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Deterioration Detection of Heavy-Duty Anticorrosion Coating Using Near-Infrared Hyperspectral Imaging †

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Abstract: Steel bridges are usually painted with anticorrosion coatings. Early detection of the deterioration of the top coat is important for preventive maintenance. To detect the exposed area of the middle coat due to the deterioration of the top coat, this study introduces near-infrared hyperspectral imaging. The exposed area of the middle coat can be detected by finding the wavelengths with large differences in the spectral characteristics of both coats. Moreover, principal component analysis was applied to hyperspectral data. Principal component analysis can accurately detect the exposed area of middle coats based on differences in spectral characteristics in the near-infrared region of the coating.

Keywords: nondestructive inspection; hyperspectral imaging; anticorrosion coating

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1. Introduction

Steel bridges are painted with multiple-layered heavy-duty anticorrosion coatings for corrosion protection, as shown in Figure 1. The degradation rate of heavy-duty anticorrosion coatings differs depending on the type and thickness of the coating. After the top coat with excellent weatherability deteriorates, the coating deteriorates rapidly when the middle coat is exposed. At present, the middle coat exposure is inspected visually, which is non-quantitative and inaccurate. Thus, Sakata et al. [1] developed a quantitative evaluation of the deterioration of coatings using near-infrared measurement for high efficiency and remoteness.

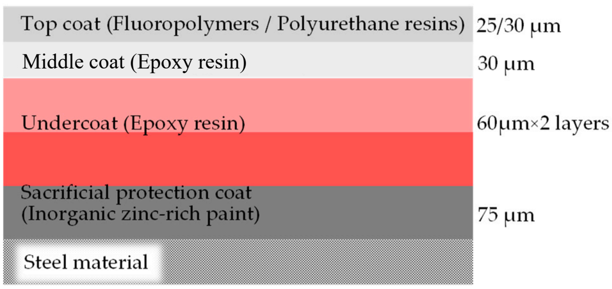


Figure 1. Schematic illustration of heavy-duty anticorrosion coating.

However, this method requires the spectral characteristics of the coating to be measured in advance and a bandpass filter to narrow the sensitivity wavelength range of the infrared camera. This makes it difficult to apply the method to the unknown spectral characteristics of the coating. This study employed hyperspectral imaging, which combines spectral and image measurements. This method is effective in detecting exposed areas of the middle coat by effectively utilizing wavelength information, even for coatings with unknown spectral characteristics. The deterioration state of the coating can be detected with high accuracy by conducting spectral feature analysis on the measurement data. This study employed principal component analysis, a type of multivariate analysis, to improve the accuracy of the detection of exposed areas of the middle coat by hyperspectral imaging.

2. Principles of Hyperspectral Imaging

The spectral characteristics of infrared rays absorbed by a substance vary depending on the chemical structure of the substance. The infrared absorption spectra showing these characteristics have a pattern unique to each substance and have been used for structural analysis and qualitative analysis of substances. Kishigami et al. [2] performed near-infrared measurements only in a specific wavelength range using the infrared spectral characteristics of the coatings. This measurement could detect exposed areas of the middle coating with good contrast. However, various paints with different chemical compositions are generally employed in heavy-duty anticorrosion coatings, and in most cases, their spectral absorption characteristics are unknown. This study performed hyperspectral imaging to detect the exposed areas of the middle coat for coatings. Hyperspectral imaging combines spectroscopic and imaging measurements and is widely applied in various fields, including remote sensing. A hyperspectral camera consists of a spectrometer mounted in front of an infrared camera. A single vertical line of light flux is spectrally split by the spectrometer and measured using a horizontal row of pixels on an infrared image sensor. The hyperspectral camera is then scanned horizontally to construct a three-dimensional data cube consisting of two-dimensional position information (x, y) and wavelength spectral information (λ) for each pixel. A spectral image can be constructed from the data cube that displays the infrared intensity at specific wavelengths and highlights the differences in absorption and reflection characteristics of materials at specific wavelengths. A hyperspectral camera can acquire infrared intensity data for each wavelength in the near-infrared region of 900 to 1700 nm, divided into 640 segments. In passive infrared measurement by sunlight, the infrared intensity is insufficient in some wavelength regions due to the infrared absorption by water vapor and carbon dioxide in the atmosphere. Therefore, the hyperspectral measurement was carried out by the active infrared measurement using an active lighting source of video light with a halogen lamp.

3. Measurement Results of Near-Infrared Hyperspectral Imaging

The near-infrared hyperspectral imaging technique, applicable to in-service bridges, was employed to improve the detection of exposed areas of the middle coat due to the deterioration of the top coat for the heavy-duty anticorrosion coatings. The target bridge is a long-span bridge that has been in service since 1988, and the coating was repainted in 2001. The paint of the heavy-duty anticorrosion coating is a fluoropolymer for the top coat and an epoxy resin for the middle coat. Figure 2 presents an example of the measurement results for near-infrared hyperspectral imaging. Figure 2a,b show the visible image and the average intensity image created over the entire wavelength range, respectively. The blue and orange points in Figure 2b are the remaining area of the top coat and the exposed area of the middle coat, respectively. Figure 2c shows the spectra of the top and middle coats at each point in Figure 2b. The spectra of the top and middle coats have a large difference in spectral intensity at the wavelength of 1200 nm. Thus, Figure 2d shows a spectral intensity image at a wavelength of 1200 nm. The average infrared intensity image does not clearly detect the exposed area of the middle coat, whereas the spectral image can detect the exposed area of the middle coat with relatively good contrast. The exposed areas of the middle coat can be clearly detected by choosing the optimum wavelengths with large differences in infrared reflection intensity between the top coat and middle coat using near-infrared hyperspectral imaging.

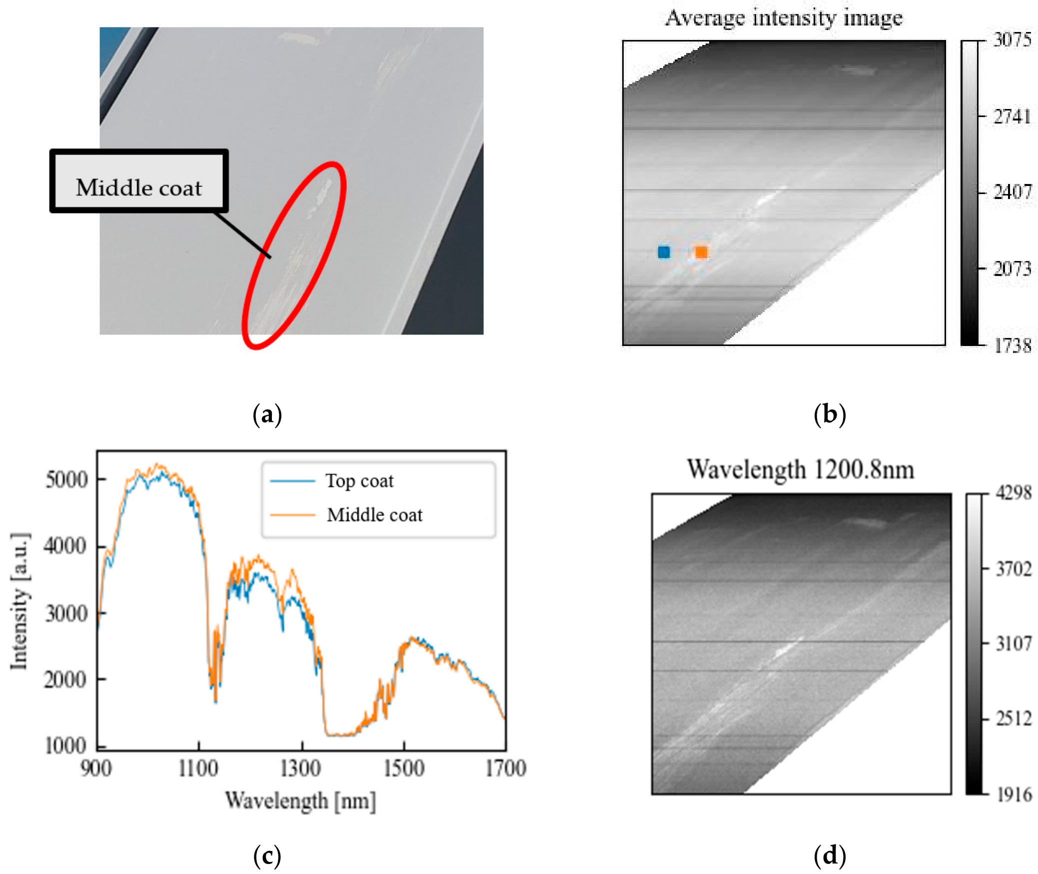
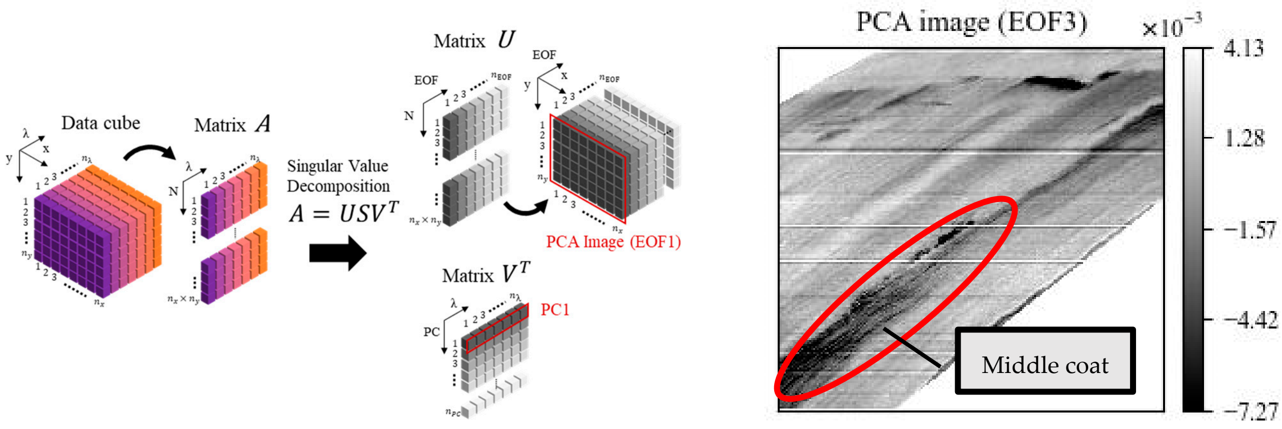


Figure 2. Measurement results of near-infrared hyperspectral imaging on in-service bridges: (**a**) Visible image of measurement area. (**b**) Averaged infrared image. (**c**) Infrared spectral characteristics of top and middle coats. (**d**) Spectral image at 1200 nm.

4. Improvements in Detection Accuracy for Coating Deterioration by Principal Component Analysis

In hyperspectral imaging on in-service bridges, it is difficult to measure all members under similar scanning conditions. As shown in Figure 2c, the infrared reflections of the active illumination cannot be fully captured, and the spectral intensity is insufficient in some areas due to atmospheric absorption. Therefore, the principal component analysis (PCA) [3], which is one of the multivariate analyses, was applied to the hyperspectral data analyses to improve detection accuracy. PCA is a data analysis method that captures and highlights data characteristics in terms of multiple variables. Specifically, the data cube is transformed into a single matrix A and then decomposed into three matrices by singular value decomposition, as shown in Figure 3a. In particular, each column of matrix U is an EOF image, which enables the extraction of features of the data cube in a two-dimensional image. Smoothing processing and scattered light correction were applied as preprocessing to the data cubes in order to improve the accuracy of spectral analysis. Smoothing is a process to reduce random noise in a spectrum. This study employed the Savizky–Golay method [4], which can process the entire data at high speed. Scattered light correction is processed to reduce the baseline variation of the measurement data because the baseline of the spectrum differs for each pixel due to scattering effects caused by the surface properties of the measurement object and unevenness in the illumination intensity. In the present study, Multiplicative Scatter Correction (MSC) [5] was employed. PCA was performed on the hyperspectral measurement data after applying this preprocessing.



(**a**) (**b**)

Figure 3. (**a**) Principal component analysis for the data cube of hyperspectral imaging; (**b**) PCA image of measurement area of Figure 2.

Figure 3b shows the results of applying PCA to the hyperspectral data in Figure 2. The PCA method can detect exposed areas of the middle coat more clearly than the spectral image and can also detect unevenness of the top coat and differences in the remaining thickness with high accuracy. This indicates that PCA can be employed with hyperspectral data to detect the deterioration state of the coating with high accuracy.

5. Conclusions

For the purpose of maintaining anticorrosion coatings on steel bridges, this study developed near-infrared hyperspectral imaging that can detect the deterioration of heavy-duty anticorrosion coatings using the spectral characteristics of coatings in the near-infrared region. In hyperspectral imaging on in-service bridges, the exposed areas of the middle coat due to deterioration of the top coat can be detected by comparing data in the wavelength region where there is a large difference in the intensity of infrared reflection between the top and middle coats. In other words, near-infrared hyperspectral imaging can find the optimum wavelength range for detecting the exposed areas of the middle coat, even if the spectral characteristics of the coating are unknown. The exposed areas of the middle coat could be detected with high accuracy by employing PCA for hyperspectral data. Actual structures differ depending on coating parameters (coating composition, type of paint, exposure period, sunlight conditions, etc.). Thus, it is also important to apply the system to bridge inspections in a common way for coatings with different specifications. Further studies will be conducted to detect the deterioration of coatings under different conditions using near-infrared hyperspectral imaging.

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