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Effect of Reinforcing Bar on Rayleigh Wave Propagation on Concrete Structures

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This paper presents results on a study of the Rayleigh wave scattering in concrete with a steel bar using transient elastic waves. To study the characteristics of the scattered waves induced by a steel bar in concrete, a three-dimensional finite element method was adopted. A case for elastic wave propagation parallel to the steel bar is discussed. The effect of the cover thickness and steel bar diameter on the Rayleigh wave was studied. To confirm the numerical investigations, a concrete specimen containing a steel bar was made, and corresponding transient elastic wave experiments were conducted. It is believed that the result of this study can serve as an important reference in a nondestructive evaluation of concrete with a steel bar.

Keywords : Concrete, Nondestructive test, Rayleigh wave, Reinforcement

1. INTRODUCTION

In the literature of the field of nondestructive evaluation, the ultrasonic pulse velocity (longitudinal wave velocity) of concrete specimen has been utilized to predict the strength of concrete (ACI 228.1R–03). Experimental observations have showed that the pulse velocity is related to the strength of concrete with a reasonable level of accuracy. Recently, Wu et al. (1995) proposed a method for determining the dynamic elastic properties of plain concrete specimens using transient elastic waves. In their method, the Rayleigh wave velocity was determined based on the cross correlation method, while the longitudinal wave velocity was determined by measuring the longitudinal wave–front arrival. The wave–front of the longitudinal wave was directly identified from the tangential component of the surface response. Through this method, the concrete dynamic elastic properties can be determined through a single transient elastic wave experiment with the utilization of a pair of horizontally polarized conical transducers.

In this paper, the influence of a steel bar on the transient elastic wave propagation with the steel bar is examined. To study the characteristics of the scattered waves induced by a steel bar in concrete, a three–dimensional finite element method was adopted. The case for elastic wave propagation parallel to the steel bar is discussed. The effects of the cover thickness and steel bar diameter on the Rayleigh wave measurement were studied and discussed. To confirm the numerical investigations, a concrete specimen with a steel bar was created, and corresponding transient elastic wave simulation were conducted.

2. Simulation

2.1 Modeling

In this paper, the aforementioned finite element method was adopted to simulate the case of a three–dimensional propagation of transient elastic waves in concrete with a steel bar (ABAQUS 2004). In this study, the concrete is assumed to be an isotropic

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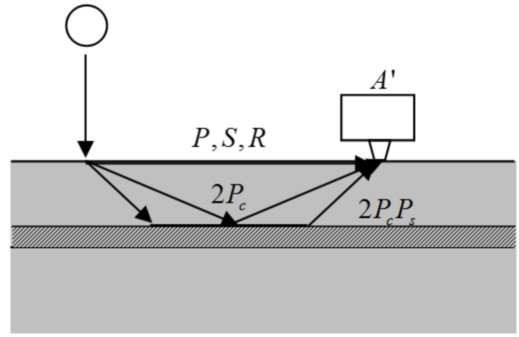


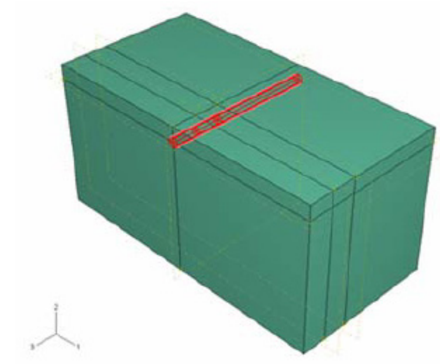
Fig. 1. Elastic wave path and test configuration

linearly elastic medium. In addition, the concrete is taken as homogeneous under the assumption of a large wavelength-to-aggregate size ratio. The density, longitudinal and transverse wave velocities of the steel bar were assumed to be 7,850kg/m^3, 5,920m/s and 3,230m/s, respectively. Those of the concrete were assumed to be 2,380kg/m^3, 4,220m/s and 2,500m/s.

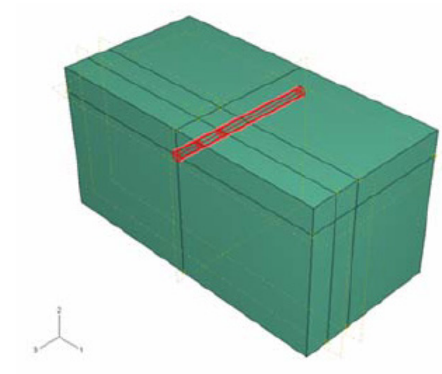
As shown in Fig. 1, the source-receiver line (the line that connects the impact source and the receiver) is parallel to the axial direction of the steel bar. The received wave signal consists of the skimming longitudinal (P) and transverse (S) waves, the Rayleigh wave (R), and those waves that are scattered by the steel bar. The received wave signals include the reflected ($2P_C$) and refracted ($2P_CP_S$) waves from the steel bar. Given that the wave speeds of the steel bar are greater than those of the concrete, at some distance away from the source the refracted wave ($2P_CP_S$) arrive earlier than the direct longitudinal wave (Wu et al. 2000).

Fig. 2 shows the geometry of the finite element model. The half-space was designed to have enough thickness and width to disregard the reflection from boundaries. The boundary condition was then meaningless by disregarding all reflection waves. Here, for conveniency, fixed boundary was assumed except the upper surface of the model. The red color cylinder is the reinforcing bars and the cover determines its location from the upper surface.

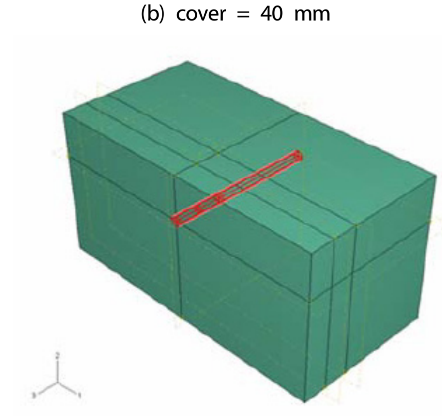
The left side of the model in Fig. 2 is assigned by symmetric boundary to the direction of cross section. At the center of the left-side surface, an impact induced wave was applied. The impact induced wave was mimicked by a half-sine 5



(a) cover = 20 mm



(b) cover = 40 mm



(c) cover = 80 mm

Fig. 2. Finite element modeling

square function ($\sin^5 t$) in 10N magnitude. The frequency of the surface wave is determined by the contact time (tc). The location of receiver, A' in Fig. 1, is 50mm apart from the impact location, where the lateral responses were recorded. In Fig. 3, it was expected that there would be differing central frequency and its wavelength according to the contact time. Therefore, the influence of steel bars depends on the contact time of

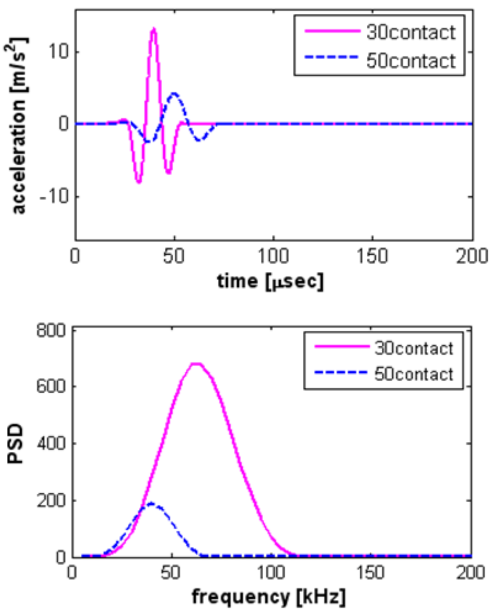


Fig. 3. Signals with different contact time

impact source, which controls the wavelength as a result.

Mesh refinement provides accurate results of simulation, however it inherently increases run time of software. In the purpose of simulating the wave propagation, the mesh size also controls to construct the completeness of waveform. Ihlenburg (1998) proposed the use of 5 to 10 elements to represent a wavelength, and Zerwer et al. (2002) minimized it as 4 elements. Moser et al. (1999) conservatively recommends the use of 20 elements for a wavelength developed in the media, which was validated in the previous study (Kim et al., 2002). Following the previous validation allows us to have the spatial and temporal resolution as belows:

$$t_i = \frac{1}{20 f_{\max}} \tag{1}$$

$$l_e = \frac{\lambda_{\min}}{20} \tag{2}$$

The temporal resolution is assigned as the time increment (t_i) for explicit analysis, and f_{max} is the maximum freqency of interests of stress wave. The spatial resolution imposes the size of element (l_e) with the minimum wavelength of interests (λ_{min}).

The contact time to be adopted in the simulation was 25, 30, 50, and 70μsec. For example, the wavelength considering the properties of concrete becomes 35.2mm when the shortest contact time of 25 μsec is considered. Therefore, the mesh size following Eq. (2) was then 1.76mm. The corresponding time increment following Eq. (1) was 0.17 μsec. The following model adopts 1mm mesh and 0.1μsec time increment to hold the accuracy of wave propagation.

2.2 Simulation results

Fig. 4 shows the tangential component (orthogonal to the surface) of the displacement signal received at the surface receiver for the testing configuration of Fig. 1. The source function of the single force utilized in all of the numerical examples is assumed to be half-sine 5 square function ($\sin^5 t$) in 10N magnitude. The distance between the source and the receiver is 50mm, and the contact duration of the steel ball tc is assumed to be 25μs. The diameter of the steel bar is 20mm and the concrete cover thickness (the distance between the concrete surface and the top of the steel bar) is 40mm.

The solid line shown in Fig. 4 represents a half-space response of the same testing configuration without the steel bar. In the half-space response, the wave signal after the Rayleigh wave decays gradually to zero. However, the presence of a steel bar in the concrete results in a clear oscillation after the Rayleigh wave.

In the following investigations the impact duration will be fixed at 25msec for simplicity. To understand the influence of

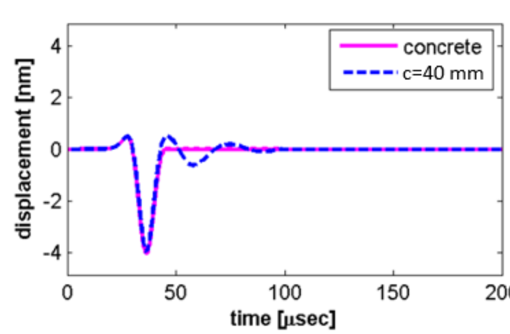


Fig. 4. Lateral displacement at the receiver

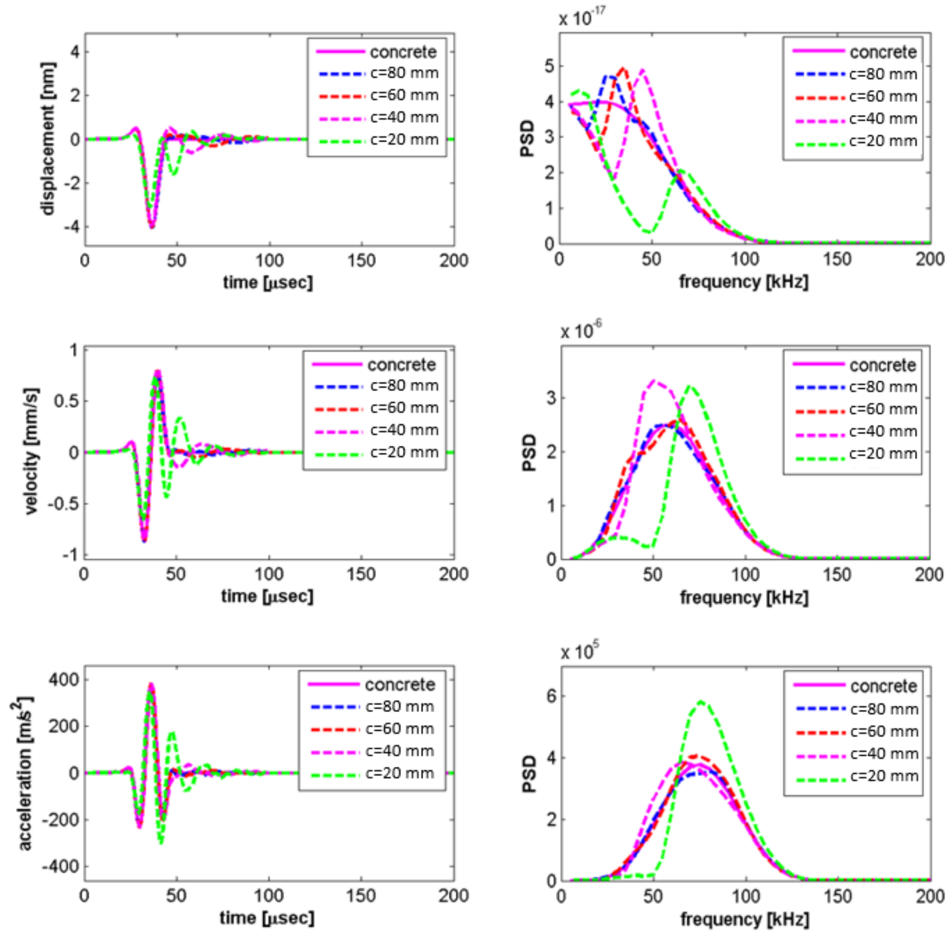


Fig. 5. The effect of concrete cover

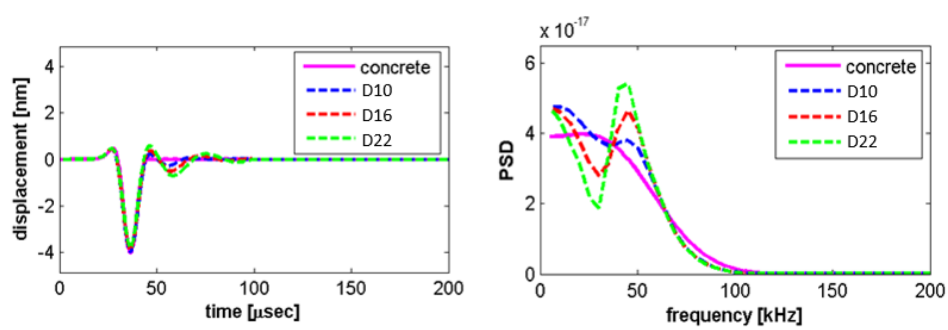


Fig. 6. The effect of the diameter of reinforcing bar

the cover thickness (c) and bar diameter (D) on the Rayleigh wave of concrete, a series of numerical simulations were performed. During the study of the cover thickness effect, one steel bar with a diameter of 20mm was placed in a concrete half space. The figures shown in Fig. 5 are the tangential components of the displacement, velocity and acceleration signals and the frequencies on the surface with the cover thickness varying from 20 to 80mm at an interval of 20mm.

In the simulation, the source-receiver line is directly on top of the steel bar along its axial direction. The distance between the impact source and the first receiver is 50mm. From a careful investigation of the figures in Fig. 5, it was noted that the smaller the cover thickness, the larger the influence of the scattering effect of the steel bar on the wave signals. As the cover thickness becomes sufficiently large (compared to the wavelength of the Rayleigh wave), the influence of the steel bar can be neglected.

To understand the effect of the steel bar diameter on the scattering of impact-induced elastic waves in a concrete half space with multiple parallel steel bars, a series of numerical simulations were performed. In the simulations, the cover thickness is 40mm and the diameters of the steel bars were 10, 16, and 22mm, respectively. As shown in Fig. 1, the source-receiver line is along the axial direction of the steel bars and is directly above the steel bar. The signals shown in Fig. 6 are the tangential components of the waves recorded at the receiver (50mm from the impact). The results in Fig. 6 show that the scattered (or reflected) signals from the steel bars with a larger diameter were added together, which then creates the signal oscillation after the Rayleigh wave lasts longer than it does when a steel bar with a small diameter is used. The amplitude of the long oscillation decreases as the diameter of the steel bars is decreased. It was noted that the trend of the signals according to the diameter in this simulation is clearer than the trend for the cover thickness.

3. Experimental analysis

3.1 Sample preparation

Table 1 shows the mix proportion used for producing the sample. The static modulus of the concrete was 31GPa and its density was 2,375kg/m^3. Note that the dynamic modulus of concrete is generally higher than the static modulus of elasticity.

The aforementioned trend on surface wave propagation was investigated with a concrete sample. The concrete sample has an embedded bar inside. The cover is controlled using a spacer having the thickness of 30mm. The 19mm-diameter

Table 1. Mixture proportions of concrete

Compressive strength	*W/C*	Unit weight (kg/m^3)			
		Water	Cement	Sand	Gravel
32 MPa	0.54	185	342	727	1012

Fig. 7. Form to produce a concrete sample

reinforcing bar was placed on the center line of a specimen. The cross section of the specimen was 200mm by 200mm, and its length was 600mm. Fig. 7 shows the form where a reinforcing bar was placed.

3.2 Wave measurement

Fig. 8 shows an experimental setup to measure the surface wave. Two accelerometers was used. The IEPE signal from the accelerometers were converted by the use of a signal conditioner. The converted voltage signal was then recorded in a oscilloscope and computer. An impact is utilized to generate a surface waves, and two receivers are used to monitor the motion of the concrete surface.

Based on the simulation results, the refections should be

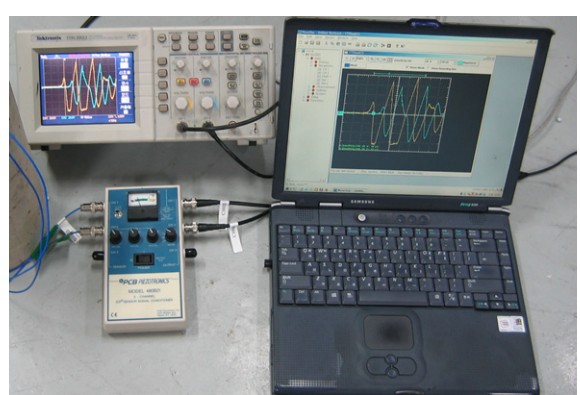
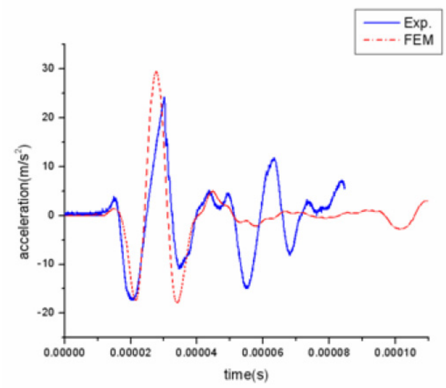
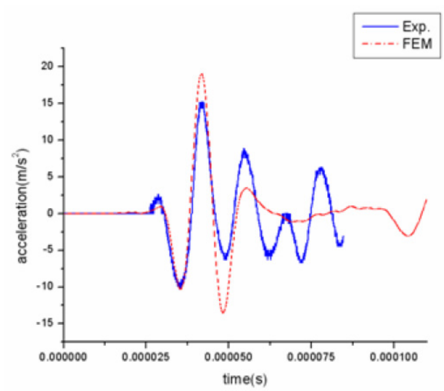


Fig. 8. Experimental setup



(a) 30 mm



(b) 60 mm from the location of an impact

Fig. 9. Waveform comparison

disregarded to investigate the surface wave. For the purpose, the signal was measured at 30mm and 60mm apart from the location of an impact. Fig. 9 shows the measured surface wave and its comparison with the simulation results. The intensity of the wave was resized to fit each other. On the first (positive), second (negative), and third (positive) peaks, two waveforms approximately coincide each other. The continued waveform of experimental measurements contains the reflections represented by spurious oscillation. The simulation traces the change of waveform when a reinforcing bar is embedded in concrete. Therefore, the investigation by the simulation is potentially extended to the experimental application.

4. Conclusions

In this paper, the elastic wave scattering in a concrete specimen with steel bar was investigated. A case for waves propagating parallel to the steel bar was examined. The results showed that the presence of a steel bar scattered the wave causing an oscillatory signal which was amended after the Rayleigh wave spike. Results of an investigation of the cover thickness and the diameter of the steel bar on the Rayleigh wave showed that if the cover thickness is large, the influence of the reinforcement on the Rayleigh wave is negligible. It was noted that the trend of the signals according to the diameter in this simulation was clearer than those for the cover thickness. To confirm the numerical investigations, a concrete specimen with an embedded steel bar was created and corresponding transient elastic wave experiments were conducted.

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