Damage assessment of steel plates bonded onto concrete slabs by laser technique

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Abstract
In Japan, ‘Steel plate bonding method’, in which steel plates are bonded onto the bottom surface of slabs with anchor bolts and resin, has been widely used for more than several decades to strengthen damaged concrete slabs. In recent years, however, the repaired bridges have been damaged again due to the debonding of adhesive resin between steel plate and concrete. In this study, a laser method is developed for remote inspection of bond conditions of steel plates. Experiments are performed using a laser system to detect various artificial defects in specimens. Also dispersive properties of guided waves in layered media are investigated to find water existence behind a steel plate.

Keywords: steel plates bonding concrete slabs, remote inspection, two beam probing interferometry, guided wave

1. Introduction
In Japan, social infrastructure facilities were built in the period of high economic growth from 1960s to 1970s. With the passage of over 50 years, their maintenance has been attracting attention in these days. For example, a lot of fatigue damage occurred in reinforced concrete slabs (hereinafter referred to as RC slabs) of road bridges due to cyclic loading of traveling vehicles. The cost for inspection of structures and facilities is increased. ‘Steel plate bonding method’ has been widely used for over 30 years to strengthen damaged concrete slabs. In recent years, however, the repaired structures have been damaged again due to the debonding of adhesive resin between a steel plate and concrete1). Since the damaged portions covered by steel plates are not visible directly, a hammering test has been conventionally applied to evaluate the integrity of bonded steel plates. In the hammering test, however, works at high elevation are necessary and the test results depend on the skill of an inspector. Therefore, remotely measurable innovative technology like as a laser based method is required to be developed. Then the inspection of highway bridges will be dramatically improved in the aspects of safety and efficiency. In this study, laboratory tests are carried out for specimens with artificial damages, which are detected by a laser measurement with relatively low frequency band. Moreover, numerical results of dispersive analyses for ultrasonic surface waves in layered media are shown to find a water layer behind a steel plate in detail.

2. Measurement in the laboratory by laser
2.1 Specimens with artificial defects
The specimens are prepared to model a part of a concrete slab bonded with a steel plate as shown in Fig.1. The thicknesses of steel plate, resin and concrete are 4.5mm, 5mm, and 100mm, respectively. Three types of defects are installed, i.e., debonding between steel plate and resin, debonding between concrete and resin, and void between concrete and steel plate. For each type, the area size of the defect is set to 200x200 mm². Furthermore, in order to reproduce the state with stagnant water in slab, holes are made to pour water into defect zones.

2.2 Two-Beam Probing Interferometry
Taking account of the situation of a real bridge, the specimen is set at a position 8m apart from the laser system. A laser excitation is irradiated by a CO2 laser to produce impulsive surface forces vertical to the square portion of the $25 \times 35 \text{mm}^2$ of a steel plate as shown in the middle of Figure 1. On the other hand, vibrations generated on a steel plate surface are detected by other two laser beams applied at two detection points spaced apart by 50 mm with the center of the laser irradiated portion, and the difference between vibrations observed at two points is measured by means of the two beam probing interferometry. This is because a single detection laser is not applicable to the measurement of vibrations excited by a CO2 laser due to noise vibration with very low frequency of a bridge slab generated by traffic loads.

2.3 Laser measurement result

Figures 2 (a)-(e) show waveforms(top figures) and frequency amplitudes(bottom figures) observed for the specimens with (a) no defect, (b) a void between concrete and steel plate, (c) the void saturated with water, (d) debonding between steel plate and resin, and (e) the debonding saturated with water, respectively. In the cases of (b)-(e), the laser for excitation was centered at $(x, y)=(10,10)$ [mm], whereas in the case (a), the center of the laser excitation was located at $(x, y)=(200,10)$ [mm].

From comparison of Fig.2 (a) with Figs. 2 (b) and (d), it is seen that the waveforms in (b) and (d) show large amplitudes just after the laser excitation, while the waveform in (a) has very small amplitude, equivalent to the noise level. In Fig.2 (b), especially, large and complex waveforms continue for long time due to vibrations of the void part of the steel...
plate. With regard to frequency amplitudes, the specimen with no defect demonstrates the frequency components below only 1kHz, as shown in Fig.2 (a), whereas for the specimens with defects, frequency components up to 5kHz can be seen in Figs.2 (b) and (d). From Fig.2 (a) and (c), on the other hand, we can see little difference for the specimens with no defect and water-filled void in both waveforms and frequency amplitudes, although the frequency components in Fig.2 (e) show relatively large values even for high frequency range, which are different characteristics from Figs.2 (c). Hence it is concluded that it is sometimes very difficult to distinguish the cases with a water-filled defect and with no defect by means of the proposed laser technique.

Water behind a steel plate is a very important factor to judge the damage state of a bridge slab. To discriminate the water condition, therefore, another approach has to be developed, and so the dispersion property of guided waves in a layered media is analyzed in the next section.

3. Theoretical analysis for dispersion of guided waves

3.1 Models

In order to investigate the effect of water on dispersion of guided waves propagating in steel plate bonding area, two models are considered as shown in Fig.3. Fig.3 (a) is the model for a healthy part of steel plate bonding and Fig.3 (b) is a water-filled model with various water layer thickness \( h_w \) of 0.045, 0.09, 0.225 and 0.45mm. The properties of layered materials are listed in Table 1. We solve dispersion equations to determine the phase velocity and group velocity for guided waves in both layered models.

![Figure 3 (a) Perfectly bonded layer model of steel-epoxy-concrete and (b) layer model of steel-water-epoxy-concrete.](image)

<table>
<thead>
<tr>
<th>Material properties.</th>
<th>Steel</th>
<th>Water</th>
<th>Epoxy</th>
<th>Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal velocity ( (C_L) ) (mm/µs)</td>
<td>5.87</td>
<td>1.5</td>
<td>2.5</td>
<td>4.0</td>
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<tr>
<td>Transverse velocity ( (C_T) ) (mm/µs)</td>
<td>3.14</td>
<td></td>
<td>1.11</td>
<td>2.45</td>
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<tr>
<td>Density ( (10^3 \text{g/mm}^3) )</td>
<td>7.8</td>
<td>1.0</td>
<td>1.12</td>
<td>2.4</td>
</tr>
<tr>
<td>Thickness(mm)</td>
<td>4.5</td>
<td>( h_w )</td>
<td>5</td>
<td>( \infty )</td>
</tr>
</tbody>
</table>

3.2 Results

Figures 4 and 5 show phase velocities \( (C_p) \) and group velocities \( (C_g) \) for the first three modes of guided waves in two layer models, respectively. The vertical axes represent the dimensionless velocities \( C_p/C_T \) or \( C_g/C_T \), where \( C_T \) is the transverse velocity in steel, and the horizontal axes show the non-dimensional wave number \( k_H \), where \( k \) is the horizontal wave number, and \( H \) is the steel thickness. Obviously, the effect of water can be seen largely in the group velocity of Mode-1 for \( kH=1-3 \). Since the water effect is not influenced by the thickness of water layer, the change of the group velocity can be used to recognize the
existence of water layer. In contrast, the dispersive properties cannot be used to estimate the thickness of water layer, because the dispersion curves for models with various water thicknesses are not so much different even in the high mode of Mode 3.

4. Conclusions

In this study, the laser inspection system using a two-beam probing interferometry method was developed for remote inspection of bond conditions of steel plates. From waveforms and frequency amplitudes obtained in the laboratory experiments, we can distinguish three conditions of no defect, debonding between steel and epoxy, and void. However, it is found that it is sometimes difficult to detect a defect when a defect is fulfilled with water. Therefore, the dispersion properties of guided waves propagating in layered media were investigated and then the possibility to detect the existence of water layer was demonstrated.

Acknowledgements

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References