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Characterizing concrete surface notch using Rayleigh wave phase velocity and wavelet parametric analyses

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HIGHLIGHTS

- A multichannel method is used to characterize surface notch depth and the orientation.
- MFCE technique is applied to process simulation and experiment waveforms.
- Wavelet transform technique is proposed to analyse R-wave waveform.
- Dispersion curve is plotted to study the change of R-wave phase velocity.

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ABSTRACT

A multichannel Rayleigh wave (R-wave) measurement technique is proposed for evaluating concrete surface notches with different orientations. In this study, numerical simulations were first conducted to examine the propagation of R-waves in steel-reinforced concrete comprising of surface notch inclining at 30°, 90° and 150° against the horizontal plane. The change of R-wave amplitude was obtained through analysis by wavelet transform (WT) and fast Fourier transform (FFT) for determining theirs correlations with the notch depth-to-wavelength ratio. Experimental measurements on concrete samples were then carried out to validate the proposed technique and its performance, particularly for cases where notch depth is greater than R-wave wavelength. Good agreement was found between the experimental results and the numerical calculations, offering good possibility for using R-waves to assess vertical and inclined surface notches in reinforced concrete with the proposed technique for R-waves acquisition and analysis.

1. Introduction

Concrete structures deteriorate over time as a consequence of pro-longed exposure to various environmental factors for instance the mechanical loading, extreme weather and other forces of nature. Surface cracking is one of the most common defects found in concrete structures. It is the result of the combined effect of drying shrinkage, thermal variation, restraint (external or internal) to shortening, subgrade settlement or mechanical actions like fatigue and overloading [1,2]. Strategic monitoring and assessment on the condition and health of these structures are needed to prevent further deterioration in the structures which will lead to fracture or even collapse due to the loss of structural integrity. Non-destructive testing (NDT) is a wide group of non-invasive analysis methods which is able to provide information about the internal condition of concrete. Elastic waves methods are amongst some of the popular NDT techniques used for detecting defects and damages in concrete structures. Surface Rayleigh wave (R-wave) that propagates along the surface of the structure had been used in the study and evaluation of the integrity of concrete structures. For example, strength gain evaluation of early-age concrete exposed to different curing conditions [3]; investigation of the relationship between R-wave velocity and porosity in dry and fully saturated mortar and porosity estimation in concrete cover from ultrasonic measurements [4]; aggregate segregation detection in asphaltic concrete based on the phase velocity and attenuation of R-wave by wedge generation technique along with an air-coupled receiving transducer with a finite-size aperture [5]; examination of concrete blocks, including subsurface cracks with different depths by ultrasound method [6]; honeycomb inspection in early-age concrete by ultrasonic surface wave [7]; application of Second Harmonic Generation (SHG) in R-waves to quantify

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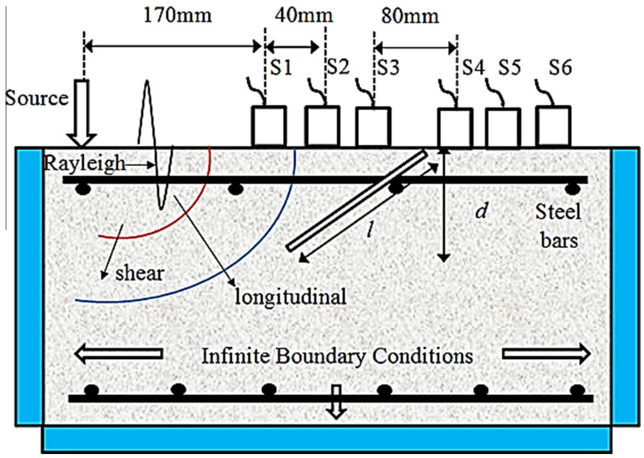

Fig. 1. Wave motion simulation model.

Table 1
Properties of steel reinforced concrete model.

Parameter	Concrete model	Reinforcing steel
Lambda, λ_m (MPa)	15,457	12,482
Mu, μ_m (MPa)	14,600	83,590
Density, ρ_m (kg/m^3)	2313	7850
P-wave velocity, V_P (m/s)	4394.92	6099.28
R-wave velocity, V_R (m/s)	2311.96	3219.95
Wavelength of R-wave, λ_R (mm)	2.31	3.22

microstructural changes and microcracks in mortar and concrete [8]; feasibility study of defects detection inside reinforced concrete (RC) structures by using elastic-wave based multi-directional Synthetic Aperture Focusing Technique (SAFT) [9].

Many efforts make use of characteristics of R-waves such as scattering and attenuation in the application of surface cracks detection and estimation. For example, non-contact, air-coupled surface wave transmission and the effects of sensor locations were investigated for partially or fully closed surface breaking crack by [10–14]. In addition, a two sensor-array methodology was implemented by [15] for effective in-place crack depth estimation based on the study of concrete specimens with vertical slits of different depths. Apart from that, Rayleigh wave dispersion and energy dissipation were analyzed to determine the locations and the depths of surface cracks in concrete beams [16]. Besides, surface crack depth estimation and the evaluation of repair effect for deteriorated concrete piers were analytically and experimentally investigated using Rayleigh waves by [17–20]. Despite these, most of the studies have been associated with estimating concrete cracks that are relatively shallow in depth and the propagation of R-waves in concrete containing an inclined crack has not been investigated in detail to the author's best knowledge. In a most recent effort, we performed multi-channel measurements of R-waves on concrete specimens with surface defects [21,22]. With the previous numerical and experimental findings serving as the fundamental and knowing the potential of R-waves as an effective means for assessing concrete cracks [23,24], the aim of this study is to establish an in-depth understanding and quantitative relations useful for characterizing the surface notch, e.g. depth and degree of inclination. A series of simulations for wave motions to examine the behavior of R-waves of varying excitation frequencies towards different depths and degree of inclinations of surface notch were carried out. The outcome of this study is considered to provide further insights on identifying the critical parameters (WT and phase velocity) for quantification of correlations that lead towards establishing a reliable assessment method for concrete structures with similar defective conditions. The simulated R-waves results for different notch depths and inclination angles were then verified through experimental measurements.

2. Numerical simulations

The simulations were conducted by employing commercial software [25] that solves two dimensional (2D) elastic wave propagation problems by temporal acoustic interrogations based on the finite difference method in the plain strain case. The fundamental equation governing the two-dimensional propagation of stress waves in a perfectly elastic medium, ignoring viscous losses is as follows [25]:

$$\rho \frac{\partial^2 u}{\partial t^2} = \mu \nabla^2 u + (\lambda + \mu)\nabla(\nabla \cdot u) \tag{1}$$

where $u = u(x, y, t)$is the time-varying displacement vector, ρ is material density, λ is first Lame constant, μ is second Lame constant, $\nabla\cdot$ is the gradient of operator, $\nabla\bullet$ is the divergence operator, ∂ is the partial differential operator, t is the time. Eq. (1) is solved at discrete points with respect to the boundary conditions of the model, which include the input source that has predefined time-dependent displacements at a given location and a set of initial conditions, while wave propagation in each distinct homogeneous phase is solved according to Eq. (1) as well [26,27].

A two dimensional steel reinforced concrete model with a dimension of 500 mm (width) $\times$ 300 mm (depth) was proposed (see Fig. 1). All materials were considered elastic without viscosity components. The mechanical properties of the concrete and steel

Fig. 2. Photograph of accelerometer sensors arranged on the upper side of concrete specimen.

Table 2
Characteristics of simulated notches.

Type of defect	Depth, d (mm)	Length, l (mm)	Degree of inclination θ, (°) to the horizontal plane	Frequency of wave, f (kHz)
Surface notch	15, 30, 45, 60, 75, 90, 120, 150	30–150 at 30 mm increment	30, 90, 150	10, 20, 30, 40, 50, 60, 80, 100, 150