}}{E_{00}} \times 100 \]  

where \( E_{0n} \) is the static (tangential) modulus of elasticity in 0 cycles and \( E_{00} \) is the static modulus of elasticity in 0 cycles.

\[ E_{0n} = E_{00} \times 100 \]  

Fig. 12 Variation of relative moduli during freeze-thaw cycles.
the compression test after n freeze-thaw cycles and \( E_{00} \) is the modulus at 0 cycles. Further, from AE rate process analysis, relative moduli \( R_n \) can be estimated as,

\[
R_n = \frac{E_{0n}}{E^*}
\]

Here \( E_{0n} \) is the tangent modulus of elasticity in the compression test after n freeze-thaw cycles. \( E^* \) is the intact modulus of elasticity estimated from Eq. (13).

These five damage parameters are compared in Fig. 12. It is found that the relative moduli by bending vibration, \( P_n \), are the lowest, suggesting the heaviest damage. Relative moduli by longitudinal vibration, \( P_{1n} \), are slightly larger than \( P_n \). As could be expected, relative moduli \( V_n \) are identical to \( E_n \) and larger than \( P_n \) to a fair degree. The relative moduli by AE rate process analysis, \( R_n \), are obtained as the largest.

Because the theoretical basis to calculate the modulus of elasticity for estimating \( P_n \) is not rational, \( V_n \) and \( E_n \) could be reasonable parameters to estimate damage in concrete. The relative damages estimated by AE rate process analysis slightly exceed the values of \( V_n \) and \( E_n \). Because AE analysis can be done for concrete without knowing the initial and intact modulus, it holds promise in terms of advantageousness and usefulness.

6. Conclusions

The elastic-wave methods of the resonance method, UT and AE, were investigated for NDE of internal damage in concrete subjected to freezing and thawing. The results are summarized as follows:

(1) Velocities determined from the first peak-frequencies of longitudinal vibration in the resonance method are 400 to 500 m/s faster than the velocities measured by UT.

(2) Vibration modes at the first peak-frequencies were determined by BEM analysis. Longitudinal vibration normally appears as a one-dimensional motion. However, not only longitudinal vibration but also bending vibration was identified. This could be one reason why the wave velocities estimated from the resonance method are always faster than those estimated by UT.

(3) The static modulus of elasticity is obtained as a tangential modulus in the compression test, while the dynamic modulus of elasticity is determined from the velocity estimated by UT. No difference was physically found between the static moduli of elasticity and the dynamic moduli.

(4) Relative moduli determined from the wave velocities in UT and from the tangential moduli could be reasonable parameters for estimating damage in concrete. Although the relative moduli estimated by AE rate process analysis might be less critical, it holds promise in terms of advantageousness and usefulness because AE analysis can be used for concrete even if the initial and intact moduli are now known.

References


