FUNDAMENTAL STUDY ON MEASUREMENT OF CRACK DEPTH OF CONCRETE BY ULTRASONIC METHOD FOR MULTIPLE CRACKS

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Abstract

Cracks width and cracks depth are indices to evaluate the degree of crack deterioration. Visual observation methods using crack scales, etc. can be used for measuring crack widths, and depth gauge methods for measuring crack depths. However, in both methods, variations in results are large owing to visual errors of the measurer, and the damage amount is difficult to evaluate quantitatively.

The authors focused on the ultrasonic method, which can estimate the quality primarily for the practical application of the measurement method for real structures. As the ultrasonic wave propagation velocity of an object obtained by measurement using the ultrasonic method bypasses the void inside the material and propagates through the shortest distance, the crack depth can be calculated from the distance between the sound velocity in the concrete as well as the probe and propagation time of a concrete member. For the measurement of crack depth by ultrasonic wave propagation velocity measurement, the various methods, which estimate crack depth from the relationship between measured propagation time and distance, have been proposed. However, these methods have been proposed as measurement methods for single cracks, and studies on a plurality of strains are scarce. Therefore, the effect on the ultrasonic wave propagation speed when a plurality of cracks is generated assuming an actual structure is examined herein.

In the propagation velocity measurement by the ultrasonic method, the propagation velocity is measured by the indirect method by placing the receiving and transmitting terminals at intervals of 50 mm from the center of the specimen toward both ends. Herein, we examine the experimental results, focusing on the crack depth and tendency of ultrasonic wave propagation speed.

Keywords: Ultrasonic; Indirect method; Depth estimation; Cracking

1. Introduction

In concrete structures, cracks caused by material and construction factors as well as small earthquakes during service periods cause structural deterioration, such as corrosion of reinforcing bars and lowering of watertightness and airtightness. Therefore, for the permanent use of a structure, a rational repair plan for the service period must be established by understanding the damage quantity of cracks quantitatively.

The author aims at the practical application of the measurement method for real structures from the viewpoint of the ultrasonic method, which can measure the material properties of structures completely nondestructively.

Various studies have been conducted to estimate crack depth by ultrasonic testing. Murakami et al. measured crack depth by the ultrasonic method and examined crack width and ultrasonic transmission using the Tc–T0 modified BS, and rightangle diffraction methods. In the case of crack depth up to 300 mm, the crack depth tends to be measured deeper as the distance from the crack and the age increase, and the correlation coefficient is the highest when the distance a from the crack is 200 mm [1]. According to Shirai et al., who attempted to improve the measurement accuracy, a 50 kHz longitudinal wave probe could be used to more reliably probe for rebar, peel, neutralization depth, and degree of combined deterioration [2].

However, these methods have been proposed as measurement methods for single cracks, and few studies have been conducted for multiple cracks that often occur simultaneously in real structures.

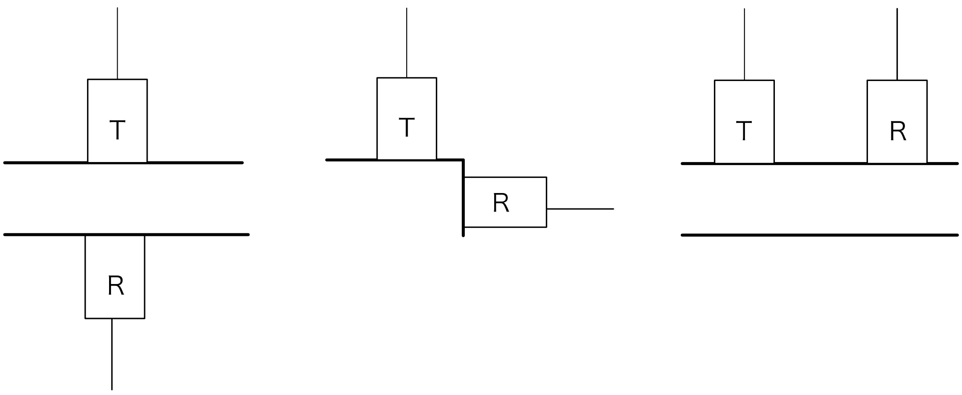
Herein, the effect of ultrasonic wave propagation velocity in the case of multiple cracks is examined.

2. Evaluation method of crack damage quantity by ultrasonic test

2.1 Types of ultrasonic test method

The diagnosis of concrete structures by nondestructive tests is performed to judge the durability of concrete and estimate its strength. As a measuring principle, a transmission and a receiving terminal are adhered to concrete. The time when an ultrasonic pulse that starts from a transmission terminal surface reaches the receiving terminal the most quickly through the inside of concrete is regarded as the propagation time, and the speed is obtained by the distance between both terminals.

As shown in Fig.1, three measurement methods exist: direct, semi-direct, and reflection methods. An ultrasonic test using the reflection method is used for the nondestructive measurement of the crack damage quantity of the transmitting terminal (transmitter: hereinafter referred to as T) and receiving terminal (receiver: hereinafter referred to as R). For ultrasonic testing, various diagnostic methods can be used, such as the Tc–T0, modified BS, right angle diffraction wave, T, delta system, and Leslie methods. In this study, the Tc–T0 , modified BS, and short-range detour wave methods were used. Each of the test method is explained herein.



(a) Direct method (b) Semi-direct method (c) Indirect method

Fig. 1 – Type of ultrasonic test

2.2 Numbering of subsections [3, 4]

(1) Modified BS method

Fig.2 shows the measurement method of crack depth estimation by the modified BS method. In this method, the transmission terminal (T) and reception terminal (R) were installed at two places, i.e., a1 and a2 (a2 = 2a1) from the crack at the same distance from the crack toward the opposite side to sandwich the crack, and the ultrasonic propagation time (T1, T2) was measured. From these measurement results, the crack depth was calculated using Eq. (1). In the British standard (BS) method, the distance between the transmitting terminal (T) and receiving terminal (R) is determined to be a1 = 15 cm and a2 = 30 cm. The modified BS method was used by arbitrarily setting the distance of the crack. Herein, the BS method is included, and the measurement was performed by the modified BS method.

$$d=a1\sqrt{((nT_1^2-T_2^2)/(T_2^2-T_1^2))} \qquad (1)$$

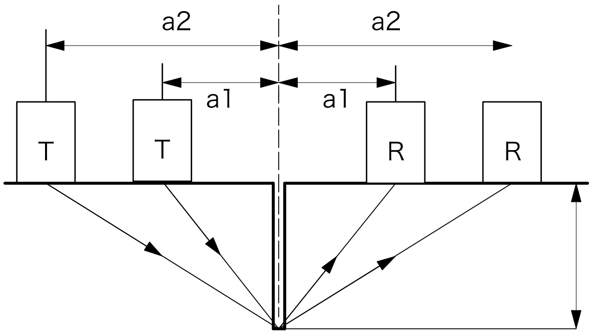
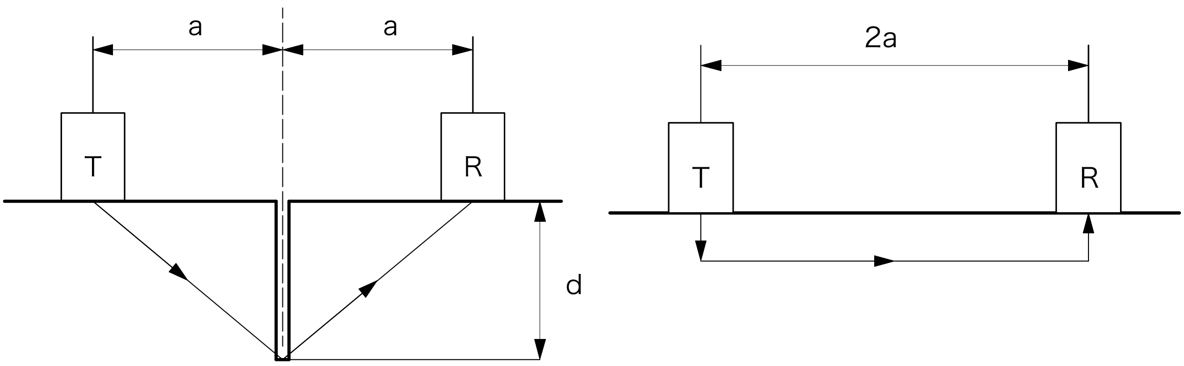


Fig. 2 – Modified BS method

(2) Tc–T0 method (L–L method)

The Tc–T0 method is equivalent to the BS method in that the same distance (a) is set from the crack in the test specimen to both ends of the crack, the transmission probe is placed on one end, and the receiver probe is placed on the other end to measure the ultrasonic wave (Tc). At that time, the crack depth is calculated using Eq. (2) with the propagation velocity measured at the distance (2a) as a reference value (T0) in the concrete of the sound part. Fig.3 shows the measurement method of crack depth estimation by the Tc–T0 method.

$$d = a\sqrt{((Tc/T0)^2-1)} \qquad (2)$$



a) Areas with cracks B) Sound area

Fig. 3 – Tc–T0 method

(3) Short-range detour method

The short-range detour wave method is similar to the BS and Tc–T0 methods in that it is centered on a crack and is directed to the opposite side to sandwich the crack. In this method, the distance (a) of the same distance is set, and the transmission terminal (T) and consultation terminal (R) are installed to measure the ultrasonic wave propagation time (T1, T2). In particular, it differs from the L–L system in that it must be installed close to the transmission and reception terminal crack. Fig.4 shows the measurement method of crack depth estimation by the short-range detour wave method.

$$d = V_0 \cdot T_c/2 \quad (3)$$

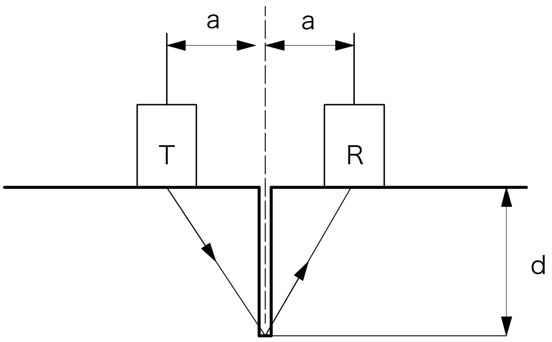


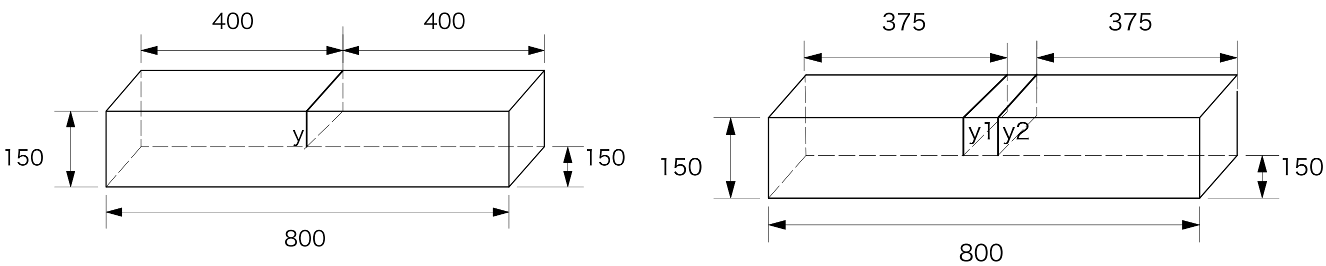
Fig. 4 – Short-range detour method

3.Outline of test specimen

3.1. Test specimens

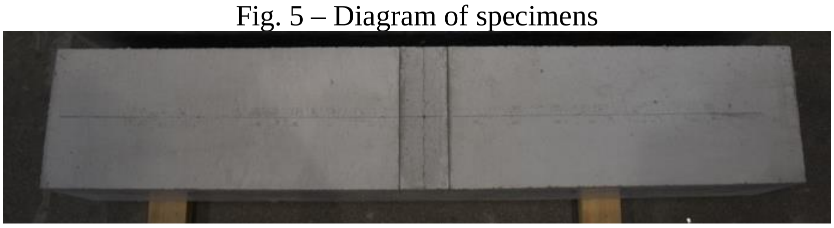
(1) Specimen form

A diagram of the test specimen is shown in Fig. 5, and a photograph of a specimen example is shown in Pic.1. The specimen measured 800 mm in length, 150 mm in width, and 150 mm in height. After placing the specimen, the mold was removed during the curing period of 21 d, and an ultrasonic test was performed during the curing period of 28 d. Herein, only the effect of the slit on the concrete surface during the ultrasonic test is examined; the test was performed on plain concrete.



a) Single slit [mm]
b) Double slit [mm]

Fig. 5 – Diagram of specimens



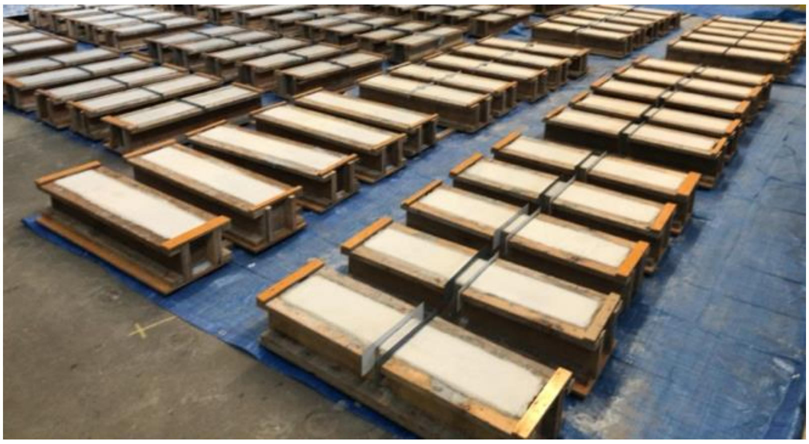
Pic. 1 – Example of test sample

(2) Type of simulated slit

The parameters of the slit shape are shown in Table 1. Two types of slits exist: 30 mm and 60 mm in depth. Furthermore, 5 patterns of slit were observed: one slit at 60 mm deep, one slit at a 30 mm deep, two slits at 60 mm deep, two slits at 30 mm deep, two slits at 30 mm deep, and one slit each at 30 and 60 mm deep. The number of test specimens was five for each case. The curing process is shown in Pic.2.

Table 1 – Specimen

Specimen	depth	slit count	rot
N-30	y = 30 mm	1	5
N-60	y = 60 mm	1	5
N-30-30	y1 = y2 = 30 mm	2	5
N- 60-60	y1 = y2 = 60mm	2	5
N-30-60	y1 = 30mm, y2 = 60mm	2	5
N-0	None	0	5


Pic. 2 – Conditions of curing (premold)

(3) Method for manufacturing simulated slit

The simulated slit was installed on the steel plate of 0.27 mm thickness coated with grease at the time of placing, and was smoothed with a gold trowel before hardening so that the surface became flat. The steel plate was removed during mold removal, and the slit formed at that time was set as a simulated slit. The specimen materials are shown in Table. 2.

Table 2 – Formula Sheet

W/C (%)	**kg/m3**				
	water	**cement**	**fine aggregate**	**coarse aggregate**	**admixture**
58	169	291	461	917	2.91

(4) Strength of concrete used

The concrete used was subjected to a compression test on a specimen made of the same material at the time of placing, and its compression strength was 24.3 MPa.

3.2 Measurement Methods

The specimens were measured at 28 d by indirect ultrasonic testing. As shown in Fig. 6, the surface with slits (top surface at the time of manufacture) was measured from the center of the test specimen to both ends at the distances of 50, 100, 150, 250, and 300 mm at equal intervals. Regardless of the number of slits, the ultrasonic propagation velocity was measured using the distance from the center of the test specimen toward both ends. Therefore, as shown in Fig. 7, in this measurement method, the transmitter and receiver are measured at the same distance from the slit in the case of one slit; however, in the case of two slits, the distance from the center is the same, but the distance from the slit is a + 25 mm.

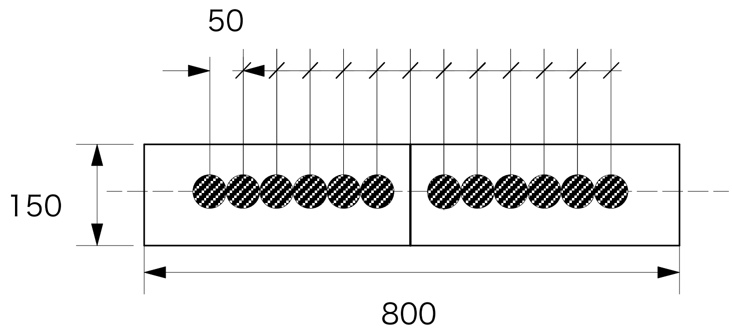
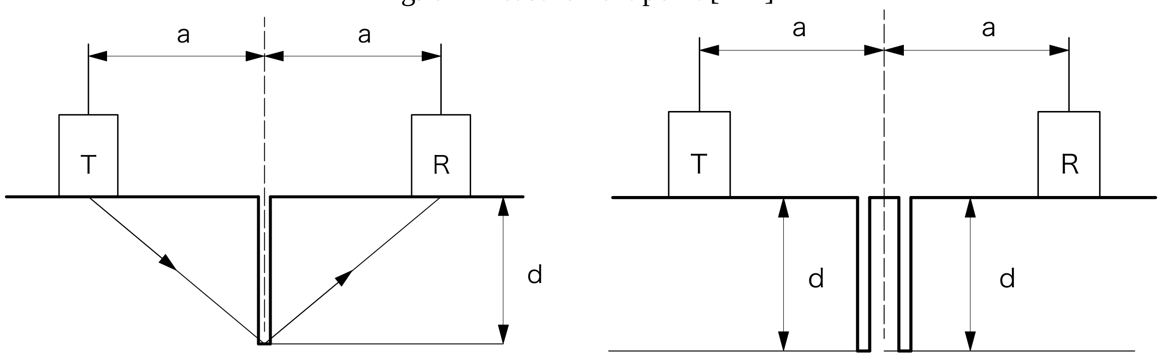


Fig. 6 – Measurement point [mm]



a) Single slit b) Double slits

Fig. 7 – Measuring method

4. Result and Discussion

4.1 Ultrasonic wave propagation time measurement result

The measurement results of the ultrasonic wave propagation time are shown in Table 3. The longer the measurement distance, the longer was the measurement time.

Table 3 – Specimen [μsec]

Specimen	50 mm	10 mm	10 mm	200 mm	20 mm	300 mm
N-30	42.1	88.1	135.9	203.9	249.6	263.2
N-60	55.9	82.8	134.2	164.1	198.3	249.8
N-30-30	43.8	93.9	119.8	163.8	196.5	253.1
N-30-60	66.6	95.5	140.5	164.7	217.6	235.9
N-60-60	53.1	99.1	130.9	174.2	200.5	253.1
N-0	40.0	73.5	112.05	122.2	185.7	237.1

4.2 Relationship between distance from center and estimated slit depth

(1) For a single slit

From the measured ultrasonic wave propagation time, the slit depth was estimated using the Tc–T0, modified BS, and short-range detour wave methods. The estimation results are shown in Table 4 and Fig.8.

For the Tc–T0 method, the estimated depth was 30% deeper when a = 50 mm and twice deeper when a = 100 mm. For the depth of 60 mm, when a = 50 mm, the depth was almost the same, and when a = 100 mm, the estimated depth was 20% shallower.

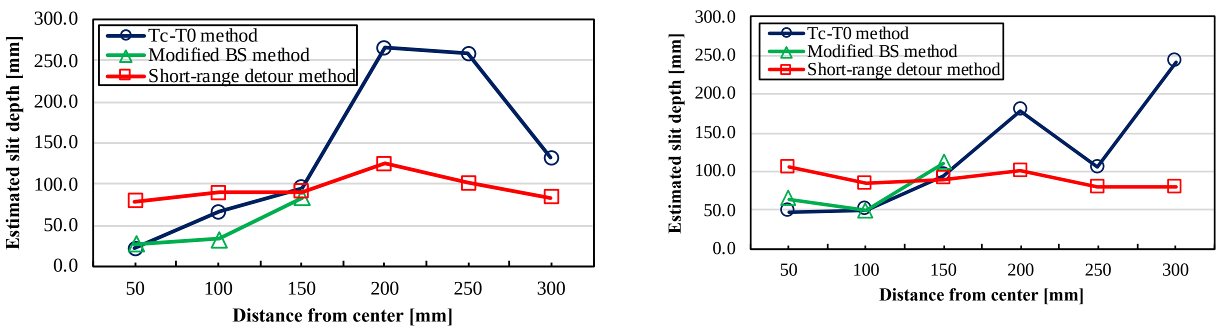
For a depth of 30 mm, the estimated depth was 10% shallower when a = 50 mm and 10% deeper when a = 100 mm. For a depth of 60 mm, it was estimated about 20% deeper than the actual depth for both a = 50 mm and 100 mm. If a = 150, the depth deviates significantly from the actual depth. Therefore, when a = 50,100 mm, the depth can be estimated to be close to the actual depth.

For the short-range detour wave method, the same depth was estimated regardless of the actual depth of the slit. The estimated slit was calculated to be deeper than the actual slit, and the calculated result differed from the actual depth.

From the results above, it can be concluded that the Tc–T0 method is the best estimation method within the range of the present experiment.

Table 4 − Specimen

Slit		Distance	Method		
Depth	**number**	**from center**	**Tc-T0**	**Modified BS**	**Short-range detour**
30 mm	1	50	21.6	27.9	78.9
		100	65.9	33.2	89.8
		150	95.7	83.8	90.9
		200	265.0	-	125.1
		250	257.8	-	100.8
		300	131.2	-	83.3
60 mm	1	50	48.4	63.8	104.8
		100	50.0	49.2	84.5
		150	95.1	111.2	89.8
		200	179.0	-	100.7
		250	105.7	-	80.1
		300	241.1	-	79.0

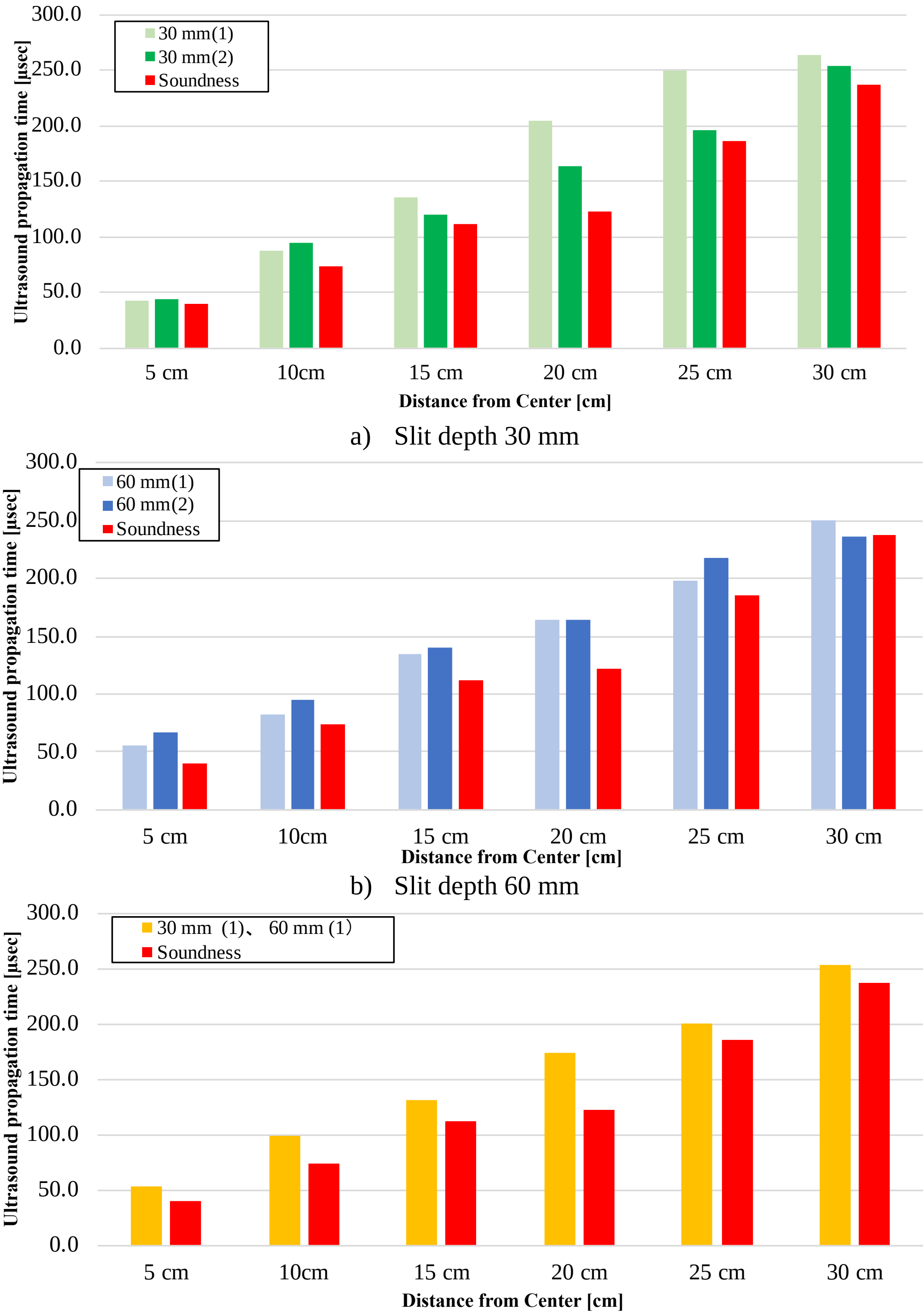


a) Slit depth 30 mm Slit depth 60 mm

Fig. 8 – Relationship between distance from center and estimated crack depth

(2) For two slits

The Tc–T0, modified BS, and short-range detour wave methods do not correspond to more than two slits because the estimation method of the slit is for estimating the distance from the slit. We compared the effect of changing the number and depth of slits on the ultrasonic propagation time. Fig.9 shows the sound test specimen and measurement results. Compared with the sound test specimen, the ultrasonic wave propagation time was longer for the test specimen with a 30 mm slit and that with both a 30 mm and 60 mm slit, while it tended to vary for the test specimen with a 60 mm slit.



c) Slit depth 30 and 60 mm

Fig. 9 – Distance from the center and relations of the supersonic wave spread time

Table 5 shows the comparison in ultrasonic wave propagation time for each specimen. The ratio of the ultrasonic propagation time of the test specimen with one slit of depth 30 mm to that with two slits of depth 60 mm, that with one slit of depth 60 mm to that with two slits of depth 30 mm, that with one slit of depth 60 mm to that with one slit of depth 30 mm, that of two slits of depth 30 mm to the test specimen, that of one slit of depth 60 mm to the test specimen, and that of two slits of depth 60 mm to the test specimen were determined.

For the specimen with two slits of depth of 30 mm, the ultrasonic propagation time ratio with the specimen with one slit with depth 30 mm was 0.8–1.1. In particular, the ultrasonic propagation time ratio was 1.0–1.1 when the depth estimation accuracy in this experiment was up to 100 mm. For the test specimen with two slits of depth 60 mm, the ultrasonic propagation time ratio with the test specimen with one slit of depth 60 mm was 0.9–1.2. As a result of examining data up to 100 mm, for which the accuracy of depth estimation was high, the ultrasonic wave propagation time ratio was 1.2, and it is considered that 2 slits were detected especially for the depth of 60 mm.

For the test specimen with one slit of depth 30 and 60 mm, the ultrasonic propagation time ratio of the test specimen with one slit of depth 30 mm was 0.8–1.3, that with two slits of depth 60 mm was 0.9–1.2, that with two slits of depth 30 mm was 1.0–1.2, and that with two slits of depth 60 mm was 0.8–1.1. While the actual slit depths were 30 and 60 mm, the ultrasonic propagation time was longer for the test specimen having a slit depth of only 30 mm. When a = 100 mm, the ultrasonic propagation time ratio was 1.1–1.3 when compared with that with one slit, and the ultrasonic propagation time ratio was 1.1–1.2 when compared with that with two slits. When a = 100 mm, the ultrasonic propagation time ratio of the test specimen of depth 60 mm was 0.9–1.2 when compared with that having one slit, and that with two slits was 0.8–1.0. In addition, as a result of examining the case in which there are 2 slits each of 30 mm and 60 mm in depth, the tendency of the ultrasonic wave propagation velocity ratio is different when compared with the case in which there is a 30 mm slit and the case in which there is a 60 mm slit.

When a 30 mm slit is provided, the ultrasonic propagation velocity ratio tends to be slightly higher than 1.0 regardless of the number of slits, and when a 60 mm slit is provided, the ultrasonic propagation velocity ratio tends to be slightly lower than 1.0 regardless of the number of slits. Hence, the depth can be determined regardless of the number of slits.

Table 5 − Comparison of the time of ultrasonic wave propagation for each specimen

Specimen Slit type : Slit count	**Distance from center**					
	50 mm	**10 mm**	**10 mm**	**200 mm**	**20 mm**	**300 mm**
30 mm:2 / 30 mm:1	1.0	1.1	0.9	0.8	0.8	1.0
60 mm:2 / 60 mm:1	1.2	1.2	1.0	1.0	1.1	0.9
30 mm:1, 60 mm:1 / 30 mm:1	1.3	1.1	1.0	0.9	0.8	1.0
30 mm:1, 60 mm:1 / 60 mm:1	0.9	1.2	1.0	1.1	1.0	1.0
30 mm:1, 160 mm:1 / 30 mm:2	1.2	1.1	1.1	1.1	1.0	1.0
30 mm:1, 60 mm:1 / 60 mm:2	0.8	1.0	0.9	1.1	0.9	1.1

5. Conclusions

In this study, the effect of the ultrasonic wave propagation speed in the case of multiple slits generated using a slit that was generated by simulation was examined on the assumption of a real structure. The conclusions are as follows:

1) For the Tc–T0 method, the estimated depth was 30% deeper when a = 50 mm and twice deeper when a = 100 mm. As for the depth of 60 mm, when a = 50 mm, the depth was almost the same, and when a = 100 mm, the estimated depth was 20% shallower. Therefore, it was considered that the depth varied depending on the depth. Meanwhile, the depth of the modified BS method was estimated to be approximately 20% for both a = 50 and 100 mm, and the depth of the modified BS method was significantly different from the actual depth when a = 150. Therefore, the depth of the modified BS method could be estimated to be approximately a = 50 and 100 mm. For the short-range detour wave

method, the same depth was estimated regardless of the actual depth of the slit. The estimated slits were deeper than the actual slits.

2) Compared with the sound test specimen, the test specimen with a slit of 30 mm and that with one slit of 30 mm and one slit of 60 mm exhibited longer ultrasonic wave propagation times, whereas the test specimen with a slit of 60 mm had a greater dispersion.
3) For the test specimen with two slits of depth 30 mm, when the depth was up to 100 mm, for which the accuracy of depth estimation was high in this experiment, the ultrasonic propagation time ratio was 1.0–1.1, and it was difficult to determine whether two slits were detected. For a test specimen with 2 slits of depth 60 mm, when the ultrasonic wave propagation time ratio was up to 100 mm, two slits were detected.
4) When the propagation times of the ultrasonic waves were compared, the two slits having the depths of 30 and 60 mm tended to be substantially the same for both the slits having the depths of 30 mm and 60 mm. Therefore, the depth could be judged regardless of the number of slits.

As described above, in the measurement of slit depth using the ultrasonic test, it was discovered that the slit depth was affected by the slit depth within the range of the present experiment regardless of the number of slits.

In the future, the slit depth and the distance between slits will be used as parameters for a plurality of slits to simulate a slit.

6. References

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