Evaluation of the surface crack depth in concrete by Impact-Echo procedures (SIBIE)

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ABSTRACT: The impact-echo method is available for estimating the surface-crack depths. This method is based on monitoring wave motions resulting from a short-duration mechanical impact. Surface displacements are detected by identifying peak frequencies in the frequency spectra. However, the frequency spectra cannot always be interpreted successfully as many peaks are often observed in the spectra. Thus, an imaging procedure to the impact-echo data which is knows as SIBIE procedure is developed. After confirming an applicability of the SIBIE procedure to estimate the depths of open surface cracks, it is clarified that the effect of water filled in the crack is inconsequent. Thus, even though the cracks are filled with water, the depths can be estimated with reasonable accuracy by SIBIE. In addition, the case where the surface cracks are repaired improperly and the void exists around the crack-tip is studied. In all the cases, surface-crack depths could be visually identified by the SIBIE procedure.

1 INTRODUCTION

In ultrasonic testing, time-of-flight technique is used to determine the surface-crack depth. When the distances from the crack to the impact point and from the crack to the sensor are known and the time between the input and the arrival of the diffracted p-wave at the sensor is measured, the depth of the crack can be calculated. However, previous results show the difficulty to measure the time of first-arrived wave. Particularly, in case of water-filled crack, if crack is not fully filled with water, first-arrived wave could give wrong information about the crack depth. In this study, frequency spectrum is analyzed by imaging procedure to visually identify the depth of a surface-crack, which is developed as the SIBIE procedure(Watanabe & Ohtsh, 2000). Thus, surface-crack depths in concrete are visualized by applying SIBIE procedure.

2 IMPACT-ECHO AND RESONANCE FREQUENCY

In the impact-echo method, elastic waves are generated by a short duration mechanical impact. Applying an impact, elastic waves are detected. Then peak frequencies are identified after FFT(Fast Fourier Transform) analysis of detected waves(Sansalone & Lin & Streett, 1998). Theoretically, frequency responses of a concrete member containing defects depend on the size of the member, the location of defects and P-wave velocity. Concerning the frequency responses, following relationships between the resonance frequencies due to the reflections and the depth of a defect are known (Sansalone, & Streett, 1997),

$$f_t = \frac{0.96C_P}{2T} \tag{1}$$

$$f_{crack} = \frac{0.96C_P}{2d} \tag{2}$$

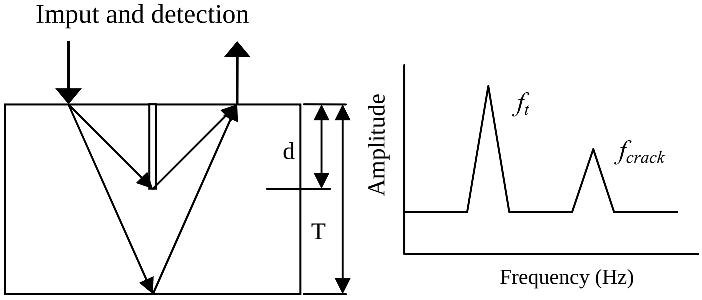


Figure 1. Frequency response of a specimen with crack.

where f_t is the resonance frequency of a plate thickness T, f_{crack} is the resonance frequency of a defect in depth d, C_p is P-wave velocity and 0.96 is a shape factor determined from geometry. The presence of these frequencies is illustrated in Figure 1.

Concerning dynamic motions of concrete members, the dimensional analysis has been carried out (Ohtsu, 1996). Among such parameters as frequency f, characteristic length L and wave velocity V, a following non-dimensional parameter α, as a ratio of characteristic length L to wavelength λ, is obtained.

$$\alpha = \frac{fL}{V} = \frac{L}{\lambda} \tag{3}$$

In the case that α is larger than 1, it is found that the frequency response is significantly influenced by the characteristic length. Considering the case that α is equal to 1, L is replaced by the thickness T and the depth of a crack d, substituting C_p to V, following relationships are obtained.

$$f_t' = \frac{C_P}{T} \tag{4}$$

$$f_{crack}' = \frac{C_P}{d} \tag{5}$$

f'_{crack} and f'_t imply the existence of higher resonance frequencies than those in Equations (4)and (5). Here, the shape factor is not taken into account.

3 SIBIE PROCEDURE

Since it is often not easy to identify the particular peaks in the frequency spectrum in the impact-echo method, an imaging procedure is applied to the result of FFT analysis as SIBIE (Stack Imaging of Spectral Amplitudes Based on Impact-Echo). This is an imaging technique for detected waveforms in the frequency domain. In the procedure, first, a cross-section of concrete is divided into square elements as shown in Figure 2. Then, resonance frequencies due to reflections at each element are computed. The travel distance from the input location to the output through the element is calculated as (Ohtsu & Watanabe, 2002),

$$R = r_1 + r_2 \tag{6}$$

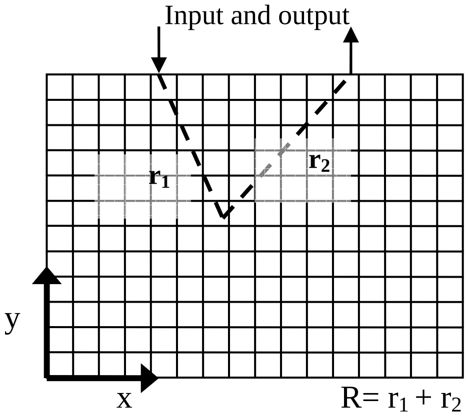


Figure 2. Spectral imaging model.

Resonance frequencies due to reflections at each element are calculated from,

$$f_{crack}' = \frac{C_P}{(R/2)} \tag{7}$$

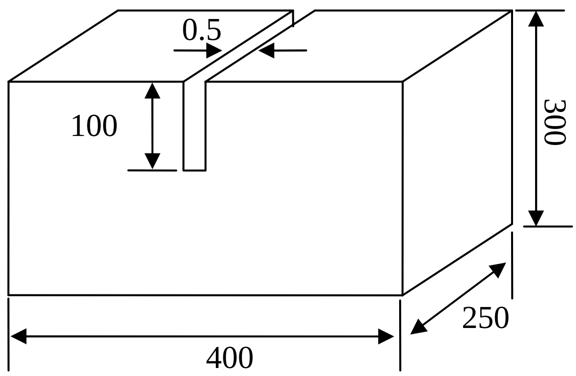
$$f_{crack} = \frac{C_P}{R} \tag{8}$$

Spectral amplitudes corresponding to these two resonance frequencies in the frequency spectrum are summed up. Thus, reflection intensity at each element is estimated as a stack image. The minimum size of the square mesh Δ for the SIBIE analysis should be approximately equal to $C_p\Delta t/2$, where C_p is the velocity of P-wave and Δt is the sampling time of a recorded wave.

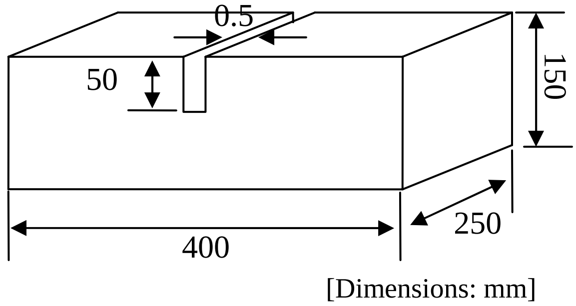
4 EXPERIMENTS

4.1 *Specimen*

Experiments were carried out in the laboratory on concrete blocks with surface-cracks of different depths. An artificial surface-crack of 0.5 mm width was located in the middle of the top surface of each specimen by placing a metal plate by casting concrete and by removing it afterwards. A rectangular parallelepiped specimen is of dimensions 400mm x 250mm x 300mm. This had a crack of 100mm depth. This specimen was tested when the crack was



(a) A rectangular parallelepiped specimen



(b) A specimen with a partially grouted crack

Figure 3. Specimens with crack.

Table 1. Mixture proportion and properties of fresh concrete

	Weight per unit volume (kg/m^3)				Max. gravel size (mm)	W/C (%)	Air-entrained admixture (cc)	Slump (cm)	Air content (%)
	Water (W)	Cement (C)	Sand (S)	Gravel (G)					
Rectangular parallelepiped specimen	182	331	746	1024	20	55	133	8	6
Specimen with a partially grouted crack	168	305	748	1183	20	55	137	5.2	6.2

Table 2. Mechanical properties of concrete at 28- day standard cured

	Compressive strength (MPa)	Poisson's ratio	Young's modulus (GPa)	P-wave velocity (m/sec)
Rectangular parallelepiped specimens	33.0	0.30	30.3	4005
Specimen with a partially grouted crack	29.9	0.22	27.1	3800

empty (air-filled) and after the crack was filled up to 80% of depth with water. Another specimen is of dimensions 400mm x 250mm x 150mm with a crack of 5 cm depth. The upper half part of the crack was then grouted to test an improperly-repaired crack. The specimens are illustrated in Figure 3. Mixture proportions of concrete are listed in Table 1, along with the slump value and air contents. Mechanical properties of concrete moisture-cured at 20^oC for 28 days are summarized in Table 2.

4.2 *Impact test*

Impact tests were conducted by shooting an aluminum bullet against the concrete surface. An aluminum bullet with a diameter of 8mm in Figure 4

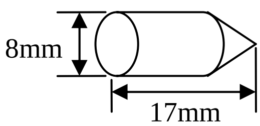


Figure 4. Configuration of the aluminum bullet.

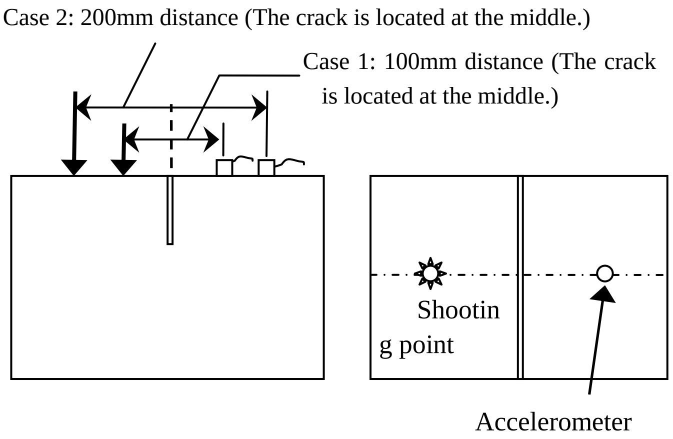


Figure 5. Location of impact test.

was shot by driving compressed air with a pressure of 0.05MPa.

Surface displacements due to the impact were recorded by an accelerometer. The accelerometers used at the detection points were of flat type and had sensitivity up to around 50 kHz. The accelerometer and shooting point are arranged as shown in Figure 5. Two cases (Case 1 and Case 2) of 100 mm and 200 mm between impact and detection were tested. Fourier spectra of accelerations were analyzed by FFT (Fast Fourier Transform). Sampling time was 4 μsec and the number of digitized data for each waveform was 2048.

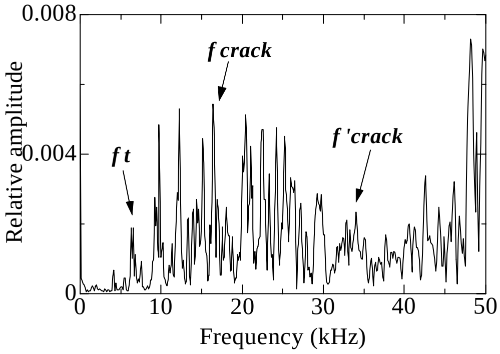
P-wave velocity, C_p, was obtained as 4005 m/s for a rectangular parallelepiped specimen and as 3800 m/s for the specimen with half-grouted crack from the ultrasonic pulse-velocity test.

5 RESULTS AND DISCUSSION

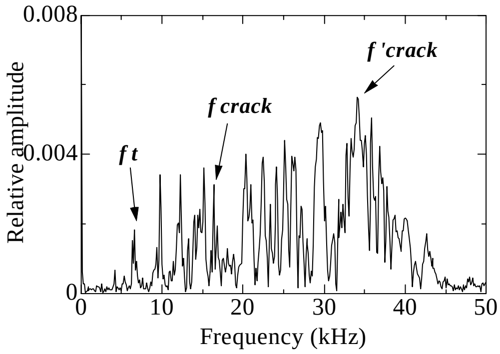
5.1 *Results of impact tests in a rectangular parallelepiped specimen*

Frequency spectra obtained are shown in Figure 6a-d. The resonance frequencies of the crack depth f_{crack} and f'_{crack} are indicated with arrows. In the Case 1, the resonance frequencies of crack at 100-mm depth, f_{crack} and f'_{crack}, were calculated as 17.9 kHz and 35.8 kHz from Equations (2) and (5). In Figure 6a, although f_{crack} is observed at approximately 17 kHz, f'_{crack} is weaker than f_{crack} . In Figure 6b, f_{crack} is observed at approximately 17 kHz and f'crack is observed at 35 kHz, although f_{crack} is not a strong peak.

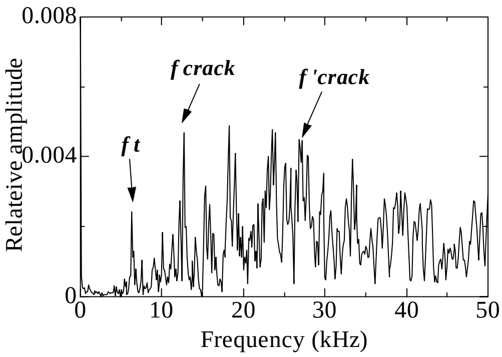
In the Case 2, the resonance frequencies of crack at 100-mm depth, f_{crack} and f'_{crack}, were calculated as 14.2 kHz and 28.3 kHz. In Figure 6c, f_{crack} is observed at approximately 13 kHz and f'_{crack} is observed at 27 kHz. However, identification is so difficult that there are many peaks in this spectrum.



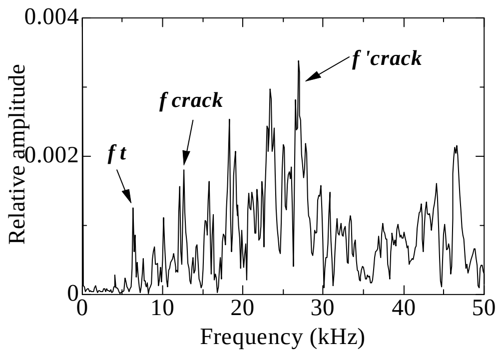
(a) Cross-section with an empty crack (Case 1).



(b) Cross-section with water-filled crack (Case 1)



(c) Cross-section with an empty crack (Case 2).



(d) Cross-section with water-filled crack (Case 2)

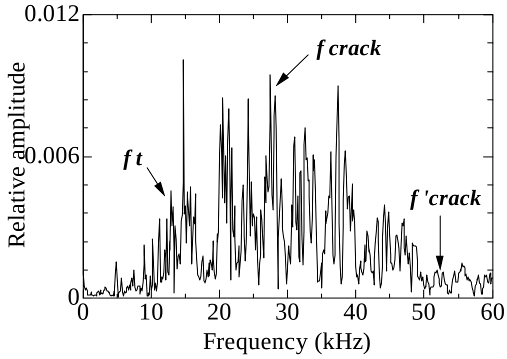
Figure 6. Frequency spectra of the specimen with a crack of 100-mm depth.

In Figure 6d, f_{crack} is observed at approximately 13 kHz and f'_{crack} is observed at 26 kHz, although f_{crack} is not a strong peak.

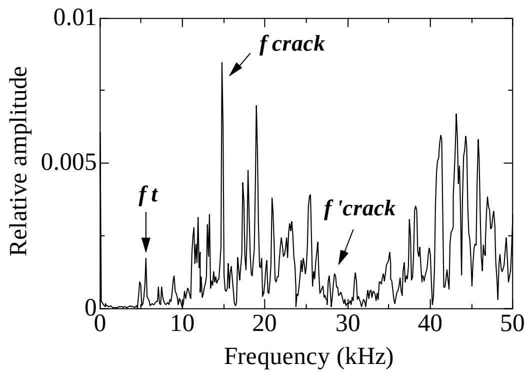
5.2 *Results of impact tests in Specimen with a partially grouted crack*

Frequency spectra obtained are shown in Figure 7a-b. The resonance frequencies of the crack depth f_{crack} and f'_{crack} are indicated with arrows. In the Case 1, the resonance frequencies of crack at 50-mm depth, f_{crack} and f'_{crack}, were calculated as 26.9 kHz and 53.7 kHz from Equations (2) and (5). In Figure 7a, although f_{crack} is observed at approximately 27 kHz, f'_{crack} is not observed clearly. In the Case 2, the resonance frequencies of crack at 50-mm depth, f_{crack} and f'_{crack}, were calculated as 17.0 kHz and 34.0 kHz. In Figure 7b, f_{crack} is observed at approximately 15 kHz, but f'_{crack} is not observed clearly.

Because there are many peaks in all frequency spectra, a human error must be included in decision of peak frequency by the impact echo method.



(a) Cross-section with a partially grouted crack (Case 1).



(b) Cross-section with a partially grouted crack (Case 2).

Figure 7. Frequency spectra of eh specimen with a crack of 50-mm depth.

5.3 *Results of SIBIE and discussion*

By using the frequency spectra shown in Figure 6(a)-(d), the SIBIE analysis was performed. Results of SIBIE are shown in Figure 8. The surface crack is indicated as white zone and water part of the crack is indicated as black zone. The mesh elements are arranged at 10-mm pitch evenly. In the figures, dark color regions indicate the high intense regions due to the resonance of diffraction. Arrows show the impact and the detection points.

Results for the specimen with an empty crack are given in Figure 8(a) and (c). Black color indicates the high intense regions which are clearly observed at 100-mm depth in front of the crack tip. Thus, it is demonstrated that the depth of a surface-crack can be visually identified by the SIBIE procedure.

Experiments were repeated on the same concrete specimen after filling 80% of the crack depth with water. By applying frequency spectra obtained from the tests, the SIBIE analysis was performed. Results for specimen with 100-mm crack depth filled with water are given in Figure 8(b) and (d). Dark color regions of diffraction are clearly observed in front of the crack tip in both cases. It is found that water had little effect on the SIBIE results. Thus, high diffractions are observed in front of the crack tip regardless of whether the crack is empty or filled with water.

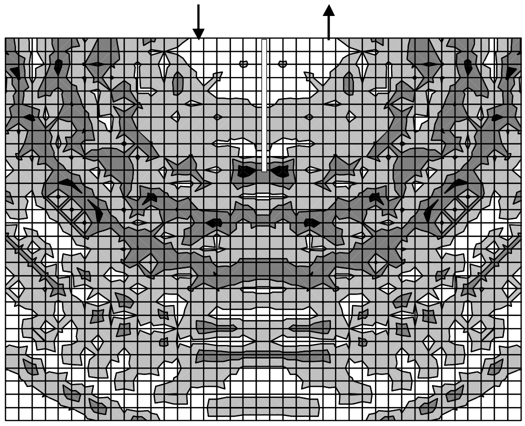
The SIBIE analysis was performed to determine when the crack is grouted improperly. A result of the SIBIE analysis is shown in Figure 9, where a crack is shown as white zone and grouted part of the crack is indicated with black zone. In Figure 9(a), it is found that the imperfectly grouted crack is visually identified. High diffraction of dark color regions are observed around the ungrouted part of the crack. In Figure 9(b), it is found that diffraction of dark color regions are not clearly observed around the ungrouted part of crack. This might be because that the measurement distance is too far against the crack depth. All SIBIE results of figures 8 and 9 show a completely symmetric picture. This is because the element of identical distance on the travel path is estimated by the same reflection intensity.

6 CONCLUSION

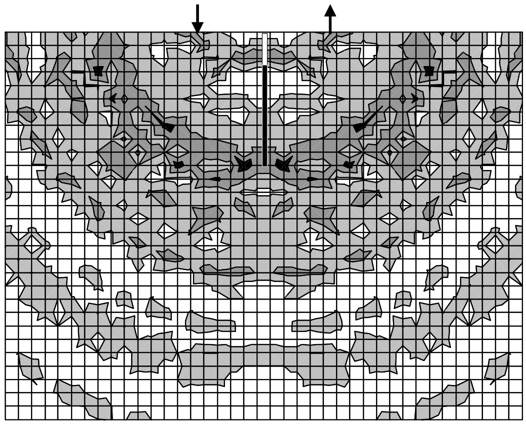
Concrete specimens with surface-cracks of varying depths were tested by applying the SIBIE procedure. The effect of the measurement distance is studied. Conclusions are summarized, as follows;

1.Specimens with a crack, and a water-filled crack were tested. In all the cases, the depths of surface-cracks can be visually identified by the SIBIE procedure.

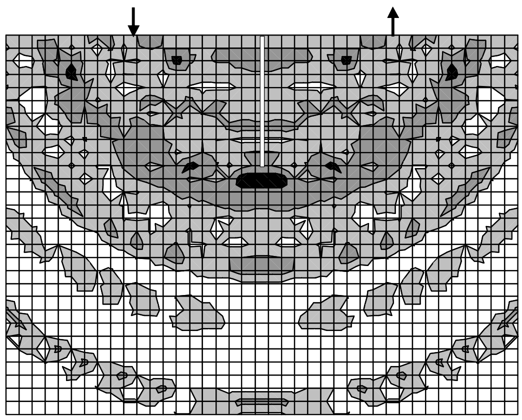
2.In case of the partially grouted crack, an ungrouted part of the crack is also clearly determined.



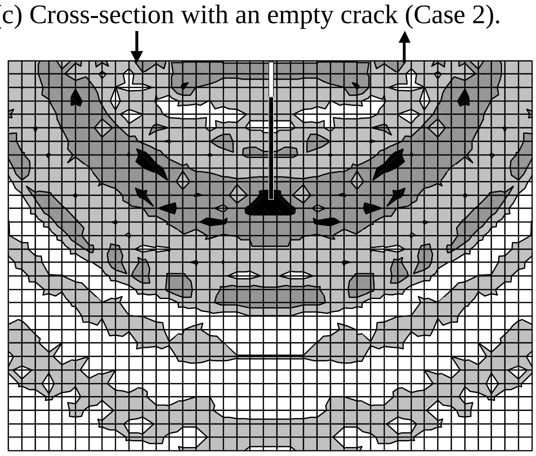
(a) Cross-section with an empty crack (Case 1).



(b) Cross-section with water-filled crack (Case 1).

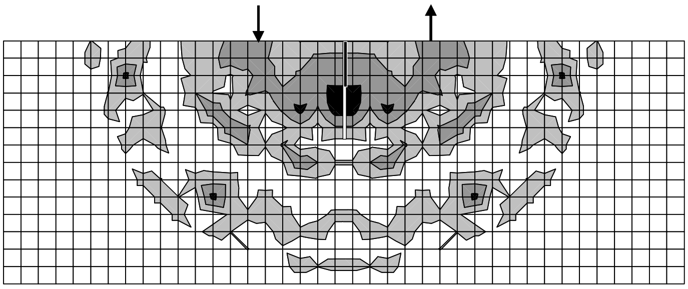


(c) Cross-section with an empty crack (Case 2).

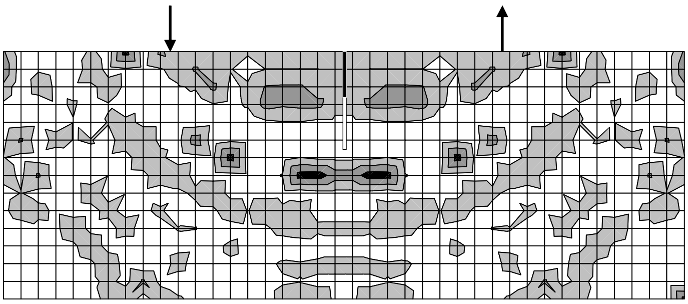


(d) Cross-section with water-filled crack (Case 2).

Figure 8. SIBIE results of the specimens with a crack of 100-mm depth.



(a)Cross-section with a partially grouted crack (Case 1).



(b) Cross-section with a partially grouted crack (Case 2).

Figure 9. SIBIE results of the specimens with a partially grouted crack.

Thus, it is demonstrated that the SIBIE procedure has a great promise to determine the depth of the surface crack.

3. It was found that results of the SIBIE analysis were dependent on the measurement distance. It is necessary to clarify the relation between the measurement distance and the crack depth.

4. In this paper, an artificial surface-crack of 0.5mm width was estimated. A fine crack is not estimated yet. It should be estimate in a future plan.

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