Accurate and Fast Damage Thickness Estimation in Concrete Using Smartphone-Mounted Handheld GPR and Spectrum Pattern Matching

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Abstract

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Abstract

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Keywords: Ground Penetrating Radar (GPR), Smartphone, Concrete, Crack, Damage, Thickness, Amplitude Spectrum, Pattern Matching

1. Introduction: Potential of GPR for damage thickness estimation

The rapid deterioration of social capital, which has been driven by economic development, has become a pressing issue common to the world, whether in developed or developing countries. In the United States, aging infrastructure became a social issue in the 1980s with the expression
"America in Ruins" [1]; in 2018, the Morandi Bridge in Genoa, Italy, which had been in service for 50 years, collapsed, killing 43 people. While there were structural problems, aging and negligent maintenance were also cited [2]. In the same year 2018, in Myanmar, the Myaung Mya Bridge, a suspension bridge, fell due to lack of maintenance, killing two people [3]. In Japan, the Sasago Tunnel collapse in 2012 killed nine people, and since then the idea of "preventive maintenance," in which measures are taken before defects occur, has become mainstream [4]. According to Japan's Ministry of Land, Infrastructure, Transport, and Tourism, estimates of maintenance and renewal costs have revealed that a shift from after-the-fact maintenance to preventive maintenance would result in a total reduction of 90 trillion yen over 30 years [5]. This is equivalent to one year of Japan's national budget.

As exemplified by the recent road cave-ins and concrete spalling accidents, damage inside structures often surfaces and leads to serious accidents. To achieve "preventive maintenance," it is necessary to quantitatively detect damage inside structures before the damage surfaces. For example, in the case of reinforced concrete, when the volume of the reinforcing steel expands due to corrosion, internal cracks occur [6]. If these cracks progress until they appear on the surface, they not only damage the aesthetics of the structure, but also lead to accidents such as concrete pieces falling off. To prevent such a situation, it is necessary to detect invisible internal cracks and perform preventive maintenance. For this purpose, technology that can detect minute damage on the millimeter order by nondestructive inspection is required ([7],[8]).

Furthermore, in tunnels, localized soil erosion around the tunnel lining can create cavities. This phenomenon, which can be caused by various factors such as water intrusion due to leakage or deterioration of the lining, dissolution of soil or bedrock, and dynamic loading, can lead from small surface corrosion of tunnel appendages to major deterioration of the structure and eventually to a reduction in the load-bearing capacity of the tunnel ([9],[10]). Countermeasures to fill the voids with injection material are often used, but to do so, it is not only necessary to nondestructively detect the damage behind them, which are invisible, but also to quantitatively know how much injection material will be needed [11].

Thus, if a single algorithm can quantitatively detect a wide range of damage thicknesses from millimeter order to 10-centimeter order, which can be caused by various factors, it will improve the efficiency of infrastructure inspections.

Current nondestructive testing to examine damage inside civil engineering infrastructure structures is based on close-up visual inspection and percussion testing. In the acoustic inspection, the person conducting the inspection strikes the concrete to be tested with a hammer, and the elastic waves generated at that
time are used to make a judgment. There is also the impact elastic wave method, which uses a steel ball to generate elastic waves instead of a hammer ([12], [13]). This method detects damage by looking at the frequency spectrum, but both are point measurements. It is time-consuming to examine all structural surfaces by point inspection, and inspection results depend on human skill and experience [14].

The main nondestructive alternatives to acoustic testing using elastic waves are ultrasonic, infrared thermography, and electromagnetic radar [15].

The ultrasonic method is a similar measurement method that uses longitudinal elastic waves, in which ultrasonic waves are transmitted from a transmitting probe and received by a receiving probe. Concrete inspection methods using ultrasonic methods have also been studied ([16]-[20]). However, like percussion inspection and impact elastic waves, ultrasonic methods are not efficient because they cannot be scanned, are point observations, and require special grease [21].

The infrared thermography method uses an infrared camera to measure the concrete surface temperature and detect cavities based on the temperature distribution conditions ([22], [23]). The temperature difference between the defective and healthy parts of the concrete is determined based on the nature of the air layer in the delaminated area, which has the effect of intercepting the heat flow generated inside the concrete. This method provides two-dimensional areal information of the structure surface. Since the depth information is compressed from the surface to a shallower range, it is suitable for obtaining near-surface information, and many previous studies have targeted lifting and delamination on the concrete surface ([24]-[30]). Although this method is certainly efficient, it is limited to only near-surface 2D information, and although it is suitable as a primary survey method, it does not provide information up to explicit depth information. Furthermore, this method has the problem that the applicable conditions of temperature are limited and are affected by external factors in the environment at the time of measurement.

Among the many nondestructive inspection techniques, we focus on GPR (Ground Penetrating Radar). GPR is an efficient nondestructive inspection method because the sensor is non-contact and depth information can be explicitly obtained while scanning.

The electromagnetic wave radar method (GPR) we are focusing on is a technology that uses the property of reflection at the boundaries of materials with different relative permittivity to determine the distance and location to an object. Due to its environmental insensitivity, high speed, convenience, and high resolution, it has been evaluated as a nondestructive inspection in various fields such as monitoring of cultural assets [31], and in the civil engineering field, this technique has been used to evaluate bridge deck plates and road pavements...
GPRs come in a variety of sizes, ranging from vehicle-mounted, hand-held, and small hand-held devices. Each has a different antenna size, and thus differs in the frequency range and amplitude of the electromagnetic waves, the distance from the surface to the antenna, and the resolution, making them suitable for different applications.

GPR sweeps electromagnetic waves in the frequency band of several hundred MHz to several GHz toward a target object and receives the reflected waves when they hit the target. The position of the target is determined from the round-trip time between the sweep and the reception. The nature of the object is also determined from information such as the amplitude intensity and phase of the reflected wave. Explicit two-dimensional information is obtained in the depth direction along the measurement line, and if multiple measurement lines are combined, the information is three-dimensional (travel direction × channel direction × depth direction). (Table 1)

<table>
<thead>
<tr>
<th>NDT method</th>
<th>Dimension of information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hammering</td>
<td>0 (point information)</td>
</tr>
<tr>
<td>Impact elastic wave</td>
<td>0</td>
</tr>
<tr>
<td>Ultrasonic</td>
<td>0</td>
</tr>
<tr>
<td>Infrared thermography</td>
<td>2 (surface information)</td>
</tr>
<tr>
<td>Electromagnetic wave</td>
<td>2 (moving direction × depth)</td>
</tr>
<tr>
<td></td>
<td>~3(moving direction × channel direction × depth)</td>
</tr>
</tbody>
</table>

The reflected wave is converted into an electrical signal at the receiving antenna and formed into waveform data at the arithmetic processing unit. There are two main ways to display this waveform data: A-scan and B-scan.

The B scan is a black-and-white grayscale image of the amplitude intensity obtained by scanning the device, as shown in the Figure 1. And the A scan is a waveform extracted and displayed in the depth direction of a single observation point. Currently, technicians mainly observe a combination of these two display modes to determine the internal conditions visually and qualitatively.
Studies have been conducted to detect damage inside concrete such as cracks and voids using GPR ([49]-[58]). Park and Uonuma et al. in [49] estimated three-dimensional shapes and volumes by incorporating synthetic aperture processing and gradients of B-scan shading intensity using multipolarimetric radar with a center frequency of 600 MHz at 20 MHz~1 GHz. Tanaka et al. [51] proposed a method to detect anomalies by evaluating the similarity of peak patterns of received signals using radar with a center frequency of 450 MHz. Both of these studies attempted detection from time-series signals and targeted air gaps on the order of 10 mm. An alternative approach is to focus on frequency ([53]-[58]), and Rodés [53] et al. analyze the possibility of analyzing the frequency spectrum of a GPR signal with a 950 MHz center frequency antenna and consider the relationship between the shape and frequency characteristics of the spectrum and the structure and condition of the pavement. They discuss the relationship between the shape and frequency characteristics of the spectrum and the structure and condition of the pavement. Although a qualitative discussion, it suggested the possibility of detection by frequency; HaiLiu et al [54] performed a time-frequency analysis to detect pavement pipe delamination and found that both the peak instantaneous frequency and its amplitude were related to the delamination gap, using a 0.8-12 GHz antennas and showed that both the peak instantaneous frequency and its amplitude were related to the delamination gap. Yamaguchi, Mizutani, and colleagues [55] used radar in the high frequency band of 3 GHz~20 GHz to detect horizontal cracks as small as 1 mm from time-variant inverse convolution operations for damage inside concrete. It was theoretically shown that cracks of less than a certain thickness cannot be detected when the uncertainty principle in the frequency and time domains is
considered. However, the most effective time-variant inverse convolution operation amplifies noise, which requires setting appropriate noise reduction filter parameters, and the inverse analysis is computationally demanding, making real-time analysis difficult. Kien et al. antennas and noted that among the factors affecting the detection of concrete delamination is the effect on the frequency peak. While some studies have focused on spectra, but most have been limited to qualitative observations, Kiyoshi theoretically discussed the effect of damage thickness on the shape of the spectrum [58]. After clarifying that the spectral shape depends on the damage thickness, he proposed to utilize the spectral centroid.

Therefore, to enable efficient infrastructure inspections, this study will conduct basic research on an algorithm for fully automated real-time evaluation, rather than based on the subjectivity and experience of engineers. The goal is to achieve quantitative estimation on the millimeter order, not just the presence or absence of damages. In doing so, we will propose a method with a small computational load to make this possible, keeping in mind that it will be implemented on a smart phone.

In this paper, Section 2 provides an overview of the GPR instrument used in this study and the experimental data, followed by an explanation of why the simplest method, estimating damage thickness from time waveform peaks, is difficult in Section 3. We then propose an algorithm that focuses on frequency characteristics in Section 4. Finally, Section 5 presents the conclusions of this study and future prospects for practical applications.

2. Radar measurement experiment using concrete specimen with variable thickness damage model

2.1. Specifications of GPR device with smart phone

In this study, the data will be acquired with the small, handheld GPR shown in the Figure 2. The small GPR is mainly used to detect rebar. This is because metals are totally reflective, and the received waveforms are highly visible. However, damage is extremely difficult to detect because the reflection coefficient of damage is small, and the signal-to-noise ratio is relatively low. Moreover, it is even more difficult to quantitatively evaluate the damage thickness.
In general, electromagnetic wave radar systems, the antenna and processing unit are basically integrated, but in the electromagnetic wave radar system used in this study, the antenna and the smartphone, which is the processing unit, are connected via Wi-Fi, allowing the smartphone to be detached from the radar body to remotely view search results in a distant location. This is the latest device. The advantages of using a smartphone for computing and drawing are that the CPU can be easily changed, data can be transmitted and data can be collected from around the world, and algorithms are expected to become more sophisticated. Table 2 shows the specification of the GPR device used in this study.
Table 2: Specification of the radar

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitted and Receiving Antenna</td>
<td>Separated (Bi-static)</td>
</tr>
<tr>
<td>Radar System</td>
<td>Pulse radar</td>
</tr>
<tr>
<td>Frequency band</td>
<td>700 MHz~3500 MHz</td>
</tr>
<tr>
<td>Measurable depth</td>
<td>450 mm</td>
</tr>
<tr>
<td></td>
<td>(For concrete with relative permittivity 6.2)</td>
</tr>
<tr>
<td>Horizontal distance resolution</td>
<td>2.5 mm</td>
</tr>
<tr>
<td>Maximum scanning speed</td>
<td>Approx. 80 cm/s</td>
</tr>
</tbody>
</table>

2.2. Experiment Summary and Data Collection

In constructing the algorithm, experiments were conducted on concrete specimens with variable damage thickness. The data from the experiments, conducted by Kiyoshi et al [58]. The data were obtained from a stack of unreinforced concrete slabs (300 mm × 300 mm × 60 mm), and measurements were taken five times each at the same damage thickness, varying every 2 mm from 2 mm to 180 mm to simulate the damage at the back of the tunnel (Figure 3). The data we are going to treat here are extracted from three adjacent points near the center of the damage, resulting in a total of 15 data points (5 times × 3 points) for a single damage thickness. The algorithm was constructed.

![Variable-thickness concrete specimens: (a) 2mm; (b) 180mm](image)

3. Reasons why it is difficult to estimate from time series signals
The simplest method for quantitatively estimating damage thickness would be to separate the peaks of reflected waves from the upper and lower boundaries and quantitatively estimate the damage thickness from the temporal distance between them (Figure 4).

![Figure 4: Schematic diagram of received waveform](image)

However, the maximum frequency of this antenna is 3.5 GHz, from which the theoretical minimum separable thickness is 43 mm. However, the actual stable peak separation was achieved from 140 mm (Figure 5). There are two main reasons for this. They are the reducible interference and the side lobes of the transmitted wave.

![Figure 5: Thickness estimated from local extreme of time wave](image)
The subtractive interference is due to the relatively small damage thickness compared to the wavelength of the GPR system. The observed received waveform is a composite of the direct wave, the reflected wave from the concrete surface, the reflected wave from the top of the crack, and the reflected wave from the bottom of the crack. The incident wave into the damage is not a perfect pulse wave, but a waveform that can be approximated by a sinc function with a time width as shown in Figure 6 shows the reflected wave from the aluminum foil imitating a rebar at 60 mm depth, the same depth as in the present experiment. Figure 7 is a theoretical waveform simulating the reflected composite wave from the top and bottom surfaces of the damage, based on the theoretical idea of Appendix A. The dotted lines indicate the reflections from the upper and lower surfaces of the damage, respectively, and the composite wave is shown by the solid line. When the gap thickness is small, such as 2 mm, the observed reflection intensity becomes very small due to subtractive interference caused by the phase inversion between the top and bottom surfaces of the gap, resulting in a low signal-to-noise ratio. The measured waveforms show that this is the case. The observed wave amplitude intensity becomes small when the damage thickness is small, and the noise ratio becomes relatively high, making it difficult in principle for the engineer to visually discriminate the damage.

**Figure 6:** Reflected waves from a rebar model at a depth of 60 mm, the same depth as the damage
Another reason is due to sidelobes. The transmitted waveform is not an ideal pulse wave and has large sidelobes spanning several hundred millimeters, so the peak from the bottom of the crack is absorbed by the sidelobes. As shown in the, the Figure 8 position of the first local maximum (red line) has not changed even though the damage thickness has increased from 2mm-180mm. Of course, the boundary can be captured by sending a higher frequency transmitted wave, but this is a hardware limitation because of the trade-off relationship between higher frequency and greater attenuation.
Figure 8: Overlapping time waveforms for damage thicknesses from 2 mm to 180 mm; The first extreme value (red line) has changed little.

Figure 9: Theoretical spectrum of typical damage thickness: 2mm, 10mm, 40mm, 100mm, 140mm, 180mm

For these two reasons, it is extremely difficult to separate the peaks at the top and bottom of the crack from the time waveform to detect the damage thickness on the millimeter order.

4. Proposed algorithm for quantitative automatic estimation of damage thickness: using frequency response

4.1. Theoretical relationship between frequency response and damage thickness

It is difficult to estimate damage thickness from the limited information of time waveform peaks, and it is necessary to use information from the entire time waveform. Furthermore, we wanted to remove the phase information and use only the relative magnitude of each frequency, so we
focused on the amplitude spectrum.

In [53], it has already been shown that the frequency spectrum varies depending on the structure and condition of the road surface, and Kiyoshi et al. theoretically demonstrated that there is a frequency dependence in the degree of subtractive interference [58]. We considered using this spectrum to estimate the damage thickness.

Figure 9 shows the spectra for different gap thicknesses, superimposed on each other. The frequency characteristic $F(\omega)$ of the incident wave is used in the Figure 11 because it is considered that the spectrum immediately after transmission from the antenna and the actual spectrum incident on the air gap may change due to attenuation by propagation and materials.
Figure 10: Comparison between theoretical and measured spectra of typical damage thicknesses Thickness: (a) 2mm; (b) 10mm; (c) 40mm; (d) 100mm; (e) 140mm; (f) 180mm

Figure 11: Spectrum of Figure 6

4.2. Theoretical relationship between frequency response and damage thickness

Considering that there are appropriate gating and bandwidth for applying DFT (Discrete Fourier Transform) to time waveforms, we determined and
optimized the smallest gating width and bandwidth of the residual average of actual and estimated damage thickness for all 1350 data using three parameters as variables. The gating width is the time width to be cut out to apply DFT, and the larger the damage thickness, the larger the gating width to be cut out. The optimization method was based on matching all data using the gating width, bandwidth start point, and bandwidth end point as three variables, and adopting the combination of the three variables that showed the smallest residual sum of squares. As a result, the gating width of 3.5 nsec and the bandwidth of 1.4 GHz to 2.9 GHz had the smallest overall residual sum of squares, and the results are shown in the Figure 12. The Figure 13 further shows pattern matching. The bandwidths in which pattern matching is performed are indicated by solid lines.

![Figure 12: Relationship between Actual & Theoretical; Gating: 3.5nsec, Bandwidth:1.4GHz~2.9GHz](image)

Not estimated correctly. Outlier
Figure 13: Spectral matching of typical damage thickness: Thickness: (a) 2mm; (b) 10mm; (c) 40mm; (d) 100mm; (e) 140mm; (f) 180mm
Although the damage thickness could be estimated more accurately than the method based on the local extremes of the time waveform, outliers were more frequent when the actual damage thickness was less than about 100 mm and could not be considered correctly from about 60 mm or less. We considered that appropriate gating widths and bandwidths exist depending on the size of the damage thickness.

Therefore, the gating width and bandwidth were optimized to minimize the sum of squared residuals under the condition that the actual damage thickness was known to be within 100 mm. As a result, a gating width of 2.0 nsec and a bandwidth of 1.3 GHz to 3.9 GHz were found to be optimal, and the results were estimated as shown in the Figure 14 below. When the damage thickness is small, the gating width that needs to be cut out is also expected to be shorter (Figure 15), and it is shorter than the total damage thickness, and it can be concluded that optimization is reasonable.
Based on this, the next optimization was performed by narrowing the range to only 100 mm or more. As a result, a gating width of 3.9 nsec and a bandwidth of 1.4 GHz~2.4 GHz were optimal (Figure 16).

4.3. Roughly determine the size of the damage

In other words, if the rough size of the damage thickness is known in advance before pattern matching is performed, the algorithm with the respective gating width and bandwidth defined can be applied to determine...
the damage thickness. In this case, it is sufficient to know the size of the damage thickness at the 100 mm border.

First, when the damage thickness is small, the amplitude intensity is also small due to subtractive interference, so we thought we could discriminate from there. The Figure 17 shows the relationship between the maximum amplitude intensity and damage thickness.

![Graph showing the relationship between maximum amplitude intensity and damage thickness.](image)

**Figure 17: Relationship between maximum amplitude intensity and damage thickness**

A different index is used to determine whether the damage thickness is greater than or less than 100 mm at 30 mm or greater. It is noted that the low-frequency component increases as the damage thickness increases (Figure 18).
Therefore, we focused on the spectral centroid of a particular band of low frequencies. We focused on the spectral centroid because it is less susceptible to spectral zeros and more robust. Focusing on the spectral centroid with a gating width of 2.8 nsec and 0.7 GHz to 0.9 GHz, the spectral centroid changes monotonically to a smaller value as shown in the Figure 19. The gating width and bandwidth are valid because they are consistent with theoretical values up to 120 mm, and it is sufficient to say that the theoretical values also change monotonically at the point where they are separated by 100 mm. When the damage is less than 26 mm, the signal-to-noise ratio is low and varies considerably, so the intensity is used to determine the value.

Figure 18: Amplitude spectra for each typical damage thickness, focusing on low-frequency components

Figure 19: Spectral centroid; Gating: 2.8 nsec, Bandwidth:0.7 GHz~0.9 GHz
4.4. Final proposed algorithm

After first roughly determining whether the value is above or below 100 mm by these two indices, pattern matching is performed with the respective gating widths and bandwidths. However, in practice, there are some values that cannot be determined whether they are 100 mm or less or 100 mm or more, so a buffer band is provided. Since it is not possible to determine whether the damage thickness is less than or greater than 100 mm between the spectral centroid of 0.8043 and 0.8059 at low frequencies (0.7 GHz~0.9 GHz), we assume that the damage thickness is within the range of 62 mm to 122 mm for those spectral centroids in between, and pattern matching is performed within that range. Pattern matching is performed within this range.

For the optimization of the buffer band, the values were determined in a different way. In the Figure 20, the horizontal axis is the gating width and the vertical axis is the residual mean (RSS), and all the results estimated for various bands are superimposed. Optimization adopts the bandwidth in which this residual mean is the smallest, but as shown in the Figure 20, the smallest gating width has no theoretical significance because the residual mean shows almost the same value when the gating width exceeds 2.5 nsec. Therefore, considering actual operation, the optimization here was limited to a gating range (~3.5 nsec) with high accuracy and as low a computational load as possible. As a result, a gating width of 3.3 nsec was found to be optimal, but the residual mean was almost the same as that of 4.2 nsec, the result of the previous method of exact optimization, and there was no change in accuracy in actual operation.

![Figure 20: Optimization of buffer zone](image)

<table>
<thead>
<tr>
<th>Average error matched over various bandwidths</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimized value</td>
</tr>
<tr>
<td>Adopted value</td>
</tr>
</tbody>
</table>
After optimization, conditions of 3.3 nsec and bandwidth of 1.4 GHz–3.0 GHz were adopted, and the matching results are shown in the Figure 21.

Therefore, it was finally decided to perform the matching in three stages between 2 mm and 180 mm, each with a different gating width and bandwidth. The gating widths and bandwidths employed are shown in the Table 3: Gating and bandwidth at each stage, respectively.

![Figure 21: Relationship between Actual & Theoretical; Gating: 3.5nsec, Bandwidth:1.4GHz-3.0GHz](image)

<table>
<thead>
<tr>
<th>Objective</th>
<th>Estimable range</th>
<th>Gating (nsec)</th>
<th>Band width (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>To estimate rough void thickness</td>
<td>Up to 28mm</td>
<td>2.8</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>More or less than 100mm</td>
<td>2.8</td>
<td>0.7 ~ 0.9</td>
</tr>
<tr>
<td>To estimate void thickness quantitatively by pattern matching</td>
<td>2mm ~ 100 mm</td>
<td>2</td>
<td>1.3 ~ 3.9</td>
</tr>
<tr>
<td></td>
<td>Buffer zone (62mm ~ 122mm)</td>
<td>3.3</td>
<td>1.4 ~ 3</td>
</tr>
<tr>
<td></td>
<td>100 mm ~ 180mm</td>
<td>3.9</td>
<td>1.4 ~ 2.4</td>
</tr>
</tbody>
</table>
The result of estimating the total damage thickness using the algorithm is shown in the Figure 22, and it is possible to quantitatively estimate from a crack of 2 mm to a cavity of 180 mm. In summary, the current algorithm for quantitatively estimating damage thickness is shown in the Figure 23. After roughly determining the damage thickness, pattern matching was performed within the determined range, which reduced the computational cost. The output time per data point is in the 0.001 second range, which is fast enough for real-time processing. The error tends to be larger when the damage thickness is smaller. This is because the signal-to-noise ratio is smaller when the damage thickness is smaller, and the spectrum changes more slowly, resulting in a larger variation in the estimated value using spectral matching alone. However, it did not at all estimate values that were far from the actual damage thicknesses, and a single algorithm could quantitatively estimate damage thicknesses for a wide range of concrete.

Figure 22: Relationship between Actual & Theoretical
Conclusion

We were able to quantitatively detect cracks from 2 mm to 180 mm without anomaly detection and on the millimeter order.

First, we showed that it is difficult in principle to use the simple method of estimating the damage thickness by its time width from the two peaks at the top of the crack and the bottom of the crack in the time waveform. The method we proposed combines two conditions, amplitude intensity and low-frequency component, to determine the rough damage thickness, and then performs spectral pattern matching within the determined damage thickness range. By roughly discriminating the damage thickness, spectral pattern matching is not only possible, but also the narrowing down of the range can be minimized, leading to a significant reduction in the amount of calculation. As a result, output of damage thickness in the 0.001 second range became possible.

On the other hand, this research was only conducted with data obtained in an experiment with an ideal model cavity, and it is necessary to challenge it in a real cavity in the future.
For the implementation of this algorithm, in addition to quantitative estimation of damage thickness, the following two main studies need to be conducted concurrently, which are the prospects.

(a) We aim to use this algorithm to eventually map the damage in two dimensions, real-time and automatically. For accurate mapping, the depth of damage must be accurately determined, which requires knowing the propagation velocity at the speed of light. To know the propagation velocity in the medium, the relative permittivity of the concrete must be estimated with high accuracy (Eq.), and an automatic algorithm for this purpose is also required.

(b) To probe and accurately map the entire inspection target, it is also necessary to accurately determine where damage exists and where it does not before applying the algorithms in this study. Efficient screening will strive to lower the computational cost. Appropriate noise reduction will also be applied to bring the algorithm closer to practical use.

Appendix A:

The modeling of the propagation of electromagnetic waves in the case of damage thickness is presented. Since it has been shown here by Kiyoshi et al. that considering multiple reflections is important in creating a theoretical spectrum [58], multiple reflections up to fifth order are considered. When the damage thickness is \( b \), the delay time for reflections from the top surface of the damage is, using the speed of light \( C \),

\[
a = \frac{2b}{C}
\]  

using the reflectance \( \gamma_{ca} \) and transmittance \( \tau_{ca} \) when the electromagnetic wave is incident from the concrete to the air layer, and the reflectance \( \gamma_{ac} \) and transmittance \( \tau_{ac} \) when it is incident from the air layer to the concrete,

The observed wave \( h(t) \) is

\[
h(t) = \gamma_{ca}f(t) + \tau_{ca}\tau_{ac} \sum_{k=1}^{n} \gamma_{ac}^{2k-1} f(t - ak)
\]

which is the same as the above. The Figure 24 shows a graphical representation of multiple reflections. The equation considers multiple reflections up to \( n \)th order, and in this study, \( n = 5 \), considering multiple reflections up to 5 orders [58].
Since the time delay in the time domain is a phase delay in the frequency domain,

\[ H(\omega) = \left( \gamma_{ca} + \tau_{ca} \sum_{k=1}^{5} \gamma_{ac}^{2k-1} e^{-j\omega ak} \right) F(\omega) \]  

(3)

If \( H(\omega) = Z(\omega) \times F(\omega) \),

\[ Z(\omega) = \gamma_{ca} + \tau_{ca} \sum_{k=1}^{5} \gamma_{ac}^{2k-1} e^{-j\omega ak} \]  

(4)

\( Z(\omega) \) is the transfer function, and the degree of the reducible interference of \( h(t) \) is frequency dependent.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This experiment was conducted by Kiyoshi, who is researcher from Mizutani Laboratory at the University of Tokyo. We thank Kiyoshi for providing the data.

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