Lamb Waves for Detecting Delamination between Steel Bars and Concrete

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Abstract: The feasibility of detecting interface degradation and separation of steel bars in concrete beams using Lamb waves is investigated in this paper. The Lamb wave can propagate a long distance along the reinforcing steel bars embedded in concrete as the guided wave and is sensitive to the interface bonding condition between the steel bar and the concrete. The traditional ultrasonic methods for inspecting defects in concrete use reflection, transmission, and scattering of longitudinal waves by internal defects. These methods are good for detecting large voids in concrete, but they are not very efficient for detecting delamination at the interface between concrete and steel bars. In this study, a special coupler between the steel bar and ultrasonic transducers has been used to launch nonaxisymmetric guided waves in the steel bar. This investigation shows that the Lamb wave inspection technique is an efficient and effective tool for health monitoring of reinforced concrete structures.

1 INTRODUCTION

Corrosion is a common cause of degradation of reinforced concrete due to adverse environmental conditions, such as acid rain or deicing chemicals used during the winter maintenance operation. The degradation includes delamination or separation of concrete and steel bar at the interface. Numerous methods, such as radiography, laser profilometer, falling weight deflectometer, automated delamict, and ultrasonic methods, have been developed for detecting these corrosion-induced defects in reinforced concrete (ACI, 1997). The ultrasonic methods use reflection, transmission, and scattering of longitudinal waves by internal defects. In these methods, the signal amplitude and the time-of-flight measurement provide information about the internal defects in concrete. These methods are good for detecting large voids in concrete, but they are not very effective for detecting delamination at the interface between concrete and steel bars. In this study, generalized Rayleigh-Lamb waves and cylindrical guided Lamb waves have been used for inspecting concrete–steel interface. Four types of specimens have been fabricated and investigated.

2 EXPERIMENTAL METHODS

Four sets of specimens have been fabricated with 0% delaminated (or perfectly bonded), 25%, 50%, and 75% delaminated interfaces. To artificially fabricate the delaminated region, PVC pipes were placed around the steel bars before placing the concrete. The pipes were extracted 6 hr after the concrete had been placed into the wooden mold. The diameter of the steel bar is 22.2 mm (7/8 inch), and the dimensions of concrete are either 127 × 127 × 610 mm (5 × 5 × 24 inch) or 127 × 76 × 610 mm (5 × 3 × 24 inch) as shown in Figures 1 and 2. The inner and outer diameters of PVC are 23.6 mm (0.93 inch) and 26.7 mm (1.05 inch), respectively, as shown in Figure 2.

Two experimental setups are used as shown in Figure 3. One setup is for relatively low-frequency transducers (10 kHz ~ 500 kHz), and the second one is for relatively high-frequency transducers (>500 kHz). Different transducer positions and transducer types (1 MHz, 150 kHz, and 50 kHz) are used as shown in Figure 4. The diameters of the transducers are 12.7 mm (0.5 inch) for 1 MHz, 25.4 mm (1 inch) for 150 kHz, and 50.8 mm (2 inch) for 50 kHz transducers.

For efficient generation, propagation, and reception of ultrasonic waves, a number of transducer holders or
the coupling mechanisms between the transducers and the steel bars are used during the experimental investigation. Figure 4(a) shows an innovative coupler geometry for transmitters (Guo and Kundu, 1999, 2000). Using this transducer holder, the angle of transmitter was set at 0°, 8°, 16°, and 24°. The receiver was located at the other end of the steel bar as shown in Figure 4(a). Figure 4(b) shows another transmitter-receiver arrangement that can efficiently generate longitudinal Lamb modes in the bar. Figure 4(c) shows a third arrangement with a new coupler geometry that can hold the transducers at an inclination angle of 25°. This holder was placed on the concrete, while the first two (Figures 4a and 4b) were placed on the steel bar.

The transmitters were activated by a tone-burst excitation using WAVETEK function generator 395 and MATEC gated 310 amplifier for high-frequency (>500 kHz) transducers and ENI1040L amplifier for low-frequency (<500 kHz) transducers. The coupling mechanism between the transducers and the steel bar converts the compressional or P-waves generated by the transducers into different modes of the guided waves. The excitation frequency was continuously varied from a minimum to a maximum value within the bandwidth of transducers. A number of peaks, which correspond to the guided wave modes generated in the specimen, were recorded by the receiving transducer. The received signal amplitude was then displayed on an oscilloscope screen as a function of frequency. The curve produced in this manner is called the V(f) curve.

3 EXPERIMENTAL RESULTS

Figure 5 shows V(f) curves of four specimens that have 0%, 25%, 50%, and 75% delamination or separation. Here, the horizontal line gives frequency (kHz) and the vertical line gives the received signal amplitude.

![Fig. 4. Different transmitter-receiver arrangements.](image)

(a) Spherical-conical coupler (Guo and Kundu, 1999, 2000),
(b) direct contact at the bar ends, and (c) coupler between concrete and ultrasonic transducers resulting 25° incident and receiving angle.
Different results are plotted along the third axis, in the out-of-plane direction. For every specimen, experiments were carried out four times to study the consistency of the experimental results. From these curves, one can see that the percentage of delamination has a strong effect on the $V(f)$ curves. The received signal strength is maximum for the 24° inclination angle. Results are consistent for all angles of inclination.

Figure 6 shows the experimental $V(f)$ curves generated by the transmitter-receiver arrangement shown in Figure 4(b). Results are shown with 1 MHz and 150 kHz transducers in Figures 6(a) and 6(b), respectively. From these curves, one can see that the percentage of delamination has a strong effect on the $V(f)$ curves of Figure 6(b) but not on those in Figure 6(a). However, scattering in the experimental results is more in Figure 6(b). Hence, this transmitter-receiver arrangement is not as effective as the one shown in Figure 4(a).

Signals generated by the transmitter-receiver arrangement of Figure 4(c) are shown in Figure 7. Figure 7(a) gives the $V(f)$ curves of specimens with 5 inch thick concrete, and Figure 7(b) shows the $V(f)$ curves for 3 inch thick concrete specimens. From these curves, one can see that the percentage of delamination has a strong effect on the $V(f)$ curves in Figure 7(b) but not in Figure 7(a). Therefore, in this case the experimental results are dependent on the distance between the surface of the concrete and the delamination. Hence, the transmitter-receiver arrangement given in Figure 4(a) is probably more desirable than the one shown in Figure 4(c). However, when the bar ends are not accessible, then the arrangement shown in Figure 4(c) can be used.

Next, it is investigated which peak in the $V(f)$ curves of Figure 5 corresponds to which Lamb mode. To this aim, dispersion curves have been theoretically generated for cylindrical Lamb waves propagating in steel bars embedded in concrete. The theory of the dispersion function generation is briefly presented in the following section. Then experimental points (frequency values corresponding to the $V(f)$ peaks) are shown on the theoretical dispersion curves.

It should be noted here that the determination of the optimum angle for the transmitter-receiver arrangement as shown in Figure 4(a) is obtained experimentally from
Fig. 6. V(f) curves for four specimens when (a) 1 MHz and (b) 150 kHz transducers are placed at the bar ends as shown in Figure 4(b).

Fig. 7. V(f) curves for two sets of specimens shown in Figure 2. (a) 5 inch and (b) 3 inch thick concrete with embedded steel bars. 50 kHz transducers are placed on the concrete surface as shown in Figure 4(c).

documented in the literature (Pavlakovic et al., 1997; Pavlakovic and Lowe, 1997). Figure 8 shows the schematic diagram of a multilayered structure. In this figure, layers 1 and 2 represent different materials of a two-layered cylinder embedded in an infinite space that is denoted as medium 3. The partial waves (L+−, SV+−,

4 THEORETICAL MODELING AND RESULTS

Here, only the solution steps are presented for wave propagation in multilayered isotropic (elastic or viscoelastic) cylinders. The detailed derivation is well
SH+) combine to form guided waves. The problem geometry is axisymmetric and infinitely long. The stresses and displacements in a cylindrical or a flat layer can be expressed in terms of the amplitudes of all waves that can exist in that layer. Then the continuity of stresses and displacements at the common boundaries between adjacent layers as well as boundary conditions at outermost and innermost surfaces are satisfied to obtain one large global matrix equation that relates the wave amplitudes to the physical constraints (Knopoff, 1964; Randall, 1967; Schmidt and Jensen, 1985; Mal, 1988; Pavlakovic and Lowe, 1997).

\[
[G][A] = 0
\]  

(1)

where \([G]\) is the global matrix and \([A]\) is a vector of partial wave amplitudes. For nontrivial solution of \([A]\), the following condition must be satisfied:

\[
\text{Det}(G) = 0
\]

(2)

Equation (2) is called the characteristic equation. Roots of this characteristic equation give dispersion curves.

Dispersion curves are computed for the problem geometry shown in Figure 8, without considering any defect (Pavlakovic et al., 1998). The problem geometry is idealized as (1) a solid steel bar embedded in an infinitely thick layer of concrete and (2) a solid steel bar in a finite thick layer of concrete. In the first case, layer 1 is steel bar and layer 2 and medium 3 are considered identical to model the surrounding concrete. In the second case, layer 2 is the concrete, with a diameter of 143 mm (5.64 inch), and medium 3 is a vacuum. The density, velocity, and material damping used in the model are shown in Table 1. Here, \(\lambda\) is the wave number. The properties of concrete are measured experimentally by using 1 MHz longitudinal and shear wave transducers. The properties of steel are obtained from the handbook (Pavlakovic and Lowe, 1997), and the attenuation in steel is ignored. The phase velocity dispersion curves for the first, second, and third flexural modes are shown in Figure 9 for both these models. The solid dots represent the experimental results. Experimental values coincide with some, but not all, dispersion curves. Wilcox et al. (1999) explain why all Lamb modes between the upper and lower limits of the frequency sweep cannot be excited by the angle beam incidence and frequency sweep technique.

The solid square corresponds to the strongest peak position and matches very well with mode F(2,11) or F(3,11) at 1.065 MHz in Figure 9(a) and F(3,17) at 1.065 MHz in Figure 9(b). A careful examination of these modes at 1.065 MHz frequency shows that for these modes the strain energy is mostly confined within the steel bar but has nonzero value at the concrete–steel interface. However, the axial and radial displacements are not vanishingly small at the interface; hence, these modes are sensitive to the delamination at the interface.

This theoretical study helps us to identify Lamb modes corresponding to every V(f) peak. Then from the appropriate mode shapes one can identify the candidate modes for efficiently detecting the delamination at the interface between concrete and steel bar.

### 5 CONCLUDING REMARKS

In this paper, it is shown that the guided waves are sensitive to the separation or delamination at the interface.

| Table 1 |
| Material used to model a steel bar embedded in concrete |
|---|---|---|---|---|---|
| Material | Density \(\text{kg/m}^3\) | Long. Vel. \(\text{m/s}\) | Shear Vel. \(\text{m/s}\) | Long Att. \(\text{np/}\lambda\) | Shear Att. \(\text{np/}\lambda\) |
| Steel | 7932 | 5960 | 3260 | 0 | 0 |
| Concrete | 2090 | 3758 | 2152 | 0.186 | 0.229 |
between steel bar and concrete. A number of transducer-receiver arrangements have been tried out to identify the most efficient way of generating Lamb waves in the specimen for detecting interface delamination. Some of the proposed arrangements can effectively produce appropriate Lamb modes that are right candidates for detecting these defects. The proposed transducer-receiver arrangements can successfully inspect reinforced concrete beams for delamination at the steel concrete interface when the bars are accessible as well as when those are not. Sensitivity of the $V(f)$ peaks to delaminations can be justified by analytically computing the mode shapes. Snell's law is used to relate the experimental $V(f)$ peaks to the theoretical Lamb modes in the dispersion curves.

6 FUTURE STUDY

The present paper gives a proof of concept with a very simple specimen. For a more realistic investigation, the following two studies should be carried out: (1) experiments on specimens having multiple steel bars and stirrups to show the effect of multiple steel bars and stirrups on this inspection technique; (2) theoretical studies to predict the measured receiver response of the test specimen having a discontinuity at the interface for a known input signal. The multiple steel bars and stirrups will affect the strength of the received signal. Numerical techniques are necessary for analyzing complex geometries involving delamination.

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