Detection of Water Ponding State on Steel Plate Using Guided Waves

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Abstract

In 1970s and later, steel plate bonding method has been widely adopted as a reinforcing method for reinforced concrete structures (hereinafter referred to as RC structures). However, after several decades passed, RC structures attached with steel plates have been re-deteriorated. It is an important theme to carry out effectively deterioration diagnosis of the RC structures for their proper maintenance and management. Especially, the influence of water on the integrity of RC structures is very crucial. In this paper, therefore, we propose a non-destructive inspection method with use of guided waves to evaluate the state of water ponding behind a steel plate. Firstly, dispersion curves of ultrasonic guided waves for a water-solid layered model are theoretically calculated. It is found that the dispersion property of guided waves for the layered model shows very strong sensitivity to water, and hence we can determine not only the existing of water ponding but the water layer thickness by investigating the dispersive property of guided waves. A swept frequency experiment of guided waves with two angle-beam ultrasonic transducers is then carried out to find the most efficient frequency for guided wave propagation, from which the thickness of a water layer can be estimated. Good agreement between experiment and theory is obtained, and thus a promising non-destructive testing method is developed for detection and evaluation of water ponding behind a steel plate.

Keywords: reinforced concrete structure, steel-plates-bonded concrete slab, water thickness, ultrasonic guided wave, dispersion property, phase velocities

1 Introduction

In Japan, more than 50 years have already passed since many highway bridges were constructed during the period of high economic growth. After starting the service, damage to highway bridges has occurred mainly in reinforced concrete slabs (RC slabs), and so far a lot of damage surveys and research have been carried out on reinforcement methods for RC slabs [1], [2]. A steel plate bonding method is one of reinforcing methods to improve the strength against a positive bending moment and enhance the durability by bonding a steel plate onto the bottom surface of a RC slab with epoxy resin and anchor bolts [3], [4]. However, after several decades elapsed since adoption of this method, re-degradation of the RC slabs has been reported due to increase of both the number and load of vehicles [5]. Furthermore, it has been reported that fatigue durability is remarkably impaired when water such as rainwater intrudes inside a RC slab in addition to wheel loads [6], [7]. The presence of water ponding on the steel plate is an important factor in the maintenance of RC slabs.

In principle, deterioration / damage situation of RC structure is visually inspected for cracked condition on concrete surface. For a concrete surface covered with the steel plate, however, the deteriorated state
cannot be checked directly by visual inspection. In that case, an impact hammer test has conventionally been used to detect a damage behind a steel plate [3]. But a hammering test depends mainly on the skill of an inspector and gives just qualitative results. Based on the demand to develop a more quantitative method, we developed a remote laser-based system using two-beam probing interferometry, in which elastic waves are generated on a steel plate by an impact laser beam and are observed by two laser probe beams [8]. The difference between two waves measured by two probe beams are recorded to eliminate the effect of low frequency vibrations due to traffic loads [9]. The laser-based method worked very well to detect a defect behind a steel plate, whereas it showed sometimes difficulty to distinguish between a debonding filled with water and no defect, and is hard to evaluate the quantity of water ponding [10].

In this paper, an ultrasonic method with use of guided waves is developed to evaluate the thickness of water ponding on a steel plate. Firstly, the dispersion curves of ultrasonic guided waves are calculated theoretically for a water-solid layered model with various thicknesses of water layer, and then the relation between excitation frequencies of guided waves and water thicknesses is derived and confirmed by experiment.

2 Characteristic equation of ultrasonic guided waves for water-solid layered model

As shown in Fig.1, consider a RC slab attached with a steel plate, for which water is stagnant on the steel plate in a damaged area. Assuming that there is a little clearance above water ponding, we can analyze the damaged zone as a two-dimensional layered model of water and steel as shown in Fig.2, where an ultrasonic guided wave propagates along the $x_1$-direction.

On the assumption that layered materials are homogeneous, isotropic and elastic ones, the longitudinal wave velocity $c_l^n$ and the transverse wave velocity $c_t^n$ in the layer $n$ ($n=w$ for water, $n=s$ for steel) are expressed by (1) and (2), respectively.

$$c_l^n = \sqrt{\frac{\lambda^n + 2\mu^n}{\rho^n}} \quad (n = w \text{ or } s), \quad c_t^n = \frac{\mu^n}{\rho^n} \quad (n = s)$$

(1), (2)

where $\lambda^n$, $\mu^n$ and $\rho^n$ are Lamé constants and density in the layer $n$, respectively. Note that a transverse wave velocity is not defined for the layer $n = w$, because of no transverse wave in water. By using the
wave velocities defined in (1) and (2), the potential functions \( \varphi^n \) and \( \psi^n \) of the wave motion in the layer \( n \) are expressed by

\[
\begin{align*}
\varphi^n & = A^n e^{i k x_1 + i \sqrt{k^2 - (c^n_2/\omega)^2} x_3} + B^n e^{i k x_1 - i \sqrt{k^2 - (c^n_2/\omega)^2} x_3} \quad (n = w \text{ or } s), \\
\psi^n & = C^n e^{i k x_1 + i \sqrt{k^2 - (c^n_2/\omega)^2} x_3} + D^n e^{i k x_1 - i \sqrt{k^2 - (c^n_2/\omega)^2} x_3} \quad (n = s),
\end{align*}
\]

where \( k \) and \( \omega \) are the wave number in the horizontal direction and the circular frequency, respectively, and \( A^n, B^n, C^n \) and \( D^n \) are unknown constant values. Substitution of \( \varphi^n \) and \( \psi^n \) into the following equations, the displacement components \( u^n_1 \) and \( u^n_3 \) and the stress components \( \sigma^n_{ij} \) can be expressed as follows.

\[
\begin{align*}
\varphi^n_3 & = \frac{\partial \varphi^n}{\partial x_1} - \frac{\partial \psi^n}{\partial x_3}, \\
\psi^n_3 & = \frac{\partial \varphi^n}{\partial x_3} + \frac{\partial \psi^n}{\partial x_1} \\
\sigma^{w}_{ij} & = A^n \left( \frac{\partial u^n_1}{\partial x_1} + \frac{\partial u^n_3}{\partial x_3} \right) \delta_{ij} + \mu^n \left( \frac{\partial u^n_1}{\partial x_j} + \frac{\partial u^n_3}{\partial x_i} \right)
\end{align*}
\]

where \( \delta_{ij} \) is Kronecker’s delta.

From the boundary conditions for each layer and the interface conditions between water and steel, we have

\[
\begin{align*}
\sigma^w_{33} & = 0 \quad (x_3 = 0) \quad (8) \\
\sigma^s_{33} & = 0, \quad \sigma^w_{33} = \sigma^s_{33} \quad u^w_3 = u^s_3 \quad (x_3 = h_w) \quad (9-11) \\
\sigma^s_{33} & = 0, \quad \sigma^s_{33} = 0 \quad (x_3 = h_w + h_s) \quad (12,13)
\end{align*}
\]

Equations (8)-(13) can be written in the following matrix form.

\[
\Sigma(k, \omega) \cdot C = 0 \quad (14)
\]

where \( \Sigma \) has the 6 \times 6 matrix components with functions of the horizontal wave number \( k \) and the circular frequency \( \omega \), and \( C^T = \{ A^w, B^w, A^s, B^s, C^s, D^s \} \). In order that (14) has a non-trivial solution \( C \neq 0 \), the characteristic equation of guided waves is obtained as follows

\[
|\Sigma(k, \omega)| = 0, \quad (15)
\]

from which the relation between \( k \) and \( \omega \) is obtained, and the phase velocity \( c_p = \omega/k \) can be determined.

**3 Estimation of water thickness on steel plate**

The phase velocity dispersion curves of the fundamental mode are shown in Figure 3. The thickness \( h_s \) of the steel plate layer is fixed to 4.5 mm which corresponds to the thickness of a common steel plate.
used in a real bridge, whereas the thickness $h_w$ of the water layer is set to various values of 0.0, 1.0, 2.0, 3.0 and 4.0 mm. Material constants used in the calculation are $\rho^w = 1000 \text{ kg/m}^3$, $c_{pw} = 1500 \text{ m/s}$, $\rho^s = 7850 \text{ kg/m}^3$, $c_{pl} = 5940 \text{ m/s}$ and $c_{ps} = 3200 \text{ m/s}$. As shown in Figure 3, for the phase velocity in the range of 3000 to 5000 m/s, it is obviously found that there is a difference among the dispersion curves of the fundamental guided waves, depending on the thickness of a water-ponding
layer. Therefore, there is a possibility that the water ponding layer thickness can be estimated by utilizing the difference in dispersive properties. In fact, if the phase velocity is fixed at a certain value, say, $c_p = 4000$ m/s, and the frequency is swept from low to high, then a guided wave will be excited at a different frequency, depending on the thickness of a water-ponding layer; e.g., 100 kHz, 140kHz and 200kHz for $h_w = 4.0, 3.0$ and 2.0 mm, respectively. Figure 4 shows the relationship between the thickness of water layer and the excitation frequency of guided waves for various phase velocities of $c_p = 3000, 4000$ and 5000m/s. Using the results in Fig.4, the thickness $h_w$ can be estimated from the excited frequency.

4 Comparison of experiment and analysis

To verify the estimation of a steel plate thickness using guided waves, proposed in the previous section, experiment on ultrasonic guided wave propagation was conducted. Photo 1 shows the specimen for a two layered model with water ponding on a steel plate. The propagation of a guided wave is measured using a pair of obliquely angled probes, as shown in Photo 2. Experimental conditions are listed in Table 1. A pair of obliquely angled probes attached on the bottom surface of the steel plate have the same nominal frequency of 500 kHz, and the interval between two probes is set to 100 mm. Tone burst signals of ten cycles are given to the probe for transmission, and the frequency is swept from 90 kHz to 300 kHz. In order to generate guided waves with the phase velocity of $c_p = 4000$ m/s at the critical angle, the oblique angles of both probes are fixed at $\theta = 43^\circ$, which is calculated using the Snell's law of $\sin \theta / c_{wdg} = \sin 90^\circ / c_p$, where $c_{wdg} (= 2728$ m/s) is the longitudinal wave velocity in the wedge of the obliquely angle probe.

Figure 5 shows waveforms of guided waves measured for various frequencies for the layered model with 2.0 mm thick water ponding on the 4.5mm thick steel plate. It is shown that among waveforms for various frequencies, the maximum amplitude is observed in the waveform at the frequency of 220 kHz. From the purple curve for the phase velocity $c_p = 4000$ m/s in Figure 4, the water layer thickness, corresponding to the frequency of 220 kHz can be estimated as 1.8 mm, which shows the estimation error of 0.2mm from the actual thickness 2mm. In the same way, the results obtained for the cases of $h_w = 3.0$ and 4.0 mm are also demonstrated by purple dots in Figure 4. From these results, it is concluded that by using our proposed guided wave method, we can discriminate the water status on presence or absence behind the steel plate, and furthermore estimate the water layer thickness within the accuracy of ± 0.5 mm.
Table 1: Experimental conditions for guided wave propagation in water-steel layered model.

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<td>Oblique Angle of probes $\theta$ [°]</td>
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Figure 5: Waveforms of guided waves measured for various frequencies for the layered model with 2.0 mm water ponding on the 4.5mm steel plate. The phase velocity is fixed at $c_p = 4000$ m/s by setting the oblique angle of probes to $\theta = 43^\circ$. 
5 CONCLUSION

With the motivation to inspect a damage state of RC slabs covered with a steel plate, an ultrasonic guided wave method was developed to estimate the thickness of water ponding on a steel plate. Using the dispersive properties of fundamental guided waves propagating in two layered media of water and steel, it was shown that the thickness of water would be estimated by experiment within the accuracy of ±0.5mm.

In this paper, a pair of obliquely angled probes of direct contact type were used for measurement of guided wave propagation. To make a more efficient measurement method, furthermore, we will develop a remote non-destructive method of guided waves, excited and received by a laser system and improve the accuracy of the method, in future. Also the guided wave method will be applied not only to the steel bonded RC slabs, but also to other types of bridge structures like a steel plate-concrete composite slab and a concrete filled I-beam grid floor, which have a steel plate with a different thickness from the steel plate bonded concrete slab.

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References


