Crack depth classification by ultrasonic measurement system with artificial neural network (ANN)

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Abstract

This technical article presents a newly developed test system for classification of surface cracks in reinforced concrete structures. With the developed system, the diffractedand reflected ultrasonic wave patterns can be obtained and used for the classification of surface cracks. The classification of surface cracks is achieved by an artificial neural network (ANN). The developed system was used to determine whether crack depth reaches reinforcing bar or not. The result of this study shows a remarkable capability of the developed system to classify the type of surface cracks according to their depths in relation to cover thickness.

Keyword: surface crack**;** ultrasonic; artificial neural network (ANN); back-propagated model; mortar

1. Introduction

Since tensile strength of concrete is just approximately one-tenth of its compressive strength, concrete is fragile in tension and cracks often develop in concrete structures [1]. If cracks penetrate beyond reinforcing bars, moisture and oxygen can easily reach the rebars and drastically accelerate corrosion of the rebars and cause reduction of cross sectional area of therebars as well as spalling of concrete cover [2]. Consequently, load carrying capacity of the structuresmay be downgraded.Without appropriate maintenance work, failure of the deteriorated structures may occur.

Information about cracks such as their locations, surface crack widths, lengths, and depths are very important for a condition assessment of cracked concrete structures. Although the locations, widths, and lengths of surface cracks can be visually inspected and measured with some basic instruments such as crack gages or digital camera [3], the information about depth of crack cannot be measured by visual inspection. Non-destructive testing (NDT) technique usually plays an important role in real practice where the information of crack depth is required. One of the most extensively employed techniques for surface crack depth measurement is a well-known "ultrasonic pulse velocity" (UPV).

Inspection engineers have been measuring crack depth by following practical standards and guidelines [4, 5, and 6]. There are also some researchers who focused in the measurement of crack depth by ultrasonic wave. Sansalone et al [7]studied the measurement of surface crack depth by time of flight techniques. They said the time of flight technique can be used to determine the depth of surface-opening crack. However, procedures for a measurement of crack depth stated in the current standards and guideline as

well as in previous research are mostly provided based on an assumption that there is no reinforcing bar penetrating through crack plane [4, 5, and 6]. The method can therefore give a considerable error when there is a reinforcing bar near the crack. Woo and Song [8]studied about the measurement of crack depth that penetrating beyond reinforcement in reinforced concrete (RC) specimens by ultrasonic method. If an inspected crack is penetrating beyond the reinforcement, the transmitted ultrasonic wave has two alternative routes to travel from a transmitter to a receiver. The first one is the travel through reinforcing bar and the other is the diffraction at the crack tip. Since the travel through rebar is usually shorter and the velocity of ultrasonic wave in reinforcement is much faster than that in concrete, ultrasonic waves travelling through reinforcing bar usually reach a receiver before the diffracted waves from the crack tip. As the results, the crack depth calculated from the first arrival of ultrasonic wave is not the true crack depth.

According to the aforementioned situation, determination of surface crack depth in relation to the location of reinforcing bar has a clear technical importance. The knowledge on whether surface cracks reach the reinforcing bar allows engineers to make a proper decision on crack repair. If the surface crack reaches the reinforcing bar, an urgent remedial action should be taken in order to retain a durability of the reinforcing bar. The knowledge on the location of crack tip in relation to the location of reinforcing bar will also be useful for an inspector to make a judgment on accuracy of crack depth measured by the traditional UPV techniques.

The objective of this study is thus to develop a new testing system developed from the ultrasonic testing apparatus and artificial neural network (ANN) in order to classify the position of crack tip in relation to the location of reinforcing bar.

2. Experimental configurations

In the experimental program, the developed testing system with the ANN classifier was applied for classifying the crack of the mortar. In the crack classification, three cases of artificial cracks were tested. The indirect measurements were used in the crack classification.

2.1 Original testing system

The system configuration of the original testing system or standard UPV system is illustrated in Figure 1a.

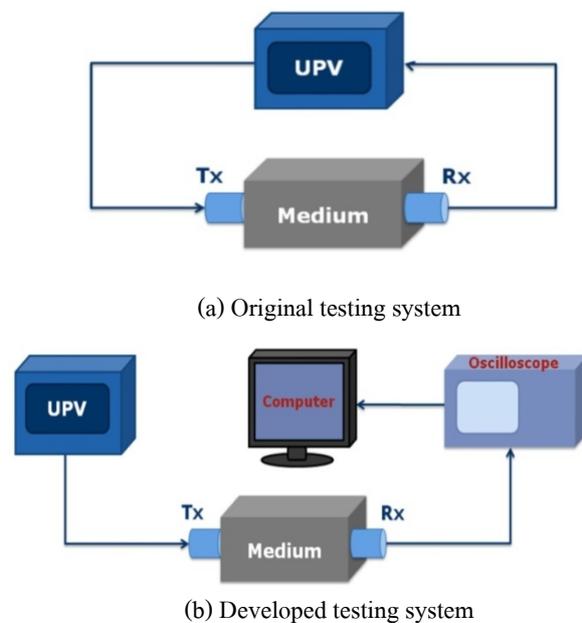(a) Original testing system

(b) Developed testing system

Figure 1 System configuration

In this system, ultrasonic wave with a nominal frequency of 55 kHz, was used. Only the travel time of the first ultrasonic wave that arrive receiver could be detected by the system. Due to this limitation, the system give only information of travel time and a further analysis on wave pattern becomes impossible.

The developed testing system is introduced to overcome this problem.

2.2 Developed testing system

The configuration of the developed testing system is illustrated in Figure 1b. In this system, an oscilloscope (TDS2012B) and a computer are added to the original system. The oscilloscope measures an ultrasonic wave patterns, which travel through the medium, in the time domain. The NI Signal Express software is employed in order to collect the wave pattern as arrays of time and corresponding amplitude. Since ultrasonic wave patterns are fully obtained, this developed system enable further analysis on the ultrasonic wave patterns in order to determine more information about defects and cracks.

2.3 Sample preparation

In this study, 100x100x500 mm mortar prism concentrically reinforced with 25-mm reinforcing steel bar were prepared with different crack configuration. The Ordinary Portland Cement type I and river sand are used to produce the mortar specimens in the proportion of 539, 269, and 1482 kg/m^3, respectively. Position of reinforcing steel bar was controlled by the application of wood plate with a hole at the center (see Figure 2a). The cover thickness was thus approximately 37.5 mm. Artificial crack was created by installing a 1.5-mm thick acrylic plate in each mold before the casting of mortar. The plate was located perpendicular to the direction of reinforcing bar at the middle of the specimen. The width of the plates was 100 mm but the height of acrylic plates was varied so that depth of the artificial cracks was varied at 25 mm, 50 mm, and 75 mm (see Figure 3). The acrylic plates were removed from the specimen during the demolding at 24 hours

after casting. In the case of the crack depth of 75 mm, the acrylic plates were split into two portions so that they can be removed from the specimen without any obstruction from the rebar.These three different crack depths represent different state of crack depth as follows:

Case I (crack depth = 25mm): Crack tip is above the reinforcing bar (shallow crack that does not reach the reinforcing bar)

Case II (crack depth = 50 mm): Crack tip is at the same level with the center of rebar

Case III (crack depth = 75 mm): Crack tip is below the rebar (crack propagation is beyond the reinforcing bar).
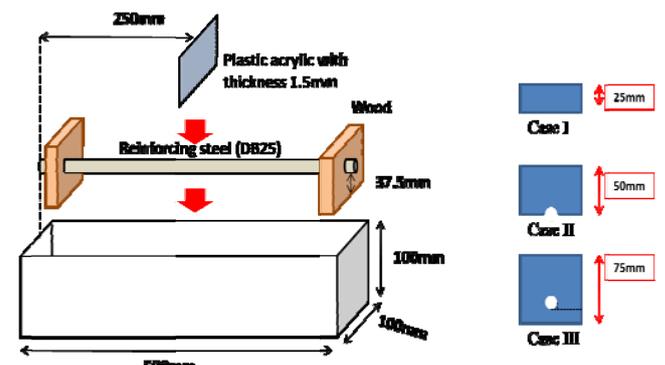
(a) Setting of rebar and acrylic   **(b)**Acrylic plate with
        platebefore casting   different depths
Figure 2 Setting of rebar and acrylic plate

2.4 Test Methods

There are three possible measurement arrangements in which the transducers of UPV equipment may be arranged on the medium. They are direct measurement, semi-direct measurement, and indirect measurement.However,in the estimation of surface crack depth, only the indirect measurement is employed. The distance between transmitter and receiver are placed on different sides of crack.

The distance from the crack to the transmitter as well as the distance from the crack to the receiver were

set to be always same (Figure3). The measurements were conducted with different distances from transmitter/receiver to the crack, namely, 50 mm, 75 mm, 100 mm, 125 mm, 150 mm, 175 mm, and 200 mm. The patterns of received ultrasonic waves werecollected for the signal processing and pattern recognition by artificial neural network (ANN).

The transmitter and the receiver were placed at different positions along the reinforcement steel. Initially, the transmitter (Tx) and receiver (Rx) wereeach placed 25 mm away from cracks and the first measurement was conducted.Then, the receiver were moved to 50 mm away from crack tip and the second measurement was conducted. The measurements were also conducted when the receiver was placed at 75 mm, 100 mm, 125 mm, 150 mm, 175 mm, and 200 mm away from the crack, respectively. After that the transmitter was placed at 50 mmaway from the crack and the measurement were conducted when the receiver was placedat 50 mm, 75 mm, 100 mm, 125 mm, 150 mm, 175 mm, and 200 mm away from cracks, respectively. The similar series of measurements were repeated for the case that the transmitter was placed at75 mm, 100 mm, 125 mm, 150 mm, 175 mm, and 200 mm from the crack, respectively.
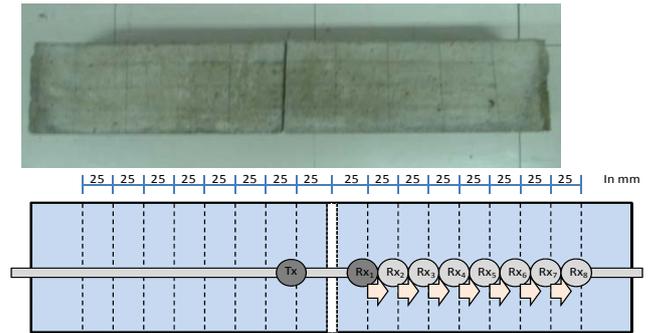

Figure 3 Illustration of example information on transducers arrangements

3. Record of ultrasonic signals

Each time-domain signal, containing 1,500 and 2,500 data points,was recorded at a sampling rate of 1,000 kHz for allcases. To obtain the frequency domain information, the time domain response was processed by Fast Fourier Transform (FFT) calculation [9]. The Power Spectral Density (PSD) of each recorded wave pattern was then obtained.The power spectral density (PSD) was defined as

$$PSD = \frac{\left| FFT \right|^2}{N} \qquad (1)$$

Subsequently, in order to remove the influence of pressure on probes during the measurement,the time-domain signal and PSD were normalized with the maximumamplitude value in each recorded wave. Figure 4 and Figure 5 show examples of the normalized wave patterns (Figure4) and PSDs (Figure5) for the case I samples (crack depth = 25mm), case II samples (crack depth = 50 mm), and case III samples (crack depth = 75 mm).Note that the figures show the example of signals obtained from the different positions of the distance betweentransducers 200 and 300mm. These normalized signals were used as an input to ANN.
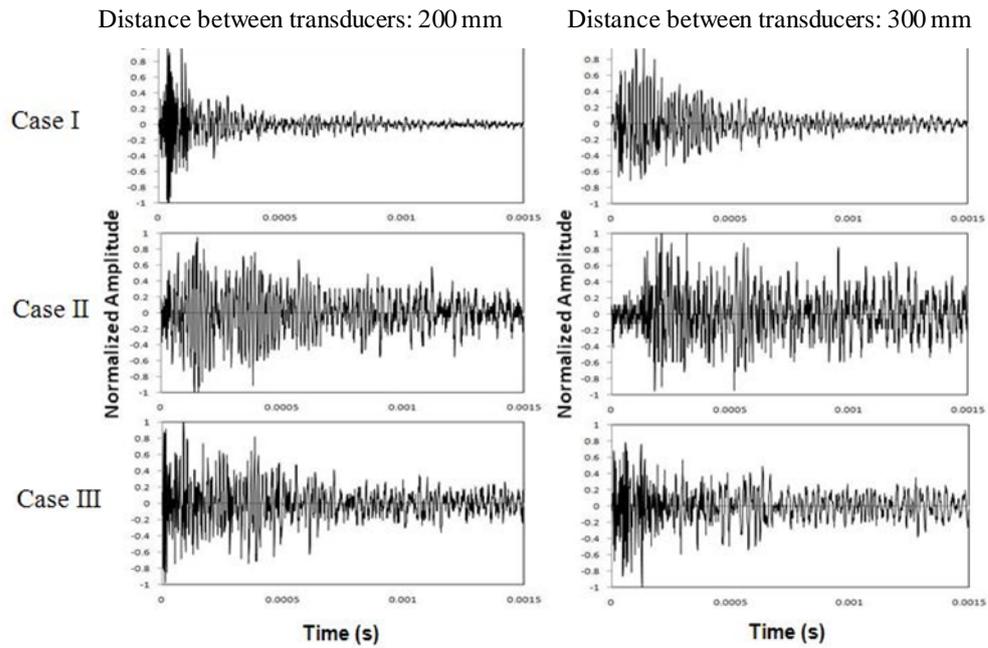
Distance between transducers: 200 mm   **Distance between transducers: 300 mm**

Figure 4 Normalized signals in time domain based on indirect measurement for crack depth estimation

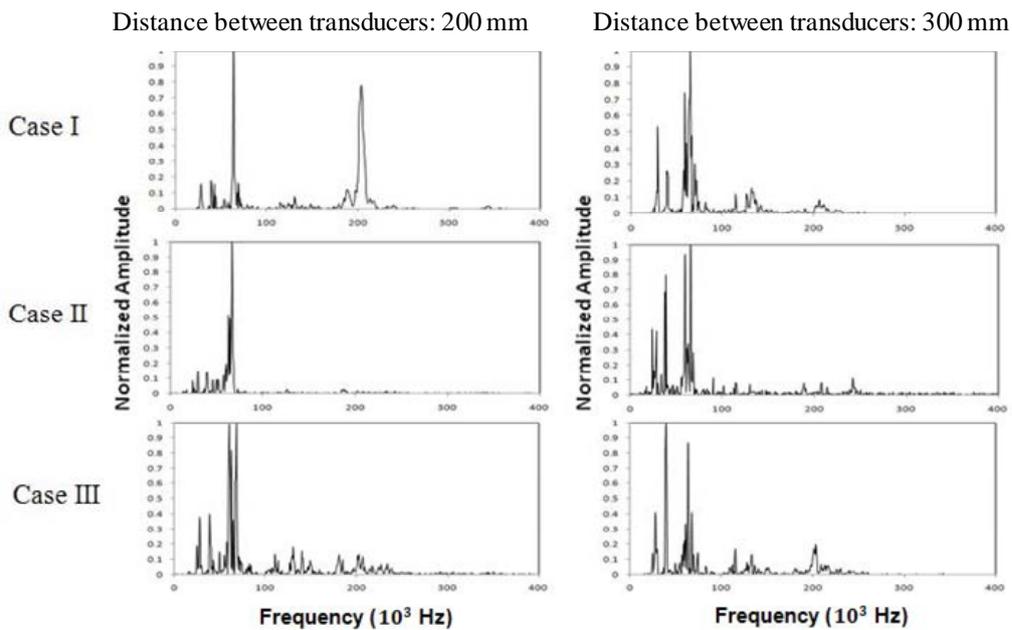**Distance between transducers: 200 mm**   **Distance between transducers: 300 mm**

Figure 5 Normalized signals in frequency domain based on indirect measurement for crack depth estimation

4. Classifications with artificial neural network

4.1 General features

Analysis on the signal was accomplished with the employment of an artificial neural network (ANN) classifier. The pattern of normalized signals obtained from the previous section were classified and verified by the ANN classifier. An artificial neural network (ANN) is an information processing paradigm that is inspired by the biological nervous systems. It is composed of a large number of highly interconnected processing elements (neurons) working to solve specific problems. An ANN is configured for a specific application, such as pattern recognition or data classification, through a learning process [10].

This study employs the back-propagated model (Figure 6) which is a feed-forward multi-layered ANNs that allow signals to travel only one way; from input to output. The feed-forward ANNs tend to be straight forward networks that associate inputs with outputs. The circles represent neurons. The neurons are arranged in a number of layers. Generally, there are three or more layers including input layer, middle (hidden) layers and output layers.
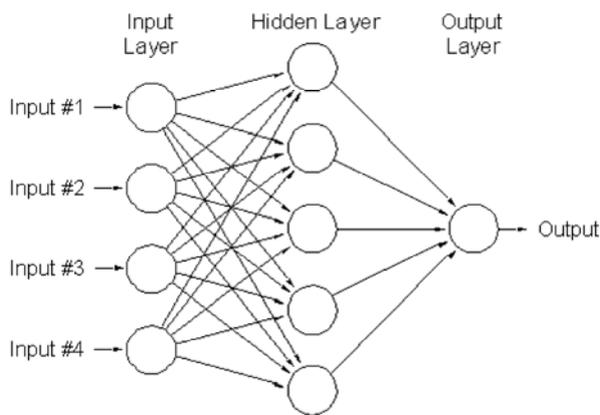

Figure 6 Back-propagated model with several input and hidden neurons and one output neuron

The neurons in hidden layers allow the network to represent and compute complicated associations between patterns. Each neuron in the hidden layer receives the weighted sum from the input layer and transfers its result to the output layer. The back propagation learning algorithm calculates the error between the generated output and targeted output and uses the estimated error to modify the weight in response to the errors. A feed forward ANN learning with back propagation algorithm written in MATLAB was used in this work. The main focus of this work was to train and test the ANN with inputs of existence crack in reinforcing steel.

4.2 Input features and parameter setting

In this work, there were totally 300 normalized amplitude arrays with different data points (1,500 and 2,500) used as the input of the network with 100 arrays for each case. The number of hidden layers was set to be 50. There is also only single case of the ANN output which can be used in their cases [1 0 0]', [0 1 0]' or [0 0 1]' which represents the mortar with crack depth of 25mm, 50mm, and 75mm, respectively.

The pattern recognition of the defect can be simulated and analyzed. The training, and testing parameters are set to be 70% and30% of the input arrays, respectively.

In this work, the 300 samples were used in the analysis. Therefore the training and testing samples are set to be 210 and 45 samples which are 70% and 30% of the input samples, respectively. Note that the indirect measurement is only employed in this work and the normalized waveform in time domain and the PSDs were analyzed separately.

5. Classification table

From the analysis, the confusion table is obtained and used to analyze the accuracy of the network. In order to make it simple, the classification results obtained with the ANN classifier are presented in the table described below. The classification rate of each case is the mean classification rate of the four network analysis.

The classification results with 1,500 data points of ANN classifier with the time domain and frequency input are presented in Tables 1and 2, respectively. The classification results with 2,500 data points of ANN classifier with the time domain and frequency input are presented in Tables 3 and 4, respectively.

Table 1 Classification results using time domain wave with 1,500 data points

Case	Training and testing samples	Mean classification rate (%)		
		Case I	Case II	Case III
Case I	Training = 210	87	8	5
Case II	Testing = 45	18	75	7
Case III		13	8	79

Table 2 Classification results using frequency domain wave with 1,500 data points

Case	Training and testing samples	Mean classification rate (%)		
		Case I	Case II	Case III
Case I	Training = 210	96	1	3
Case II	Testing = 45	0	100	0
Case III		2	3	95

Table 3 Classification results using time domain wave with 2,500 data points

Case	Training and testing samples	Mean classification rate (%)		
		Case I	Case II	Case III
Case I	Training = 210	94	2	4
Case II	Testing = 45	15	83	2
Case III		24	3	73

Table 4 Classification results using frequency domain wave with 2,500 data points

Case	Training and testing samples	Mean classification rate (%)		
		Case I	Case II	Case III
Case I	Training = 210	97	0	3
Case II	Testing = 45	1	97	2
Case III		2	2	96

From the classification results, the accuracy obtained from the classification in frequency domain signals is higher than that in time domain. This might be because the intensity of each frequency component of the reflected ultrasonic was influenced differently by different routes of propagation.And, as the results, the different patterns of the different specimens can be well used for a classification.

Increase of a number of the data pointsslightlyimproves the mean classification rates in the case that time-domain is analyzed. This indicates that using longer array as an input give better classification. However, the required training time will also be longer. But the increase of a number of the data point is almost negligible in the case that the PSD is analyzed.

6. Conclusion& recommendations

The developed testing system, implemented by the integration of UPV apparatus, oscilloscope, and ANN algorithm, can give the well-recognition crack classification and good evaluation of position of crack tip relative to the position of rebar.According to the classification results of defect detection and crack classification, employing the frequency domain signals as the ANN's input gave higher accuracy and better reliability in classification.In summary, the results show that the proposed method has a potential for the classification of crack. However, the applicability of the methods to the real cracks in reinforced concrete which is more tortuous and has more complex nature should be evaluated in the future.

Acknowledgement

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