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Sounding of subsurface concrete defects using frequency response of flexural vibration

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ABSTRACT

Standard sounding procedures such as hammer percussion and chain drag can be used to locate subsurface concrete defects, but are often subject to the individual judgement and ear of trained inspectors. However, defect depth information can be difficult to gauge by ear alone. By recording audio and analyzing the frequency content of sounding via hammer percussion, a single- and triple-link chain drag, and a novel speaker-based excitation procedure, simulated defects in concrete test slabs were detected. The speaker-based method shows the capacity to detect a similar number of defects as chain drag methods, though it is slightly less effective than the hammer method. The duration and type of the acoustic signal used by the speaker to induce vibration are important factors in performance of the speaker-based method. The detectability of a defect via all methods tested depended largely on the ratio of defect depth to defect lateral dimensions; defect detectability was shown to drop after this ratio exceeded about 0.35.

1. Introduction

1.1. Problem statement

Sounding of concrete via a variety of impactors including coins [1], steel spheres [2], hammers [3], and steel chain [4] has been shown to be capable of detecting defect locations. The depth of the defect can be estimated using a frequency analysis of the recorded contact or non-contact measurement of the response [1,2,5]. The work described herein assesses the relative performance of three readily-available impactors (hammer, chain, and speaker) in detecting voids and delaminations in concrete specimens. While hammer-based and chain-based excitation for concrete sounding are well established, speaker-based excitation for concrete sounding using microphones is unexplored. All three methods are low-cost, but the ability to accurately control and change the contact time between a speaker and the concrete surface it excites using different acoustic signals is a feature not available to hammer or chain-based methods (which require a new impactor of a different size altogether to change impact time).

1.2. Concrete sounding background

Several standard methods for sounding concrete to detect delaminations are outlined by ASTM D4580/D4580 M – 12 [6], including a chain drag procedure, which may be performed with an actual chain dragged over the concrete surface or with hammer-based tapping. This standard specifies that the detection of delaminations occurs by the operator of the test noting dull or hollow sounds [6]. This procedure is subject to the ability of the operator to identify and make note of the sound of the defect-laden concrete. The depth of the defect can be difficult to detect by ear. A hammer percussion test may be said to be a type of coin tap test that uses a hammer as the impactor [7].

To remove the subjectivity of operator variance from the tests, the sound of the impact can be recorded by a microphone and the frequency content of the acoustic recording is used to identify defects. Sun, Zhu, and Ham [4] used a microphone to record the response of the concrete for a chain drag test [4]. A hammer percussion test using a microphone to record the sound of the impact has been shown by Wu and Siegel [3] to be roughly as effective as a contact force-based measurement of the vibration response in detecting problem areas in an aircraft skin specimen. Asano, Kamada, Kunieda, and Rokugo [5] demonstrated use of a microphone and digital audio card on concrete specimens. The use of a hammer sounding technique for Pavement was demonstrated by Felicetti [8]. Cheng, Cheng, and Chiang [1] showed coin tapping recorded using a microphone could be used to detect voids in concrete specimens.

When excited by an impact, concrete of a plate-like shape will vibrate prominently in thickness and flexural modes [9]. Concrete defect

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detection by sounding uses the concept that waves travelling in the concrete are reflected at a planar air-concrete interface due to the low specific acoustic impedance of air. The impact-echo method takes advantage of this reflection of thickness mode vibration waves to detect voids [9]. For the sounding tests performed in this study, rather than measuring the vibration at the concrete surface as in the impact-echo method prescribed by ASTM C1383 – 15 [10], the concrete vibration is recorded via the reflected wave in the air in a manner similar to an air-coupled impact echo procedure such as the one described by Zhu and Popovics [11]. However, the methods of excitation used in this study (the hammer, chain, and speaker) produce contacts with the concrete specimens that have longer contact times in comparison to those involved in an air-coupled impact echo test. As longer contact times limit the maximum useful frequencies of the tests [12], flexural frequencies of vibration, which are lower than thickness mode vibration frequencies, should be the most prominent modes of vibration found in the audio recordings. That is, frequency peaks associated with the flexural modes of vibration will be the most prominent in the amplitude spectrum of the fast Fourier transform of the recorded acoustic signals.

Haya, Luo, and Uomoto [13] used an impact acoustic method coupled with wavelet analysis to observe the early part of the response signal to characterize defect strength and defect detection, and found the dominant frequency component over the total signal duration to characterize the boundary conditions or defects inside a specimen. Felicetti [8] observed a vibration of the impact device in the later part of the response signal recorded by the microphone, and used comparison of the frequency spectrums between damaged and undamaged pavement as a basis for defect detection. A similar but more cursory comparison forms the basis of defect detection in this work.

1.3. Expected flexural frequency peak

The relationship between the resonant frequency peaks associated with flexural vibration and the depth of a defect or thickness of a plate depend on the lateral size, shape, and boundary conditions of the plate [2]. In the case of acoustic sounds above the location of a planar void or delamination defect in concrete, plate thickness is the depth of the defect. In this study, the actual concrete above the defects is restricted or damped along the bottom surface to some degree by the foam (in the case of simulated voids) or plastic (in the case of simulated delaminations). Approximation of boundary conditions in the theoretical treatment of the concrete above a simulated defect to simplify calculation of expected flexural frequency peaks was used by Cheng and Sansalone [2], with simply supported boundary conditions.

Given concrete properties, lateral dimensions, plate depth, the expected frequency of vibration can be computed using closed form solutions for vibrating plates or finite element analysis. The appropriate dimensions for the specimens used in this study are shown in Fig. 1. The defect depth is shown as h, the lateral size of delaminations is shown as b, and the diameter of the voids is shown as $2a$.

Thus, the depth of a defect is the thickness of the plate of concrete that rests on top of a defect. Only the fundamental modes of vibration are considered. Impacts occur roughly over the center of defect locations, so fundamental frequencies should have the largest amplitude [2]. Higher modes of vibration are also likely to be recorded as the impact will likely not be perfectly centered. The equations used to relate the defect depth to the frequency for a thin square plate clamped on all sides are shown in a form similar to that of Leissa [14]:

$$\lambda = 2\pi f b^2 \sqrt{\frac{\rho h}{D}} \tag{1}$$

$$D = \frac{E h^3}{12(1-\nu^2)} \tag{2}$$

In which λ is a dimensionless frequency parameter that depends on boundary conditions, mode of vibration, and plate thickness ratio, f is

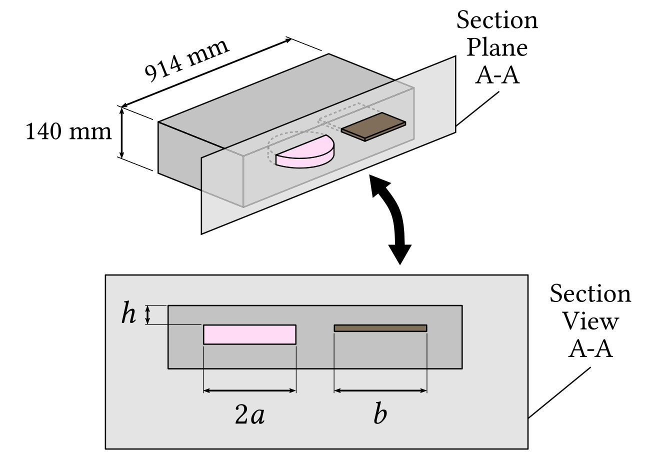

Fig. 1. Slab defect depth and lateral size for voids (left) and delaminations (right).

the frequency of vibration in Hz, b is the side length of the square plate in m, ρ is the mass density of the plate in kg/m^3, h is the thickness of the plate in m, D is the plate flexural rigidity in N·m, E is the dynamic elastic modulus in Pa, and ν is the Poisson's ratio. Leissa [14] offers a value of $\lambda = 35.998965$ for a thin plate only. A plot by Nelson [15] offers a range of normalized angular frequency ratios (ω/ω_0) as a function of thickness to side ratio (h/b) that can be used to obtain estimates of the expected frequencies for the range of plate thicknesses used in this study. This plot is shown in Fig. 2.

In the plot shown in Fig. 2, the square-box "present approximation" is the curve used for all estimations of ω/ω_0. The angular frequency for a thin plate with $h/b = 0$ is ω_0, and the angular frequency at h/b up to 0.4 can be estimated. A frequency computed using Equation (1) must be multiplied by the appropriate ω/ω_0 ratio obtained using Fig. 2 according to the h/b ratio. The h/a in Fig. 2 is equivalent to h/b in the terminology used in this work.

The equations for circular plates are also presented in a form similar to that used by Hosseini-Hashemi, Es'haghi, Taher, and Fadaie [16]:

$$\beta = 2\pi f a^2 \sqrt{\frac{\rho h}{D}} \tag{3}$$

In which β is a dimensionless frequency parameter, and a is the circle radius in m. To obtain values for β, Hosseini-Hashemi, Es'haghi, Taher, and Fadaie [16] offer a host of values for clamped circular plates.

These equations can be used to compute either a defect depth given a measured frequency, or an expected frequency from a measured depth. In order to do so, knowledge of concrete material properties and the defect lateral defect dimensions is required. The dimensionless frequency parameters that originate from published closed-form solutions of vibrating plates are also required. While extensive sounding using a grid can estimate lateral dimension information, other nondestructive methods such infrared thermography offer a more expedient alternative.

2. Specimens

Seven reinforced concrete test slabs were constructed with simulated defects to evaluate the performance of several acoustic sounding methods. Six of the slabs, numbered 1 through 6, contained simulated voids and delaminations that were introduced during casting. The remaining slab served as a control slab that was free of induced defects or imperfections, numbered slab 7. All slabs are the same nominal size: 36 × 36 × 5.5 inches (approximately 914 × 914 × 140 mm). This ensures the lateral dimensions of the plate are more than six times the thickness, in accordance with the ASTM Standard C1383 – 15 [10] definition of a plate.