STUDY ON EVALUATION METHOD FOR PAINT FILM DETERIORATION ON STEEL BRIDGE WITH IMAGE PROCESSING TECHNOLOGY

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Visual inspection method involves personal errors in evaluating according to the observer's knowledge and experience in painting and paint. This study considers that the quantitative evaluation of paint film deterioration would be possible by using image processing technology and by selecting gray-scale morphology processing from among existing image processing techniques. To examine its practicability, an extraction test was conducted on 13620 photographs of actual bridge paint film . This test extracted deterioration from paint film images and calculated its area ratio. As a result, the test showed the possibility of quantitative evaluation of the deterioration and estimating the time to repaint using it.

Key Words : steel bridge, painting, paint films, survey, deterioration, under-film corrosion, multiple correlation, image processing system, recoating.

1. INTRODUCTION

In order to evaluate deterioration of steel bridge paint film, visual inspection is currently the most widely used method. This method uses a standard chart of the degree of paint film deterioration (for example, ASTM-D610/SSPC-Vis-2-68T)[1] and indicates results from a comparison with a standard chart as the percentage of deterioration or rating number. While this method is easy, it is not free from personal errors due to difference in experience or subjective point of view, even with skilled observers [2]. Recently, the image processing technology has been studied to compute the deterioration quantitatively through image data various positions of steel surfaces.

The image processing technology has already been employed for automatic inspections, screening and other processes of industrial products. Since an image has a large amount of data, supercomputers or specified image processor has been used because of their processing speed, capacity and the like. However, recent small, general-purpose computers have achieved a higher performance and a lower price. As a result, image processor with high quality became available with personal computers, and consequently, the number of applications for image processing technology in the field of anti-corrosion measures has been increasing.

As a method to evaluate the weatherproof properties of stainless steel, for example, Nakata et al.[3),4),5)] and Muto et al.[6),7),8)] analyzed geometrical features of rust using image processing.

Nishimura et al.[9),10)] developed equipment for automatic image analysis of rust on stainless steel surfaces. Shima et al.[11)] developed image processing software for quantitative evaluation of rust on stainless steel. Sato et al.[12)] and Kondo et al.[13)] applied image processing to rust analysis of plating materials and to corrosion and damage analysis of pipelines respectively.

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Yamamoto [14), 15)] used aerial photographs for evaluating the damage of building roofing materials and analyzed corrosion morphology in three dimensions.

In the methods of Nakata et al., Muto et al. and Nishimura et al., the subjects for photographs used as objects for image processing were limited to small test pieces, and a fixed CCD camera was used to input image. To achieve uniform lighting and to keep color tone constant, indirect illumination was used. In addition, a scale used for quantitative evaluation of deteriorated parts had to be taken in the same photograph. Likewise, the method by Shima et al. used indirect illumination to prevent reflection on the surface of all subjects.

Because bridges are outdoor structures, it is difficult to photograph them through a fixed focal length lens. In addition, nonuniformity in lighting can occur on the surface of paint film under sunlight and artificial illumination like strobe lights during photographing. It is difficult to exclude a shadow by other sections of the bridge or stains on the surface of paint film.

In the method of Sato et al., painted steel specimens were deteriorated with sea water artificially, and photographed by a color video camera under appropriate illumination. While observing each test piece on the monitor, they adjusted displayed color tone until the color tone matched the actual corrosion. Through thresholding of the matching image, they derived an area ratio of rusting (%). However this method requires long inspection time and much experience, because an inspection must attain a match in color tones while observing the monitor.

Yamamoto used full color image processing to extract deteriorated parts according to color differences. However, it is difficult to extract deteriorated parts without the premise that color development of each colors is uniform at least within an image. However, as discussed before, it is very difficult to take pictures of uniform color tone in outdoor bridge structures.

In the method by Kondo, an inspection robot with ultrasonic inspection equipment obtains data while it runs inside a pipeline, and the data is analyzed by image processing. But, Kondo's concept of image processing is different from this study where the object which is photographed and images of deteriorated parts are taken by a video camera.

As discussed above, photographing methods or image processing methods used in previous studies are thought to be impractical for inspecting painting of outdoor bridges.

Therefore, we have developed and reported a "paint film deterioration diagnosis system [16), 17)]" which performs a diagnosis of paint film deterioration from the image information of paint film surface. This article reports specifically about the extraction technique of deteriorated part necessary for quantification of paint film deterioration. This report mainly discusses image processing technology, especially about gray-scale morphology processing.

2. DIFFERENCE BETWEEN SIMPLE THRESHOLDING AND GRAY-SCALE MORPHOLOGY

This study considers practical paint film inspection and is premised on evaluating paint film deterioration without using special instruments or techniques. Therefore, we made investigations for extracting and evaluating paint film deterioration using a general-purpose camera and home video images.

In order to distinguish the deteriorated parts from the normal parts in the images of paint film, thresholding is generally performed by the following methods:

1) Percentile method
2) Modes method
3) Ohtsu method
4) Differential histograms method
5) Dynamic thresholding

On the other hand, gray-scale morphology processing used in this study is an image processing technique in which a gray image is subjected to set operations based on mathematical morphology. Conventionally, descriptions of image processing have been widely used as transformation of pixels. In mathematical morphology, on the contrary, regions of an image are considered as sets of pixels, and its image processing is performed by subjecting these sets to various set operations. Therefore, mathematical morphology is suited to extract shapes and regions such as paint film deterioration. The principle which gray-scale morphology processing extracts deteriorated parts of paint film is shown in Fig.1.

Usually, the deteriorated parts of paint film such as rust and cracking are relatively dark compared with surrounding normal paint film surfaces. This is schematically represented by Fig.1(a).

To extract deteriorated parts from such images, discrimination at certain brightness (that is, deciding a darker part than the specified brightness as a

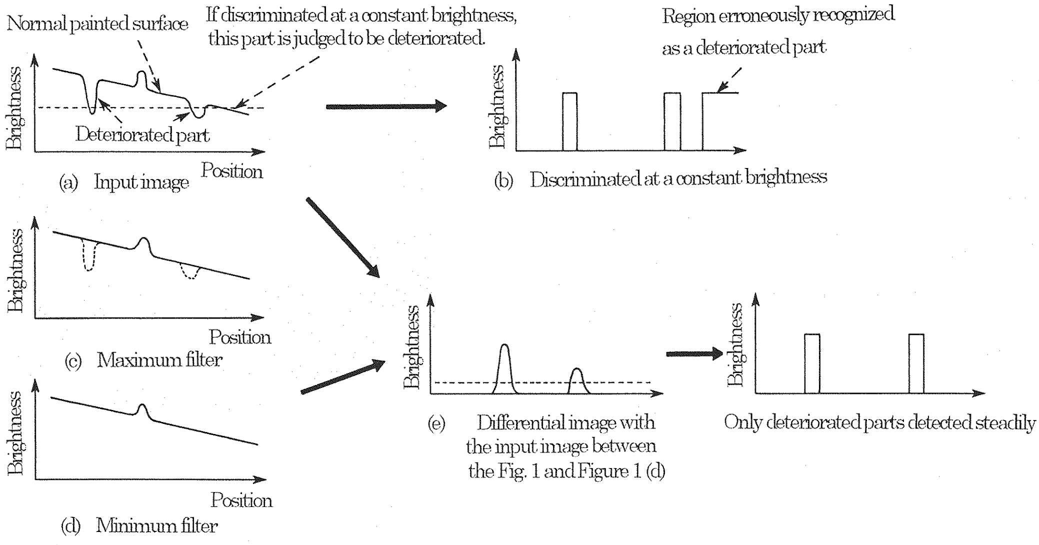


Fig. 1 Principle of Gray-scale Morphology Processing

deteriorated part and a brighter part as a normal paint film surface) may be applied, but the results are poorer than those of visual inspection. The healthy area is sometimes extracted as a deteriorated area if the specified brightness (threshold) is not obtained in the area. Conversely, deteriorated area also may not be extracted if the threshold value is assumed to be larger that the brightness of the deteriorated area (Fig.1(b)).

In the gray-scale morphology processing, the input image in Fig.1(a) is subjected to maximum filtering first. Maximum filtering is the process of converting brightness at a point P in the image to brightness at the brightest point in its neighborhood. As a result, a region within the range of the neighborhood (filter size) which is also darker than the neighborhood is converted to the same brightness as the neighborhood and filled in as a deteriorated part (recognized to be a deteriorated part) (Fig.1(c)).

Next, the image in Fig.1(c) is subjected to minimum filtering. Minimum filtering is, in contrast with maximum filtering, the process of converting brightness at a point P in the image to brightness at the darkest point in its neighborhood. As a result, the image made brighter on the whole through maximum filtering can be returned to original brightness. However, regions once recognized by maximum filtering as deteriorated parts do not return to original brightness. Therefore, the image obtained is just the same as the input image in Fig.1(a) except that only deteriorated parts (dark points as compared with the neighborhood) have been eliminated (Fig.1(d)).

The differential image between Fig.1(a) and 1(d) shows deteriorated parts only and this image doesn't change by illumination variations.

As a region extraction method is applicable when there are illumination variations in the image, the gray-scale morphology method is summarized as the technique that the brightness at each point in the image is compared with its neighborhood brightness and only relatively dark regions are extracted and recognized as deteriorated parts.

For threshold discrimination, described from 1) to 4), the threshold value is constant over the entire image. Therefore, stable extraction of deteriorated area is impossible for the outdoor pictures which have various color tones within one picture. In such a case, no valid results can be obtained. The threshold discrimination described in 5) is applicable for these outdoor pictures, though there are some problems listed below.

1) It cannot be applied to brightness nonuniformity existing in a local region of a picture.
2) It cannot be applied if the object extends over multiple regions and the extracted shape is discontinuous at the boundary between adjacent local regions.
3) The processing needs complex computation and takes a long time.

On the other hand, the gray-scale morphology method can also be applied to an image in which averaged brightness varies. At the same time, the form of an extracted object is never discontinuous, because the filtering process continuously compares relative brightness with the neighborhood. In addition, the processing is simple and extraction is possible in a short time.

As discussed above, this study tried extraction of deteriorated parts of paint film on steel bridges using the gray-scale morphology method. Images (original images) of actual bridges were subjected to gray-scale morphology processing and simple thresholding to extract deteriorated parts of paint film. Both extraction results of deteriorated parts of paint film by gray-scale morphology processing and by simple thresholding are shown in Photo.1.

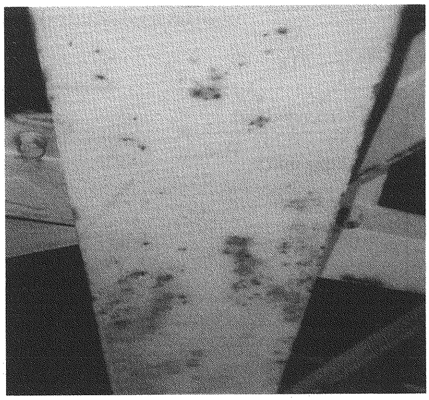
3. EXTRACTION TEST USING GRAY-SCALE MORPHOLOGY

(1) Selection of paint film deterioration phenomena to be evaluated

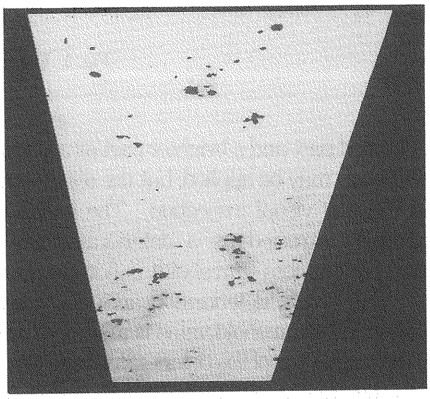
Paint film deterioration includes rust, peeling, cracking, chalking, discoloration, gloss reduction, and blistering. In image processing, however, extracting all of these deterioration phenomena requires a large amount and a long time of processing and therefore is not practical. We examined existing literature to see whether or not the deterioration phenomenon extracted through image processing can contribute to an exact evaluation of the degree of paint film deterioration of steel bridges.

From a chemical point of view, paint film deterioration phenomena occurs when molecular bonds are severed [18), 19), 20)]. An investigation from this point of view leads to the claim that photo-oxidation induces deterioration of the upper layer of paint film and this phenomenon begins with the decomposition of polymer compounds. During decomposition, gloss reduction, discoloration and wear on the paint film, etc. become visible. But, cracking in the topcoat is what starts corrosion by allowing chlorine, nitrogen oxides, sulfur oxides and the like into the interior of the paint film.

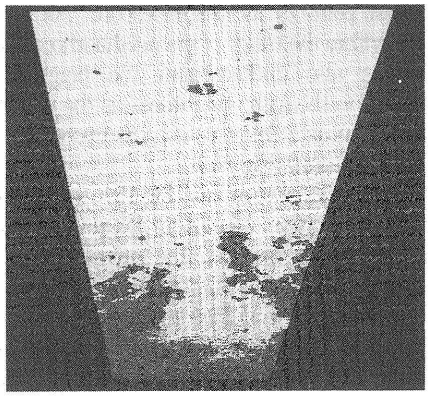
Paint film cracks in the top coat that starts corrosion cannot be seen visually and are not macroscopic. Corrosive intrusion become possible even when these microscopic fine cracks appear. There is thought that cracking in the top coat causes no problem if the under coat is sound. With the recent



(a) Original image



(b) Extraction by gray-scale morphology processing



(c) Extraction by simple thresholding

Photo. 1 Extraction example of paint film deteriorated parts on actual bridge (lower face of bottom flange) advancement in measurement techniques, however, this is found to be false. This has also been proven to be false from theoretical considerations and results from various accelerated life tests [21), 22), 23)].

When considering paint film deterioration phenomena chemically, cracking and peeling should be considered to be important in addition to rusting as major deterioration indicators for the evaluation. We assumed that when the top coat began to exhibit signs of deterioration such as rust, cracking and peeling, deterioration of that film would proceed with increasing rate.

In this study, therefore, the extraction of deteriorated paint film through image processing was directed mainly to rusting, cracking and peeling.

(2) Extraction test using sample photographs

We examined the possibility of extracting and quantifying deteriorated paint film parts by gray-scale morphology processing. This section describes an extraction test using sample photographs from actual bridge paint surfaces and discusses the results.

a) Selection of sample photographs

The Japan Highway Public Corporation conducted a paint film inspection on 533 bridges from 1989 to 1990. The 13620 photographs were used as sample photographs for the extraction test. These photographs were sorted by structural components first and then compounded by image similarity. From these pictures, typical images were drawn for examples according to the following classes (class A～D) described below. The sampling was narrowed down to 44 images and these images were used as sample photographs thereafter.

Class A: Photographs in which paint film deterioration is distinct to the human eye, i.e. image processing is thought to be comparatively easy.

Class B: Photographs in which both stain and paint film deterioration are present and their distinction is difficult to detect.

Class C: Photographs with multi-structural components are present. Distinction between deterioration area and brightness changes made by lighting was studied.

Class D: Photographs containing halation, dark photographs as a whole because of insufficient exposure, out of focus and have indistinct images.

b) Extraction test procedure

The extraction test is as follows. In this test, an image processing system with built-in gray-scale morphology processing was used. The system

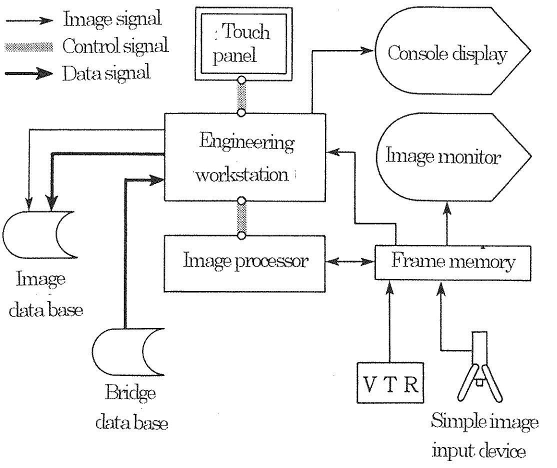


Fig. 2 Configuration of image processing system

configuration is shown in Fig.2.

1) Selecting sample photographs, and inputting image data by using an image inputting device.
2) Extracting deteriorated parts of the paint film by gray-scale morphology processing.
3) Computing the number of pixels of both the evaluated area and deteriorated area. Calculating the area ratio of them.

4. RESULTS OF EXTRACTION TESTS

An extraction test was performed on 44 sample photographs and the test results were put in order by class of the photographs as shown in Table 1. The test results are described below as follows.

1) In Class A photographs, whose paint film deterioration exhibited a distinct contrast to its surroundings, it was recognized. It was possible to quantify the area ratio of the deterioration part.
2) In Class B and D photographs, whose images had low contrast in color, the extraction of deteriorated parts alone was sometimes difficult depending on the condition of the image. For indistinct images that were out of focus, the extraction of deteriorated parts was difficult in the presence of a feeble contrast area such as stains and chalking. In order to solve this problem, we have prepared a photographing manual and adjusted exposure, focusing, and use of a flash so that pictures must be suitable for image processing.

Table 1 (1) Test results for the extraction of deteriorated parts using the gray-scale morphology method

Class	No.	Deterioration type	Results of image processing					
			Applicability of image processing		Number of deteriorated parts	Assessment area (1) (number of pixels)	Deteriorated area (2) (number of pixels)	Area ratio (%) (2)／(1)
A	1	Rust on lower face and end of bottom flange	◎	—	106	1.04448E+05	6.30300E+03	6.0346
	2	Rusting (rust points) on the entire web fact surface	◎	—	281	2.28646E+05	3.51100E+03	1.5356
	3	Rusting (rust points) on lower face of bottom flange	◎	—	98	1.79588E+05	1.36500E+03	0.7601
	4	Peeling and rust on vertical stiffening member	◎	—	55	1.15375E+05	3.67600E+03	3.1861
	5	Peeling on truss member	◎	—	79	1.11520E+05	5.43800E+03	4.8763
	6	Peeling (interlayer peeling) on sway bracing	◎	—	92	5.85800E+04	4.57100E+03	7.8030
	7	Peeling on web face	◎	—	28	2.06640E+05	5.15700E+03	2.4956
	8	Cracking on web face	◎	—	859	2.43780E+05	2.61770E+04	10.7380
	9	Cracking on painting test board	△	Extraction of all defects is difficult.	—	—	—	—
B	1	Concurrent presence of chalking and rust points on lower face of bottom flange	▲	Distinction is unclear between chalking and rust points.	—	—	—	—
	2	Same as above (excepting more amount of rust)	▲	Same as above	—	—	—	—
	3	Concurrent presence of chalking, rust and peeling on web face	△	Extraction of peeling is possible, but distinction of others is unclear.	—	—	—	—
	4	Concurrent presence of chalking, rust and stain on lower face of bottom flange	▲	Distinction is unclear between rust and stains.	—	—	—	—
	5	Concurrent presence of rust, rust stains and stain on web face	▲	Distinction is unclear between rust and rust stains.	—	—	—	—
	6	Same as above	◎	—	312	1.25339E+05	1.01630E+03	8.1084
	7	Concurrent presence of pattern on steel step board and rust, cracking and peeling on web face	◎	—	27	1.32080E+05	2.8600E+02	0.0217
	8	Presence of both deposited paint mist and shadows cast from various members on the web face	◎	—	206	1.50968E+05	9.92300E+03	6.5729
	9	Rust stains on web face	▲	Distinction is unclear.	—	—	—	—
	10	Presence of both rust and stains on the lower bottom flange face	○	Distinction is unclear between rust and stains.	331	1.73740E+05	1.28570E+04	7.4001
	11	Cracking, rust and stains on the web face in addition to girder shadows	◎	—	21	1.52180E+05	9.8300E+02	0.6459
	12	Presence of both chalking and blistering rust on lower bottom flange face	◎	—	29	1.65648E+05	1.40100E+03	0.8457

(Note) ◎ : Image processing is possible, ○ : Extraction of paint film deterioration is possible but distinction of the types of deterioration is unclear, △ : Extraction is impossible in parts of the paint film deterioration, ▲ : Further examination is necessary in both photographing methods and image processing methods.

Table 1 (2) Test results for the extraction of deteriorated parts using the gray-scale morphology method

Class	No.	Deterioration type	Applicability of image processing		Number of deteriorated parts	Assessment area (1) (number of pixels)	Deteriorated area (2) (number of pixels)	Area ratio (%) (2)/(1)
C	1	Presence of both several girders with peeling on the web face and on the bottom flange	◎	—	37	3.84920E+04	8.76300E+03	22.7657
	2	Presence of both peeling on the web face and shadows from stiffeners and sway bracing	◎	—	15	2.57600E+05	1.87000E+04	72.5932
	3	Presence of both rust on lower bottom flange face and peeling on the inner girder's web face	◎	—	121	7.05600E+05	2.81800E+03	3.9938
	4	Presence of both cracking on the inner girder's web face and shadows from horizontal and vertical stiffeners	◎	—	4	7.72500E+04	1.41000E+02	0.1825
	5	Presence of both rust on the sway bracing assembly and rust and peeling on the gusset	◎	—	46	4.19840E+04	3.50400E+03	8.3460
	6	Presence of both rust on the lower bottom flange face and rust on the steel bearing	△	Shadows of bolt and rivet heads were extracted concurrently.	—	—	—	—
	7	Presence of both rust on cross beams and on the sway bracing assembly	◎	—	90	1.49583E+05	4.02600E+03	2.6915
	8	Presence of both rust on the lower bottom flange face and on bolted splices	◎	—	191	7.32160E+04	2.96600E+03	4.0510
	9	Presence of both rust on the lower bottom flange face and on the sway bracing	◎	—	135	1.21890E+05	4.63700E+03	3.8042
	10	Presence of both rust on the lower bottom flange face splices and on bolt shadows	△	Shadows of bolt heads were extracted concurrently.	—	—	—	—

(Note) ◎ : Image processing is possible, ○ : Extraction of paint film deterioration is possible but distinction of the types of deterioration is unclear, △ : Extraction is impossible in parts of the paint film deterioration, ▲ : Further examination is necessary in both photographing methods and image processing methods.

Even for pictures in such an adverse condition, extraction was possible for deterioration exhibiting a distinct contrast such as cracking if a brightness difference with the surroundings was present.

3) In Class C photographs, various components were present in a complex combination. For a distinct image of the targeted deteriorated part, it was possible to quantify the area ratio of deterioration by specifying components other than the components to be evaluated.

4) Exact extraction of deteriorated parts was possible. However, distinction was impossible between rust, cracking and peeling.

It was found that the extraction of deteriorated parts is available for photographs taken at the site and with shading by using the gray-scale morphology processing excluding unusual cases. Even for the pictures that seem to be difficult to deal with, the "photographing manual" makes these pictures available to receive image processing by adjusting their brightness and photographing areas suitable.

5. CONSIDERATION

(1) Influence of camera angles on extraction of deteriorated parts

In image processing, it is thought that the distortion of an image has an adverse effect on extraction exactness in terms of area ratio of deterioration. Accordingly, an examination was conducted to

Table 1 (3) Test results for the extraction of deteriorated parts using the gray-scale morphology method

Class	No.	Deterioration type	Applicability of image processing		Results of image processing: Number of deteriorated parts	Assessment area (1) (number of pixels)	Deteriorated area (2) (number of pixels)	Area ratio (%) (2)/(1)
D	1	Shadows from overhanging floor slabs cast onto outer girder's web face, causing bright and dark images of rust on web face	▲	Extraction is difficult in shadowed areas.	—	—	—	—
	2	Image out of focus, and rust points on lower bottom flange face is obscure.	◎	—	81	1.51852E+05	1.6200E+03	1.0668
	3	Presence of both stains and rust points in dark photographs	▲	Extraction is difficult in dark areas.	—	—	—	—
	4	Cracking on web face in dark photographs	▲	Extraction is difficult in dark areas.	—	—	—	—
	5	Cracking and blisters on web face in dark photographs	▲	Same as above	—	—	—	—
	6	Shadows from overhanging floor slabs cast onto outer girder's web face, causing bright and dark images cracking and rust on web face	△	Extraction of small deteriorated parts is difficult	—	—	—	—
	7	Image blisters with halation	△	Same as above	—	—	—	—
	8	Blisters in remarkably chalked parts	△	Same as above	—	—	—	—
	9	Interlayer peeling of paint film on L-shape steel in depth but its image has halation	◎	—	78	5.98400E+05	4.04800E+03	0.67647
	10	Peeling on the lower upper flange face but its contrast is indistinct	▲	Extraction is difficult in areas of indistinct brightness difference.	—	—	—	—
	11	Stains on web face out of focus	△	Preferential extraction of stains.	—	—	—	—
	12	Indistinct rust points in striped stains on lower bottom flange face	▲	Extraction of rust points is difficult.	—	—	—	—
	13	Rusting in brush marks	◎	—	1	1.60457E+05	1.51400E+03	0.9436

(Note) ◎ : Image processing is possible, ○ : Extraction of paint film deterioration is possible but distinction of the types of deterioration is unclear, △ : Extraction is impossible in parts of the paint film deterioration, ▲ : Further examination is necessary in both photographing methods and image processing methods.

establish the influence of camera angles on extraction exactness in terms of area ratio of deterioration by taking photographs of a rectangle target with a known area with the camera angle varying from 90 degrees (normal to rectangle target) to 10 degrees.

To examine the influence of different lenses at the same time, three lenses with focal lengths of 35 mm, 50 mm and 180 mm were used. The relation between camera angles and the distortion factor are shown in Fig.3. The distortion factor was derived using Equation (1)

$$dx = (1 - Ax/Ao) \times 100 \quad (1)$$

dx : Distortion factor (%)

Ax : Area (m^2) of the rectangle derived from a photograph taken at various camera angles, using the image processing system

Ao : Area (m^2) of a rectangle at a camera angle of 90 degrees (normal to rectangle)

Fig.3 indicates that image distortion increases rapidly for camera angles less than 70 degrees. At a camera angle of 70 degrees, the distortion factor is 9%. In other words, the actual deteriorated area becomes 9% smaller than original size when a camera angle is 70 degrees.

In another study [24], we derived an evaluation criterion (see **Table 2**, called the "evaluation criterion" hereafter). If this criterion is applied to the area ratio of deterioration here, there is no change in evaluation results at a camera angle of 70 degrees even if a distortion factor of 9% is taken into account.

However, at a camera angle of 60 degrees, resulting in a distortion factor of 24%, changes occur in the evaluation results. The necessity for repainting is dictated by an area ratio of deterioration of 3%, around which Grade C or D may be changed to Grade B.

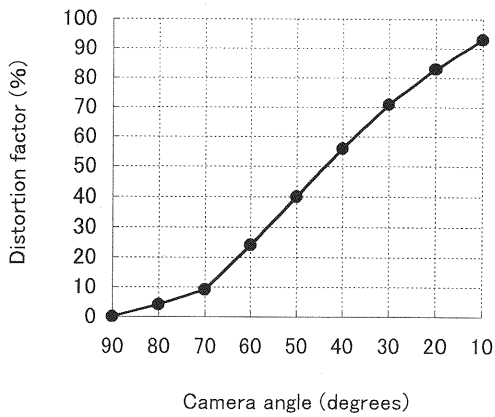
As a result, this system can be used for quantifying deteriorated parts from photographs taken at an angle within 20 degrees to the right or left or upward or downward from its normal direction. The subjects were photographed using the entire field of the lens frame, and no difference in distortion was found for the different lenses used.

(2) Influence of parameters on the extraction of deteriorated parts

From the extraction test results shown in **Table 1**, it was found, with the exception of special cases, that the deteriorated parts of paint film can be extracted even from a photograph with shade by using gray-scale morphology processing. For photographs marked with △ (extraction is impossible in part of paint film deterioration) and with ▲ (further examination is necessary in both photographing methods and image processing methods), we thought that deteriorated parts could not be extracted because of no contrast between deteriorated parts and their surroundings.

In the gray-scale morphology processing, it is necessary to set up parameters such as the maximum and minimum filter size and the threshold for brightness difference between deteriorated and normal parts. Fundamentals of gray-scale morphology processing are the arithmetic operations for converting from an input image to output pixel values as maximum pixel values (max operation) in a prescribed region (neighborhood), called a construction element, and as minimum pixel values (min operation). These operations respectively correspond to the logical sum (OR) and logical product (AND) for a binary image. The filter size denotes the size of the neighborhood subjected to a max or min operation.

In gray-scale morphology processing, deteriorated areas smaller than the filter size are considered to be deteriorated parts. Therefore, it is impossible to extract deteriorated parts larger than the filter size even if they exhibit a remarkably large brightness value differences. That is, a brightness variation in a region larger than the filter size remains unchanged after subjected to max and min operations, and



Camera angle (degrees)	90	80	70	60	50	40	30	20	10
Distortion factor (%)	0	4	9	24	40	56	71	83	93

Fig. 3 Relationship between camera angle and distortion factor

Table 2 Criterion for evaluating paint film deterioration [24)]

Rust size (mm)		e	d	c	b	a	a
Area ratio of deterioration (%)		10 or over	5 to less than 10	3 to less than 5	1 to less than 3	0.05 to less than 1	less than 0.05
l	10 or over	E	E	E	E	D	C
m	3 to less than 10	E	E	D	D	C	C
n	1 to less than 3	D	D	C	C	B	B
o	0.1 to less than 1	D	C	C	B	B	B
p	less than 0.1	D	C	B	B	B	A

(Note) The evaluation grades in the table are as follows.
A : Good paint film, B : Fair paint film, C : Needs to be under observation, D : Keep under observation with repainting in mind, E : Requires repainting.

therefore cannot be detected from the difference of the original image.

As for extracting deteriorated parts using gray-scale morphology processing, adjustment of parameters to optimum values by manual operation is not practical because of cost and processing time. From a reliability point of view for image processing, it is desirable that the deteriorated part extraction results are hardly influenced even if these set parameter values are somewhat changed. Then, we examined the influence of these parameter values in terms of area ratio of deterioration.

The sample photographs used for the examination were selected from the photographs used in Section 3. For examining filter sizes, 10 photographs with different deterioration sizes on the image were sampled. In this examination, the photographs of painted surfaces were all processed in monochromatic image. Therefore, the difference of painted color is considered to have not-negligible influence on adjustment of parameters. For the examination of threshold value, 11 photographs of different painted colors were sampled.

For this examination, filter size was varied for the selected sample photographs in 7 gradations from 10 to 70 and threshold value was varied in 9 gradations from 10 to 50 to obtain a relationship between respective parameters and the area ratio of deterioration.

Filter size results are shown in **Fig.4**. For filter size values set 10 to 30, the area ratio of deterioration obtained exhibited an almost constant value. Thus, a stable extraction of deteriorated parts was found to be possible. For images containing comparatively large paint film deterioration, filter size should be increased to extract the deteriorated part. However, such a large deterioration requiring appropriate filter size of more than 30 should have been repainted some years ago on structural maintenance viewpoint and such deterioration are out of the scope of a paint film inspection. Therefore, setting filter size to 10 to 30 is considered to be feasible.

Although there was some scattering for the threshold values as shown in **Fig.5**, it was found that setting threshold values of 20 to 30 extracted the deteriorated parts the best. In this study, however, images of painted surfaces were all processed as monochromatic images, and no consideration was given to painted colors. It is generally thought that optimum threshold values vary with painted colors. Accordingly, we decided to derive the threshold value for each painted color in order to improve the exactness for the extraction of deteriorated parts. This is discussed in Section 5.(3) .

(3) Influence of Painted Colors on the Extraction of Deteriorated Parts

Painted colors used in the examinations were (red, blue, green, yellow, ivory and gray) used on steel bridges by the Japan Highway Public Corporation. Likewise in Section 5 (2) above, 5 photographs were selected for each color from the 13620 photographs, and the mean, variance and threshold values of brightness of their images were obtained using this system. As a result, it was found that there is a strong relationship among brightness mean (m), brightness variance (σ^2) and optimum threshold value (t) as follows :

$$40\times(t-m)/\sigma+128=a\times m+b \qquad (2)$$

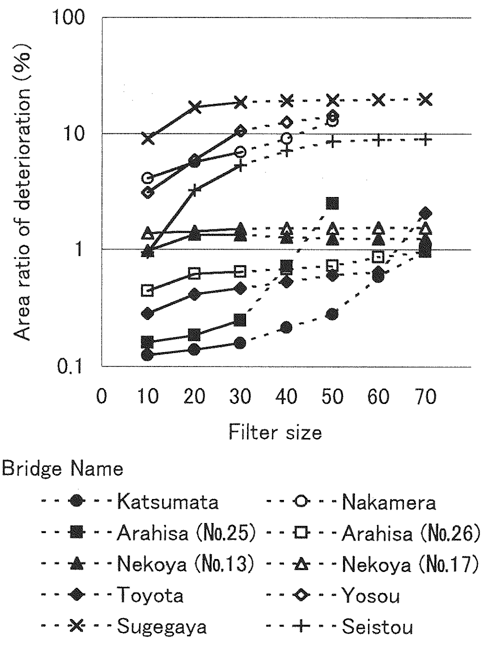
This means that once optimum values for coefficients a and b are derived for each painted color in advance, the threshold value can be derived from the brightness mean and brightness variance of that image. Then, we examined the parameters using the sample photographs described above in order to calculate parameters a and b for each painted color.

In this examination, an expert on paint film inspection extracted paint film deterioration from each sample photograph precisely, using this system. The threshold value and filter size for these were then derived.

From the derived threshold value and the brightness mean of the image after the gray-scale morphology processing, parameters a and b were calculated for each painted color by Equation (2). These are shown in **Table 3**.

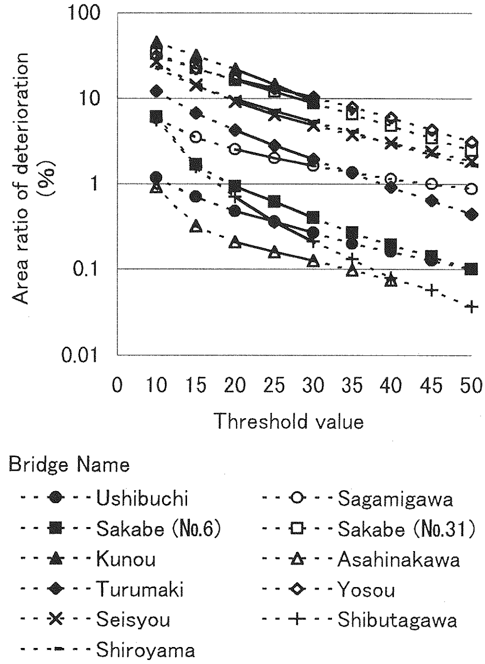
Next, we installed a linear regression function containing the parameters shown in **Table 3** into the system so that the system automatically set threshold value for each painted color. Then, we conducted an extraction test to examine whether the automatically calculated threshold values were valid or not. Results are shown in **Table 4**. Here, the evaluation performed by automatically calculating threshold value is referred to as "evaluation by automatic threshold," and the evaluation performed by an expert with adjusting parameters manually is referred to as "evaluation by optimum threshold." The evaluation criterion shown in **Table 2** was used for evaluating the degree of deterioration.

According to **Table 4**, the results from "evaluation by automatic threshold" generally agree with results from "evaluation by optimum threshold." Thus, it was proved that the optimum threshold value for extracting deteriorated parts can be derived from the



(Note) In this figure, the solid line indicates the range in which deteriorated parts are well extracted, and the broken line indicates the range in which some deteriorated parts cannot be extracted.

Fig. 4 Influence of filter size on area ratio of deterioration



(Note) In this figure, the solid line indicates the range in which deteriorated parts are well extracted, and the broken line indicates the range in which some deteriorated parts cannot be extracted.

Fig. 5 Influence of threshold value on area ratio of deterioration

linear regression function installed in this system.

For the 6 colors used in steel bridge painting, it was verified that paint film deterioration can be automatically extracted with a high degree of exactness by incorporating the filter size and threshold values obtained in this examination into the system. Where painted colors are extremely faded or discolored, exact extraction may be difficult. However, accuracy of extraction can be improved by checking the extraction results in the final confirmation process and inappropriate pictures can be corrected or eliminated.

Table 3 Parameters of linear regression function

Painted color	a	b	Painted color	a	b
Red	−0.37	154.24	Yellow	−5.74	173.30
Blue	−3.36	153.07	Ivory	2.21	155.09
Green	−0.919	134.76	Gray	−15.05	215.36

$40\times(t-m)/\sigma+128=a\times m+b$

(4) Correlation between area ratio of deterioration derived by visual observation and by this system

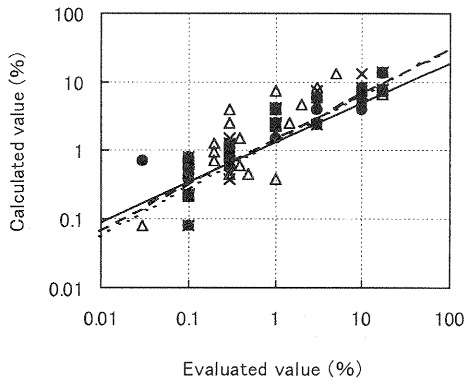
We compared area ratio of deterioration derived by this system with area ratio derived by visual observations in order to examine the relationship between the two.

For 36 photographs on actual bridge paint film, two experts on paint film inspection and a non-expert evaluated the area ratio of deterioration while comparing it to the SSPC Standard Charts1). We call their result " evaluated value." Next, area ratio of deterioration was computed by this system for the same 36 photographs and we call the result "calculated value." The relationship between evaluated and calculated values is shown in Fig.6.

Table 4 Evaluation results by regression line for each painted color

Painted color	Evaluation by optimum threshold			Evaluation by automatic threshold		
	Threshold value	Area ratio of deterioration (%)	Grade	Threshold value	Area ratio of deterioration (%)	Grade
Red 1	22	13.4	E	25	8.94	E
Red 2	13	1.27	D	12	0.72	D
Yellow 1	5	5.71	C	5	7.54	C
Yellow 2	7	0.929	C	5	1.61	D
Ivory 1	9	5.29	D	9	4.99	D
Ivory 2	6	0.749	D	5	0.88	D
Green 1	7	0.134	C	6	0.15	C
Green 2	7	0.828	D	6	0.98	D
Blue 1	9	2.99	D	5	5.84	D
Blue 2	8	3.35	D	8	1.57	D
Gray 1	10	3.15	D	15	1.043	D
Gray 2	10	0.058	D	14	0.057	D

(Note) The evaluation grades in this table are as follows.
A: Good paint film B: Fair paint film C: Needs to be under observation. D: Keep under observation with repainting in mind. E: Requires repainting.



● Evaluated value by expert 1 (correlation coefficient 0.914)
× Evaluated value by expert 2 (correlation coefficient 0.906)
△ Evaluated value by non-expert (correlation coefficient 0.831)
—●— Regression line by expert 1 ($\log Y = 0.58 \log X + 0.27$)
-×- Regression line by expert 2 ($\log Y = 0.69 \log X + 0.30$)
—△— Regression line by non-expert ($\log Y = 0.67 \log X + 0.35$)

Fig. 6 Correlation of paint film area ratio of deterioration

According to **Fig.6**, the evaluated value by the non-expert and the calculated values were somewhat different with the correlation coefficient of 0.831. The evaluated value by the experts and the calculated value however were almost the same with the correlation coefficient 0.906 to 0.914.

We applied this system to the SSPC Standard Charts to extract deterioration as an area ratio. As a result, a correlation coefficient of 0.995 was obtained between the area ratio of deterioration indicated on the Standard Charts and the indicated values.

As stated above, the area ratio of deterioration calculated by this system was the same as the value evaluated by experts on paint film inspection as well as with the indicated value of the SSPC Standard Charts. We believe this shows practicability of quantifying paint film deterioration by this system.

(5) Examination of practicability as an expert system

While SSPC Standard Charts evaluate in terms of area ratio, our other study [24] evaluates the degree of paint film degradation in terms of area ratio, weighted according to their size. This is because there is a strong correlation between the size of a rust spot on the paint film surface and the degree of corrosion on the steel under that paint film. The larger the rust spot on the paint film, the higher the degree of corrosion under the paint film. This is clearly understood from results of inspection on actual bridges.

Experts on paint film inspection usually consider the corrosive environment and painting system when making an evaluation and estimate the corrosion under the paint film from the condition of the paint film surface. On the other hand, this system can only provide information on the paint film surface such as area ratio of deterioration and size of rust spots. We evaluated this system in terms of practicability by fitting the area ratio of deterioration values and the size of rust spots derived by this system into **Table 2**, showing evaluation criterion derived in our other study [24].

For examining practicability, we compared values from area ratio of deterioration derived by this system and the results from putting them into **Table 2** with values from area ratio of deterioration and paint film grade which the experts on paint film inspection determined through visual comparison with SSPC Standard Charts. Results of both evaluations are shown in **Table 5**.

According to **Table 5**, the evaluation results by the experts on paint film inspection are almost the same as

Table 5 Comparison between visual observation and evaluation using this system

Evaluation	Evaluation by visual observation		Evaluation by system	
Bridge name	Area ratio of deterioration (%)	Grade	Area ratio of deterioration (%)	Grade
Kuno	17	E	9.792	E
Tsurumaki (1)	0.1	B	0.102	B
Tsurumaki (2)	0.1	B	0.070	B
Tsurumaki (3)	3.0	E	1.585	D
Kawasaki	3.0	E	3.220	D
Suzukawa (1)	0.1	B	0.173	D
Suzukawa (2)	0.1	B	0.151	C
Sagamigawa	1.0	D	2.183	D
Katayama	0.3	C	0.345	C
Ushibuchigawa	0.3	C	0.286	D
Sakabe (1)	3.0	E	0.798	C
Sakabe (2)	3.0	E	1.633	D
Yoso	3.0	E	4.045	D

the evaluation results by this system. Therefore, the practicability of this system as an expert system, is verified. Some differences are seen between both evaluations. This is because visual observation evaluates dense rust spots in terms of apparent area ratio as one set while this system calculates the area of each individual rust spot. In other words, this system evaluates in terms of area ratio more precisely and, therefore, we may claim that the quantitative reliability is higher. For images marked with ▲ in Table 1, phenomena other than paint film deterioration phenomena are present (for example, rust stains and stain). For such an image, complex processing such as adjusting threshold value or excluding those area, is necessary for image processing. Therefore, with simplifying operations and improving exactness, we have now prepared a photographing manual to avoid taking photographs that will be marked with ▲.

6. CONCLUSIONS

In this study, an image processing system was used to quantify characteristic quantities of deterioration from photographs of deteriorated paint film. An attempt was also made to evaluate the degree of deterioration by fitting quantity values into the evaluation criterion set up in our other study [24].

We chose gray-scale morphology processing from existing image processing techniques and examined its practicability by conducting an extraction test on actual bridges photographs of paint film. As a result, we drew the following conclusions.

1) It was found that quantitative extraction of deteriorated parts of paint film is possible by using gray-scale morphology processing even on images with varying brightness such as steel bridge paint film photographs taken outdoors.
2) It was found that photographs used in quantifying paint film deterioration using the image processing system[16),17)] developed in this study must be taken at an angle within 20 degrees to the right or left or upward or downward from a normal setting to be evaluated.
3) It was found that for extracting deteriorated parts of paint film using gray-scale morphology processing a filter set to 10 to 30 and a threshold value set to 20 to 30 produces excellent extractions on deteriorated parts.
4) For each of the six painted colors commonly used in steel bridge painting, the coefficients for linear regression were derived from the image brightness mean after being subjected to the gray-scale morphology processing. Exact automatic extractions on deteriorated parts of paint film were possible by using this linear regression function.
5) The area ratio of paint film deterioration extracted using this system was the same as evaluation results made by experts on paint film inspection with the SSPC Standard Charts. Therefore, we believe that this system has successfully demonstrated the practicability of quantifying paint film deterioration.
6) We evaluated characteristic quantities of paint film deterioration quantified by this system by placing quantity values into the evaluation criterion derived in our other study[24)]. As a result, the evaluation by this system was the same as evaluation results obtained by experts using visual observation on paint film. This verifies the practicability of this system as an expert system.
7) This study demonstrated the validity of image processing as a technique to determine the deterioration degrees of paint film on steel bridges. In a series of our studies on determining the deterioration degrees of paint film on steel bridges, we have made an attempt to estimate residual life of paint film from the relationship between deterioration present under the paint film surface and the degree of corrosion on the steel surface.

Eventually, we aim to construct an expert system which can estimate the time to repaint from paint film inspection results. In this study, a method for quantifying characteristic quantities of paint film deterioration was successfully established. This indicates the possibility of estimating the residual life of paint film by accumulating time-series data on paint film deterioration.

REFERENCES

1) ASTM, Standard Method of Evaluating Degree of Rusting on Painted Steel Surface. D-610-68 (Steel Structures paint Council, SSPC-Vis-68T).
2) Makoto Kamiya, Hiroshi Fujiwara, and Masaru Miyake: Compiled the Results of a Questionnaire on Determining the Time in Repainting Steel Bridges, Japan Steel Structure Association, Presentation Drafts for 17th Session of Iron Structure Painting Technology Forum, June 1994.
3) Junji Nakata, Toshio Shibata, and Yuji Sakata: Evaluation of Stainless Steel Weather Resistance by Image Analysis, Proceedings of the 40th Session of Corrosion and Rust Prevention Forum, pp.369-372, 1993.
4) Junji Nakata and Toshio Shibata: Image Analysis of a Model Pattern for Weather Resistance Rusting Spot Distribution, Proceedings of the 41st Session of Corrosion and Rust Prevention Forum, pp.453-456, 1994.
5) Junji Nakata and Toshio Shibata: Applying Image Processing Technology to Stainless Steel Weather Resistance Evaluations, Papers from the 110th Session of Corrosion and Rust Prevention Symposium, pp.1-12, 1996.
6) Izumi Muto, Eiji Sato, and Hiroshi Kihira: Image Analysis of Stainless Steel Rusting Behavior in an Atmospheric Environment, Proceedings of the 40th Session of Corrosion and Rust Prevention Forum, pp.373-376, 1993.
7) Izumi Muto and Hiroshi Kihira: The Present State and Problems of Weather Resistance Evaluation Methods for Stainless Steel, Bosei Kanri (Corrosion Control), 38, pp.2-7, July 1994.
8) Izumi Muto: Quantitative Analysis of Stainless Steel Atmospheric Corrosion Behavior through Image Processing, Papers from the 110th Session of Corrosion and Rust Prevention Symposium, pp.13-22, 1996.
9) Toshiya Nishimura and Yoshiaki Shimizu: Effects of Humidity Cycle Corrosion Test Conditions for Rust Formations on Stainless Steel, Zairyo to Kankyo (Materials and Environment), Vol.44, No. 10, pp.550-556, 1995.
10) Toshiya Nishimura and Yoshiaki Shimizu: Evaluation of Rust Formation on Stainless Steel, Papers from the 110th Session of Corrosion and Rust Prevention Symposium, pp.23-35, 1996.
11) Mitsugu Shima and Katsuya Watanabe: Evaluation of Rust Formation on Stainless Steel through Image Processing, Proceedings of the 42nd Session of Corrosion and Rust Prevention Forum, pp.167-170, 1995.
12) Yukihiro Sato and Kosuke Moriwaki: Considerations on Simple Methods for Corrosion Evaluations through Image Processing, Bosei Kanri (Corrosion Control), 35, pp.12-15, March 1991.
13) Munetaka Kondo: Application of Corrosion and Damage Analysis to Pipelines, Papers from the 110th Session of Corrosion and Rust Prevention Symposium, pp.72-80, 1996.
14) Masahiro Yamamoto: Three-dimensional Analysis of Corrosion Morphology by Image Processing, Zairyo to Kankyo (Materials and Environment), Vol.45, pp.315-322, 1996.
15) Masahiro Yamamoto: A Corrosion Evaluation Method for Roofing Materials Using Full Color Image Processing, Zairyo to Kankyo (Materials and Environment), Vol.46, pp.90-94, 1997.
16) Hiroshi Fujiwara, Sadao Degawa, Yukihiro Kawano, and Shozo Sugano: A Study on a Paint Film Deterioration Diagnosis System for Steel Bridges as an Application of Image Processing Technology, Proceedings of the 48th Annual Conference of the Japan Society of Civil Engineers, Part I, I-215, pp.578-579, September 1993.
17) Masaru Miyake, Hiroshi Fujiwara, and Takaaki Akai: Developing a Paint Film Deterioration Diagnosis System for Steel Bridges, Proceedings of the 50th Annual Conference of the Japan Society of Civil Engineers, Part I, I-A359, pp.718-719, September 1993.
18) Takeyuki Tanaka: Physical Properties of Coated Film and their Evaluation Method, Riko Shuppansha (Riko Publishing Co.), pp.219-220, 1986.
19) Shozo Sugano: Diagnosis of Paint Film Deterioration, Denryoku Doboku (Electric Power and Civil Engineering), No. 223, pp.99-113, November 1989.
20) Eiki Takeshima: A Method for Predicting the Durable Life of Painted Steel Plates, Toso Gijutsu (Painting Technology), pp.91-99, March 1983.
21) Noboru Masuko: Occurrence and Progress of Corrosion under Paint Film, Boshoku Gijutsu (Corrosion Prevention Technology), No. 30, No. 12, pp.699-704, December 1981.
22) Akira Okuda: Characteristics and Diagnosis of Lined Film Deterioration, Papers from the 154th Session of Regular Meeting by the Corrosion and Rust Prevention Department of the Society of Materials Science, Japan, pp.7-24, January 1990.
23) Hiroshi Fujiwara and Shozo Sugano: A Study on the Correlation between Paint Film Deterioration and Corrosion under Paint Film on Steel Bridges, Journal of Structural Mechanics and Earthquake Engineering, Japan Society of Civil Engineers, No. 537/I-35, pp.167-181, April 1996.
24) Japan Highway Public Corporation: Procedure for Maintenance and Repair, Steel Bridge Painting, May 1988.