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EVALUATION OF CRACK DEPTH IN REINFORCED CONCRETE STRUCTURE USING ULTRASONICS

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A method to evaluate the depth of a surface-opening crack in reinforced concrete (RC) member by ultrasonic testing (UT) is studied. Experimental studies are performed to understand the interaction between the size of crack and arrangement of reinforcement. For this end, specimens with a surface-opening crack are made and tested. The effect of reinforcement on the estimated crack depth is studied by applying a model which takes into account P-waves diffracted at the tip of crack and the reinforcement. Concerning the effect of crack surface, the ratio of crack width to crack depth is found to be available for compensating the roughness of crack face.

Key Words: NDT, ultrasonics, reinforced concrete, surface crack, crack depth, mixture proportion, probe location, reinforcement, crack width

1. INTRODUCTION

Recently, it become in urgent demand to evaluate structural integrity of existing structures due to aging problem in Japan. Accordingly it is desirable to establish a method by which deterioration of reinforced concrete (RC) can be evaluated practically. Thus, ultrasonic testing (UT) method is expected as a promising NDT to evaluate cracks in reinforced concrete (RC) members. It is well known that the depth of a surface-opening crack in a concrete member can be determined from the diffracted time of compressive (P-) waves at the tip of the crack, although the results are found to be affected by reinforcements and crack faces.

In the case that the reinforcement is located close to probe locations, the crack depth is not correctly evaluated. This is because P-wave propagation is influenced by the difference of elastic modulus and specific gravity between concrete and steel [1), 2)].

On the other hand, when the width of a surface crack is narrow, the estimated value also becomes ambiguous because the P-wave could travel at the shallow parts of the crack [3)].

In order to evaluate the crack depth using the ultrasonic P-waves, thus it is important to confirm the effects of reinforcement and crack faces for quantitative estimation. To clarify these effects, locations of the reinforcement and crack faces are experimentally examined. Additionally as a basic study, relationships among P-wave propagation, mixture proportion and probe locations are studied.

2. EVALUATION OF CRACK DEPTH

In order to measure the crack depth by ultrasonics, one transmitter and two receivers are used in this study [4)]. Two receivers are located on the opposite side of the crack apart the same distance (L) from the transmitter as shown in **Fig.1.** The transmitter and the receivers are of the same resonant type. After a pulsed ultrasonic wave is generated by the transmitter, P-waves arrive at the two receivers. First P-wave arrives at Receiver 1 which propagate in the concrete. This arrival time is indicated as t_o. Another receiver (Receiver 2) initially responds to the arrival of P-wave diffracted from the crack tip. The arrival time of diffracted P-wave is indicated as t_c. Then the depth d of the surface-opening crack can be determined from Eq.(1) (Tc-To method [2)]).

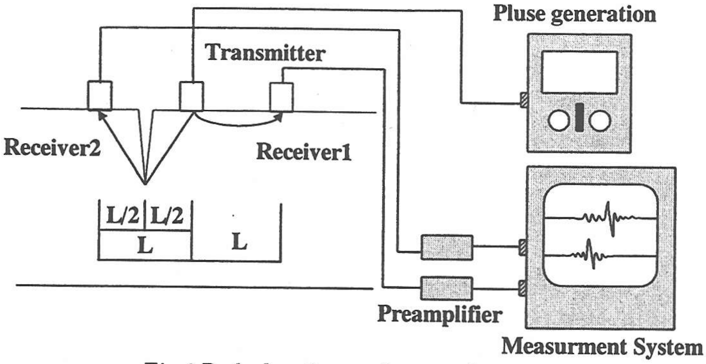


Fig.1 Probe locations and measuring system

Table 1 Mixture proportions

mix No.	maximum size of aggregate (mm)	W/C (%)	s/a (%)	air content (%)	unit weight of water (kg/m³)	slump (cm)
A1	5	50	----	1.7	227	---
A2	10	50	45	1.0	160	8.0
A3	20	50	45	1.0	160	8.0

Table 2 Mechanical properties

mix No.	specific gravity	compressive strength (MPa)	tensile strength (MPa)	Young's modulus (GPa)	Poisson's ratio	P-wave velocity (m/s)
A1	2.26	62.7	4.7	27.4	0.2	4420
A2	2.42	66.2	4.59	36.7	0.2	4850
A3	2.42	61.2	4.26	40.4	0.2	4950

$$d = \frac{L}{2}\sqrt{\left(\frac{t_c}{t_o}\right)^2 - 1} \qquad (1)$$

Ultrasonic waveforms are amplified 40 dB by a preamplifier and driven to a measuring system. For the measurement, two types of ultrasonic probes of 15 kHz resonance frequency and 60 kHz were used as both the transmitter and the receiver. Each probe was attached to concrete surface with silicon grease. The transmitted pulse-wave of 20 nanosecond rise-time and of 300 voltages was input by a pulse generator.

3. MIXTURE PROPORTIONS OF CONCRETE AND LOCATION OF PROBE

Ultrasonic wave could be affected by attenuation and reflection from the boundary of aggregate[5]. When ultrasonic testing is carried out in concrete structure, it is important to conform the effect on composition of concrete. Therefore the maximum size of aggregate is controlled from 5 to 20 mm in mixture proportions of concrete as given in **Table 1.** Mechanical properties of concrete are listed in **Table 2.** In this study, mix A1 represents mortar specimens and those of A2, A3 are concrete with 10 mm and 20 mm aggregate sizes.

In order to evaluate the crack depth, it is necessary to study the effect of the probe position on the traveled ultrasonic waves. The shape of the specimen and the probe locations tested are presented in **Fig.2**. Five receivers are placed on the surface of a concrete specimen, the velocity of P-waves is measured at all locations 1, 2, 3, 4, and 5 right after a ultrasonic pulse wave is generated by a transmitter. Two specimens for each mixture were made and examined . The velocities measured are evaluated as the relative velocity ratio to P-wave velocity at the center of the specimen (from transmitter A to receiver 3). Here the probes of 60 kHz resonance type were only employed.

Figure 3 shows the results of relations between the relative velocity ratio and the distance from the transmitter to the receiver. The results of P-wave transmitted through the specimen are shown in **Fig.3 (a)** and those of traveled on concrete surface are shown in **Fig.3(b)**. In regard to the mixture

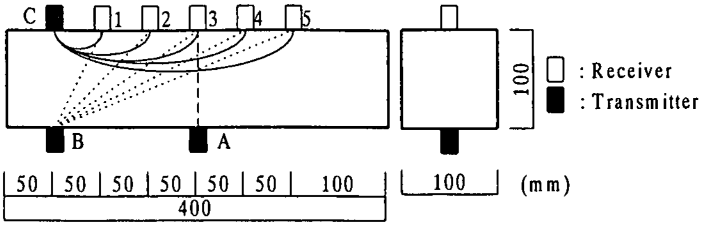
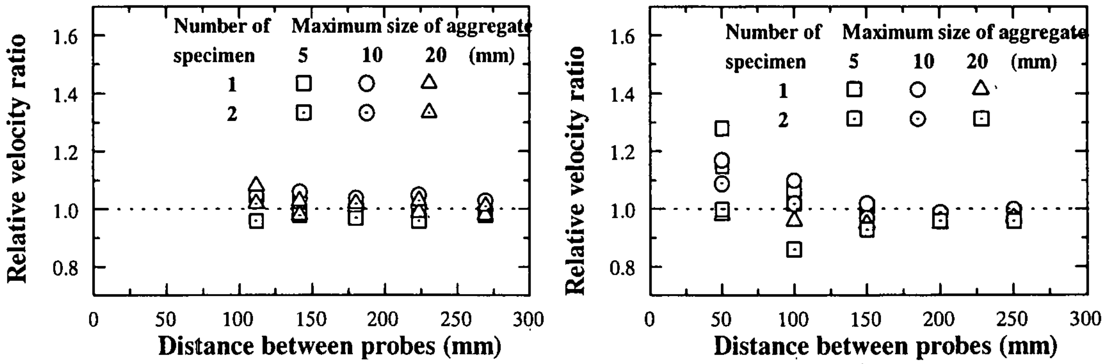


Fig.2 Probe location



(a) P-wave transmitted due to the transmitter at B

(b) P-wave traveled on concrete surface due to the transmitter at C

Fig.3 Velocity ratios of the transmitted P-waves in concrete

Table 3 Mixture proportions of concrete

W/C (%)	s/a (%)	air content (%)	unit weight per volume (kg/m^3)			
			W	C	S	G
50	45	4.5	166	334	802	1021

Table 4 Mechanical properties of concrete

specific gravity	compressive strength (MPa)	tensile strength (MPa)	Young's modulus (GPa)	Poisson's ratio
2.29	32.4	3.29	32.9	0.2

proportion and probe locations, relative velocity ratio scarcely change when the distance between two probes are wider than 150 mm. In the case that the distance between the probes is wide enough, the effect of the distance errors become small. In this study, the ultrasonic wavelength (velocity over resonance frequency) was calculated as longer than 70 mm. Thus the maximum size of aggregate is shorter than the wavelength. In this case, the results are not affected by the size of aggregate. For attenuation[6], the probes with resonance frequency lower than 100 kHz is practical in concrete. From these results, the effect of the aggregate sizes is not taken into account for the estimation of crack depth.

4. REINFORCEMENT

(1) Specimens

To study the effect of the reinforcement on the traveled P-waves, RC members (20 x 50 x 140 cm) with artificial opening-crack were made as shown in **Fig.4**. Mixture proportions and mechanical properties of concrete are listed in **Tables 3** and **4**. Aggregate used is crashed stone with the maximum size of 20 mm. Conditions of RC specimens are summarized in **Table 5**. In order to evaluate the effect of reinforcement diameters, two types of reinforcement which are 13 and 19 mm in diameter are arranged. The reinforcement is arranged at 25 mm cover thickness. Three types of artificial cracks of 50, 75 and 100 mm depths and 0.3 mm

Table 5 Condition of RC specimen

size of reinforcement diameter (mm)	artificial crack depth (mm)
13	100
19	50, 75, 100

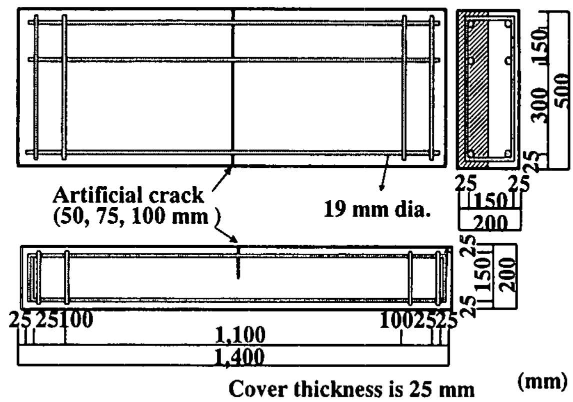


Fig.4 Specimen with artificial opening-crack

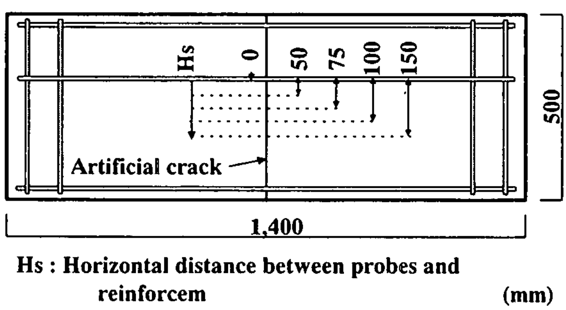


Fig.5 Probe locations of the specimen with artificial opening- crack

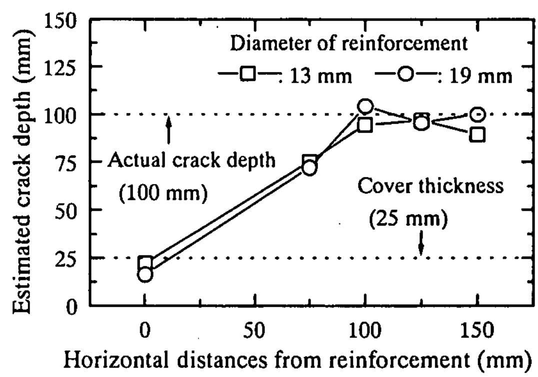


Fig.6 Effect of reinforcement in variation of diameters and locations

width are introduced, respectively.

(2) Effect of reinforcement diameter

As seen in **Fig.5**, the horizontal distances (*Hs*) between probes and the reinforcement are controlled from 0 to 150 mm. For investigating the effect of P-wave paths, the distances from the transmitter to the receiver (spaces of probes *L*) are varied as 150, 200 and 300 mm. Probes of 60 kHz (R6) resonances were used in this case.

Figure 6 shows the results on the relationship between the estimated depth and the distance H_s for two specimens. These are averaged values for the cases where the distances (L) between the probes, transmitter and receiver are 150, 200 and 300 mm. As shown in the figure, the estimated values agree with the actual depth if the distance H_s is longer than 100 mm regardless of the diameter of reinforcement. At right above the reinforcement (H_s = 0 mm), the averaged values of the estimations are about 30 mm which is almost equal to the cover thickness. This result suggests that P-wave is reflected at the surface of the reinforcement. Therefore, the relationship between the actual crack depth and the estimated values is studies, taking into account the presence of reinforcement.

(3) Relationship between the actual crack depth and the estimated value

To evaluate the influence of reinforcement on estimated of crack depth, RC specimen with artificial crack in **Fig.5** was tested again. In this case, the horizontal distance of 25 mm was added for evaluation. In addition, both probes of 15 kHz

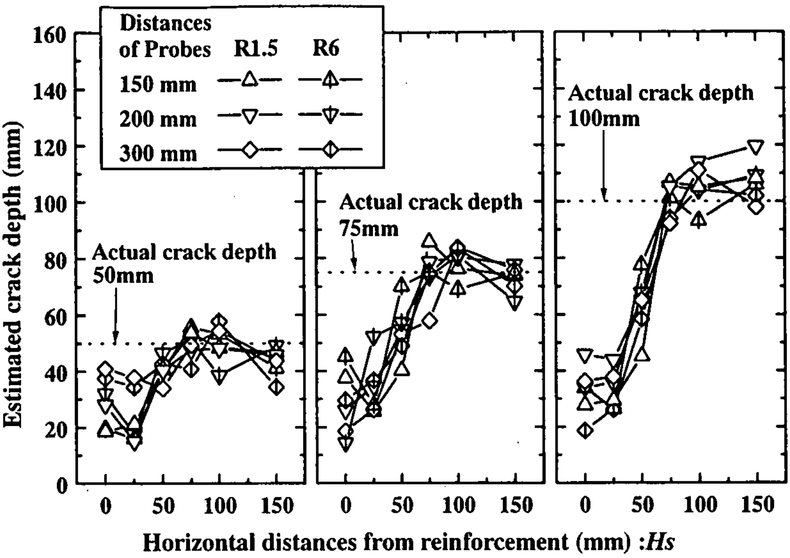


Fig.7 Effect of reinforcement location on the estimation of crack depth

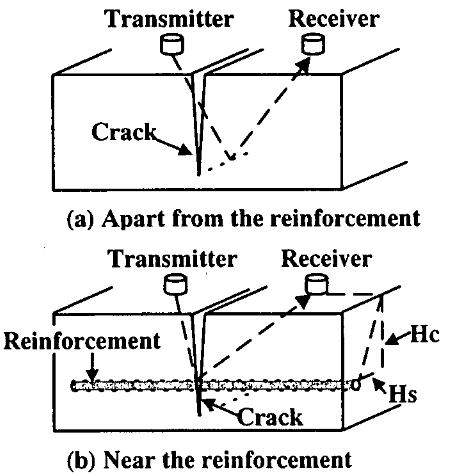


Fig.8 Reflected waves at the crack and the reinforcement

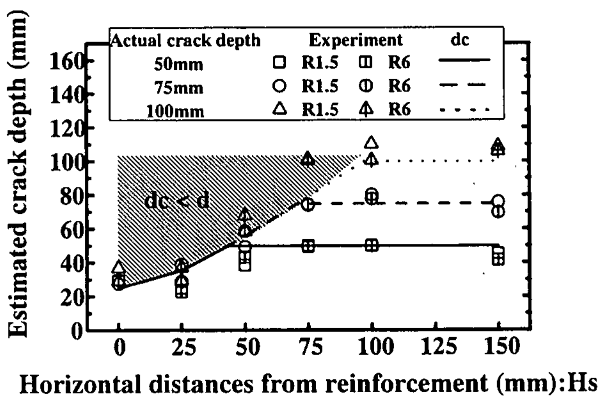


Fig.9 Estimated crack depth in the experiments and relations of d_c and d

(R1.5) and 60 kHz (R6) resonances were used. **Figure 7** shows results on the relationship between the estimated crack depth and the distance H_s. The estimated values agree with the actual depth only if the distance H_s is longer than the crack depth. At right above the reinforcement (H_s =0), the estimated values are again about 25 mm which is equal to cover thickness. On the other hand, the effects of probes types are in consequent .

(4) Effect of reinforcement on the estimation of crack depth

To clarify the effect of reinforcement, reflected P-wave path model was studied as shown in **Fig.8**. P-waves diffract either at the tip of crack (**Fig.8** (a)) or the surface of reinforcement (**Fig.8 (b)**). In the case that P-wave reflects at shallow position due to the reinforcement above the crack tip, the calculated depth (d_c) is expressed by the following equation,

$$d_c = min\ (d, d_r) \qquad (2)$$
$$d_r = \sqrt{H_s^2 + H_c^2}$$

where H_s is the horizontal distances between probes and reinforcement and H_c is cover thickness.

Averaged values of **Fig.7** are plotted in **Fig.9**, and the estimated d_c from Eq.(2) and averaged values of **Fig.7** are compared. According to the

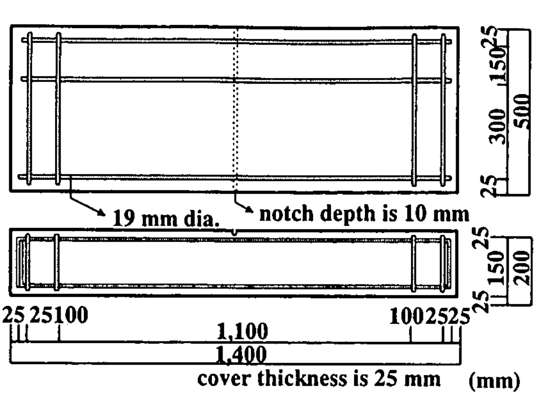


Fig.10 Specimen of flexural cracks

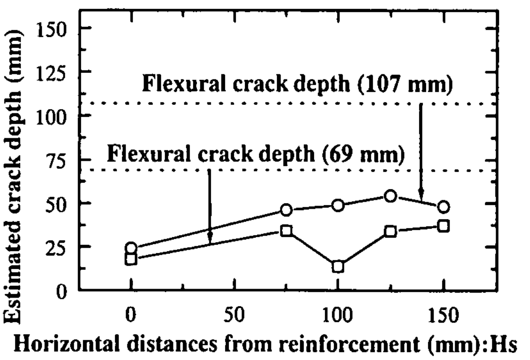


Fig. 11 Estimated vales on flexural crack depth

results, the effect of reinforcement on the estimation of crack depth could be compensated. In the case that the location and the cover thickness of the reinforcement are determined using radar or other techniques, the crack depth d in the ultrasonic testing can be limitedly estimated with reasonable accuracy when $d_c > d$.

5. CRACK SURFACES

(1) Estimation of flexural crack depth

Generally, the surface of the flexural crack in concrete is of complicated nature, because of its extension along the surface of aggregate. As already been confirmed, the ultrasonic wave could transmit in a crack of which width is narrower than 0.3 mm[3]. When the width of the surface flexural crack is narrow enough (i.e. less than 0.3 mm), ultrasonic P-waves could travel at the shallow part than the tip of the crack for roughness of the faces. To study the influence, the depth of flexural crack was evaluated after a crack was introduced by flexural load at the middle of the RC specimen. The crack locations were controlled using notch. **Figure 10** shows RC specimen of which the mixture proportions and mechanical properties are already given in **Tables 3** and **4**. Probes of 60 kHz (R6) resonance were used and their locations are the same as those in **Fig.5**. After two types of depths of around 50 mm and 100 mm were generated and the specimens were unloaded, the depth of flexural cracks were measured.

The Average flexural crack depths observed at both sides of the specimen under loading were 67 mm and 107 mm respectively. Relationships between horizontal distance H_s from reinforcement and estimated crack depth are shown in **Fig.11**. Results evaluated are less than a half of actual depth regardless of the horizontal distances from reinforcement. These results suggest that P-waves could travel through the crack faces which are close each other. Consequently, a relationship between the crack width and the estimated value is studied.

(2) Relationship between crack width and estimated value

The effect of crack faces on the estimation was examined by controlling the widths of surface cracks in RC specimen under flexural loading. In order to control the crack depth, two cases of specimens with 150 mm thickness (reinforcement ratio is 1.2 %) and 200 mm thickness (reinforcement ratio is 0.8 %) were made as shown **in Fig.12.** In both specimens, reinforcement of 19 mm in diameter was arranged at 20 mm cover thickness. The balanced steel ratio was 4.9 %. Flexural cracks were controlled by a notch at the center of specimen. For all specimens, mixture proportion is the same as **Table 3**.

A relationship between the actual crack depth (d) developed under flexural load and the estimated depth by ultrasonic technique was studied. As shown in **Fig.13**, the crack was introduced by flexural load at the middle of the specimen and the width was controlled from 0.1 to 0.5 mm. The actual depth was measured as a mean value of both sides.

In the experiment, it was observed that the tip of flexural crack reached to nearly the neutral axis when the surface crack width (w) extended over 0.1 mm, and then it hardly expanded. Relative ratios of the estimated crack depth to the actual depth are shown in **Fig.14**. Although a tend of the result is different depending on the specimen type (thickness 150 and 200 mm), the relative ratio reaches to 1.0 with the increase in the width of

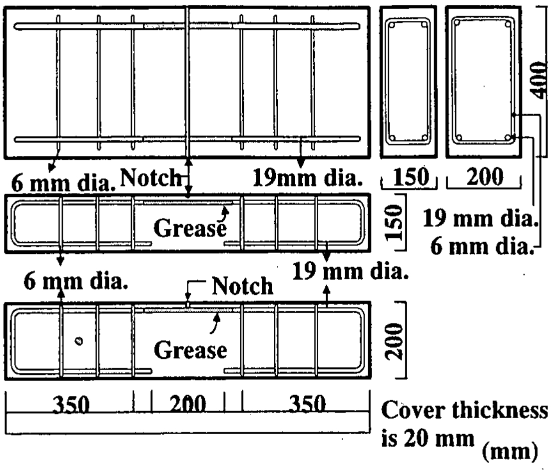


Fig.12 Specimen of flexural cracks

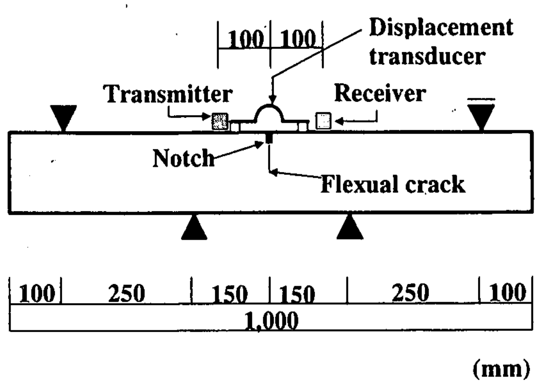


Fig.13 Loading test method and transducer locations

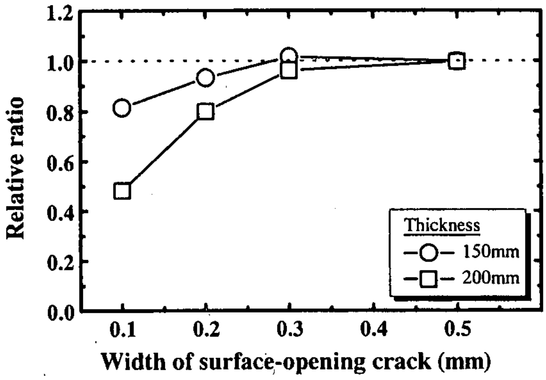


Fig.14 Width of surface crack and relative ratios on crack depth

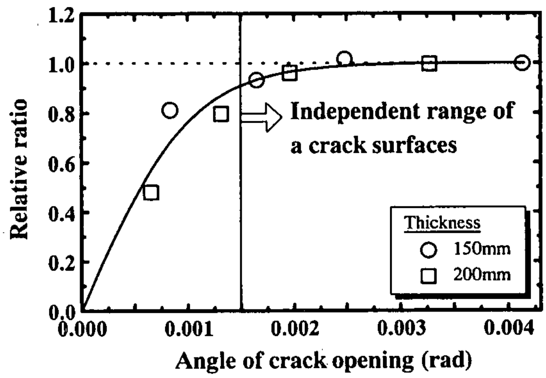


Fig.15 Angle of crack opening and relative ratios on crack depth

surface crack. Thus, the results were rearranged concerning the relationship between the relative ratio and the angle of crack opening θ ($\theta = w/d$), and are shown in **Fig.15**. This result indicates a quantitative relationship between the relative ratio and the angles of crack opening. Thus, the crack depth can be evaluated by using the ultrasonic technique when the angle of crack opening is larger than 0.0015 rad.. In practical evaluation of the crack depth in RC members, the width of surface crack is readily measured. Therefore, the estimation can be performed with no effect of the crack faces under the condition that the angle (w/d) is larger than 0.0015 rad..

6. CONCLUSIONS

The depth of surface-opening crack is estimated by using diffracted ultrasonic P-waves, although the estimations is affected by probe location, reinforcement, crack faces and so on. When the crack depth is evaluated by the ultrasonic waves, these effects should be quantitatively compensated. In this paper, the basic study is performed with respect to the depth of the surface-opening crack.

The influences of transmitted P-waves on mixture proportion and probes location are evaluated in concrete specimens. Then the effects of estimated crack depths on reinforcement and crack faces are studied by using RC specimens. The results are summarized, as follows:

1. Traveling times of ultrasonic P-wave are hardly affected by the maximum size of aggregate because it is normally smaller than the wavelength of P-wave.
2. The P-wave velocity is independent of the distance between the transmitter and the receiver, if it is wider than 150 mm.
3. The depth of surface crack can be determined accurately by compensating the effect of

reinforcement and cracking surfaces.

4. The effect of the reinforcement on the estimated depth of surface crack can be discriminated from P-waves paths which are diffracted at the tip of a crack or the surface of reinforcement.
5. The crack depth can be correctly estimated without the effect of roughness of crack faces in the case that the ratio of crack width to the crack depth is over 0.0015.

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超音波による鉄筋コンクリート部材の表面ひび割れ深さ評価

内田昌勝・大津政康・辻伸幸・岡本享久

鉄筋コンクリート部材の表面に発生したひび割れの深さの非破壊検査，超音波法が簡易でかつ比較的精度が良いため多く用いられているが，実際の構造物においては，推定値が鉄筋の存在やひび割れ界面の状態などによって変化することが知られている．本研究では，コンクリートの配合条件，探触子の配置条件が超音波の伝播挙動に及ぼす影響を検討した後，人工ひび割れを導入したモデル試験体を作製し，鉄筋の種類や配置条件がひび割れ深さの推定結果に及ぼす影響範囲を定量的に評価した．さらには，ひび割れ界面の状態が推定結果に及ぼす影響を検討するため，曲げひび割れ幅を変化させて実験した結果，開口角度(≒表面ひび割れ幅／深さ)が一定値以上であればひび割れ界面の影響を受けずにひび割れの深さを評価できることが明らかになった．