Internal Discontinuity Detection in Concrete by Lamb Waves

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ABSTRACT

The feasibility of detecting anomalies or discontinuities in concrete beams using lamb waves is investigated in this paper. The traditional ultrasonic methods for inspecting discontinuities in concrete use the reflection, transmission, and scattering of longitudinal waves by internal discontinuities. Signal amplitude and time of flight measurements provide information about the internal anomalies in concrete. However, these methods are time consuming, and as will be shown in this paper, the traditional techniques often fail to detect imperfections, cracks, and voids. In this paper, the potential of the lamb wave technique to detect these anomalies in large concrete beams is investigated. The lamb wave technique is found to be reliable for detecting such anomalies.

Keywords: nondestructive testing, ultrasonic testing, concrete inspection, highway infrastructure, lamb waves.

INTRODUCTION

The existence of discontinuities in concrete structures is inevitable due to the low tensile strength of concrete (Park and Patilay, 1979). Invisible cracks in concrete create a major difficulty for monitoring structures. Therefore, it is important to estimate the proper time to repair, rehabilitate, or strengthen the structures. There is a growing need, therefore, for nondestructive testing (NDT) techniques to assess the condition of concrete structures to predict their future performance and monitor the repair process.

In spite of a number of NDT methods with sophisticated techniques available today, very few techniques are applicable for inspecting concrete structures efficiently. If applied properly, NDT can make a significant contribution towards evaluating and monitoring building safety as well as developing advanced construction technology. In addition, the ability to determine the anomalies of concrete structures is vital using NDT techniques is gaining popularity. The techniques that are currently used are primarily destructive and may require random coring, drilling, or otherwise removing part of the structure for testing. Some of the proposed NDT techniques are also cumbersome and may require sophisticated equipment. The technique presented in this paper gives an efficient NDT method to detect internal damage in concrete structures.

NDT OF CONCRETE

In spite of recent developments in testing equipment and technology, the use of NDT for testing concrete poses many difficulties. Compared to NDT of metal and metal based materials, NDT of concrete is a relatively immature discipline. The heterogeneous nature of concrete and the lack of a universally accepted technique for the NDT of concrete are two main reasons why concrete testing technology lags behind that for structural metals.

Concrete is a multiphase material consisting of coarse aggregate comprising particles of more than 5 mm (0.2 in) in diameter, fine aggregate, sand, and cement. The coarse granular structure, such as the relative concentration of the constituent particles, the degree of compaction, the moisture content and the nature and amount of anomalies present, gives rise to a high degree of acoustic scattering and, therefore, attenuation. For this reason, testing is usually done at kilohertz frequency range. In addition, the presence of steel rods gives rise to more complications for testing of reinforced concrete.

It is well known that there are existing codes or standards available to be used as guidelines for construction materials other than concrete. For instance, the American Society of Mechanical Engineers (ASME) code is commonly used for construction of boilers and pressure vessels, the American Petroleum Institute (API) code for construction in the petroleum industry, and the American Welding Society (AWS) code for the construction of steel structures. In such cases, the application of NDT is well specified. However, for civil construction involving concrete, there is no specific code or standard currently available that can be used as a guideline for the selection and application of suitable NDT methods or for the acceptance and rejection criteria. Due to these facts, the NDT community should have a wide knowledge of NDT applications, so that the appropriate NDT technique can be selected for use in a particular case.

Concrete experts have been interested in detecting internal anomalies and determining the properties of concrete by NDT techniques for many decades and a number of NDT techniques have been used for concrete testing. However, the visual testing techniques are still the most popular technique. Eighty percent of anomalies in concrete are found by visual inspections (Bray and Stanly, 1997). Among more advanced techniques, the ultrasonic pulse velocity technique has been standardized (ASTM C578-85). Advantages and disadvantages of this technique have been discussed by a number of researchers (Schickert and Wagonhousen, 1955; Jones, 1963; Malhotra and Einarson, 1991; Peppoles, 1994). Impact echo is also a popular ultrasonic technique for concrete testing (Krause et al., 1995; Presley and Johnson, 1994; Samboloe and Sistel, 1999). Other NDT techniques that have been used for concrete testing include acoustic emission, thermographic imaging, ground penetrating radar, laser interferometry, falling weight deflectometer, and laser profilometer.

A BRIEF REVIEW OF LAMB WAVES

Lamb waves, also known as guided plate waves, are elastic shear waves that are observed in plates. They are guided by the plate surface boundary, which acts as a waveguide. In other words, waves that propagate in a plate and satisfy the plate boundary conditions at both surfaces of the plate are known as lamb waves. There are an infinite number of lamb wave modes that could propagate in a plate. Different lamb modes can be generated by changing the signal frequency and the incidence angle of the transmitter. In a homogeneous plate, these modes can be classified into two main groups, according to the direction of the particle displacement: symmetrical and antisymmetrical modes. The wave velocity depends on the plate thickness, the frequency, the mode order, and the material properties.

Lamb waves propagate dispersively in the plane of the plate through the entire cross section. Lamb waves can also be launched in curved plates and pipes. Cylindrical lamb waves (or cylindrically guided waves) propagate along a pipe. This technology is being exploited by investigators to detect anomalies in pipes (Sikk and Barton, 1997; Avisel, 1998; Rose et al., 1998; Chen and Kundu, 1998; Guo and Kundu, 2000).
Advantages of Using Lamb Waves

With the conventional ultrasonic methods mentioned above, the area under inspection at any instant is limited to the region covered by the transducer. As a result, this method is very time consuming because the transducer must be placed on every point of the structure that is to be tested. In contrast, the lamb wave can be excited at one point of the structure and can propagate over a considerable distance depending on the wavelength. With the pitch catch arrangement, a receiving transducer kept at a distance can pick up the propagating signals that contain information about the integrity of the region between the two transducers. Therefore, the lamb wave testing technique can test a comparatively large region in a short time.

The entire thickness of the plate can be inspected by different lamb modes exciting different depths of the plate. From the mode shapes (stress and displacement profiles across the plate thickness) of individual lamb modes one can conclude which lamb mode should be sensitive to what depth of the plate. This makes it possible to detect anomalies near the surface as well as those inside the plate. Since each mode has its own mode shape, sensitivity of one mode to a specific anomaly at a depth will vary from that of another mode that has a different mode shape.

Detection of anomalies by conventional ultrasonic methods is based on the principle of ultrasound being reflected or scattered by the discontinuities. Therefore, the wavelength determines the smallest size anomaly that can be detected by a certain signal. Small anomalies are difficult to detect by signals of the low frequencies used for concrete testing. The lamb wave method is very promising for detecting small anomalies because anomaly detection does not depend only on the reflection of the waves from discontinuities, but on how the waves interact with them. This important interaction affects the voltage amplitude versus frequency V(f) curves in two ways. The peak amplitude corresponding to a particular mode may change because of the presence of a discontinuity or there may be a frequency shift of the peak amplitude. These were used by Mustafa et al. (1996) to image disbands in the tear strip in the pitch catch arrangement with the angle wedge transducers.

In summary, lamb waves are used because they offer an improved testing potential due to their multimode characteristics, sensitivity to different types of discontinuities, propagation over large distances, guiding character that enables them to follow curvature and reach hidden or burned parts and the capability of in situ testing.

EXPERIMENTAL INVESTIGATION

Under this investigation a number of specimens have been fabricated and tested by different lamb modes. The first step of lamb wave testing is to produce lamb waves inside the specimen. To this aim two transducers of 50 kHz resonance frequency are placed over an anomaly-free plate specimen. The transmitter is excited by a continuous wave or tone burst signal. The generated signal is amplified and then used for exciting the transmitter. The signal frequency is continuously varied between 25 and 200 kHz. The receiving transducer receives the signal after its propagation through the specimen. The received signal amplitude is then displayed on an oscilloscope screen as a function of frequency. The gate position is placed near the beginning of the received signal (the “gate” represents the time window for the received signal used to generate the V(f) curve). This is done to avoid collecting signals after those are reflected by other boundaries. Therefore, the early part of the received signal should be affected by the presence of the anomaly. The experimental setup is similar to the one developed by Ghosh and Kundu (1998) and Ghosh et al. (1998) and is shown in Figure 1.

Kundu et al. (1996), Maslov and Kundu (1997) and Yang and

![Figure 1 — Schematic of the experimental setup.](image)
Different dips along the frequency axis are observed when the transducer angle is changed because of the generation of different lamb modes. In this manner, by monitoring the transducer angles and dips of the reflected signal spectra, the lamb wave dispersion curves can be experimentally generated. For testing a plate with lamb waves, the transducer angle (θ) is set by selecting a specific lamb mode for testing. Then the transducer is placed and excited in the tone burst mode.

Finally, the signal frequency is set at a value corresponding to a lamb mode of interest. The specimen is then inspected with this transmitter receiver arrangement.

**P- and S-wave Speed Measurement in Concrete**

During concrete testing, low frequency waves should be used to decrease the attenuation of wave energy due to scattering at the mortar aggregate interfaces. If the wavelength of the propagating wave is less than the maximum size of the aggregate, the aggregate causes undesirable scattering of waves at mortar aggregate interfaces. As a result, a low frequency signal is needed for concrete testing. For example, when the wavelength of a wave is 10 mm, the concrete's P-wave speed is 4 km/s (2.5 m/s), frequencies lower than 4/(0.1) = 400 kHz should be used to reduce scattering and attenuation. The concrete appears homogeneous to the low frequency waves (Sanfilippo and Caliri, 1991).

The P- and S-wave speeds in concrete can be measured experimentally. The direct through transmission measurement was used for determining the P-wave speed. The S-wave speed was then obtained using the expression of the S-wave speed in terms of the Poisson's ratio and P-wave speed.

\[
V_{P} = \frac{V_{S}}{\sqrt{\nu (1-\nu)}}
\]

In our experiment the signal wavelengths for P-waves in the frequency range between 33 and 116 kHz is between 76 mm and 35 mm (3 and 14 m), that is, much larger than the aggregate size of 10 mm (0.4 m). For a lamb wave speed of 3.41 km/s (14 m/s), for the transducer inclination angle of 16 degrees, the signal wavelength is even larger. As a result, wave scattering at the interfaces between the aggregate particles and mortar is negligible. In addition, the acoustic impedance of aggregate and that of the mortar are very close; this further reduces the scattering at the mortar aggregate interface.

**Sample Preparation**

Two types of beam specimens measuring 1 by 0.3 by 0.2 m (39.4 by 11.8 by 7.9 in.) with different types of anomalies in various locations were cast. Each type was cast in duplicate. Internal anomaly geometry and location in the concrete beam are shown in Figure 3. The specimens are denoted as specimen one and two. Specimen one contained no anomaly on the left hand side. The signal from this region is denoted as the reference signal or anomaly free signal. On the right hand side, specimen one included a honeycomb anomaly. Specimen two contains an acrylic inclusion and a crack on the left and right hand sides, respectively. These concrete specimens are shown in Figure 3.

**V0 Curve**

Various internal frequencies and harmonic curves of lamb waves were generated using a constant frequency of 110 kHz. The receiver for lamb waves was placed between the transducer and concrete beam. The lamb waves were generated at the transducer, propagated through the concrete beam, and were observed at the receiver due to the Lamb waves scattering and attenuation.

**EXPERIMENTAL RESULTS**

Through this experimental setup, various lamb wave scattering techniques were used to inspect concrete. By placing transducers on the concrete beam, lamb waves are generated, and a receiver measures the lamb waves. This allows for the visualization of the lamb waves' propagation and reflection.
did not have any reinforcement. Proportions of mixes used to fabricate the beams are summarized in Table 1. The maximum aggregate size was 10 mm (0.4 in.).

The concrete beam specimens were cast in wooden forms. Specimen one was cast in three layers. Each layer was vibrated using an electric vibrator. The simulated anomaly was placed on the right-hand side of the beam. When the first layer was vibrated, a plastic cylinder 0.12 m (5 in.) in diameter and 0.25 m (10 in.) long was placed and filled with only aggregates (same size aggregates as the concrete mix but without any mortar). Then the second layer of concrete was placed and the plastic cylinder was removed after the second layer had been vibrated. In this manner a honeycomb anomaly zone was fabricated. Finally, the third layer was cast and vibrated.

Specimen two was cast in two layers. The simulated cracks were placed slightly above the midplane. Simulated anomaly positions and types are summarized in Figure 2. The artificial crack was fabricated by placing a water filled sealant bag measuring 0.18 m (5.9 in.) by 0.12 m (5 in.) filled with fast setting cement. After the specimen had cured, holes were drilled through the midplane of the beam and sealed with concrete. Then the specimen was cast and vibrated. Twenty four hours after casting, the beams were stripped and watered at regular intervals for 28 days. While casting the two specimens with internal anomalies, three more cylinders were also cast to measure the concrete properties. Concrete properties measured from these three cylinders by the standard 28 day compression test are shown in Table 2.

**V(f) Curve**

Variation of the received signal voltage as a function of the signal frequency is denoted as the V(f) curve. Changes in the V(f) curves are caused by the internal anomalies. A number of V(f) curves were generated in the region of the beam, keeping a constant distance of 0.2 m (7.9 in.) between the transmitter and the receiver to study the repeatability of the experiment. When both the transmitter and receiver are located on the same side of the concrete beam (Figure 1), then generalized lamb waves propagate from the transmitter to the receiver. V(f) curves generated by the generalized lamb waves show good consistency and sensitivity to discontinuities. Similar V(f) curves generated by the conventional through transmission technique lack both consistency and sensitivity to discontinuities.

**EXPERIMENTAL RESULTS**

**Through Transmission Technique**

V(f) curves generated by the conventional through transmission technique are shown in Figure 4. These curves are generated by placing the transmitter and the receiver on the top and bottom surfaces of the specimens shown in Figure 3. Hence, the transducers are located 0.1 m (12 in.) apart facing each other and the specimen is in between the two transducers. A thin film of petroleum jelly was used over the contact area between the transducers and the specimen. Figures 4a and 4b show some difference between the V(f) curves generated by the defective and nondefective zones. However, the curves are not consistent and the difference is not very clear. Only the cracked zone gives a noticeably weaker signal than the anomaly free zone (Figure 4b). Signals from the zones containing the honeycomb and the inclusion anomalies are very close to those from the anomaly free zone.

**Lamb Wave Technique**

The V(f) curves generated by the generalized rayleigh-lamb waves are shown in Figures 5, 6 and 7 for both defective and nondefective zones. One can see the noticeable difference between the V(f) curves from the defective and defect free zones, unlike the V(f) curves of Figure 4, obtained from the through transmission testing.

**Experimental Results for Specimen One**

V(f) curves for both anomaly free and honeycomb regions of specimen one are shown in Figure 5. The transducers were inclined at an angle of 15°. The inclination angle corresponds to a phase velocity of 3510 km/s (3.4 m/s) (see Equation 1). The V(f) curve for the 15° angle of incidence was generated several times to study the consistency of the results. Two
not change in the presence of discontinuities, but their amplitudes do. Another significant observation in this figure is that the crack gives a greater change in amplitude than the acrylic inclusion. The crack also gave a larger change of $V(f)$ in the through transmission testing (Figure 4b).

It is interesting to note that the peak near 79 kHz is strongest for the acrylic inclusion, weak but detectable for the honeycomb inclusion, and barely detectable for the crack. It should be also noted here that while discontinuities reduce the strength of most lamb modes, peak values corresponding to few other modes in fact increase in the presence of discontinuities, indicating that the geometry changes due to the presence of discontinuities help the propagation of some lamb modes.

$V(f)$ Curves for the Normal Incidence

The purpose of this testing is to show how an inclined transducer position can significantly improve the lamb wave testing. This testing was carried out in the anomaly-free and honeycomb zones of specimen one, using both water and petroleum jelly as the coupling medium. The experiment was repeated several times to see the consistency of the experimental results.

Normal Incidence with Water Coupling

Computed $V(f)$ curves are shown in Figure 7. Only one prominent peak near 53 kHz is observed. The peak amplitude is significantly affected by the presence of the honeycomb anomaly.

Normal Incidence with Petroleum Jelly Coupling

Figures 8 shows $V(f)$ curves over honeycomb and anomaly-free zones when petroleum jelly is used as the couplant. The experiments were carried out several times. Clearly, the difference

Experimental Results for Specimen Two

For specimen two, two prominent peaks near 53 and 116 kHz are observed, and shown in Figure 6. These peak positions are identical to those for specimen one. Weaker peaks are observed near 28, 79, 95, 150, and 172 kHz. The positions of the prominent peaks do

![Figure 5](image)

**Figure 5** — $V(f)$ curves over non-defective zone (continuous lines) and honeycomb region (dotted lines).

![Figure 6](image)

**Figure 6** — $V(f)$ curves over the non-defective zone (continuous), region containing the acrylic inclusion (dotted), and the cracked region (dotted).

![Figure 7](image)

**Figure 7** — $V(f)$ curves for transducers placed normal to the specimen surface with water used as the couplant; the continuous curves signify the anomaly-free zone; the dotted curve represents the honeycomb zone.

![Figure 8](image)

**Figure 8** — $V(f)$ curves over the non-defective zone (continuous curves) and honeycomb zone (dotted curves) when the transducers are in direct contact with the specimen. Petroleum jelly is used as the couplant.
between the $V(t)$ curves for defective and nondefective zones are much less prominent in this case. This is due to the fact that the applied stress between the transducer and the specimen affects the received voltage amplitude when petroleum jelly is used as the coupling agent. This is not the case for water coupling. As a result, fluctuations in the peak amplitude value are considerably greater when petroleum jelly was used as the coupling agent.

CONCLUSION

The main objective of this investigation was to study if Lamb waves can detect internal anomalies in large concrete beams. The experimental results show that it is possible to detect such anomalies. Three types of anomalies — honeycombs, acrylic inclusions and cracks — have been successfully detected by the Lamb wave technique. Superiority of the Lamb wave technique over the conventional ultrasonic technique has also been demonstrated.

It is also shown that water coupling gives better results than petroleum jelly coupling, and that the inclined transducer position is more efficient than the vertical position.

ACKNOWLEDGMENTS

This research was financially supported by the National Science Foundation under contracts number CMS-9000345 and CMS-9091382 and EPR grants W86N34-14 and EP-F2414/C110. The views presented are those of the writers and do not necessarily represent the views of the funding agencies. The writers would like to acknowledge the experimental help provided by P. Karpur of Allied Signal during this investigation.

REFERENCES


