Detection of Defect in Tendon for Pre-stressed Concrete Structures using Electric Signal; Numerical Simulation Studies

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Abstract The pre-stressing in concrete structures is a popular construction method these days. One of the main problems is degradation of the structures due to the corrosion of the pre-stressing tendon that frequently generates serious damage. Hence, the corrosion detection in tendons is very important to maintain the health of the pre-stressed concrete (PSC) structures. In this study, a numerical simulation is conducted to find the feasibility of detecting corrosions by using an electric signal. For the numerical simulation, COMSOL multi-physics program which can apply the electric signal is used. The simulation is performed by modeling a set of pre-stressing tendons and ducts placed inside of the PSC structure. The ducts are filled with cement grout, and the corrosions are assumed to occur on the pre-stressing tendons. The electric signal applied at a starting point of the PSC ducts and reflected signal at the positions of corrosions is analyzed. It is confirmed that the electric signal varied as the corrosion rates changed. When the corrosion rate increased, the reflected electric signal tended to increase as well. As the corrosion detecting method is developed further, the method can be applied on pre-stressing concrete structures based on the numerical simulation modeling and results.

1. Introduction

Recently, pre-stressed concrete (PSC) is a popular construction method in the world [1]. In the United States, construction of the PSC structures has steadily increased since 1950 as shown in Figure 1, and nearly 50% of the bridges have been constructed as the PSC Bridges [1]. Pre-stressed concrete bridges are consisted of steel strands, and the soundness of the tendon is important for the safety of the bridge that compressive force is applied beforehand to the tension side of concrete members using tendons. The tensioned tendons have voids inside the tendon due to bleeding and unfilled grout. Moisture containing chloride, between tendons, flows and induces corrosion which is generated due to voids, thereby increasing a possibility of cross-sectional loss and fracture of steel strands [2]. Therefore, voids and reduction in cross-sectional area of steel strands due to corrosion are very important indices in maintenance and management of the evaluation of PSC structure's condition and safety.

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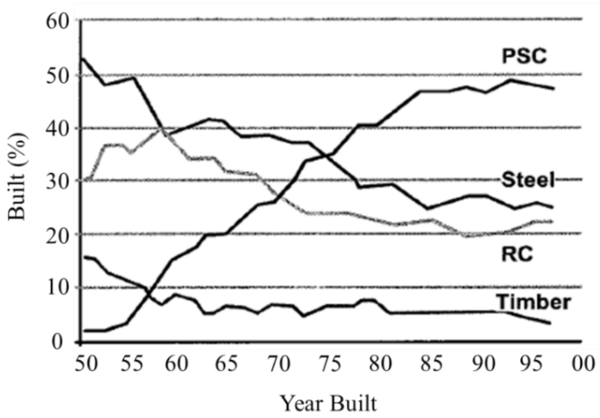

Figure 1. Construction trends according to USA bridge type [1].

The state of tendon's cross section loss, grout void, and so on are currently being evaluated using Nondestructive Test (NDT). There are various methods such as visual inspection, electromagnetic wave inspection, acoustic wave inspection, and etc. in the non-destructive inspection methods [3].

However, current methods have some disadvantages that every inspection has to be done by hand while moving along the tendon and measuring accurate location of the defects is difficult because enough space for detecting machine to be installed cannot be provided when internal design of a structure is complicated. In order to solve this defecting measurement problem, a study has conducted a fault detection study adopting time-frequency domain reflectometry (TFDR) of tendons with different locations of corrosion and void [4]. Finding locations of defects is important; however, assessing the state of the defects is even more important as degree of defects is the judgement criterion when evaluating the safety of the PSC structures. More precise detection is possible if the defect location and corrosion rate are confirmed. In this study, numerical simulation is conducted to compare the tendency of reflection waves according to the corrosion rate changes in tendon modeling based on the theory and method of [4]. A simulation is performed by modeling a 2D axisymmetric model similar to tendons placed inside of the PSC bridges and placing corrosions at some points. Through this, possibility of applying corrosion measurement of PSC structure using TFDR measurement method is examined.

2. Methodology

2.1. Time-Frequency Reflectometry

Reflectometry is the method of detecting positions and state of defects by analyzing the signal returned from defect points or the end of a diagnosis object after applying the certain electric signal to the object. Time Domain Reflectometry (TDR) and Frequency Domain Reflectometry (FDR) are standard methods of reflection evaluation. TDR locates the position of the defect by analyzing the return signal by applying pulse or step signal in the time domain. FDR analyzes the position of the defect by analyzing the return signal. TFDR is applied in this study which has more accurate and better performance than the conventional reflection signal methods because it analyzes the return signal by applying the Gaussian envelope shape signal and simultaneously analyzes the signal in time and frequency domains [5], [6]. The design of the input signal requires three parameters: center frequency, band width, and time width.

2.2. COMSOL Multiphysics

In this study, the COMSOL program was used to simulate the process of detecting defects occurring in the tendon of the PSC structure. The COMSOL program supports various governing equations and enables multiple physical analyzes. In order to apply the TFDR method, RF module that can set electromagnetic waves, impedance, and frequency is used.

2.3. Verification

In [4], experimental results and the numerical simulation results are compared by generating arbitrary defects in parallel copper and stainless steel of 10 meters in length and designing a similar model in simulation. The possibility of detecting defects using simulation is confirmed by comparing the experimental results with the numerical simulation. While copper and stainless steel were considered as parallel transmission lines when applying electrical signals in the experiment [4], the PSC tendons are assumed as the transmission lines in which ducts and strands are arranged in parallel in this study. As a result, because electrical signals are applied to parallel transmission lines in both cases, simulation of this study can be conducted by only changing the physical properties of the copper and stainless steel transmission lines to the physical properties of the PSC tendon.

3. COMSOL simulations

3.1. Simulation of corrosion rate

Simulation is conducted to verify the results of defects with different corrosion rates in PSC structures. The corrosion condition of the strand inside the tendon was modeled by reducing the cross-sectional area of the strand where the corrosion occurs [7]. As shown in the Figure 2, corrosions of three cases according to the change of corrosion rate (10%, 30%, 50%) are designed on the tendon of 10 m length. Width of the reduction in cross-sectional area was 0.1 m, which was from 6.5 m to 6.6 m away from the left side of the Figure 2. All properties are the same except for the corrosion rate.

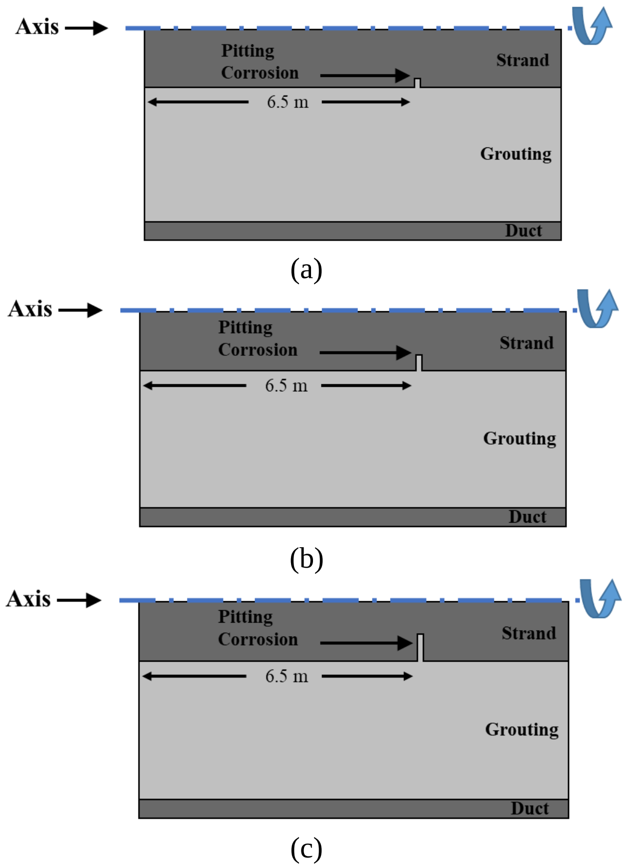

Figure 2. 2D Axis modelling having different corrosion rate: (a) 10%; (b) 30%; (c) 50%.

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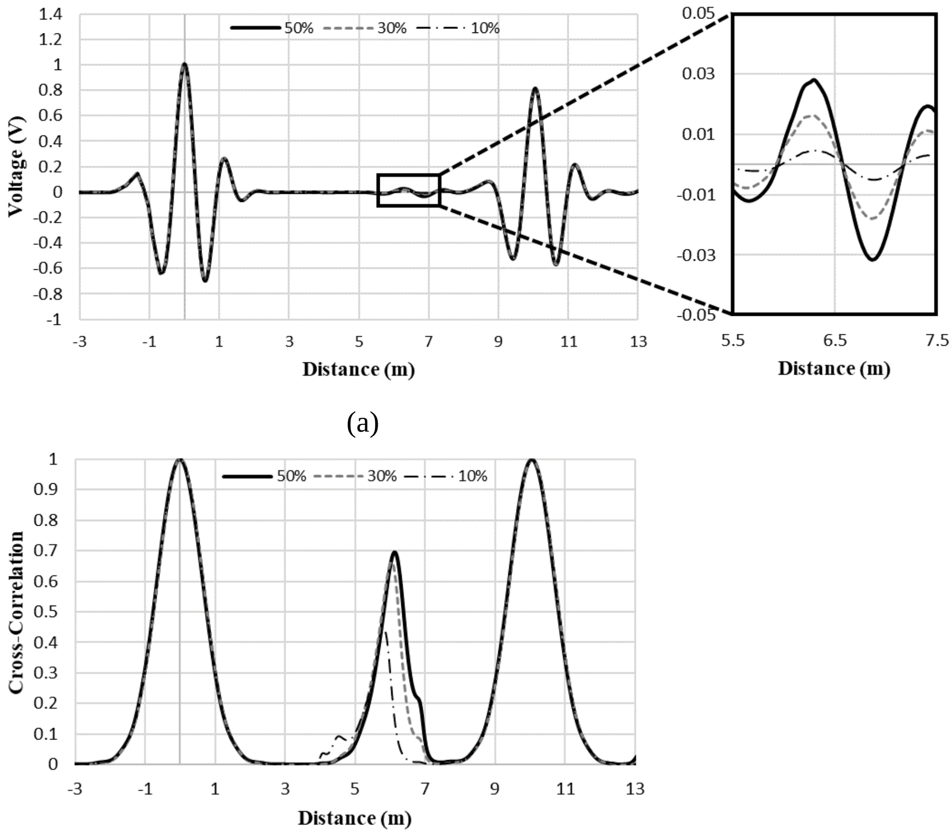
3.2. Analysis

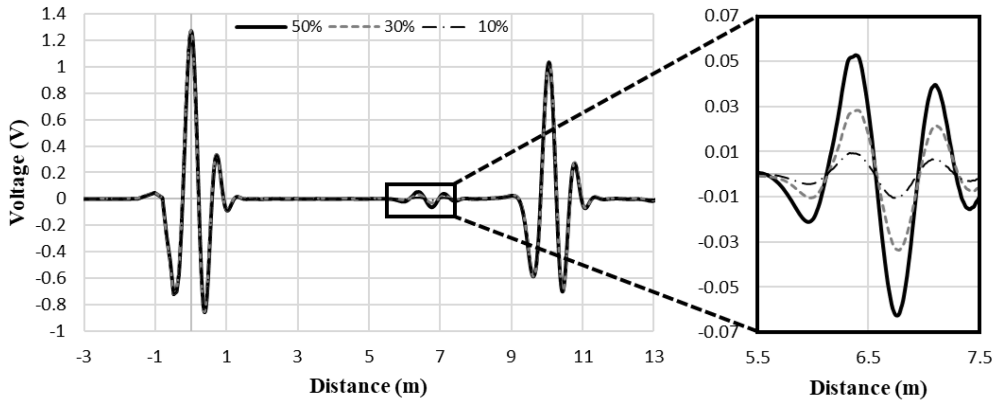
Figure 3 shows the results when center frequency is 80 MHz, band width is 100 MHz, and time width is 40 ns. Resulting graphs in time domain are converted to cross-correlation function graphs for more accurate comparison and analysis. The cross-correlation between the input signal and the reflected signal is expressed from 0 to 1 through normalization [5]. 1 means that the input signal is most similar to the reflected signal. Figure 3(b) shows that a large impedance change occurs and the reflected signal is generated at 10 m because the end point (10 m) of the model is disconnected. The correlation value with the input signal is 1 in the cross-correlation function graph. Figure 3(b) shows that the defect is measured at 5.83 m when the corrosion rate is 10%, the defect is measured at 6.04 m when the corrosion rate is 30% and the defect is measured at 6.14 m when the corrosion rate is 50%. The upper part of Table 1 shows that as a corrosion rate decreases, the error rate of the defect detection increases and the magnitude of the reflected signal decreases. Maximum error was 10%. And a higher resolution input signal is required for more accurate defect location measurements. Figure 4 shows the results when center frequency is 120 MHz, band width is 200 MHz, and time width is 25 ns. Figure 4 (a) shows that when the high-resolution input signal is applied, the wavelength is shortened compared to the previous signal. As shown in the lower part of Table 1, when the higher resolution input signal is applied, the error to the defect position can be reduced.



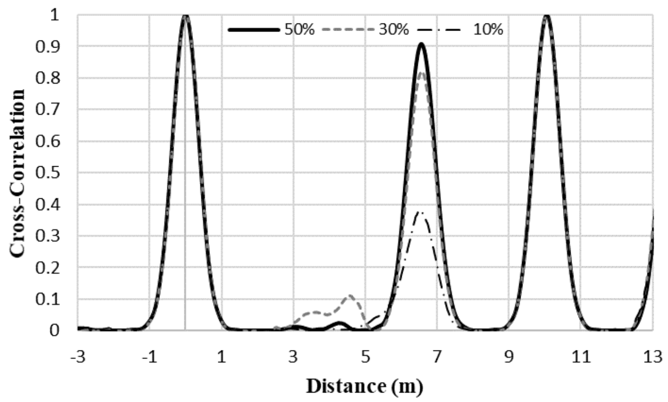
(a)

(b)

Figure 3. Graph of change in corrosion rate: (a) Voltage; (b) Cross-Correlation function.



(a)



(b)

Figure 4. Graph of change in corrosion rate with higher resolution input signal: (a) Voltage; (b) Cross-Correlation function.

Table 1. Defect measurement error according to corrosion rate.

Signal spec	Corrosion rate (%)	Defect location (m)	Measurement location (m)	Error (%)
f_0[a] = 80 MHz B[b] = 100 MHz T[c] = 40 ns	10	6.50	5.83	10.31
	30	6.50	6.04	7.08
	50	6.50	6.14	5.54
f_0[a] = 120 MHz B[b] = 200 MHZ T[c] = 25 ns	10	6.50	6.53	0.46
	30	6.50	6.57	1.08
	50	6.50	6.56	0.92

[a] Center Frequency
[b] Band Width
[c] Time Width

4. Conclusion

In this study, numerical simulation is conducted to compare the tendency of reflection waves about the corrosion rate changes in the tendon based on the theory and method studied [4]. When an electric signal is applied to the tendon, an error occurred at the defect position. The error of the defect position greatly decreases to approximately 1% when the higher resolution input signal is applied. The error can be reduced by adjusting the center frequency, bandwidth, and time width according to the length and material properties of the diagnosis object. In this study, only numerical analysis data is used to detect defects about the corrosion rate inside the tendon. In future study, experimental results and numerical analysis results are required after the fabrication of the specimen such as numerical analysis modeling. And further research on the exact electrical properties of steel and concrete can improve the research. This allows numerical analysis of the various voids and corrosion conditions that can occur in PSC structures. In addition, if further researches on numerical analysis of PSC structures with various different shapes and types of defects are conducted and result data are collected, the position and state of the corrosion can be accurately determined by comparing the obtained reflected signal with the collected data.

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