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Study on Simplified Calculation of Ultrasonic Method for Detecting Void in Concrete Filled Steel Tube Based on Sound Velocity

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Abstract

Arch rib is the key mechanical component of concrete-filled steel tubular arch bridge. It is of great engineering value to detect the void of arch rib efficiently and accurately. Aiming at the problem that the ultrasonic method can not realize the quantitative detection of the void height of the arch rib, a simplified calculation formula for the detection of the void height of concrete-filled steel tubular by the ultrasonic method based on the speed of sound is derived and established by combining the theoretical derivation, the model experiment and the real bridge experiment. The feasibility and accuracy of the calculation formula are verified by the model experiment and the real bridge experiment. The results show that the simplified calculation for the detection of the void height of concrete-filled steel tubular by the ultrasonic method based on the speed of sound has high accuracy, which can be used for the discrimination of the void condition of concrete-filled steel tubular and the simplified calculation of the void height, and provides a theoretical basis for the quantitative evaluation of the void height of concrete-filled steel tubular arch rib.

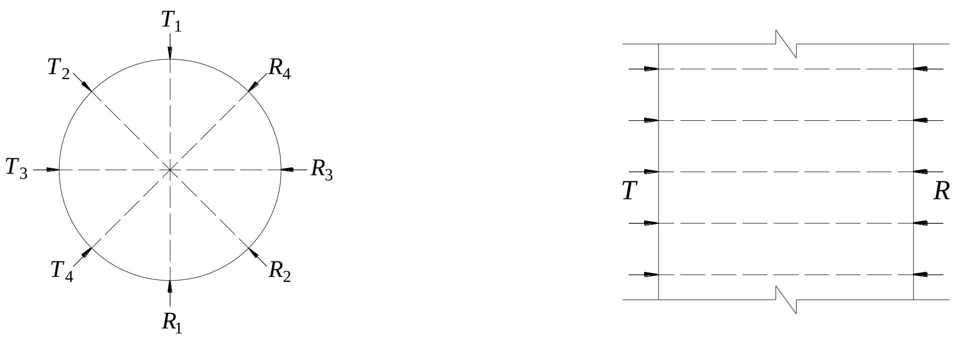
Keywords: Concrete filled steel tube, arch rib, ultrasonic method, sound velocity, void height, simplified calculation.

1. Introduction

Arch rib is the key mechanical component of concrete-filled steel tube arch bridge. The cooperative work of steel tube and core concrete is the basis for the performance of concrete-filled steel tube components. During the construction and operation period of concrete-filled steel tubular arch bridge, due to the influence of construction technology, technical level, external load environment and other factors, concrete-filled steel tubular arch bridge is prone to void [1, 2], which seriously weakens the section characteristics and bearing capacity of concrete-filled steel tubular members [3], and threatens the overall safety of concrete-filled steel tubular arch bridge. It is very important to detect the void disease of concrete-filled steel tubular arch rib efficiently and accurately. Among the numerous detection technologies for the arch ribs of concrete-filled steel tubular arch bridges [4], ultrasonic detection is a reliable and effective detection method, which can accurately reflect the density of concrete pouring in the steel tube. The damage accumulation of core concrete in the steel tube under axial compression load will inevitably cause the change of density. Therefore, ultrasonic technology can be used to detect the damage state and density of concrete-filled steel tube under load [5-7], and there are many related researches. Xu [8] et al applied ultrasonic testing technology to test small diameter concrete filled steel tube specimens, Tan [9,10] et al analyzed four possible ultrasonic first wave propagation paths and theoretical calculation formulas of sound time in the void zone of concrete filled steel tube by ultrasonic measurement method, based on the comparative test of ultrasonic testing, Chen[11] pointed out that ultrasonic technology can accurately detect the damage state of concrete-filled steel tubular under axial compression [12], Zhu [13] et al revealed the relationship between ultrasonic frequency and propagation distance in concrete, Wang [14] et al carried out ultrasonic testing of specimens with different sizes under compression and revealed the variation law of ultrasonic wave velocity under load, Godinho [15] et al studied the method of ultrasonic detection of early concrete cracks, Chen [16] et al inspected the debonding defect between the steel tube wall and concrete by infrared thermal imaging method, supplemented by ultrasonic method to detect the internal cavity of concrete-filled steel tube, and verified the feasibility and convenience of this method by model test and practical engineering, Lei [17] et al used ultrasonic technology to comprehensively detect and analyze the concrete-filled steel tube in the concrete arch bridge of Wushan Yangtze River Bridge, which proved the feasibility of ultrasonic technology to detect the void defects of concrete-filled steel tube, Du [18] et al used ultrasonic detection technology to detect and evaluate the pouring quality of concrete-filled steel tube of Chaoyang East Bridge in Liaoning Province, which proved that it was feasible to use ultrasonic technology to test the defects of concrete-filled steel tube for arch bridge, Shi [19] et al revealed the propagation path of ultrasonic wave in the void specimen based on the model test. To sum up, the current research on the detection of concrete-filled steel tubular arch rib void is not sufficient. Although the ultrasonic method has high reliability, it is difficult to realize the rapid detection of arch rib in large quantities, and the quantitative detection of void height can not be achieved, which directly or indirectly reduces the detection efficiency and accuracy of concrete-filled steel tubular arch bridge, and increases the detection cost and detection cycle. Therefore, a simplified calculation formula for detecting the void height of concrete-filled steel tubular by ultrasonic method based on the speed of sound is derived and established in this paper, which can be used for the discrimination of concrete-filled steel tubular void and the simplified calculation of void height. The feasibility and accuracy of the formula are verified by model experiments and real bridge experiments, which provides a theoretical basis for the quantitative evaluation of concrete-filled steel tubular arch rib void.

2. Principle of Ultrasonic Detection of Concrete Filled Steel Tube Void

Ultrasonic method (ultrasonic pulse method) is a common nondestructive testing method [20, 21], in this method, an ultrasonic detector with waveform display function was adopted to measure the acoustic parameters of ultrasonic pulse wave in concrete, such as propagation speed (sound speed for short), first wave amplitude (wave amplitude for short) and received signal dominant frequency (dominant frequency for short), and the defects in concrete according to these parameters and their relative changes were determined. According to the structural characteristics and stress characteristics of concrete-filled steel tube, the radial measurement method is usually used when ultrasonic method is used to detect the void of concrete-filled steel tube. The radial measurement can be done first. The transmitting transducer (*T* transducer for short) and the receiving transducer (*R* transducer for short) shall be kept on each ring line of concrete-filled steel tube through the center of the circle, and tested along the ring direction. The acoustic time, amplitude and dominant frequency shall be read point by point. Schematic diagram of ultrasonic detection of concrete filled steel tubes was shown in Figure 1.



(a) Cross sectional schematic diagram (b) Side schematic diagram

Figure 1 Schematic diagram of ultrasonic method for detecting concrete filled steel tube component

Ultrasonic testing equipment is generally composed of transmitter and receiver. The electrical signal is converted into ultrasonic wave by transmitter, the converted ultrasonic wave was sent to the surface of arch rib or the interior of concrete through the probe. The returned reflected signal was captured by the receiver and was converted into an electrical signal for subsequent analysis. After amplification and digital processing, the received ultrasonic signal is usually displayed as a waveform or acoustic image, which reflects the reflection of ultrasonic at different depths and material interfaces. If there are voids in arch rib, the reflection intensity will be reduced, the propagation time will be extended, the signal will be attenuated when the ultrasonic wave passes through these areas. Based on the analysis of ultrasonic signal, the position of void area can be accurately located, and even its size and shape can be estimated. The ultrasonic detection results are mainly used to characterize the void situation through the change in the depth of chromatogram. Ultrasonic testing equipment was shown in Figure 2.

Figure 2 Equipment photo for ultrasonic testing

3. Establishment of Simplified Calculation Formula for Void Height of Concrete Filled Steel Tube

Basic assumption: The void is composed of air, and its sound wave propagation speed is equal to the propagation speed of sound waves in the air, concrete is free from defects such as voids and cracks.

Schematic diagram of the cross-section of hollow concrete filled steel tube component is shown in Figure 3, diameter of steel tube is D, outer radius of steel tube is R, inner radius of steel tube is r, wall thickness of steel tube is t, center point of the void area corresponding to concrete filled steel tube is O, angle corresponding to the void area of concrete filled steel tube is θ, height corresponding to the void area of concrete filled steel tube is h.

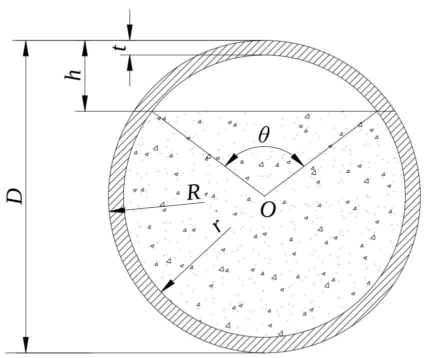


Figure 3 Schematic diagram of void cross-section of concrete filled steel tube

As for the void of concrete filled steel tube, when the void height is 0, when the void parts are all concrete, the speed, time and distance of sound passing through the void parts are v_c, t_c and h respectively. when the void height is h, when the void parts are all air, the speed, time and distance of sound passing through the void parts are v_a, t_a and h respectively. When considering the void gap between steel tube and concrete, cracks or cavities in concrete and other defects, the measured average speed, measured time and distance of sound passing through the void are v_m, t_m and h respectively.

$$h = v_c t_c \tag{1}$$

$$h = v_a t_a \tag{2}$$

$$h = v_m t_m \tag{3}$$

By transforming the above three formulas, the average converted sound velocity v_m can be obtained, as shown in equation (4).

$$v_m = \frac{h}{t_m} = \frac{h}{h/v_a - h/v_c} = \frac{v_a \times v_c}{v_c - v_a} \tag{4}$$

The calculation formula for the void height of concrete filled steel tube is shown in equation (5).

$$h = v_m t_m = \frac{v_a \times v_c}{v_c - v_a} \times \left(\frac{D}{v_m} - \frac{2t}{v_g} - \frac{2r}{v_c}\right) \times \frac{1}{2} \tag{5}$$

In equation (5), h is the void height of steel tube concrete, outer diameter of steel tube is D, inner diameter of steel tube is r, thickness of steel tube is t, sound velocity of steel tube is v_g, sound velocity of concrete is v_C, sound velocity of air is v_a.

When equation (5) is applied to calculate the void height of concrete filled steel tube, if the calculation result of h is negative, it indicates that there is no void at the measuring point.

4. Experimental Verification

4.1 Experimental verification 1

According to reference [22], a concrete filled steel tube component with a spherical crown type void defect was designed and fabricated, as shown in Figure 4, layout of measuring points is shown in Figure 5, steel tube in component is *Q*345, length × outer diameter × wall thickness of the component is 1.5m × 0.62m × 0.01m, size of the void defect is 0.4m (axial direction of component) × 0.314m (radial direction of component), void height is 5*mm*, *ZBL-U5100* ultrasonic detector and ultrasonic matching method were adopted to detect void defects in concrete filled steel tube component.

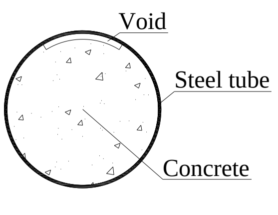


Figure 4 Schematic diagram of voids in concrete filled steel tube component

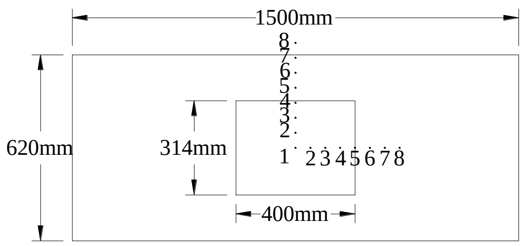


Figure 5 Schematic diagram of measuring point layout for concrete filled steel tube components (mm)

Void height of concrete-filled steel tube component in the literature was calculated by equation (5), where the outer radius of steel tube was taken as 0.31m, the inner radius was taken as 0.30m, the wall thickness of steel tube was taken as 0.01m, the sound velocity of steel tube was taken as 5900m/s, the sound velocity of concrete was taken as 3700m/s, and the sound velocity of air was taken as 343m/s. The calculation results were compared with actual ultrasonic detection results in the literature, and the comparative analysis results were shown in Figure 6 and Figure 7.

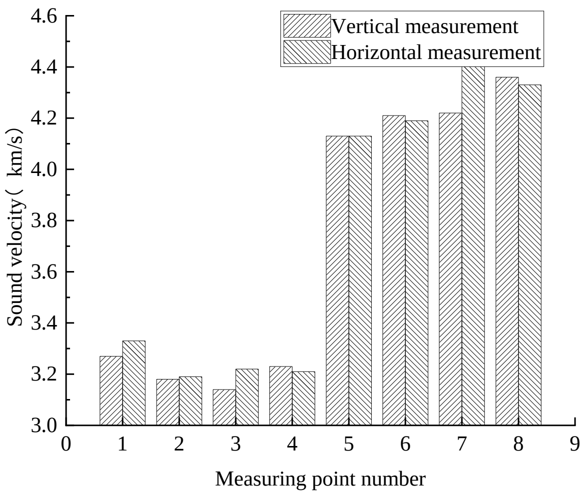


Figure 6 Actual measured values of sound velocity at each measuring point

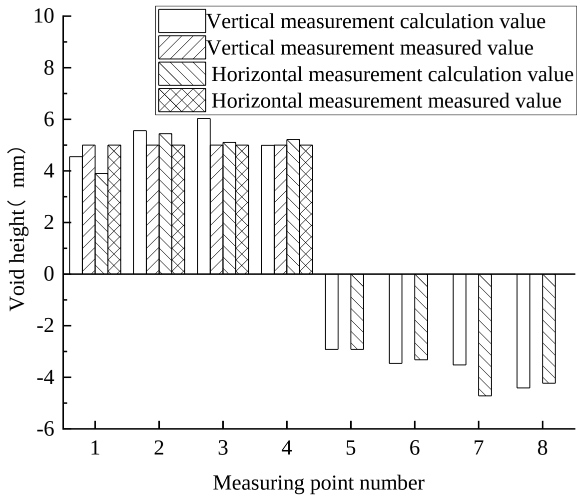


Figure 7 Theoretical and measured values of the clearance height at each measuring point

Among measurement points of vertical measurement, for the measurement point with negative theoretical calculation value of void height, it means that the measurement point has no void part, which is consistent with the actual measurement. For the measurement point with positive theoretical calculation value of void height, it means that the measurement point area has void part. The maximum value of sound velocity in void area was 3.27km/h, the minimum value was 3.14km/h, and the average value was 3.205km/h. The maximum theoretical value of void height was 6.03mm, the minimum value was 4.55mm, and the average value was 5.2825mm. The maximum value of the measured value of the void height was 5mm, the minimum value was 5mm, and the average value was 5mm. The maximum difference between the theoretical calculation value and the measured value of the void height was 1.03mm, the minimum difference was 0.01mm, and the average difference was 0.2825mm. The calculation formula has high accuracy.

Among measuring points of transverse measurement, for the measuring point with negative theoretical value of void height, it means that the measuring point area has no void part, which is consistent with the actual measurement. For the measurement point with positive theoretical value of void height, it means that the measurement point area has void part. The maximum value of wave velocity in the void area was 3.33km/h, the minimum value was 3.19km/h, and the average value was 3.2375km/h. The maximum theoretical value of void height was 5.445mm, the minimum value was 3.9mm, and the average value was 4.916mm. The maximum value of the measured value of the void height was 5mm, the minimum value was 5mm, and the average value was 5mm. The maximum difference between the theoretical value and the measured value of the void height was 1.1mm, the minimum difference was 0.103mm, and the average difference was 0.084mm. The calculation formula has high accuracy.

In summary, the use of formula (5) to determine the voids in concrete-filled steel tube arch rib was consistent with the actual voids in concrete-filled steel tube arch rib. The simplified calculation formula for ultrasonic detection of voids in concrete-filled steel tubes based on sound velocity has high computational accuracy.

4.2 Experimental verification 2

A half through concrete-filled steel tubular arch bridge has a total length of 310m, a calculated span of 280m, and a rise span ratio of 1/4.48, catenary was adopted for main arch axis, and an arch axis coefficient of m=1.5. The arch rib is a concrete-filled steel tubular truss structure. The upper and lower chords of each rib are two φ1000mm concrete-filled steel tubular chord tubes with a thickness of 20*mm* and 24*mm*, C55 self compacting shrinkage compensating concrete was used for the concrete in the steel tube. The chord of main arch was made of *Q*355*C* steel. Schematic diagram of longitudinal section of concrete filled steel tube arch bridge was shown in Figure 8, schematic diagram of measuring point layout at arch foot was shown in Figure 9.

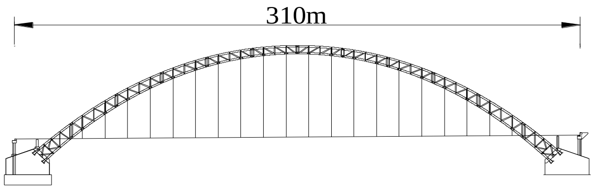


Figure 8 Schematic diagram of longitudinal section of concrete filled steel tube arch bridge

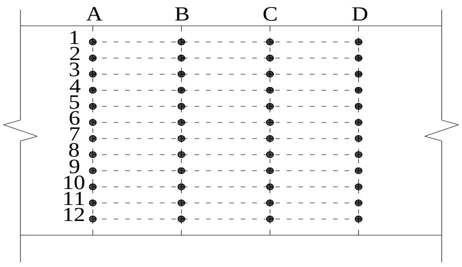


Figure 9 Schematic diagram of measuring point layout at arch foot

The ultrasonic method was used to detect void at arch foot of the left outer arch rib. Limited to article space, only part of the ultrasonic detection results were listed here and compared with the theoretical calculation results. The comparison results were shown in Figure 10 and Figure 11. It can be seen from Figure 10 and Figure 11 that the void condition of arch rib judged by the proposed formula was consistent with actual void condition of arch rib, which has high accuracy.

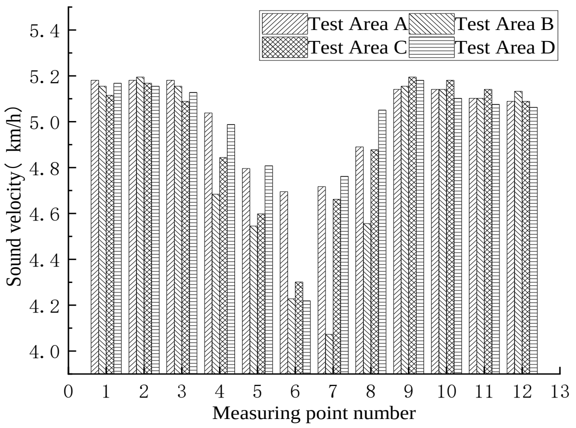


Figure 10 Actual measured values of sound velocity at measuring points in each measuring area

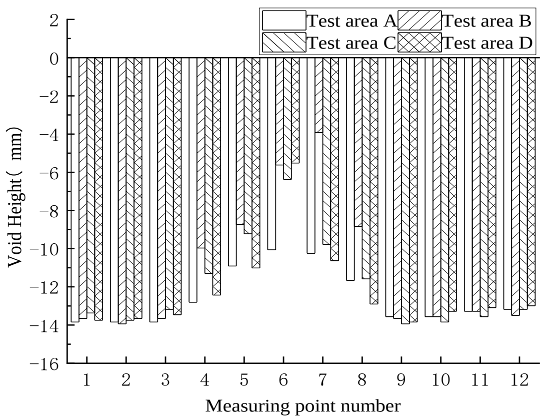


Figure 11 Calculated values of void height for measuring points in each measuring area

Among the measurement points in each measurement area of the left outer arch rib, for the measurement points with negative theoretical value of void height, it means that the measurement point has no void part, which was consistent with the actual measurement. For the measurement point with positive theoretical value of void height, it means that the measurement point has void part. The maximum value of wave velocity in the four void measurement areas of *A*, *B*, *C* and *D* was 3.27km/h, the minimum value was 3.14km/h, and the average value was 3.205km/h. The maximum theoretical value of void height was 6.03mm, the minimum value was 4.55mm, and the average value was 5.2825mm. The maximum value of the measured value of the void height was 5mm, the minimum value was 5mm, and the average value was 5mm. The maximum difference between the theoretical value and the measured value of the void height was 1.03mm, the minimum difference was 0.01mm, and the average difference was 0.2825mm. The results show that the simplified calculation formula of ultrasonic method based on sound velocity for detecting concrete filled steel tubular void has high calculation accuracy.

5. Conclusions

In this paper, theoretical derivation, model test and real bridge test are combined to study the simplified calculation of ultrasonic method based on sound velocity for detecting concrete-filled steel tubular voids. The basic principle of ultrasonic method for detecting concrete-filled steel tubular voids was analyzed, and the simplified calculation formula of ultrasonic method based on sound velocity for detecting concrete-filled steel tubular voids was derived and established. The feasibility and accuracy of the calculation formula were verified by model test and real bridge test. The results show that the void discrimination results of the calculation formula proposed in this paper were consistent with the measured void results, and the calculation formula has high accuracy, which can be used for the discrimination of concrete-filled steel tubular voids and the simplified calculation of void height.

Acknowledgments

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