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Abstract

Non-Contact Detection of Steel Corrosion Using Sub-Terahertz Waves †

Riku Kurashina [1], Chihiro Kobayashi [1], Tomoya Nishiwaki [1,*], Akio Tanaka [2], Tadao Tanabe [3], Hitoshi Hamasaki [4], Daisuke Sato [5] and Koji Arita [5]

1 Graduate School of Engineering, Tohoku University, Sendai 980-8579, Japan; kurashina.riku.r2@dc.tohoku.ac.jp (R.K.); chihiro.kobayashi.t7@dc.tohoku.ac.jp (C.K.)
2 Department of Architecture, Nippon Institute of Technology, Miyashiro 345-8501, Japan; tanaka.akio@nit.ac.jp
3 Department of Engineering and Design, Shibaura Institute of Technology, Tokyo 135-8548, Japan; tanabet@shibaura-it.ac.jp
4 School of Architecture, Shibaura Institute of Technology, Tokyo 135-8548, Japan; hamasaki@shibaura-it.ac.jp
5 Constec Engi, Co., Tokyo 143-0006, Japan; sato-daisuke@cons-hd.co.jp (D.S.); arita-koji@cons-hd.co.jp (K.A.)
* Correspondence: tomoya.nishiwaki.e8@tohoku.ac.jp
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Abstract

A feasibility study was conducted on the detection of corroded rebars inside concrete using sub-THz waves. In this study, spectral measurements were performed with a reflection-type system in the 20–50 GHz frequency range. Measurements were conducted on steel plates corroded in salt water and on concrete specimens containing these corroded plates. The results confirmed that reflectance decreases as corrosion progresses. Furthermore, it was demonstrated that the presence or absence of internal steel plates and corrosion can be detected up to a cover thickness of 20 mm. The frequency spectral peaks and their periodicity also provided a means to estimate the cover thickness.

Keywords: sub-terahertz wave; corrosion; non-contact; non-destructive test; spectra

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1. Introduction

With the increasing demand for longer service life of infrastructure, the importance of maintenance work has grown as part of efficient and practical management strategies for reinforced concrete structures. Conventional non-destructive testing (NDT) methods, such as ultrasonic testing, enable evaluation of internal conditions; however, their reliance on contact-based measurements limits their applicability in areas with restricted access or severe structural deterioration [1]. Infrared thermography allows remote sensing but is restricted to surface-level information [2]. Consequently, remote measurement techniques capable of assessing the internal state of concrete are attracting significant attention and have become a key focus of current research [3,4].

In this study, we conducted a fundamental investigation aimed at developing a remote and non-contact method for detecting corrosion of embedded steel in concrete using sub-terahertz (sub-THz) waves, which offer excellent transmission and linear propagation characteristics. Laboratory-scale spectrum measurements were performed on flat steel plates both in isolation and embedded in concrete to evaluate their frequency-dependent response.

2. Measurement Methods and Materials

2.1. Outline of Experiments

Figure 1 illustrates the measurement system used in this study. To enable practical application to real structures, a reflective measurement setup was adopted, with all instruments placed on one side of the target. The sub-THz wave source comprised a microwave generator combined with a frequency multiplier capable of amplification over the 18–52 GHz range, sweeping from 20 to 50 GHz in 0.2 GHz intervals. The sub-THz beam was focused onto the specimen and detector using a Teflon lens, whose position was adjusted accordingly. An absorber was employed to reduce unwanted external reflections.

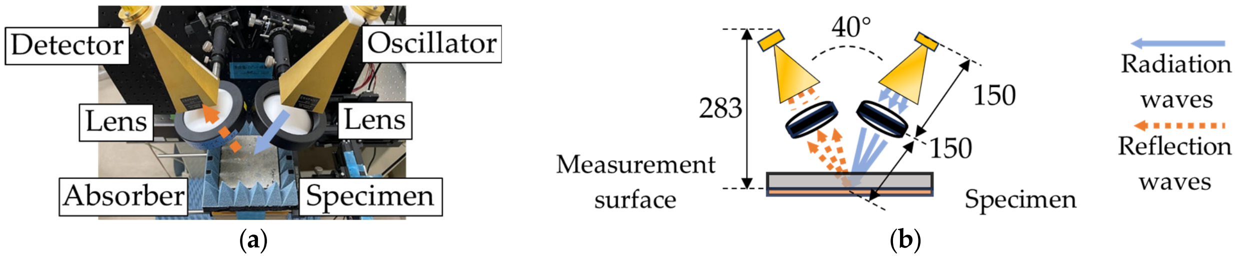

Figure 1. The image of the measurement system used: (**a**) Pictures. (**b**) Schematic diagram (unit: mm).

Measurements were conducted on steel plates with varying degrees of corrosion, using both bare steel plates (steel specimens) and specimens in which the steel plates were embedded in concrete (steel-embedded specimens). For each specimen, an additional uncorroded specimen (control) was prepared, and the reflectance of each specimen was calculated from the measured detection voltage using Equation (1).

$$\text{Reflectance}(-) = \frac{\text{Detection voltage of specimens (V)}}{\text{Detection voltage of control specimens (V)}} \quad (1)$$

2.2. Materials

Figure 2 provides an overview of the test specimens. The steel specimens were fabricated from SPCC-equivalent plates and corroded over several weeks through salt spray and repeated wet–dry cycling. For the steel-embedded specimens, concrete with a water–cement ratio of 0.55 was cast to cover the corroded steel plates. After demolding, the specimens were cut into 100 mm × 100 mm sections with concrete cover thicknesses of 10 mm, 20 mm, and 30 mm. Prior to measurement, all specimens were dried at 90 °C for one day.

Figure 2. An image of specimens: (**a**) Steel specimens. (**b**) Steel-embedded specimens (unit: mm).

3. Results and Discussion

3.1. Reflection of Steel Specimens

Figure 3a shows the reflectance spectrum of the steel specimens. Reflectance was calculated as a relative value based on a control. Overall, reflectance decreased as corrosion progressed. The reduction is considered to result from increased surface roughness caused by corrosion products, which scatter the sub-THz waves, as well as changes in the dielectric properties caused by corrosion. As shown in Figure 3b, most measured frequencies exhibited a negative correlation between corrosion duration and reflectance. In contrast, certain frequencies, e.g., 29.4 GHz in Figure 3c, showed little to no change. These results show that, excluding specific frequencies, reflectance from the steel surface decreases with corrosion, and this trend is clearer when suitable frequencies are selected.

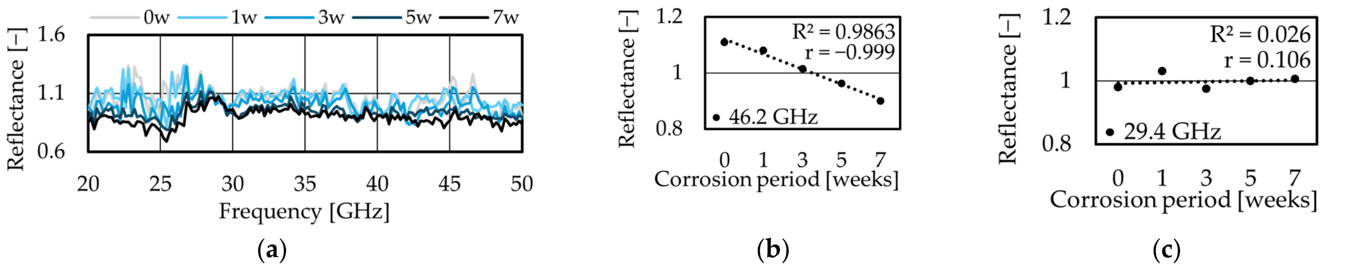

Figure 3. The reflectance of steel specimens: (**a**) Frequency spectra of steel plates with different corrosion periods. (**b**) 46.2 GHz results with negative correlation. (**c**) Uncorrelated 29.4 GHz results.

3.2. Detection of Steel Corrosion Inside Concrete

Figure 4 shows the measurement results of steel-embedded specimens. Reflectance was calculated as a relative value based on a control, which served as the reference. In the specimen with 10 mm covered, a periodic increase in reflectance was observed as corrosion progressed. Comparing this with the detection voltage values shown in Figure 5, the occurrence of peak values is related to the frequencies at which the detection voltage of the reference specimen attenuates. It is assumed that corrosion on the steel surface causes a shift in the frequencies at which attenuation occurs, resulting in a difference from the reference and producing higher reflectance.

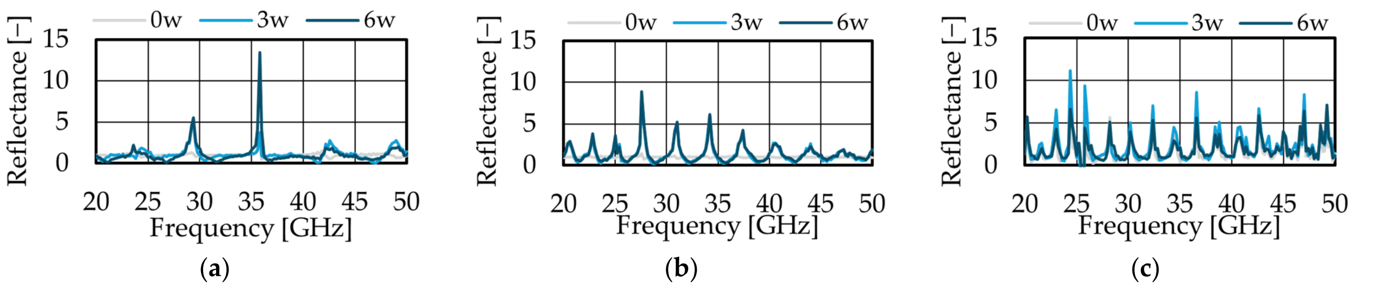

Figure 4. Frequency spectra of steel-embedded specimens with different corrosion periods: (**a**) 10 mm covered. (**b**) 20 mm covered. (**c**) 30 mm covered.

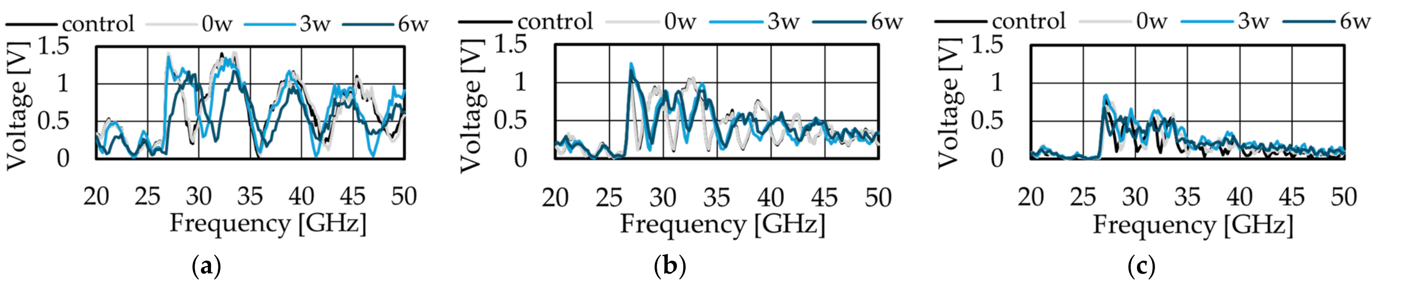

Figure 5. Detection voltage distribution of steel-embedded specimens: (**a**) 10 mm covered. (**b**) 20 mm covered. (**c**) 30 mm covered.

A similar trend was observed in the specimen with 20 mm covered. However, in the specimen with 30 mm covered, high reflectance was observed even in uncorroded conditions, and no significant difference due to corrosion was detected. This may be attributed to a shift in the attenuation frequencies between the control and 0 w with 30 mm covered. Possible reasons for this shift include external factors such as coarse aggregate within the specimen. It is necessary to increase the number of specimens and verify the reproducibility of the phenomena to clarify the spectral change trends caused by corrosion.

The reflectance peaks shown in Figure 4 appeared at roughly regular intervals depending on the cover thickness. Figure 6 illustrates the relationship between cover thickness and the interval of these peaks. Regardless of the presence of corrosion, the interval between frequencies at which peaks occur becomes narrower as the cover thickness increases. The results were generally consistent with the theoretical interference values for reflected waves from the concrete and steel surfaces, assuming a concrete relative permittivity of 6 as shown by the line. This result suggests that it may be possible to estimate cover thickness during measurement.

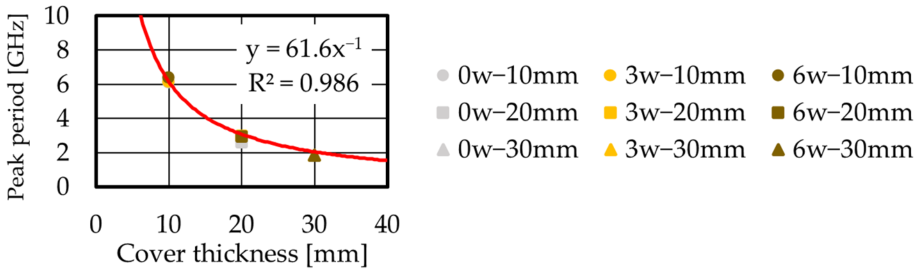

Figure 6. The relationship between cover thickness and peak period.

4. Conclusions

In this study, we conducted measurements using sub-terahertz waves to detect steel corrosion inside concrete. The findings are as follows:

(1) The reflectance spectra of steel specimens were measured using frequencies ranging from 20 to 50 GHz, and a decrease in reflectance due to corrosion was observed at many frequencies.

(2) Measurements of steel-embedded specimens revealed periodic increases in reflectance associated with corrosion. Comparison with uncorroded embedded specimens indicated that corrosion could be detected in steel plates with up to 20 mm covered.

(3) It was shown that the spacing between reflectance peaks can be used to estimate cover thicknesses of 10, 20, and 30 mm.

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