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Experimental studies on void detection in concrete-filled steel tubes using ultrasound

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HIGHLIGHTS

- A novel method is proposed to quantify the voids in a CFST.
- A chromatogram can be generated by analyzing the matrix of ultrasound travel time.
- The chromatogram can show the position and geometry of the voids in CFSTs.

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ABSTRACT

Due to shrinkage and/or inadequate compaction during concreting, voids may develop in a concrete-filled steel tube (CFST) between the concrete core and outer steel tube, which reduce the confinement effect of the steel tube on the concrete core, and further, decrease the load-carrying capacity and ductility of a CFST. In this study, an ultrasonic technique is utilized for quantifying voids in CFSTs by analyzing the ultrasound travel time in them. Four potential travel paths are identified in CFSTs with/without pre-set voids. By making a comparison of the experimental and theoretical ultrasound travel time, the actual ultrasound travel path is determined in CFSTs. Further, by analyzing the matrix of ultrasound travel time obtained from experiment, a novel method is proposed to generate the chromatogram of the distribution of ultrasound travel time, which is utilized to quantify the voids in a CFST. The chromatogram intuitively shows the position and geometry of the voids in CFSTs and is in reasonable agreement with the pre-set voids. This study, therefore, establishes a new method for quantifying voids in a CFST through the ultrasonic technique.

1. Introduction

In the pursuit of good structural performance, low costs and/or a large floor space in modern structures, concrete-filled steel tubes (CFSTs) have been widely adopted as structural elements, such as truss elements in arch bridges and columns in high-rise buildings. In a CFST, the outer steel tube provides the lateral confinement to the concrete core so that the concrete compressive strength can be significantly enhanced. Meanwhile, local buckling of the steel tube can be restrained by filling it with concrete, resulting in a CFST's load carrying capacity to be greater than the sum of the individual component load carrying capacities i.e. steel tube and concrete core column [1]. To achieve the expected confinement effects with loading being transferred between the two materials, it is necessary to ensure excellent bonding between the concrete core and the steel tube. However, de-bonding between concrete and steel is almost inevitable in a CFST, which can be classified into two categories, i.e. shrinkage voids and near-wall cavity voids caused by deviation in deformation between steel and concrete [2]. The defects in a CFST can reduce the confinement effect of the steel tube on concrete, consequently decreasing its load-carrying capacity and ductility. Therefore, it is significant to quantify the internal defects in a CFST to assess its structural performance using the nondestructive testing (NDT) methods.

So far, several NDT methods have been developed for applications in civil engineering community, such as ultrasonic testing [3], acoustic emission [2], infrared thermography [4] and the impact-echo method [5]. Among them, the ultrasonic testing method has become one of the most popular NDT techniques due to its versatility and convenient mode of operation. It has been

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verified as a promising technique for the evaluation of crack propagation in concrete [6,7], delamination of concrete bridge decks [8], defects inside plain and reinforced concrete [9], corrosion of steel reinforcement [10] and local yielding of steel structures [11]. However, it is still very challenging to use the traditional ultrasonic testing method to detect the de-bonding in composite elements in civil engineering structures, e.g. fiber reinforced plastic (FRP) confined concrete and CFSTs. Although the ultrasonic tomography can detect voids in concrete, the results are usually affected by the sizes and shapes of coarse aggregates [12]. Particularly, it is difficult for ultrasonic waves to penetrate deep into a highly attenuative material, e.g. epoxy resins used in the matrix of composite materials. In response to this, Feng et al. [13] developed an electromagnetic imaging technology to detect the de-bonding between FRP and concrete. However, the electromagnetic ultrasonic waves failed to penetrate the steel tube. Therefore, it cannot be used for assessing CFSTs. Meanwhile, some researchers tried to utilize ultrasound to evaluate defects in CFSTs based on the difference in velocities travelled by ultrasound in steel and concrete [14,15], respectively. Their results showed that concrete quality in a CFST can be qualitatively classified based approximately on the difference in ultrasonic velocity picked up from experiment. However, it is almost impossible to determine the positions and geometries of voids in CFSTs using their method. Therefore, when quantitative detection of de-bonding (i.e. determination of both the positions and geometries of voids) in CFSTs is a matter of concern, the extent of application and effectiveness of ultrasonic technology remains as an under-researched topic. Recently, a piezoelectric (PZT) ceramic transducer-based method [16] has been widely used in the detection of de-bonding in composite reinforced concrete [17], steel reinforced concrete [18,19] and CFSTs [20,21]. However, it is necessary to embed these sensors into concrete during its casting, which limits its applications on existing structures [22]. Therefore, the development and implementation of NDT technology for convenient and direct detection of de-bonding in CFSTs is still a challenge in civil engineering field.

In response to this problem, this paper aims at developing a de-bonding detection method for CFSTs using the traditional ultrasonic technology. The previously mentioned ultrasound methods identified the de-bonding based on the variations in ultrasound velocity, amplitude, and frequency, however, the proposed method in this study will employ only the ultrasound travel time to quantify the two types of de-bonding. By comparing the ultrasound travel time obtained from experiment and theoretical analyses, the ultrasound travel paths in CFSTs with the two categories of de-bonding voids can be obtained. Moreover, by analyzing the ultrasound travel time obtained from experiment at a number of testing points in a CFST, a matrix of ultrasound travel time can be derived. Further, the chromatogram of the distribution of ultrasound travel time can be constructed, which can intuitively reflect the outline of voids, consequently enabling quantitative evaluation of defects in a CFST. It is expected that the method proposed in this study can provide new insight by using ultrasound travel time, as the only required input data, for detecting the position and geometry of voids in a CFST. This would characterize ultrasonic technology as a simple, convenient and effective technique with an inherent low cost for detection of voids in CFSTs.

2. Ultrasound travel path

The two categories of de-bonding in CFSTs depend on the origins of formation [2]. One is caused by concrete shrinkage, resulting in circumferential voids between the concrete core and the outer steel tube. Its characteristic is that the thickness and length of the de-bonding gap are small, but the scope along the circumference is large. The other category of de-bonding is caused by the poor compaction during concrete casting, resulting in voids forming near the inner wall of a steel tube. Its characteristic is that the length of the de-bonding area along the axial direction of a CFST is large, but the scope along the circumference is small. According to Fermat's principle, the ultrasonic wave would be transmitted along the path of least travel time. Since the ultrasound velocity is 340 m/s in air and 4000–6000 m/s in concrete, the ultrasonic wave may bypass the void area and transmit along the path of least travel time. Therefore, the ultrasound travel time τ will increase if there are defects existing in a CFST. Meanwhile, the path of the ultrasonic wave is complex due to the effect of the steel tube wall. Therefore, the path should be determined in advance to quantify voids in a CFST.

When the ultrasonic actuator and receiver are symmetrically positioned on the points A and A' (see Fig. 1) along the radian direction of the circular cross-section of a CFST, there are four potential paths that the ultrasonic wave can transmit in a CFST: (1) penetrate the wall of the steel tube and the concrete core of a CFST with no void, i.e. straight from Points A to A' as shown in Fig. 1(a); (2) bypass the void area and transmit along the wall of the steel tube from Points A to B, then travel straightly through the concrete, i.e. from Points B to A' as shown in Fig. 1(b); (3) penetrate the void area and transmit straight through concrete, i.e. from Points A to A' as shown in Fig. 1(c); and finally (4) transmit along the wall of the steel tube only, i.e. from Points A to A' through Point B as shown in Fig. 1(d) without through concrete.

In a well-compacted CFST, the ultrasonic wave will travel following Path 1 as shown in Fig. 1(a). The corresponding ultrasound travel time τ_1 can be calculated using Eq. (1).

$$\tau_1 = \frac{2t}{v_s} + \frac{D-2t}{v_c} \tag{1}$$

where, t is the thickness of the steel tube wall, D is the outer diameter of the steel tube, v_s is the ultrasound velocity in steel, and v_c is the ultrasound velocity in concrete.

In a CFST with a void, the potential ultrasound travel paths are Paths 2, 3 and 4 as shown in Fig. 1, and have the corresponding

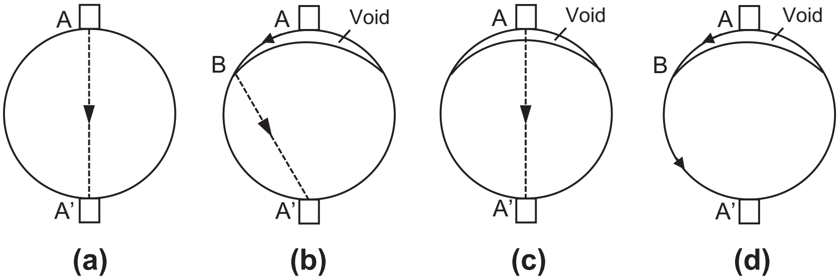

Fig. 1. Four potential paths of ultrasound transmission.