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Nondestructive evaluation of the depth of surface-breaking cracks in concrete pipes

Yanjun Yang, Maria Anna Polak *, Giovanni Cascante

Civil and Environmental Engineering Department, University of Waterloo, Waterloo, Canada, ON N2L3G1

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ABSTRACT

Surface-breaking cracks affect the material and structural properties of concrete pipes. Therefore, the nondestructive evaluation of the crack depth is important to assess the serviceability of these pipes, which are commonly used in underground infrastructure and trenchless installations (micro-tunneling). This paper presents theoretical, numerical and experimental results for the depth evaluation of surface-breaking cracks. The wall of a concrete pipe is represented as a plate in the numerical and the analytical studies. In the experiments, an ultrasonic piezoelectric transmitter is used as a source. The propagation of the ultrasonic pulse is analyzed using the wavelet transform. A newly proposed wavelet transmission coefficient (WTC) is measured using an equal spacing configuration for the crack depth evaluation in concrete pipes and concrete plates. The results from laboratory and in situ tests show good potential for the practical application of the WTC for the depth evaluation of surface-breaking cracks.

1. Introduction

Near-surface damage in concrete structures mostly takes the form of cracking (Lin and Su, 1996). Surface-breaking cracks affect concrete properties and structural integrity; therefore, the nondestructive evaluation of crack depth is important for structural monitoring, strengthening and rehabilitation. Concrete pipes are commonly used in underground infrastructure and trenchless installations (micro-tunneling). They are used for sewer and water pipelines, and the structural integrity is essential for their strength and environmental safety. Cracking in concrete pipes is produced by loading, corrosion, manufacturing, and installation errors. These cracks are an indication of the long-term residual strength and the possibility of leakage. Trenchless pipe inspection procedures typically include CCTV cameras and laser surface scanning, which provide information on surface features, e.g. existence of a crack and their surface width. However, no robust and accurate nondestructive method exists that can allow assessment of the depth of cracks that are visible on the surface. This research addresses this problem and provides theoretical basis for using acoustic waves for evaluation of the depth of cracks.

Nondestructive techniques based on wave propagation are useful because they are non-intrusive, efficient and cost effective. A mechanical wave can be a compressional wave (P-wave), a shear wave (S-wave) and/or a surface wave (Rayleigh wave). Each type of wave carries different energy and travels with a different velocity.

Previous studies for the depth evaluation of surface-breaking cracks in concrete used diffracted P-waves (Sansalone et al., 1998). However, surface waves exhibit better properties for the characterization of near surface defects (Rix et al., 1990), because (a) surface waves dominate the surface response (Miller and Pursey, 1955), they carry 67% of the wave propagation energy for low frequency excitations, and present lower geometrical attenuation because the propagating wave front is cylindrical; (b) the penetration depth of Rayleigh waves (R-waves) depends on their frequency.

Most of the R-wave energy concentrates at a depth of one-third of their wavelengths (Hevin et al., 1998). The transmission of R-waves through a surface-breaking crack depends on the crack depth; this depth sensitivity is the basis for the so-called Fourier transmission coefficient (FTC) method (Popovics et al., 2000; Song et al., 2003). R-waves only exist in a half-space (one traction-free surface, where any stress in the direction outward normal to the surface points is null; this surface condition is used as a boundary condition to solve the equation of wave motion, and thus surface wave propagation is obtained); whereas in a plate (two traction-free surfaces at the top and bottom of a plate; the pipe's wall can be modeled as a plate), Lamb modes are generated. Fundamental Lamb modes behave like R-waves at high frequencies, because their wavelengths are small relative to the plat (Yang, 2009), because the two receivers are aligned with the source and at different distances from the source. The FTC calculation requires the use of an explicit time window for the identification of the first arrival of surface waves, and the selection of a reliable frequency range.

This paper presents theoretical, numerical and experimental results. First, theoretical aspects of Lamb modes are discussed

* Corresponding author. Tel.: +1 519 888 4567x35325; fax: +1 519 888 4349.
E-mail address: polak@uwaterloo.ca (M.A. Polak).

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including signal processing techniques and modeling of the source. A theoretical transfer function for the wave propagation of Lamb modes is presented, which can be used to study changes of Lamb modes in the time and frequency domains as a function of distance. The maximum amplitude of the wavelet transform is found to vary with distance because of the dispersion of Lamb modes and the participation of multiple Lamb modes in the response. Then, numerical simulations are conducted to study the wave propagation of Lamb modes through a surface-breaking crack with different depths. The surface response is dominated by the fundamental Lamb mode. These results provide the foundation for subsequent laboratory tests.

A recently proposed wavelet transmission coefficient (WTC) method for the depth evaluation of surface-breaking cracks in concrete pipes is used (Yang et al., submitted for publication); the WTC method gives a global coefficient that is correlated with the crack depth. To reduce the effects of reflections from the crack, a new equal spacing configuration is used in the WTC method. In laboratory tests, an ultrasonic transmitter with central frequency at 50 kHz is used as a source; the 50 kHz frequency is appropriate for the concrete plate tested (thickness 80 mm), because the two fundamental Lamb modes have converged to the R-wave mode. The new method is also used for real concrete pipes, and it shows good potential for practical applications. The proposed methodology has the potential to be used in general for the condition assessment of concrete pipes, and this NDT assessment is more objective than the current methodology indicated in the PACP codes (NASSCO, 2009) that is based only on the description of surface cracks. The methodology presented here is for the evaluation of depth of surface-breaking cracks in concrete pipes, and it is not intended to be used for leak detection such as Echo Logics/NRC LeakFinder™ technology for metal pipes.

2. Theoretical background

2.1. Surface wave propagation

Surface waves propagate along the surface of a medium, and the propagation energy concentrates at a depth that depends on the frequency. High frequency components propagate at a shallow depth; while low frequency components propagate deeper. This important feature makes Rayleigh waves (R-waves) suitable for the depth evaluation of a surface-breaking crack. R-wave energy concentrates at the depth of one-third of the wavelength ($\lambda/3$) (Hevin et al., 1998). In the presence of a surface-breaking crack, the cut-off wavelength λ_{cut} is related to the crack depth d by:

$$\lambda_{cut} = \frac{d}{3} \tag{1}$$

where $\lambda_{cut} = C_R/f_{cut}$; C_R is the R-wave velocity and f_{cut} is the corresponding cut-off frequency. For frequencies higher than f_{cut}, R-waves are mostly reflected from the crack; while for frequencies lower than f_{cut}, R-waves propagate through the crack.

For the case of a plate (two traction-free surfaces), different Lamb modes are generated. The wave propagation of Lamb modes is governed by the Rayleigh-Lamb-frequency equation (Graff, 1991):

$$\frac{\tan(\beta h)}{\tan(\alpha h)} + \left[\frac{4\kappa^2\alpha\beta}{(\beta^2-\kappa^2)^2}\right]^{\pm 1} = 0 \tag{2}$$

where $\alpha^2 = \kappa^2 - \omega^2/C_P^2$; $\beta^2 = \kappa^2 - \omega^2/C_S^2$; C_P and C_S are the P-wave and S-wave velocities, respectively; ω is the angular frequency; κ is the wave number; h is half the thickness of a plate. The exponent +1 represents the solution for symmetric Lamb modes; whereas the exponent -1 represents the solution for the anti-symmetric Lamb modes. The particle motion with respect to the center of the plate is symmetric for symmetric Lamb modes; whereas, it is anti-symmetric for the anti-symmetric Lamb modes (Graff, 1991). As different solutions to Eq. (2), symmetric Lamb modes S0, S1 $\cdots$, and anti-symmetric Lamb modes A0, A1 $\cdots$, are solved. They have different mode shapes with respect to the depth of a medium (for example, displacement vs. depth), and are characterized with the dispersion curves, which define a relationship between the phase velocity and frequency. In the dispersion curves, lower Lamb modes appear earlier at low frequencies; while higher Lamb modes appear later at high frequencies.

For a concrete plate with P-wave velocity $C_P = 4800$ m/s, S-wave velocity $C_S = 2770$ m/s and half the plate thickness $h = 40$ mm, the dispersion curves are shown in Fig. 1 using Eq. (2). Fundamental Lamb modes (symmetric S0 and anti-symmetric A0) show dispersion at low frequencies (frequency components propagate at different velocities); their phase velocities converge to the R-wave velocity ($C_R = 2550$ m/s) at frequency 50 kHz, where the corresponding wavelength is $\lambda = 51$ mm. For frequencies higher than 50 kHz, the fundamental Lamb modes show a non-dispersive behavior as the R-wave mode. Therefore, the fundamental Lamb modes can be useful for the depth evaluation of a surface-breaking crack. For other plate/pipe wall thicknesses, similar graphs to Fig. 1 can be created, indicating frequencies that can be considered as the onset of Lamb waves propagating without dispersion or with only slight dispersion.

2.2. Signal processing techniques

The Fourier transform is a common technique in signal processing, which projects a time signal $g(t)$ on a set of complex exponential functions $[\exp(-j\omega t)]$ by a convolution (Qian, 2002):

$$G(\omega) = \int_{-\infty}^{\infty} g(t)\exp(-j\omega t)dt \tag{3}$$

where j is the imaginary unit. The Fourier transform $G(\omega)$ is a complex function with spectral amplitude given by $|G(\omega)|$.

The two variable signal $g(t,x)$ is a 2D function of the time and space; its 2D Fourier transformation $G(\omega,\kappa)$ changes the time information into the frequency domain, and the spatial information into the wave number domain (Zerwer et al., 2003):

$$G(\omega,\kappa) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} g(t,x)\exp[-j(\omega t - \kappa x)]dtdx \tag{4}$$

The results from the 2D Fourier transform are plotted in frequency-wave number domain, where different wave propagation modes can be analyzed.

The wavelet transform of the time signal $g(t)$ replaces Fourier complex exponentials by a family of functions generated by dilations and translations of a wavelet $\phi(t)$; it is defined (Qian, 2002):

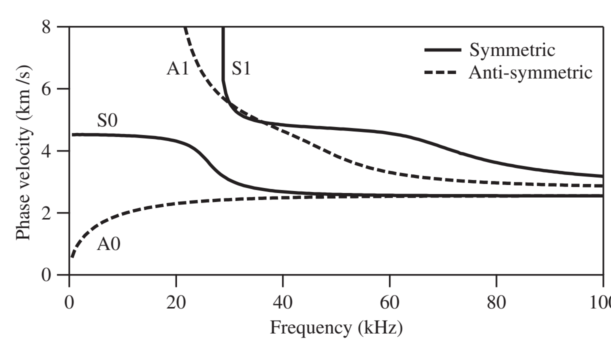

Fig. 1. Theoretical dispersion curves for a concrete plate ($C_P = 4800$ m/s, $C_S = 2770$ m/s, $C_R = 2550$ m/s, $h = 40$ mm).