Curing Monitoring Method for Underwater Curing Resin Coatings Using Ultrasonic Spectrum Analysis

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1. Introduction

Corrosion by seawater occurs in offshore structures. Underwater coating method is one of the current repair methods for such corrosion. In this method, divers apply underwater curing resin on site and create the coating layers on the structure. Ultrasonic thickness measurements are sometimes used to evaluate the repair results of the coating after the final cure. If the coating could be characterized during the curing, it would be possible to judge whether the repair proceeds as expected without waiting for the final cure.

This study aims to propose a curing monitoring method for underwater curing resin coatings applied on a metal plate. Ultrasonic reflection spectra are used to estimate the properties of a coating layer.

2. Experiment

In this study, the specimen was a 0.33 mm thick polymer layer bonded on a 10 mm thick stainless-steel plate. The polymer was underwater curing resin consisting of epoxy resin and polyamide amine.

The experimental setup is shown in **Fig. 1**. Ultrasonic waves were incident normally on the specimen placed in water by applying a voltage from a pulser-receiver to an immersion transducer with a nominal frequency of 5 MHz. The reflected wave from the specimen was received by the same transducer and measured with an oscilloscope. The waveforms were transferred to a PC.

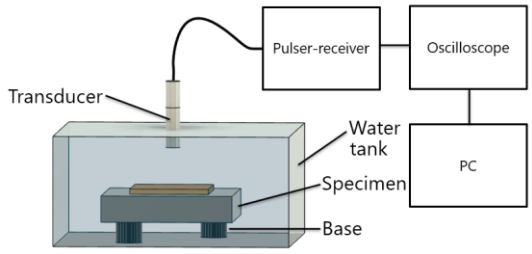

Fig. 1 Experimental setup

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The measurement was carried out for the coating specimen every 3 minutes. The surface reflected wave was also measured for a single stainless-steel plate with a thickness of 10 mm, used as a reference waveform. The acquired waveforms were analyzed by fast Fourier transform to obtain the reflection spectra.

3. Theoretical model

As shown in **Fig. 2**, the specimen is modeled as a viscoelastic layer of thickness h sandwiched between water and stainless steel, which are semi-infinite media. When a longitudinal plane wave is normally incident on this structure from the water side, the reflection spectrum can be expressed as [1)]

$$R = \frac{r_{\mathrm{wc}} + r_{\mathrm{cs}} \exp(2\mathrm{i}kh)}{1 + r_{\mathrm{wc}} r_{\mathrm{cs}} \exp(2\mathrm{i}kh)} \qquad (1)$$

where k is wavenumber in the layer and $\mathrm{i} = \sqrt{-1}$. r_{wc} and r_{cs} are stress reflection coefficient between water and coating and between coating and substrate, respectively.

The amplitude of the reflection spectrum takes local minima at the resonance frequency of the coating layer, which can be approximated as [1)]

$$f_n^{\mathrm{R}} = \left(n - \frac{1}{2}\right)\frac{c}{2h} \qquad (2)$$

where $n = 1, 2, \ldots,$ and c is the wave velocity of the polymer.

4. Estimation methods

The resonance frequency at which the reflection spectrum has a local minimum is extracted, and the wave velocity of the polymer c is estimated using Eq. (2). Then, using the obtained wave velocity,

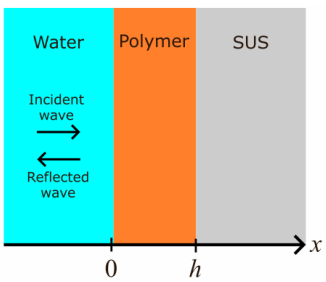

Fig. 2 Model of three-layer structure

the loss factor is estimated. The evaluation function for the loss factor is defined as

$$J_j(\zeta) = \sum_{m=1}^{N} \left\{ \frac{R_{\mathrm{E}}(f_m) - R_{\mathrm{T}}(f_m, \zeta_j)}{R_{\mathrm{T}}(f_m, \zeta_j)} \right\}^2 \quad (3)$$

where $R_{\mathrm{E}}(f_m)$ is the experimentally obtained reflection spectrum at frequency $f = f_m$, and $R_{\mathrm{T}}(f, \zeta_j)$ is the theoretical reflection spectrum calculated by Eq. (1). In the frequency range of $|f - f_n^R| < 1\mathrm{MHz}$, the evaluation function $J_j(\zeta)$ is calculated for $\zeta_j = j\Delta\zeta$, where $\Delta\zeta = 0.001$, $j = 1, 2, \ldots,$ and $0 \le \zeta_j \le 0.7$, and ζ_j which minimizes $J_j(\zeta)$ is obtained as the estimated loss factor. It is noted that the density and wave velocity of the water and stainless-steel, and the density and thickness of the polymer are assumed to be known *a priori*.

5. Results and discussion

The reflection spectrum 5 hours after the mixing of epoxy resin and polyamide amine is shown in **Fig. 3**. The minimum of the reflection spectrum existed at around 5 MHz due to ultrasonic interference. Since the wave velocities of polymers are usually measured to be about 2 km/s in previous studies, this resonance frequency seemed the 2nd-order resonance. Then the wave velocity of the polymer was calculated by Eq. (2). This calculation was performed on each experimental data to estimate the change of the wave velocity with the curing time. The results are shown in **Fig. 4**. The wave velocity decreased in the initial stage of the curing and reached a minimum value 1 hour after the start of curing. Then it began to increase up to $c = 2.3\ [\mathrm{km/s}]$ at 10 hours after the mixing.

Next, the loss factor ζ was estimated by finding ζ_j which minimized the evaluation function $J_j(\zeta)$ in Eq. (3). The theoretical reflection spectrum was obtained from Eq. (1) using the estimated wave velocity and loss factor of the polymer and is shown in **Fig. 3**. The theoretical reflection spectrum well

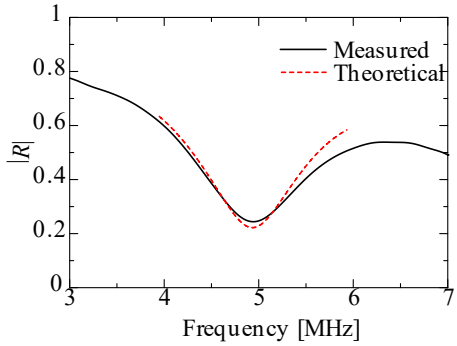

Fig. 3 Reflection spectrum 5 hours after the mixing

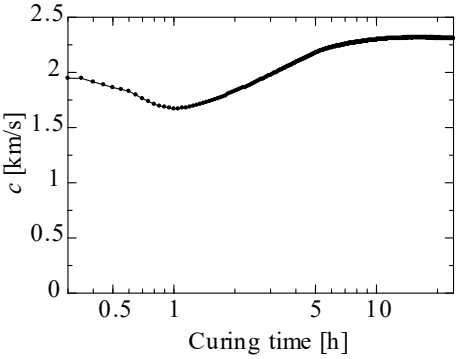

Fig. 4 The change of the wave velocity of polymer

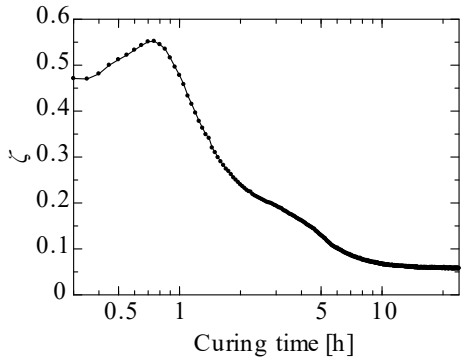

Fig. 5 The change of the loss factor of polymer

reproduced the measured result.

This evaluation was performed on each data to estimate the change of the loss factor with the curing time. The results are shown in **Fig. 5**. The loss factor increased in the initial stage of curing, reached a maximum 45 minutes after the start of curing, and then began to decrease down to $\zeta = 0.06$ at 11 hours after the mixing.

6. Conclusions

In this study, we proposed a curing monitoring method for underwater curing resin coatings by ultrasonic spectrum analysis. When ultrasonic waves were incident on a specimen in water, a local minimum of the reflection spectrum appeared due to ultrasonic interference. The resonance frequency was used to estimate the wave velocity of the polymer, and then the loss factor was estimated by comparing experimental and theoretical spectra. This method can be used to monitor the wave velocity and loss factor of the polymer layer.

References

1) Mori, N. & Hayashi, T. (2023). Ultrasonic interference and critical attenuation in metal-plastic bilayer laminates. Journal of Sound and Vibration, 547, 117531.