NDT-Defect Detection on Concrete using Ultrasonic: A Review

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ABSTRACT

Non-destructive test (NDT) is widely used in industrial applications due to its reliability as well as flexibility. Rather than other methods, NDT is more suitable and practical to be performed in order to detect flaws and deterioration in concrete structures. This paper provides a review by studying various research works on concrete by performing ultrasonic technique NDT. In particular, the working principle of ultrasonic NDT, type of sensor and techniques adopted in ultrasonic NDT are briefly described in this paper. Further research based on preliminary data will be conducted to improve previous experimental work.

Keywords: Non-destructive test, concrete structure, ultrasonic tomography

1. Introduction

Concrete refers to a composite material that is widely used for construction, especially in large critical infrastructure systems such as bridges, pavements and buildings due to its high durability, low production cost and strength flexibility. Degradation of concrete may be affected by environmental factors, mechanical overloading, high-temperature exposure, the routine of application of deicing salts and also due to repeated freezing and thawing cycles [1][2], which in time lead to a distributed network of cracking damage in the concrete structure, including fine cracks. Hence, concrete evaluation is very essential to determine the strength and quality of either new or old concrete infrastructure. The common practices that have been implemented to assess the condition of concrete infrastructure are visual inspection and destructive test method. Visual inspection is not reliable as the hidden damage and deterioration cannot be captured [3]. While the destructive test method seems more suitable and economically beneficial, the implementation of the destructive test may cause complete damage to the concrete specimen. As a result, Non-Destructive Testing (NDT) is required to provide an accurate and sensitive result for an effective monitoring and maintenance procedures of a concrete structure.

NDT is the process of materials' analysis that is performed without destroying the internal structure of test materials. It is performed to determine flaws as well as detect variation in structures, presence of cracks and other physical discontinuities that might contribute to loss of strength in the concrete structure without causing any damage to the test materials. NDT is performed by adopting several techniques considering the type of materials to be tested, the type of defect, and the location of the occurring defect [4]. These developed methods can be grouped into two, the active and passive technique [5].

i. Active technique – Requires a test agent to be applied to the test specimen. The result (if there is the presence of defect) can be captured by some parameters, before being magnified and registered.
   Example: radiography, ultrasonic method, and magnetic particle method

ii. Passive technique – Involves the process of observing and supervising the test materials in several conditions, such as in normal load atmosphere or repeated loading to find the deterioration or imperfection in specimens.
   Example: leak examination, visual test, and acoustic emission

Table 1 is a summary of NDT methods employed for the evaluation of materials. The ultrasonic method is a promising and effective method to determine various types of flaws in materials. Hence, this paper will focus on NDT to detect defects of concrete structures by using the ultrasonic method.

Table 1. NDT methods for the evaluation of materials [6]

NDT Method	Defects/Material Properties Normally Evaluated
Visual inspection	Surface defects/damages, changes observed in transmitted or reflected light
Radiography	Internal and surface discontinuity, radiographic density variation and geometrical dimension of defects or discontinuities
Ultrasonic	Elastic modulus, variation of material homogeneity, geometric dimension of defects and discontinuities, residual stress
Magnetic particle methods	Surface and subsurface defects in magnetic materials
Eddy current	Surface and subsurface defects and damages in electrically conducting materials
Liquid penetrant	Defects open to the surface in all except highly porous materials
Acoustic emission	Accumulation of damage during services, initiation of cracks, failure of structural component/assemblies, leak in closed/sealed components/containers
Infrared thermography	Porosity, moisture, delamination, density variation

2. NDT Ultrasonic Tomography

Ultrasonic tomography is a technical combination of the ultrasonic sensor and the image reconstruction [8]. It is a non-destructive technique that enables the mapping of an internal section of a structure from multiple projections to generate a two-dimensional image, which contains the information property of the structure. A tomography system consists of transmitter, receiver, a signal conditioning circuit, and a data acquisition system. The transmitter sends a signal through the testing material which will be detected by the receiver. The signal will then be amplified, filtered and converted to DC signal. The data acquisition system will digitize the signal and send it to a computer. An image reconstruction algorithm is then utilized, which enables the required information to be displayed [7]. The advantages of using ultrasonic sensors in tomography systems includes its safety, rapid response, non-invasive aspects and low energy levels.

2.1 Work Principle of Ultrasonic Testing

The basic operation principle of ultrasonic testing is similar to the echo-sounding. A short ultrasonic pulse is sent to generate stress wave in concrete materials. This evaluation system consists of a transmitter and receiver circuit, transducer tool, and display devices. The stress wave generated is sent using a sending transducer and received by the receiving transducer. Vibrations or high-frequency sound is propagated through the specimen and the time of wave propagation is measured. The time and distance of the travelling stress wave through the test materials enables the determination of the location, size, orientation, and other properties of defects on the concrete structure [8]. An ultrasonic wave travelling into concrete is directly proportional to the strength and age of the concrete [4]. The wave will be diffracted around the discontinuity area when defects are found.

2.2 Type of Sensor

The sensor is the most important part for NDT on the concrete structure. Transducers with frequencies range within 20 kHz to 150 kHz are always used as they are much suitable for concrete measurement. One of the most popular transducers and commonly used for NDT is a piezoelectric crystal. This type of sensor generates ultrasonic waves by exciting the piezoelectric element by an electrical voltage signal in spike-shaped, causes it to vibrate at its resonant frequency. There are two different types of operation of an ultrasound transducer [9]:

i. Contact transducers – Used for direct contact inspections, which are generally hand manipulated, hence, it is more sensitive to the operator pressure. The advantages of this transducer are:
   - Save time, hence increase the accuracy of path length for indirect readings
   - Designed ergonomically so that they are easy to grip and move along a surface
   - Consists of replaceable wear plates to increase their duration of life
   - Elements are protected in a rugged casing, which enables them to withstand sliding contact with other materials

ii. Non-contact transducers – Utilized a medium, such as air or gas, to transmit the sound wave energy into the testing materials.

2.3 Technique for Ultrasonic NDT

The most common applications adopted in ultrasonic NDT are Pulse Velocity Method (PVM) and Pulse Echo Method (PEM).

i. Ultrasonic Pulse Velocity Method (PVM) or Through-Transmission Method:

   Ultrasonic PVM employed an ultrasonic pulse to generate waves on a tested concrete structure. An ultrasonic pulse is produced by an electro-acoustical transducer, which is positioned in contact with the specimen as ultrasonic waves cannot travel through air or vacuum. The ultrasonic pulse will undergo repeated reflections at the boundaries of a distinct phase of materials within the concrete once it is induced from a transducer. A complex system of stress waves consists of longitudinal (compressional), shear (transverse) and surface (Rayleigh) waves are generated. The receiver senses the fastest waves which are the longitudinal waves. Hence, homogenous concrete material (without the presence of defects and cracks) has a higher velocity compared to the non-homogenous one.

   Ultrasonic PVM is applicable to assess the uniformity of concrete structure, also to detect its internal defects and crack depth [10]. As shown in Figure 1, PVM uses a pair of ultrasonic transducers to measure the time-of-flight of the longitudinal wave. There are three different techniques of probing that can be adopted, in which all of these techniques, similarly, require access to two opposite sides of good surface condition to give accurate and precise velocity values [4]:

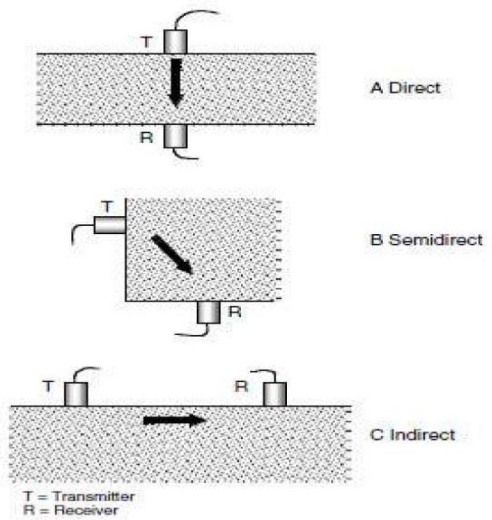


Figure 1. Various positions for probing transmitter and receiver [4]

i. Direct (cross) probing – The transmitter and receiver are located opposite to each other.
ii. Semi-direct probing – The transmitter and receiver are located on any two perpendicular surfaces of the specimens
iii. Indirect (surface) probing – The transmitter and receiver are located along the same surfaces of the specimens.

The formula below is used to compute the velocity of ultrasonic pulse to characterize the concrete properties [11]:

$$Calculated\ velocity = \frac{Expected\ distance\ of\ travelling\ waves}{Time\ recorded} \quad (1)$$

ii. Ultrasonic Pulse Echo Method (PEM)

Ultrasonic PEM is the simplest and most effective methods for NDT. This method can be assessed to thick concrete, internal honeycomb, cold joint and delamination [10]. Transmitter introduces a stress pulse into the concrete materials on its accessible surface. The propagation of pulse into the concrete is then reflected by cracks, voids, or delamination. This reflected wave is known as echo, which is recorded at the surface by the same transducer. The output of the receiver is either displayed on an oscilloscope or stored for further processing. Different from PVM, PEM requires only one point to propagate the short pulse into the testing concrete. The reflected echoes generate the compressional and shear waves, that determine the strength of the material [12].

3. Discussion on Experimental Work

Several experiments of ultrasonic NDT on concrete structure have been found in the literature [6][13][14][15][16][17] . A laboratory experiment was carried out to determine the location and size of defects in concrete specimens by using the acoustic ultrasonic tomographic technique [13]. A 1000×1000×1000mm of concrete slabs was constructed with intact of a step-like defect model as shown in Figure 2. The experimental results recorded in Figure 3 has successfully identified the position and size of the defect area in concrete members.

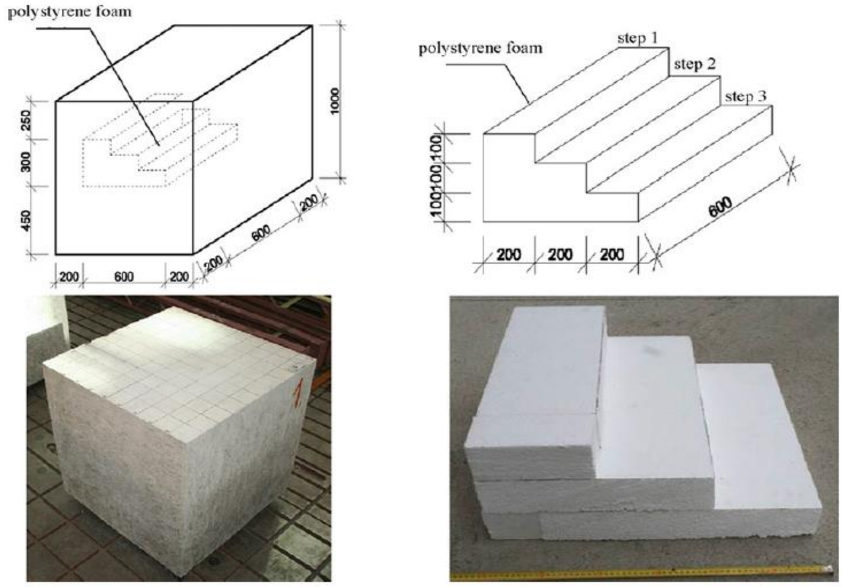


Figure 2. The concrete specimen and the dimension of step-like defect modelled from polystyrene foam [13]

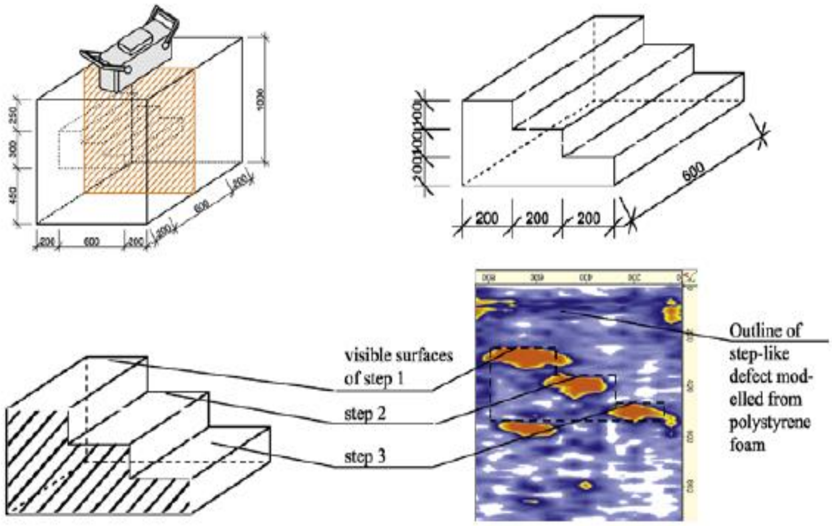
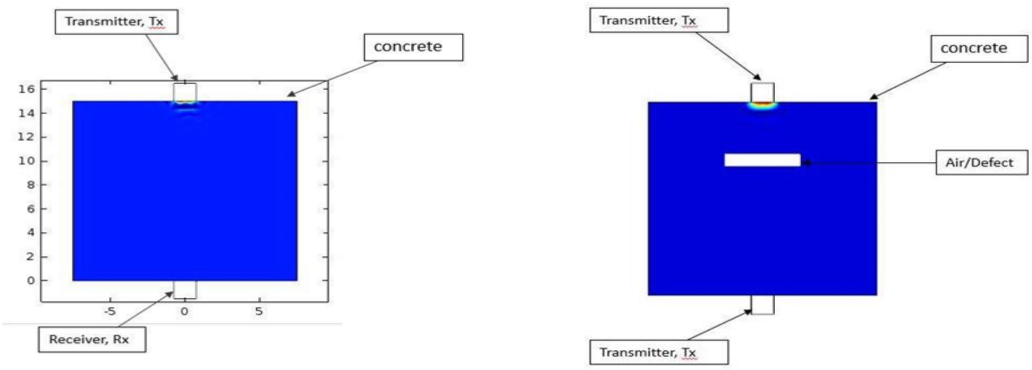


Figure 3. Result obtained by ultrasonic tomography for concrete specimen constructed [13]

Also, another experiment has been setup to detect defect area in concrete by adopting ultrasonic NDT method [18]. As shown in Figure 4, a non-homogenous system (concrete structure with the presence of defect and crack) was constructed by using COMSOL Multiphysics and analysed by referring to a homogenous system (concrete structure without any defect). Both ultrasonic receiver and transducer were placed at both ends of the concrete structure with a range of frequencies between 50kHz to 150kHz. Various probing methods were adopted in order to obtain the exact location of the crack or defect area. Once data are collected from the experiment, the defect image is constructed by using sensitivity mapping technique.



(a) (b)

Figure 4. Concrete structure system (a) Homogenous system (b) Non-homogenous system [18]

The defect area is shown as in Figure 5 by using sensitivity mapping technique developed by MATLAB software. The data were obtained from the output signal at the receiver from both homogenous and non-homogenous system and compared in terms of their amplitude.

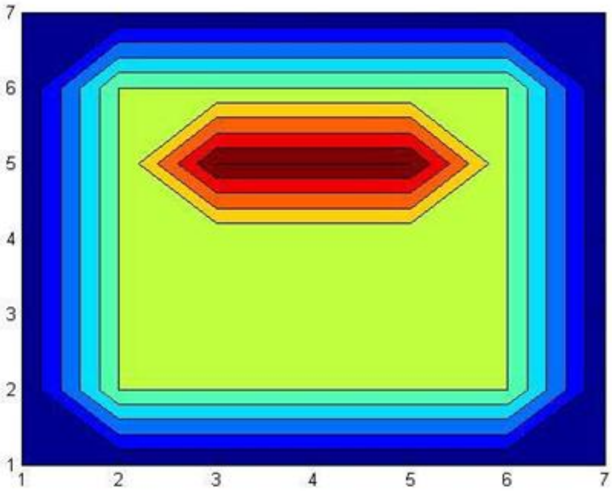


Figure 5. The defect image constructed using Sensitivity Mapping Technique [18]

4. Conclusions and Future Works

This paper provides a critical review and precise information of the NDT on detection of defect in concrete structures. The working principle of ultrasonic NDT for the concrete structure is briefly described. The consideration of the type of sensor selected and the ultrasonic technique used whether Pulse Velocity Method (PVM) and Pulse Echo Method (PEM) are very crucial to be discussed. Also, experimental work found in the literature were included in this paper. As a conclusion, further research to improve the ultrasonic tomography NDT for concrete-defect detection are in progress. Current research attempt to verify the data obtained from program software by constructing an actual model of the homogenous and non-homogenous concrete system, so that a real device can be developed and easily used on-site.

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