INFO #: 13063265

UNIVERSITY OF ARIZONA
Ehsani, Mohammad

SHIP VIA: ARIEL 129.82.31.248

**Order No inst of Info

FILLED ON: 11/6/2002

Infotrieve, Inc.
7666 Market St.
Canton, MI  48187
Phone (734) 459-9699 ext 8 or (800) 422-4633
Fax  (734) 459-5280

SHIP TO: 4935 / 4935

UNIVERSITY OF ARIZONA
Ehsani, Mohammad

Ehsani@arizona.edu

Please contact us if you have questions or comments regarding this article
Email: service@infotrieve.com  Phone: (800) 422-4633

CUSTOMER INFO

FAX: 621-2560

ARTICLE INFORMATION

ACI MATERIALS JOURNAL

99(3):292-299.

Jung, Kandu, Ehsani
A New Nondestructive Inspection Technique fro

NOTES:

CCD  1250

SHIIP VIA  ARIEL 129.82.31.248

ORDER # -241623
BILLING REF  Faculty
ORDERED ON 11/5/2002
FILLED ON  11/6/2002

ATTENTION:  Ehsani, Mohammad
INFO # 13063265

This document is protected by U.S. and international copyright laws. No additional reproduction is authorized. Complete credit should be given to the original source.
A New Nondestructive Inspection Technique for Reinforced Concrete Beams

by Young-chul Jung, Tribikram Kundu, and Mohammad R. Ehsani

This paper investigated the feasibility of detecting internal defects (cracks, honeycombs, and inclusions) in reinforced concrete (RC) beams using ultrasonic guided waves. Experiments were carried out on full-scale beams. It is shown that for RC beam inspections, the guided wave technique was better than the conventional stress wave techniques. The difference between the ultrasonic signals from the good and defective regions of the concrete beam was found to be much greater for the guided wave technique in comparison to the through-transmission or reflection mode ultrasonic techniques carried out in the same frequency range. Another advantage of the guided wave technique is that the guided waves have multiple modes of propagation. This paper also discusses how to generate the most efficient guided wave mode by adjusting signal frequency and angle of incidence.

Keywords: cracking; reinforced concrete; tes.

INTRODUCTION

Random sampling of concrete, such as coring, drilling, or otherwise removing part of the structure to permit visual inspection of the interior has been traditionally used to investigate the health of concrete structures. In recent years, however, the need is growing for sophisticated and reliable nondestructive testing (NDT) techniques to assess the condition of concrete structures.

The technological development of NDT techniques for concrete structures lags behind that of metals, composites, and even biological materials. For example, 40 years ago, the technology of the ultrasonic inspection of the human body and that of concrete were at approximately the same level. Presently, however, the ultrasonic inspection of the human body is undoubtedly at a much more advanced level.

The existence of defects occurring from material imperfections, such as honeycomb or voids, and inclusions in RC structures initiates cracks that lower the load-carrying capacity of the element. Consequently, there is growing interest in developing nondestructive testing techniques to detect such defects in concrete structures.

Defects in concrete structures can be divided into two categories: external and internal. Most external defects that occur during the hardening stage of concrete can be easily found by visual inspection. These defects include shrinkage cracking, scaling (loss of surface mortar or mortar surrounding aggregate particles), spalling (removal of a portion of the surface concrete), and popouts (breakout of the surface of concrete). Internal defects such as honeycomb or voids, inclusions, internal tension cracks and corrosion of embedded reinforcement, however, cannot be detected by visual inspection. These invisible defects in concrete structures create a major difficulty in health monitoring of these structures. Hence, it is hard to estimate the appropriate time to conduct a repair, rehabilitation, or strengthening of the structures before the cracks reach a critical stage.

NDT methods that are used today for concrete inspection are visual inspection, stress wave methods for structures and deep foundations, nuclear methods, magnetic and electrical methods, penetrability methods, infrared thermography, and radar technique (ACI Committee 228 1998). Current stress wave methods include the ultrasonic through-transmission pulse velocity technique (Ndih and Malhoira 1991), ultrasonic echo (Alexander and Thornton 1989), impact echo (Sansalone 1997), spectral analysis of surface waves (Nazarian, Stokoe, and Hudson 1983), sonic echo (Rausche and Seitz 1983), impulse response (Davis and Hertlein 1990), impedance logging (Paquet 1991), crosshole sonic logging (Levy 1970), and parallel seismic technique (Davis 1995). All of these methods have been discussed in ACI 228.2R (ACI Committee 228 1998). None of these commonly practiced methods use guided waves for RC beam inspection that is proposed in this paper. Because the guided wave propagation characteristics in beams (Mukadi, Dutta, and Dunn 2001) are very similar to the Lamb wave propagation characteristics in plates, in this paper the terms, “guided wave” and “lamb wave” are used interchangeably.

LITERATURE REVIEW

Concrete experts have been interested in detecting internal anomalies and determining properties of concrete by NDT techniques for many decades, and a number of NDT techniques have been developed for concrete inspection. The visual inspection technique, however, is the most popular technique (Higgins 1981; Manning 1985). Among the more advanced techniques, only the ultrasonic pulse velocity technique has been standardized (ASTM C 597-83[91] “Standard Test Method for Pulse Velocity Through Concrete”) and the impact echo method has been developed to a stage where it can be standardized. Even with this standardization, the accuracy of most of its applications, including the strength assessment, is unacceptably low (Popovics, Komlos, and Popovics 1995).

Advantages and disadvantages of this technique have been discussed in the literature (Jones 1962; Malhoira and Carino 1991). Impact echo is also a popular ultrasonic technique for concrete inspection (Pessiki and Johnson 1994; Sansalone et al. 1998). A detailed description of the NDT techniques that have been used for concrete inspection has been reported in ACI 228.2R (ACI Committee 228 1998).

MS No. 01-338 received October 12, 2001, and reviewed under Institute publication policy. Copyright © 2002, American Concrete Institute. All rights reserved, including the making of copies without permission is prohibited by copyright laws. Permission for permitted reproduction will be granted for a fee. Permission to reproduce and circulate the material in any form is prohibited, unless permission is obtained from the copyright proprietor. Permission discussion will be published in the March-April 2003 ACI Materials Journal if received by December 1, 2002.
Concrete itself is a multiphasic material consisting of coarse aggregate comprising particles of more than 5 mm in diameter, fine aggregate, sand, water, and cement. The highly heterogeneous nature gives rise to a high degree of acoustic scattering and, therefore, attenuation. For this reason, the ultrasonic pulse velocity testing is usually carried out at low frequencies in the 50 to 250 kHz range. In addition, the presence of steel reinforcing bars introduces more complications in the testing of reinforced concrete members.

So far, only a few investigations have been carried out with ultrasonic signals to study the influence of reinforcement in concrete structures by relating the elastic wave speed to the amount and geometry of reinforcement in concrete. Due to the presence of reinforcing bars, the ultrasonic pulse velocity measured in reinforced concrete is found to be higher than that in plain concrete. This is because the pulse velocity in reinforcing bars (normally steel reinforcing bars) is 1.2 to 1.9 times faster than that in plain concrete. Jones and Faccarini (1969) concluded that parameters that affect the pulse velocity measurement are the proximity of the transducers to the reinforcing bars, the dimensions, number, and orientations of the reinforcing bars, and the pulse velocity in the surrounding concrete. This study showed that the reinforcing bars parallel to the direction of wave propagation have a stronger effect on pulse velocity than when the bars are normal to the wave direction. The distance between the transducers and reinforcement and the quantity of reinforcement are also important parameters. For heavily reinforced members, however, when the reinforcement is placed in two or more directions, the estimation of the pulse velocity is almost impossible. Because the presence of reinforcing steel significantly affects the pulse velocity measurements, it was recommended to choose path lengths that avoid the influence of the reinforcement. If that is not possible, then the pulse velocity needs to be corrected.

Chung (1978) and Bungey (1984) studied the pulse velocity correction factor in reinforced concrete. The wave velocity in reinforced concrete is lower than that of steel bar, but greater than the wave speed in the surrounding concrete. Reinforcing bar diameter influences the pulse velocity. Applying these research results to real structures, however, is not always possible because those studies assumed that the size and location of the reinforcement are known, which is not always the case for structures in the field. Furthermore, the pulse velocity in the field (steel or concrete) can be affected by age, weather, moisture, and overall condition of the structure. Avoiding the reinforced region is almost impossible without previous information about the structure.

**LAMB WAVE INSPECTION TECHNIQUE**

Most ultrasonic methods require transducers to generate compressional or shear waves. These sound waves illuminate only a small portion of the total volume of a large specimen under inspection, therefore, the transducer must be moved from one point to its neighboring point and then to the next to interrogate the entire volume. This is a time-consuming operation and it is easy to miss some damaged regions when every point is not inspected. The presence of reinforcing bars affects the test results significantly when applied to reinforced concrete members. The Rayleigh wave technique has been developed for inspecting pavements. This method avoids many difficulties associated with compressional wave techniques. However, because the Rayleigh waves excite only the near-surface regions, this technique has not been used to detect internal defects in concrete beams. Guided Lamb waves can also overcome the shortcomings associated with the compressional waves and can be used for beam inspection as outlined in this paper.

**What are Lamb waves?**

Lamb waves, also known as guided plate waves, are elastic stress waves that are observed in plates (Mal and Singh 1991; Rose 1999). They are guided by the plate surface boundary. In other words, two parallel plate surfaces work as the wave guide. Hence, waves that propagate in a plate and satisfy stress-free boundary conditions at both surfaces of a plate are known as Lamb waves. Contrary, Rayleigh waves satisfy the stress-free boundary conditions at only one surface of a solid. Lamb waves have an infinite number of modes corresponding to different types of vibration of the plate. Some modes have a large particle motion near the surface (high surface sensitivity), while others have more intense motion near the middle of the layer. Different Lamb modes can be generated by changing the inclination angle of the transmitter. In a homogeneous plate, these modes can be classified into two groups according to the direction of the particle displacement: symmetric and antisymmetric modes. The wave velocity depends on the plate thickness, signal frequency, mode order, and material properties.

Lamb waves propagate dispersively in the plane of the plate through the entire cross-sectional area. Guided waves can be also launched in beams, curved plates, and pipes. Wave propagation characteristics of guided waves in beams (having four surfaces) are similar to those of plates and hence, the guided waves in beams are often called Lamb waves (Mukadd, Datta, and Dunn 2001). Elastic waves in pipes propagate along a cylindrical geometry, instead of a flat geometry as in a flat plate. That is why guided waves in pipes are called cylindrical guided waves or cylindrical Lamb waves. Propagation characteristics of cylindrical guided waves are being explored by Guo and Kundu (2000, 2001) and other investigators (Rose, Jiao, and Spanner 1996; Alleyne and Cawley 1997) to detect defects in pipes. The guiding characteristic of Lamb waves enables them to follow curvature and reach hidden or buried parts, or both.

**RESEARCH SIGNIFICANCE**

Ultrasound-based traditional NDT methods are not very efficient for detecting internal defects because of the presence of reinforcing bars, internal aggregate, and microcracks that scatter ultrasonic signals in concrete. Dependence of the signal strength on the contact pressure is another drawback of the conventional ultrasonic nondestructive evaluation techniques for concrete inspection. Using guided waves can overcome many shortcomings associated with the traditional ultrasonic methods. This paper presents the guided wave technique specifically to detect internal defects in RC beams.
that contain information about the integrity of the region between the two transducers. Therefore, the Lamb wave inspection technique monitors a comparatively large region and requires less time.

The entire thickness of the plate can be inspected by exciting different modes that interrogate different depths of the plate. This makes it possible to detect defects near the surface as well as those inside the plate because each mode has its own sensitivity to each defect along the depth. For instance, Kundu et al. (1996) compared the longitudinal wave scanning (C-scan) technique and the Lamb wave scanning (L-scan) technique for composite plates and proved the superiority of the L-scan images over conventional C-scan images.

In addition, detection of defects by conventional ultrasonic methods is based on the principle of ultrasound being reflected or scattered by the defects. Therefore, the wavelength determines the smallest size defect that can be detected by certain signal. Small defects cannot be detected by signals of low frequencies that are typically used for concrete inspection. On the other hand, the Lamb wave method is more promising for detecting small defects because defect detection does not depend exclusively on the reflection of the waves from defects, but on how the waves interact with them. This important interaction affects the \( V(f) \) (voltage amplitude versus frequency) curves in two ways. The peak amplitude, corresponding to particular modes, may change because of the presence of a defect or a frequency shift of the peak amplitude.

In summary, Lamb waves are used because they offer improved inspection potential due to their:

- Multi-mode characteristics;
- Sensitivity to different types of flaws at various depths;
- Propagation over long distances;
- Guiding characteristics that enable them to follow curvature and reach hidden or buried parts, or both;
- Capability of in-place testing using only one surface of a structure; and
- Shorter inspection time.

**EXPERIMENTAL PROGRAM**

To produce Lamb waves in a concrete beam, two transducers (54 kHz central frequency) are placed over the beam 300 mm apart \( L = 300 \text{ mm} \) in Fig. 1(a). The tone-burst (single frequency continuous wave) excitation is then used to activate the transmitting transducer and generate the ultrasound. The excitation frequency is varied from a minimum to a maximum value within the bandwidth of the transducer. The receiving transducer receives the reflected signal after its propagation through the specimen (Fig. 1(a) and 2). The received signal amplitude is then displayed on an oscilloscope screen as a function of frequency. At certain signal frequencies, the received signal shows peaks that correspond to the Lamb waves generated in the beam \( V(f) \) curve in Fig. 2). The experimental setup is similar to the one developed by Ghosh and Kundu (1998) and shown in Fig. 2.

To generate the voltage amplitude-versus-frequency curve, or \( V(f) \) curve, the following parameter values are set:

- Starting frequency for the frequency sweep = 20 kHz;
- Frequency step size = 4 kHz;
- Final frequency = 180 kHz;
- The number of cycles generated at the starting frequency of the frequency sweep is 10. At higher frequencies, this number increases because more pulses are generated at higher frequencies for the same time of excitation;
- Acquisition mode is peak to peak, meaning that the
peak values, as a function of frequency, are plotted to generate the V(f) curves; and

- Signal and gate controls: The gate, or the receiving window, is positioned in the early part of the received signal, near the arrival time of the first signal, but after two or three cycles. The long tail of the signal is not recorded to avoid multiple reflected signals from the beam-ends.

Signals are collected by a data acquisition board with a 2 MHz sampling frequency. Note that the sampling frequency is 10 times the maximum frequency (180 kHz) of the recorded signal. This is needed for smooth recording of the received signal.

Inspection detail

Obtaining the dispersion curves is the first step necessary to find what signal frequency and angle of incidence can generate a specific Lamb mode. To do so, the P and S wave speeds of the reinforced concrete beam specimen must be determined. There is no simple method to find those values, however, because of the complex interaction between steel bars and concrete. The pulse velocity method cannot be applied because of the presence of steel bars. One can follow Jones and Facacaro (1969) to approximate these values.

If one can satisfy \( L_3/\sqrt{L_3} \) between 1/12 and 1/6, and \( c/\sqrt{L_3} \) between 1/4 and 1/5, then the P and S wave speeds in the reinforced concrete will be the same as plain concrete, within a maximum error of 8% (Jones and Facacaro 1969). \( L_3 \) is the total path length through steel, and \( c \) and \( L \) are shown in Fig. 1.

\[
L_3 = \sum_{i=1}^{n} Q_i
\]  

where
\[
Q_i = \text{diameter of the } i\text{-th steel bar;}
\]
\[
L = \text{total path length; and}
\]
\[
a = \text{distance between transducer and reinforcement.}
\]

Determination of suitable incident angle

Theoretical approach—Because different modes have different regions of sensitivity through the thickness of the material, selection of the appropriate mode is important for efficient inspection. This can be done by first computing dispersion curves and mode shapes. Dispersion curves, however, are very sensitive to the material properties. Because there are uncertainties in the material properties of the reinforced concrete beam, the optimum angle and frequency are obtained experimentally.

Experimental approach—By generating the V(f) curves for different angles of incidence, the received signal amplitude (as a function of signal frequency) and incident angle (transducer inclination angle) can be obtained experimentally for the setup shown in Fig. 1(a). Figure 3 shows how the received signal voltages amplitude varies with the incident angle and signal frequency. From Fig. 3, it can be seen how the received signal strength increases at low frequencies and large incident angles (20 to 40 degrees). The transducer resonance frequency is 50 kHz; that is why at higher frequencies (>125 kHz), the signal strength is almost zero. The signal also attenuates quickly at higher frequencies. It should be noted in Fig. 3 that near 100 kHz, a relatively strong mode exists at higher angles. This high-frequency mode is found to be very stable and consistent. After repeated experiments, it was concluded that at a 25-degree angle of incidence, a strong and reliable Lamb mode near 100 kHz can be generated in the reinforced concrete beam.

SAMPLE DESCRIPTION AND EXPERIMENTAL RESULTS

Plain concrete beams were inspected by Jung, Kundu, and Ehsani (1999) using Lamb waves. That investigation showed that the Lamb wave technique is superior to the conventional ultrasonic through-transmission and reflection mode inspection techniques for detecting defects in plain concrete. The main goal of the present paper is to investigate if Lamb waves can be used to inspect internal damages in steel RC beams. The experimental results will show that it is possible to detect defects in large RC beams by using Lamb waves.

In an earlier study (Jung, Kundu, and Ehsani 1999, 2001) on plain concrete beams (without any reinforcement), three types of defects (crack, honeycomb and plexiglas inclusion) were successfully detected by the Lamb wave technique. It was also shown in that study that water-coupling produces better results than Vaseline-coupling. An inclined transducer position is more efficient than a vertical position.
Table 1—Properties of mixtures used to fabricate beams

<table>
<thead>
<tr>
<th>Ingredients</th>
<th>Amount, kg</th>
<th>Ingredient description</th>
<th>Mixture ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>298.5</td>
<td>Low alkali</td>
<td>0.166</td>
</tr>
<tr>
<td>Water</td>
<td>140.5</td>
<td></td>
<td>0.078</td>
</tr>
<tr>
<td>Sand</td>
<td>624.5</td>
<td>Standard surface; dry</td>
<td>0.348</td>
</tr>
<tr>
<td>Rock</td>
<td>728.5</td>
<td>10-mm maximum size</td>
<td>0.406</td>
</tr>
<tr>
<td>Water-reducing admixture</td>
<td>1.2</td>
<td>WRDA-64</td>
<td>0.002</td>
</tr>
<tr>
<td>Total</td>
<td>1792</td>
<td>Standard mixture</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Table 2—Experimentally obtained material properties of three concrete cylinders made from above concrete mixture

<table>
<thead>
<tr>
<th>Material properties</th>
<th>Specimen 1</th>
<th>Specimen 2</th>
<th>Specimen 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-wave speed, km/s</td>
<td>4.02</td>
<td>4.06</td>
<td>4.03</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.22</td>
<td>0.24</td>
<td>0.19</td>
</tr>
<tr>
<td>S-wave speed, km/s</td>
<td>2.40</td>
<td>2.38</td>
<td>2.49</td>
</tr>
<tr>
<td>Density, kg/m³</td>
<td>2195</td>
<td>2160</td>
<td>2186</td>
</tr>
<tr>
<td>Young's modulus, GPa</td>
<td>2.30 x 10⁶</td>
<td>2.29 x 10⁶</td>
<td>2.45 x 10⁶</td>
</tr>
</tbody>
</table>

Similar defects in reinforced concrete beams are investigated in this paper.

Sample preparation

Reinforced concrete beams with dimensions 305 x 203 x 1016 mm were fabricated. Longitudinal reinforcement consisted of four 965-mm-long No. 7 Grade 60 bars; transverse reinforcement was comprised of 254 x 152 mm No. 3 Grade 40 stirrups placed at 137 mm spacing (Fig. 4(a)). Internal defect geometry in the reinforced concrete beam is shown in Fig. 4(b). Two beam specimens are denoted as RC1 and RC2. Specimen RC1 contained no defect on the left half, and a honeycomb defect on the right half of the beam. An artificial crack was fabricated on the right half of RC2, and the plexiglas inclusion (to simulate foreign material inclusion) was placed on the left half. Properties of mixtures used to fabricate the beams are summarized in Table 1. The maximum aggregate size was 10 mm (3/8 in.).

The RC beam specimens were cast in wood forms. RC1 was cast in three lifts. Each layer was vibrated with an electric vibrator. The simulated defect was placed on the right side of the beam. When the first layer was vibrated, a plastic cylinder (127 mm [5 in.] diameter and 254 mm [10 in.] long) was placed and filled with only aggregates (same size aggregates as the concrete mixture, 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 defect zone was artificially fabricated. Finally, the third layer was placed and vibrated.

RC2 was cast in two layers. The simulated crack was placed slightly above the mid-plane. Simulated defect positions and types are summarized in Fig. 4(b). The artificial crack was fabricated by placing an air-filled Ziploc bag (152 by 127 mm [6 x 5 in.]) inside concrete. After the specimens were cast, they were covered with plastic sheets to minimize moisture loss. Twenty-four h after casting, the forms were stripped and the specimens were moist-cured for 28 days. Concrete compression tests for standard 28-day cylinders were carried out to find the material properties that are shown in Table 2.

Fig. 4—(a) Positions of steel reinforcing bars and stirrups in reinforced concrete beams of dimensions 305 x 203 x 1016 mm (12 x 8 x 40 in.); and (b) geometry of concrete beams and internal defects, and their locations in plain concrete beams (Note: Length units in mm).

Lamb wave technique

The V(f) curves generated by the guided waves are shown in Fig. 5 and 6 for the plain concrete beam and for the reinforced concrete beam, respectively. V(f) curves for both defective and defect-free zones are presented. In Fig. 5, multiple V(f) curves over defective and defect-free zones are plotted side by side, then those curves are connected to generate a surface as shown in the three-dimensional plots of Fig. 5. Multiple curves are generated by recording the received signals several times for the same transmitter-receiver arrangement. A 300 mm distance between the transmitter and the receiver is kept constant for all Lamb wave experiments. The experimental scattering may be attributed to the change in humidity and other surrounding environmental conditions. For each plot along the axis marked "No of tests," the first half of the tests are over the defect-free region and plotted in the rear; the second half of the tests (plotted in the front) are over the defective region. It is noted that some variability exists from one experiment to the next. There is a noticeable difference, however, between the V(f) curves from the defective and the defect-free zones. Clearly this difference is much stronger than the experimental scattering that exists from one V(f) curve to the next, over the defect-free as well as the defective regions.

Experimental results for RC beams

The V(f) curves for both defect-free and defective regions of RC beams (RC1 and RC2 of Fig. 5(b)) are shown in Fig. 6. The transducers were inclined at an angle of 25 degrees and the V(f) curves were generated a number of times to study the consistency of the results. The inclination angle corresponds to a phase velocity V_p = 5.41 km/s (obtained from Snell’s law, V_p = V_c sinθ, where V_c = compressional or P-wave speed in the coupling medium). V(f) curves are plotted as three-dimensional plots in Fig. 6. In the three-dimensional plots along the axis marked "No of tests," the first half of the tests are over the defect-free region; the remaining half of the tests (plotted in the front) are over the defective region.
LAMB WAVE MEASUREMENT (PLAIN CONCRETE)

Concrete Beam: Defect-free and Honeycomb

Amplitude vs. Frequency (kHz)

# of tests: 10, 20, 30, 40, 50

Concrete Beam: Defect-free and Creep

Amplitude vs. Frequency (kHz)

# of tests: 10, 20, 30, 40, 50

Concrete Beam: Defect-free and Inclusion

Amplitude vs. Frequency (kHz)

# of tests: 10, 20, 30, 40, 50

Fig. 5—V(f) curves shown as three-dimensional plots over defect-free, as well as defective regions, in plain concrete beams. Along axis marked “# of tests,” first half of tests are over defect-free region and plotted in rear; second half of tests (plotted in front) are over defective region. Note drastic reduction in peak values over defective region.

LAMB WAVE MEASUREMENT (REINFORCED CONCRETE)

Reinforced Concrete: Defect-free and Honeycomb

Amplitude vs. Frequency (kHz)

# of tests: 10, 20, 30, 40, 50

Reinforced Concrete: Defect-free and Creep

Amplitude vs. Frequency (kHz)

# of tests: 10, 20, 30, 40, 50

Reinforced Concrete: Defect-free and Inclusion

Amplitude vs. Frequency (kHz)

# of tests: 10, 20, 30, 40, 50

Fig. 6—V(f) curves shown as three-dimensional plots over defect-free, as well as defective regions, in reinforced concrete beams. Along axis marked “# of tests,” first half (1 to 10) of tests are over defect-free region and plotted in rear; second half (11 to 20) of tests (plotted in front) are over defective region. Note drastic reduction in peak values over defective region.

These three-dimensional plots visually show variations in the peak values at different frequencies arising from multiple tests; they also show how these peak values are drastically reduced in the presence of defects. Two strong distinguishable peaks—one at 53 kHz and the second one at 116 kHz—are observed. The wavelengths corresponding to these two Lamb modes are 102 and 46.6 mm, respectively. Clearly the maximum aggregate size (9.5 mm [3/8 in.]) is much smaller than the wavelength. Hence, the propagating waves do not see these aggregates as the heterogeneity in the medium.

Wenker peaks are observed at a few other frequencies. These V(f) curves clearly show that the amplitudes of the signal are significantly reduced due to the presence of defects inside the specimen. The positions of the prominent peaks, however, are not changed because of the presence of defects.

It is for this reason that even an approximate measure of the amplitude of the received pulse is often of value in detecting the presence of voids. Another important observation in this figure is that, in comparison to the honeycomb or Plexiglas inclusion, the crack gives a greater change in amplitude.

V(f) curves for both defect-free and defective regions of RC beams (RC 1 and RC 2 of Fig. 4(b) generated by the conventional ultrasonic method (Fig. 1(b) and (c)) are shown in Fig. 7 and 8. For Fig. 7, the transducers were placed in the pitch-catch arrangement side-by-side on top of the RC beam with Vaseline coupling (Fig. 1(b)). For Fig. 8 the transducers were placed on the top and bottom of the RC beam with Vaseline coupling to generate through-transmission ultrasonic signal in the beam (Fig. 1(c)). The V(f) curves have been generated a number of times to study the consistency of the results.

Figures 7 and 8 show that defects affect the signal to some extent; the difference between the V(f) curves over defective and defect-free regions, however, is not as clear and consistent as that in Fig. 6.

CONCLUSIONS

Lamb wave testing on reinforced concrete was carried out to study the applicability of the Lamb wave technique when inspecting large RC beams. The experimental results show that it is possible to detect defects in a large RC beam using Lamb waves. Three types of defects (honeycomb, Plexiglas inclusion, and cracks) have been successfully detected by the Lamb wave technique. The presence of defects does not change the phase velocity of the strong Lamb modes significantly, but the strengths of some Lamb modes are greatly reduced by the defects.

The key conclusions that can be drawn from this study on RC beams are:

- The Lamb wave technique gives stronger differences in the ultrasonic signal strengths from the defective and defect-free regions in comparison to the conventional ultrasonic through-transmission and reflection mode pulse-echo inspection techniques.
- Defects in RC beams can be detected by this technique without complex arrangements of sensors and having no previous knowledge about the reinforcement locations.

ACI Materials Journal/May-June 2002

297
ULTRASONIC TESTING (INDIRECT MEASUREMENT)

Fig. 7—(a) Defect-free and honeycomb; (b) defect-free and crack; and (c) defect-free and inclusion. Vf(1) curves shown as three-dimensional plots over defect-free, as well as defective regions, in reinforced concrete beams. Along axis marked "# of tests," the first half of tests are over defect-free region and plotted in rear; second half of tests (plotted in front) are over defective region. Transmitter and receiver are placed side-by-side on same surface of beam (See Fig. 1(b)). Compared to Fig. 6, this is much more noisy, and signals from defective regions cannot be clearly distinguished from those from defect-free regions.

- Since Lamb waves propagate over a long distance, this technique is faster and less expensive compared to the conventional ultrasonic techniques; and
- Correct angle of inclination of the transducers is important. The optimum angle can be obtained experimentally.

ACKNOWLEDGMENTS

This research was carried out under NSF Grants CMS 9800345 and CMS 9805182. The views expressed are those of the authors and do not necessarily represent the views of the funding agency.

REFERENCES


Jones, R., 1962, Non-Destructive Testing of Concrete, Cambridge University Press.


Kundu, T.; Maslov, X.; Karpur; P.; Mastakes, T. E.; and Nicolaua, P. D.,

ACI Materials Journal/May-June 2002
1996, "A Lamb Wave Scanning Approach for Mapping of Defects in (0/90)
Titanium Matrix Composites," *Ultrasonics*, V. 34, pp. 43-49.
Prentice Hall, N. J.
Testing of Concrete*, CRC Press.
Manning, D. G., "Detecting Defects and Deterioration in Highway 
Structures," *National Cooperative Highway Research Program Synthesis 
of Highway Practice 118*, July.
Guided Waves in a Layered Plate with Rectangular Cross Section," 
*Proceedings of the 7th ASME NDE Topical Conference*, C. Darvesh 
Method," *Handbook on Nondestructive Testing of Concrete*.
Nazarian, S.; Stokoe, K. H., II; and Hudson, W. R., 1983, "Use of 
Spectral Analysis of Surface Waves Method for Determination of Moduli 
and Thickness of Pavement Systems," *Transportation Research Record 
Ecole des Ponts et Chaussees, Paris, France, Mar.
Pesslki, S., and Johnson, M., 1994, "In-Place Evaluation of Concrete 
Strength Using the Impact Echo Method," *New Experimental Techniques 
for Evaluating Concrete Material and Structural Performance*, SP-143, D. J. Stevens and M. A. Lisa, eds., American Concrete Institute, Farmington 
ISO 8047 (Entwurf) to Several Standards on Determination of Ultrasonic 
Pulse Velocity in Concrete," *Proceedings, International Symposium on 
Rausch, F., and Selz, J., 1983, "Integrity Testing of Shafts and Caisson, 
Specialty Session on Shafts and Caissons," ASCE Annual Convention, 
University Press.
Sansonone, M.; Lin, J.-M.; and Streett, W. B., 1998, "Determining the 
Depth of Surface-Opening Cracks Using Impact-Generated Stress Waves 
and Time-of-Flight Techniques," *ACI Materials Journal*, V. 95, No. 2, 
Mar.-Apr., pp. 168-177.