THE BEHAVIOR OF ULTRASONIC WAVES PROPAGATING IN CONCRETE USING THE ULTRASONIC-PULSE METHODS TO MEASURE THE DEPTHS OF CRACKS IN CONCRETE

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Abstract: With a system of two sensitive accelerometers connected to a high-resolution of oscilloscope, the paper proposed an arrangement of accelerometers to monitor the pulse waves generated by an ultrasonic transducer when performing a surface measurement on concrete. The velocities of the logitudinal wave (the P-wave) and the Rayleigh wave (the R-wave) were estimated by reading the responses of the wave in time domain. The results were in a good agreement with the estimated P-wave velocity by a direct measurement using the ultrasonic apparatus. A similar arrangement was performed on concrete cracks to predicted the depths. The results were very close to the actual depths with errors well within ±1 cm.

Keywords: Ultrasonic, Nondestructive, Cracks, Elastic Wave, Rayleigh Wave

1. INTRODUCTION

Recently, there has been growing interest in using the transient elastic stress wave to solve some of the non-destructive testing (NDT) problems of structures. Martin and Forde[1] used hammers to generate pulse wave to study the concrete properties. The impact hammers they used were steel tipped, and the receivers were cylindric ultrasonic transducer. Wu *et al*[2-3] used a small steel ball to generate pulse wave to determine the concrete properties and the depth of surface-breaking crack in concrete. They also utilized the same way to generate wave, and adopted a heterogenous finite difference formulation to detect the depths of surface-breaking crack in metal material and the cavity or inclusion in concrete[4-5]. The receivers used were NBS conical transducers[6] with tip diameter about 1.5 mm. These transducers basically consist of a piezoelectric element.

Carino and Sansalone began work on the impact-echo method in 1983 for strength determination and flaw detection in concrete. Following the method, they and their co-workers[6-12] developed the techniques to dectect the the thickness, cracks, voids, embedd steel bars and bond quality in many kinds of concrete structures, and gained many achievements. Like the ones Wu used, the wave generator used for the impact-echo method are also a small steel ball and the receivers are the NBS conical trasducers. One important factor for the method to be succesful is the contact time of the impact steel ball on concrete. For normal concrete, the required contact time ranges from about 15 to 80 μs such that the stress waves have range of frequencies to be less than about 80 kHz, and be able to penetrate concrete up to 1.5 m.

The ultrasonic wave techniques were developed earlier than the impact echo method, and have been coded in many national standards[13-16]. The ultrasonic wave is also a transient elastic stress wave, and generally generated by a piezoelectric transducer and received by another piezoelectric transducer. The waves generated are an attenuating sinesoidal-like functions. Unlike steel ball impact, which normally gives only one short pulse, the ultrasonic device successively give pulse wave for every time interval, and the pulse train are very long in general.

To avoid the impediment problems of high frequency wave, the ultrasonic devices designed for concrete detection are those of low frequency range. Most of the transducers are designed with frequency of 50 kHz to 60 kHz. Two forms of electronic timing apparatus and display are available, one of which uses a cathode ray oscilloscope on which the received pulse is displayed in relation to a suitable time scale, the other uses an interval timer with a direct reading digital display. The apparatus are now cheap and become very popular, especially the one with digital display. These digital instruments are compact and portable, and very suitable for in-site application. However, it may cause difficulties in the measurements due to the long contact time of the ultrasonic wave pulse.

Another defect of the ultrasonic apparatus frequency occurs when the two transducers are placed on the same surface to measure pluse velocity. The stress waves generated by a point source have two bulk waves, the longitudinal wave (P-wave) and the transverse wave (S-wave), and a surface wave, the Rayleigh wave (R-wave). As mentioned in literatures,[3,12] the S-wave usually gives a trivial contribution to the amplitude of the received signal in a semi-infinite solid surface measurement, and the R-wave usually gives the largest contribution despite its propagating velocity is slowest. Therefore, the receiving transducer might be triggered by the P-wave or the R-wave even the former arrives first. The amplitude needed to trigger a transducer is substantially depending on the mass and infra-structure of the transducer. The ultrasonic transducers used for concrete detection are usually large with a cylindrical diameter up to 4 or 5 cm. In many circumstances, the amplitude of the P-wave onset is too small to trigger the transducer, and gives a wrong estimation of the P-wave velocity.

Another vexation on the same surface measurement also concerns the diameter of the ultasonic transducer. The large diameter of transducer is hardly treated as a point source or point receiver compared to the measurement scale. Should the transmit distance between two tranducers be defined from the centers of the transducers or from the edges or when developing the prediction formulation? Different distance definitons will give different velocity estimations with a same trasmit time reading. Some literatures[16] use the center-to-center definition of distance, while the others[14] use the edge-to-edge.

The purpose of the present study is to expose the wave behavior when using the ultrasonic transducer as the wave source to perform the same surface measurement on concrete. Instead of using the ultrasonic transducer as the receiver, two accelerometers connected to an oscilloscope are arranged to monitor the wave pulse on a concrete specimen. One of the accelerometers is placed on concrete with a distance from the source transducer to receive the wave pulse. The other is placed on the source transducer to monitor the initial time when the pulse is generated. The transmit times of waves between the two accelerometers are then read from the wave responses on the oscilloscope. Both the P-wave and R-wave velocity are estimated. The result of the P-wave is in a good agreement with the direct measurement of P-wave by placing the two ultrasonic transducers on opposite-faces of the specimen. Meanwhile, the wave source is found be generated from edge of the transducer. Finally, with a similar arrangement of accelerometers, a formulation for predicting the depth of a surface-breaking crack in concrete is developed.

2. PULSE VELOCITY MEASUREMENT ON CONCRETE

From the theory of waves in elastic solid media, It is known that, the surface response of a homogeneous elastic half-space due to a point impact consists of three parts, i.e., the longitudinal wave (P-wave), the transverse wave (S-wave), and the Rayleigh wave (R-wave). The wave velocities are functions of density, Young's modulus of elasticity, and Poisson's ratio.[12,17] The ratios between the P-, S- and R-wave velocities are functions only of Poisson's ratio. The P-wave has the fastest velocity, while the R-wave is slowest.

When a pulse is generated on the surface of a homogeneous elastic media, the pulse velocity can be determined by measuring the transmitting time T between two transducers on the surface of the media. If the distance between the two transducers is L, the velocity is

$$C = \frac{L}{T} \tag{1}$$

In the measurement, one of transducers could be a pulse wave source, and the other is a receiver. It also can be that both of the transducers are receivers. The pulse wave is generated by a wave generator.

The P- and S-waves are bulk waves. They propagate in as well as on the media, while the R-wave propagate only on surface of the media. If the source and receiver are placed on opposite faces, only the P-wave could be measured due to the maximum amplitude of the P-wave and the small amplitude of the S-wave in that region.[12]

If the pulse wave source and receiver are on the same face, all of the three waves could be measured. However, it is known that as the receive location moves away from the source point, the relative amplitudes of the P-wave and the S-wave become small as compared with that of the R-wave.[3] It is also known that, in the earliest arrive pulse waves at the receiver, there is almost no clear displacement jump at the arrival of the S-wave in the wave displacement response for it is swamped by the very large displacement jump at arrival of the R-wave. Therefore, when the pulse source and the same face, only the velocities of the P- and R-wave are possibly observed.

Unlike the metallic materials which are usually assumed homogeneous, concrete consists of cements and aggregates of different sizes. However, as the wavelength of elastic wave is much larger than characteristic size of the aggregate, concrete still can be assumed to be homogeneous in general. The elastic wave obeys the fundamental equation of wave propagation

$$C = f\lambda \qquad (2)$$

where f is frequency, and λ is wavelength. For normal strength concrete, P-wave velocities vary from about 3000 to 5500 m/s. The microcracks and air voids in concrete typically have dimensions of a few centimerers or less. Normally, the ultrasonic pulse waves with frequency of 60 kHz or lower will have wavelengths of about 5 cm or longer. These waves propagate through concrete as though it were a homogeneous medium.

3.PROBLEMS OF SURFACE MEASUREMENT ON CONCRETE

The techniques of detecting the depth of a surface-breaking crack in concrete using the ultrasonic pulse has been described in the "CRC Handbook" by Malhotra[16] and in British Standard "BS 1881: Part 203".[14] The method developed by Malhotra is sometime called the To-Tc method. The method is shown as in Fig. 1. The two transducers are placed at distance L on opposite sides of the crack and equidistant from the crack to measure the transmit time T_c. The two transducers are then placed on the same concrete with a distance $2L$ but with no crack between them to measure the transmit time T_o. The depth of crack is

$$d = L\sqrt{\left(\frac{T_c}{T_o}\right)\left(\frac{T_c}{T_o}\right)^2 - 1} \qquad (3)$$

The arrangement of the transducers recommended in BS 1881 is shown as in Fig. 2, where the two transducers are also placed at equidistance from the crack. Two distance values, L_1 and L_2, are chosen and the transmit times are measured respectively. The depth of the crack is given by

$$d = \sqrt{\frac{(L_2T_1)^2 - (L_1T_2)^2}{T_2^{\,2} - T_1^2}} \qquad (4)$$

where T_1 is the transmit time when the distance is chosen as L_1; T_2 is the transmit time when the distance is chosen as L_2. In BS 1881, it suggests that L_1 and L_2 are used 150 mm and 300 mm respectively.

Figure 1. The To-Tc method

The equation becomes

$$d = 150\sqrt{\frac{4T_1^{\,2} - T_2^{\,2}}{T_2^{\,2} - T_1^2}} \qquad (5)$$

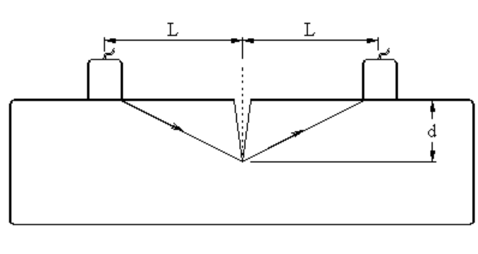
However, in many cases, the ultrasonic pulses are hardly received with the suggested distance 300 mm for some ultrasonic apparatus.

Note that the distances defined in Fig. 1 and Fig. 2 are different. The former is from the center of the transducer to the crack, whereas the latter is from the edge of the transducer to the crack. The diameters of ultrasonic transducers for concrete measurement are up to 4 or 5cm. With the same measured transit time, different definitions of distance will give different estimated values of pulse velocity. The definition of the To-Tc method will give a higher velocity value. The ultrasonic apparatus are now cheap, compact and easy to carry and to use. It becomes very popular for concrete detection. Especially the digital instruments, the transmit time is read directly. However, the users are usually vexed by the aforementioned distance definition problem.

Another defect of ultrasonic apparatus concerns the trigger time of the transducer. The users usually assume the receiving transducer is triggered by the onset of the P-wave. However, since the mass of the transducer is heavy, the small amplitude of the onset of P-wave may not have enough energy to trigger the transducer. Instead, it is triggered by the late arrival of the R-wave, which has much larger amplitude than the P-wave. This makes the estimations of pulse velocity or the depth of crack become incorrect.

4. IMPROVEMENTS ON THE SURFACE MEASUREMENTS

To understand the behavior of the ultrasonic pulse generated by the ultrasonic transducer, the receiving transducer is replaced by a sensitive accelerometer. Another accelerometer is placed on the ultrasonic transducer generates the pulse wave to monitor the initial time when pulse is generated. Both the accelerometers are connected to a high-resolution oscilloscope. With the amplitude response of the



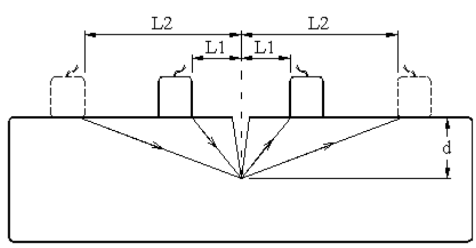


Figure 2. The BS 1881 method

pulse shown in the time domain of the oscilloscope, the arrival times of the P-wave and R-wave are read, and the P-wave and R-wave velocities are calculated.

With the predicted P-wave velocity C_P, an a similar arrangement for detecting the depth of a crack is proposed. The arrangement is shown as in Fig. 3. The ultrasonic transducer is placed at a distance L_1 from the crack. One accelerometer is placed on the transducer. The other one is placed on the other side of the crack at a distance L_2 from the crack. The depth of the crack can be obtained as

$$d = \sqrt{\left[\frac{(C_P T)^2 + L_1^{\,2} - L_2^{\,2}}{2C_P T}\right]^2 - L_1^{\,2}} \quad (6)$$

where T is the transmit time between the two accelerometers. If L_1=L_2=L, the equation becomes

$$d = \sqrt{\left(\frac{C_P T}{2}\right)^2 - L^2} \quad (7)$$

This equation will be used to evaluate the depths of crack in the following experiment.

5. EXPERIMENTAL ARRAINGEMENTS AND RESULTS

To demonstrate the proposed steps for measuring the P- and R-wave velocities and to test the proposed arrangement and formula for predicting the depth of crack, a 51cm×16m×25cm concrete specimen was cast. A slot with 2 mm width and 10 cm depth was introduced at the mid-length of the specimen to simulate a surface-breaking crack. A ultrasonic pulse of 54 kHz is generated by the Proceq TICO digital instrument. The accelerometers are the PCB 353B65 connected to a LeCroy LT322 oscilloscope. With the oscilloscope, the recording length and sampling rate are set to be 10 ms and 1 Ms/s respectively. In other words, there will be 10^5 sampling points and the resolutions of time domain and frequency domain are 0.1 μs and 100 Hz respectively.

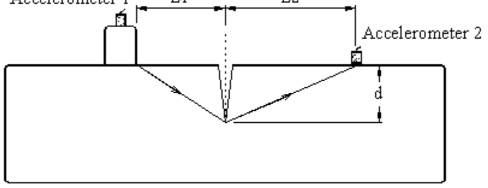


Figure 3. The arrangement of accelerometers for measuring the depth of a crack

On the specimen, one accelerometer was placed on the ultrasonic transducer to perform the velocity measurement. The other is placed at distance 15cm from the edge of the transducer with no crack between them. The responses of channel 1 and 2 are shown at the top and the bottom respectively in Fig. 4. The top response indicates that the pulse wave is a downward sinusoidal-like function following with an attenuating sinusoidal-like function. The contact time is more than 1 ms. The bottom response indicates that the wave received from accelerometer 2 is essentially an attenuating sinusoidal-like function. However, the initial time of the pulse wave and the arrival times of the P-wave and R-wave are difficult to be read out in Fig. 4.

The responses shown in Fig. 4 are enlarged by setting the range of time from 2 ms to 500 μs and obtain the responses shown as in Fig. 5. The arrow on top figure in Fig. 5 indicates the initial time of the pulse wave. The two arrows on bottom figure indicate the arriving time of the P-wave and the R-wave respectively. From the figures, the transmit times of the P-wave and the R-wave are read as 38.96 and 64.46 μs, which give the velocities C_P=3850 m/s and C_R=2327 m/s respectively. The ratio C_R/C_P is then 0.604. It is noted that the arrival time of the P-wave is observed by an initial small rise in the wave response, while the arrival time of the R-wave has big downward jump. The small rise of the P-wave indicates the P-wave is a compression wave.

A direct measurement of the P-wave velocity performed by placing the two ultrasonic transducers on the side-faces of the specimen gave a velocity of 3819m/s, which is very close to the predicted value. Meanwhile, it is also can confirmed that the pulse is initially transmit from the edge of the transducer, and distance definition of edge-to-edge of transducer is more suitable. However, a measurement of the P-wave using the Proceq TICO by replacing the second accelerometer with the receiving transducer was read a transmit time of 56.3 μs, which gives a velocity of 2664 m/s. The measured was not the P-wave velocity; and it was not the R-wave velocity either. The results are arranged in Table 1 for comparison.

With C_P=3850 m/s, the detection of the depth of the crack was performed by choosing four arrangements of L_1=L_2=L=5, 10, 15 and 20 cm. Fig. 6 shows the responses of the arrangement of L=5 cm. The arrows on the top response and the bottom response indicate the initial time of the pulse wave and arrival of the P-wave respectively. The transmit time of the P-wave is read as 60.65 μs. However, the arrival time of the R-wave is hard to be read for the crack obstructs the R-wave propagation. Note that there is a small drop at the arrival time of the P-wave. This character indicates that the P-waves diffracted by the crack is a tension wave.

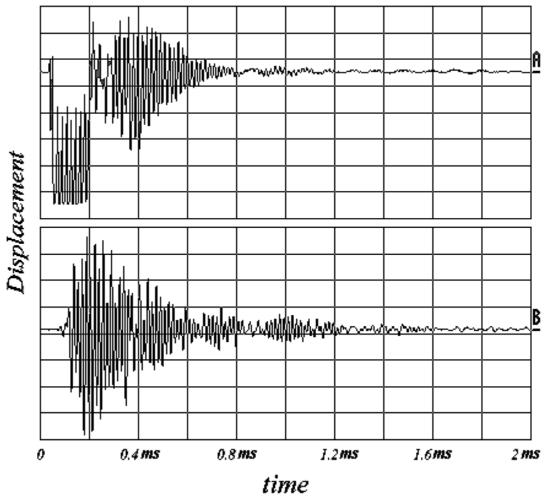


Figure 4. The wave responses at accelerometer 1 and 2 when performing the surface measurement of the P-wave and the R-wave velocities (time length=2 ms)

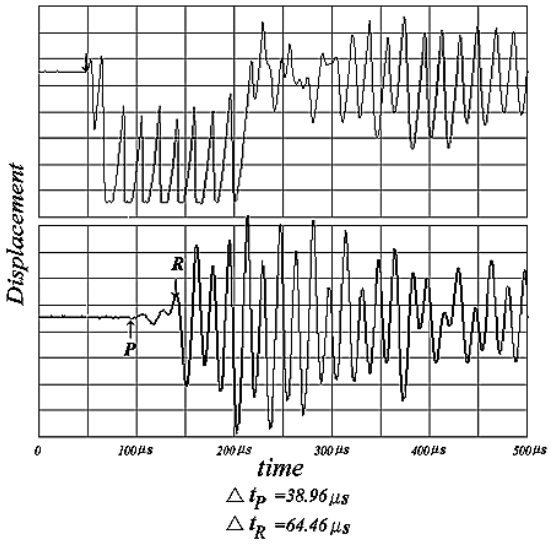


Figure 5. The wave responses at accelerometer 1 and 2 when performing the surface measurement of the P-wave and the R-wave velocities (time length=500 μ s)

Measurement	L (cm)	Wave Type	T (μs)	C_P or C_R (m/s)
Surface measurement using accelerometers	15	R	64.46	2327
		P	38.96	3850
Direct measurement using ultrasonic transducers	16	P	41.9	3817

Table 1. The P-wave and R-wave velocity of surface measurement using accelerometer and the P-wave velocity of the direct measurement using ultrasonic transducer

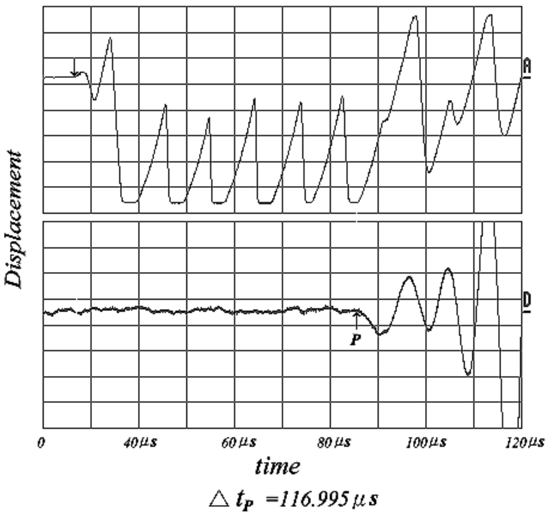


Figure 6. The wave responses at accelerometer 1 and 2 when performing the measurement of the crack

d_{actual} (cm)	C_P (m/s)	L (cm)	T (μs)	$d_{predicted}$ (cm)
2	3858	5	27.4	1.71
		10	52.8	1.93
		15	78.59	2.19
		20	104.21	2.02
10	3850	5	60.65	10.1
		10	74.55	10.29
		15	95.01	10.52
		20	116.995	10.54
20	3876	5	105.91	19.9
		10	114.81	19.87
		15	130.1	20.26
		20	143.2	19.23

Table 2. The estimated depths of specimen cracks

With L=5 cm and T=60.65 μ s, the prediction of the depth using Eq. (7) gives a value of 10.1 cm. The result is very close to the actual depth of 10 cm and is arranged in Table 2. The results of the other three arrangements are also arranged in Table 2. Table 2 shows that all the predicted values are slightly higher than the actual depth. But the errors are quite within ± 1cm.

To investigate if the proposed method could be applied to the shallow depth and large depth of cracks as well, the same steps of measurement were performed on two 51cm×16cm×25cm concrete specimens with 2 cm and 20 cm depths of cracks respectively. The P-wave velocities were measured as 3858 m/s and 3857 m/s respectively. The predicted depths of each specimen of the four adopted distances of L are also arranged in Table 2. Table 2 shows that all the predictions are very close to the actual depths, and the errors are well within ±1 cm.

6. CONCLUSIONS

The ultrasonic device successively generates transient pulse wave for every time interval. Each pulse wave is an attenuating sinusoidal-like function with contact time more than 1 ms. The ultrasonic waves propagating on the surface of concrete can be monitored by a sensitive accelerometer connected to a high-resolution oscilloscope. The P-wave and R-wave velocities can be measured by placing two accelerometers on the same surface of concrete. The P-wave measured is a compression wave. The arrival time of the P-wave is read at the onset of a small rise in the wave response, while the arrival time of the R-wave is at the first big downward jump.

With the proposed arrangement of the two accelerometers, a depth of a concrete crack can be accurately measured with the accelerometers placed at a distance range of up to 20 cm from the crack. The P-wave diffracted by the crack is a tension wave. The arrival time of the P-wave is read at the onset of a small drop in the wave response. The R-wave is hard to be read in the wave response of the measurement on a crack.

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