Condition Assessment of Concrete Beams with Irregular Defects Using Surface Waves

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Abstract

Previously individual surface-breaking cracks in concrete were examined successfully by monitoring the changes in velocity and attenuation of surface waves. However, an overall assessment methodology for the structural elements with irregular defects has not been in the scope. The motivation of this study is to extract reliable diagnosis features from the surface waves in order to evaluate the condition of concrete elements with irregularly distributed defects. Therefore, six laboratory scale concrete beams with different defect volumes are produced by mixing Styrofoam pellets in the fresh concrete mix. The ultrasonic tests are conducting by implementing a multi-channel testing configuration and the recorded surface waves are analyzed by employing techniques such as wavelet and 2D Fourier transforms to determine the attenuation and dispersion respectively. Despite the complex structure of the defect patterns, promising results are obtained from attenuation and dispersion based features, as 100% change in both is observed for 30% defect volume.

Keywords: Condition assessment, concrete, ultrasonic waves, attenuation, dispersion, wavelet transform

1 Introduction

The condition of materials can be evaluated by monitoring the surface wave characteristics, such as attenuation and phase velocity. The most common ultrasonic tests available in the market are ultrasonic pulse velocity (UPV) and impact echo (IE); both base on the measurement of P-wave velocities [1,2]. While the first one is primarily used to evaluate the material thickness, the latter one is preferred to detect individual flaws. On the other hand, the spectral analysis of surface waves (SASW) provides information on the variation of the material properties with depth by investigating the wave dispersion [3].

Cracking in concrete is caused by different reasons and, therefore occurs in various forms. Since the previous studies on the assessment of the cracks focused primarily on the depth, the cracks were modelled as clear-cut notches in the laboratory environment [4,5,6]. These studies revealed satisfactory results using the frequency dependent wave features. Whereas distributed defects with different volume and orientation were also studied in time and frequency domains by Aggelis et al. [7,8,9], and the effect of the material heterogeneity on the surface wave characteristics was presented successfully. Nevertheless, the interpretation of the signals recorded during the ultrasonic tests can be improved by utilizing advanced signal processing techniques.

Hereby, a diagnosis procedure aiming the overall assessment of the concrete elements is discussed. The investigations are performed on concrete beams with distributed voids which are generated by mixing Styrofoam pellets with the concrete paste. A multi-channel test configuration, which allows assessing larger section, is implemented to capture the surface waves propagating in the beams. The relationships between the total defect volume and the wave properties, namely attenuation coefficient and phase velocity dispersion are investigated. Wave
attenuation is determined by utilizing discrete wavelet transform while the dispersion is extracted from two-dimensional Fourier transform. A new index representing the cumulative variation in the phase velocity with respect to a reference dispersion curve is defined to quantify the total amount of discrete defects [10]. Lastly, the beams are cut into sections and tested under compression to measure their strengths.

2 Condition Assessment Methodology

2.1 Attenuation

Wave attenuation occurs due to geometric radiation and material damping. The spatial attenuation coefficient \( \alpha_x \), which is associated with the material damping, is determined from a propagating wave by

\[
\alpha_x = \frac{1}{x_2 - x_1} \left[ \ln \left( \frac{A_x}{A_i} \right) - \beta \ln \left( \frac{x_2}{x_1} \right) \right]
\]

[11]. \( A_i \) is the wave quantity at distance \( x_i \) with respect to the excitation source, and \( \beta \) is the geometric attenuation constant, which is taken -0.5 for the surface waves due to their cylindrical wave-front. The wave quantity \( A_i \) can simply be the amplitude in time signal, or any magnitude associated with a specific frequency obtained from the signal processing techniques, such as Fourier or wavelet transforms. Wavelet transforms are more beneficial over the conventional Fourier transforms since temporal information is preserved after the transformation. The continuous wavelet transform (CWT) of a signal, \( p(t) \), is given as [12]:

\[
WT(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} p(t) \psi^* \left( \frac{t - b}{a} \right) dt
\]

where \( \psi(t) \) is called the mother wavelet function, \( a \) is the dilation parameter (scale) and \( b \) is the location parameter for time shift. The dilated and shifted wavelet function is denoted as \( \psi(t - b/a) \), and \( \psi^* \) is its complex conjugate. Eq. 1 enables to investigate any particular frequency by substituting the appropriate scale parameter \( a \). However, if a larger frequency range is within the consideration, any \( p(t) \) can be decomposed into its sub-signals, each is associated with a specific frequency band-width, by performing the discrete wavelet transform (DWT) which requires the following discretized the mother wavelet [12]:

\[
\psi_{j,k}(t) = \frac{1}{\sqrt{a_j^i}} \psi \left( \frac{t - k \tau_0 a_j^i}{a_0^i} \right)
\]

where \( j \) and \( k \) are integers, the fixed dilation step \( a_0 = 2 \), and the translation factor \( \tau_0 = 1 \). In this study, DWT is preferred to determine the attenuation as it is demonstrated by Kirlangic et al. [10] as a reliable and convenient method.

2.2 Dispersion

The wave propagation in a bounded medium is complicated due to multiple wave reflections between the boundary surfaces. In the case of a plate, the interaction of reflected waves generates Lamb modes as defined with the Rayleigh-Lamb frequency equation [13]:
\[
\frac{\tanh(\beta d)}{\tanh(\alpha d)} + \left[ \frac{4\alpha \beta \kappa^2}{(\kappa^2 - \beta^2)^2} \right]^{\pm 1}
\]  

(3)

where \( \alpha^2 = \kappa^2 - \omega^2/V_p^2 \) and \( \beta^2 = \kappa^2 - \omega^2/V_s^2 \). \( V_p \) and \( V_s \) are the P-wave and S-wave velocities, whereas \( \kappa, \omega \) and \( d \) are the wave-number, the angular frequency and the medium thickness respectively. The Lamb modes are dispersive due to their frequency dependency. Experimentally the dispersion in wave propagation is determined by utilizing a multi-channel test configuration, which allows acquiring multiple time signals simultaneously at different locations. Then the two-dimensional Fourier transform (2D FT) of the captured signals is performed to obtain a two-dimensional spectrum in frequency-wavenumber domain (f-k plot), where the incident, reflected and transmitted waves can be identified. The peaks in the plot are used to compute the phase velocities which constitute the dispersion curve of each event [14]. In the case of a homogeneous half-space medium, the dispersion curve appears as a straight line with a slope equal to \( V_R \). However, any disruption in the phase velocity due to any anomaly appears in the f-k plot which is used to interpret the damage condition.

In this work, the dispersion curves attained from experiments are used to define a diagnostic parameter called “dispersion index” (DI), which relates the dispersion in phase velocity \( V_{ph} \) to the defect volume as [10]:

\[
DI^{(Damaged)} = \sum \Delta V_{ph}^{(Damaged)}(f)/V_{ph}^{(Intact)}(f)
\]

(4)

where \( \Delta V_{ph}^{(Damaged)}(f) = \left| V_{ph}^{(Damaged)}(f) - V_{ph}^{(Intact)}(f) \right| \). The dispersion index is basically the cumulative variation in phase velocity normalized respect to the reference dispersion curve obtained from the intact specimen.

3 Experimental Procedure

Six laboratory scale beams (110x15x10 cm\(^3\)) with different void volumes are produced. Spherical Styrofoam pellets of 7 mm diameter are mixed with the concrete batch to create the defects. For each beam, a separate batch is mixed in a machine mixer using the same amount of ingredients (29.7 kg coarse aggregate, 21.4 kg sand, 7.1 kg Type I Portland cement, and 4.3 kg water). The pellets are added in the fresh concrete as to create 0%, 5%, 10%, 15%, 20% and 30% void in volume. Each beam is named after its pellet content in volume (e.g. B05). Casting is performed without using any vibrator to prevent the pellets rise in the fresh concrete. Following the ultrasonic tests, the beams are cut into sections (10x15x10 cm\(^3\)), where air voids caused by the poor compaction are also observed in addition to the pellets as shown for B0 and B30 in Fig. 1 revealing that the total void volume in the beams is larger than the pellet volume.

The compressive strength of the beam sections is measured in accordance with CSA A23.2-9C [15]. The average strength of the beams drops around from 50 to 10 MPa with increasing void volume (Fig. 2). The overall trend justifies the gradual increase in the defects with decreasing strength. However, B15 and B20 display approximately the same strength, which can be attributed to their close total void volumes (the air volume in addition to the pellet volume).
The ultrasonic test instrumentation consists of a piezoelectric transmitter (50 kHz resonant frequency) driven by a pulser, 18 accelerometers (Dytran 3055B3, 35 kHz resonant frequency, 1 Hz - 10 kHz flat response, 504.1 mV/g sensitivity), two 12 channel power supplies (PCB 483A), and Genesis 24 channel data acquisition system. All of the accelerometers are screwed into the nuts fixed permanently along the center line of the beams as to cover a length of 40 cm on the beams (Fig. 3). The transmitter is located 30 cm away from the beam edge, while the receiver spacing and the source offset to the first receiver are 2 and 6 cm respectively.
4 Data Analyses

The selected time histories recorded on the intact beam (B0) and the one with the most defects (B30) are shown in Fig. 4. Larger amplitudes arriving later than the wave-front are observed in the signals captured by the receivers further from the source, especially for the beams with less defect volume, which should be caused by the constructive behavior of the incident and the reflected events. Therefore, prior to the attenuation and dispersion calculations, the time signals are windowed in order to reduce the effect of the reflection. The P-wave and R-wave velocities, shown on the time histories in Fig. 4, are calculated based on the arrival times and found as 4534 m/s and 2384 m/s respectively for B0, and both drop gradually with increasing void volume as displayed in Fig. 5.

![Figure 4. Time histories for (a) B0 and (b) B30.](image)

![Figure 5. (a) P-wave velocity, (b) R-wave velocity.](image)

4.1 Attenuation

The recorded signals are initially windowed using a 0.125ms long Tukey window to reduce the effect of the reflections. Then the signals are decomposed by DWT followed by the Fourier transforms of the sub-signals. The sub-signals associated with the frequency bandwidth of 31-62.5 kHz, which overlaps with the transmitter’s bandwidth, are chosen to determine the
attenuation. The attenuation trends shown in Fig. 6a represent the dissemination of the spectral energy of these sub-signals for B0 and B30. Since the beams have equal dimensions, the contribution of the geometrical attenuation to the total attenuation should be same for all beams. Therefore, the deterioration level is evaluated based on the total attenuation $\alpha$ by fitting the attenuation trends to $e^{\alpha(x_1-x_l)}$, where $x_l$ is the distance to the transmitter. The computed coefficient $\alpha$ for each beam is displayed in Fig. 6b. Although, B15 does not follow the trend, the overall increase in attenuation is apparent with 130% increase for 30% defect volume.

![Figure 6. (a) Attenuation trends, (b) Attenuation coefficient vs. void volume.](image)

4.2 Dispersion in Phase Velocity

The time windows used to determine the attenuation coefficient is also employed prior to the dispersion calculations in order to magnify the incident waves in the f-k plot derived from the 2D Fourier transform. The phase velocity $V_{ph}$ is obtained for each frequency by selecting the associated wave-number pointed by the maximum peak as indicated in the f-k plots given for B0 and B30 in Fig. 7a,b. The reference dispersion curve, which represents the first antisymmetrical Lamb mode, is constituted up to 120 kHz by curve-fitting the curve obtained from B0 (Fig. 7c).

The experimental dispersion curves for all beams are presented in Fig. 8 along with the analytical ones that are derived for a concrete plate of 10 cm thickness using Eq. 3, where $V_p = 4534$ m/s and $V_s = 2615$ m/s in accordance with the experimental findings, while Poisson ratio $\nu$ is taken 0.2. Although the analytical solution is provided for the plates, it is in good agreement with the experimental curves. Since the beams are excited on their symmetrical axis, the torsional modes that might occur in beam geometry are not excited effectively. The disruption in the phase velocities pictured in Fig. 8 is quantified with the dispersion index as defined by Eq. 4 and the results are shown in Fig. 9. The general correlation reveals a linear trend, however B15 does not fit the line justifying the result obtained from the attenuation. Nevertheless, the change in the DI between B05 and B30 is almost %100 which makes it a prominent parameter for diagnosis.
Figure 7. The f-k for (a) B0, (b) B30, and (c) the reference dispersion curve obtained from B0.

Figure 8. Experimental dispersion curves along with the theoretical Lamb modes.

Figure 9. Dispersion index vs. void volume.
5 Conclusions

The correlation of the defect volume with the wave attenuation and dispersion are investigated in order to develop the condition assessment procedure for concrete elements with irregular defects as summarized in Fig. 10. The attenuation coefficient is determined by performing the discrete wavelet transform, whereas the dispersion index is obtained from the 2D Fourier transform. Due to the random distribution of the defects, tracking any Lamb mode conversion is not possible as it is the case for the surface breaking notches. Therefore, monitoring the cumulative variation in phase velocities within a certain frequency range is more suitable to evaluate the severity of the damage. Despite the complex structure of the defect patterns and beam geometry, promising results are obtained from the attenuation and dispersion based assessments, as both reveal approximately 130% and 100% change respectively for 30% defect volume. In the future, this pilot study is planned to be extended for the beams with more intermediate defect volumes in order to validate the reliability of the methodology.

![Signal processing algorithm](image)

**Figure 10. Signal processing algorithm.**

References