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RESEARCH INTO THE CORRELATION BETWEEN THE DETERIORATION OF THE PAINT FILM ON STEEL BRIDGES AND THE CORROSION OCCURRING BENEATH THE PAINT FILM

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Generally, the recoating of steel bridges is determined by visual observation of the paint surface. However, the relationship between the paint film deterioration and corrosion beneath the paint is uncertain. In this research, deterioration of paint was evaluated in the cases of six steel bridges located in differing environments by means of an image processing system, and corrosion beneath the paint was measured using the replica method. As a result, coefficients of multiple correlation of 0.7~0.9 were found to exist between the paint film deterioration and the corrosion existing beneath the paint film. This result indicated the possibility of accurate determination of the time for recoating.

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

1. INTRODUCTION

There are some 2500 steel bridges under the supervision of the Japan Highway Public Corporation (hereinafter referred to as JH), extending a total of some 370km and having a painted surface area totalling twenty million square meters. More than about 8% of this painted area is repainted every year.

The cost of carrying out this recoating amounts to approximately 6.6% of the highway maintenance expenditure, and this recoating and the associated cost is expected to increase in the future with the increase in the number of such bridges (area to be painted). Reducing the cost of this recoating work is one of the current JH research themes.

As a part of this research, the authors are involved in the development of a "Degree of Paint Film Deterioration Diagnostic System"[1), 2)]. The research described in this report was performed to provide a means for the "determination of recoating time" as part of this system.

It is known that paint films exposed to the atmosphere are affected by the ultraviolet rays of the sun, and oxygen and moisture in the air, resulting in the changing of high polymer films into low molecular weight compounds[3), 4)]. This process is generally referred to as paint film deterioration.

The methods widely adopted for evaluating this deterioration process can be broadly divided into the following two groups:

1) Laboratory methods using various analytical apparatus to determine the molecular level variation of the paint film.
2) On-site survey methods based mainly on visual observation to evaluate the overall condition of the paint film.

The laboratory methods are used mainly in the case of research or accident investigation, and the on-site survey methods are mainly adopted for macroscopic evaluation, as in the case of determining the necessity of recoating steel bridges.

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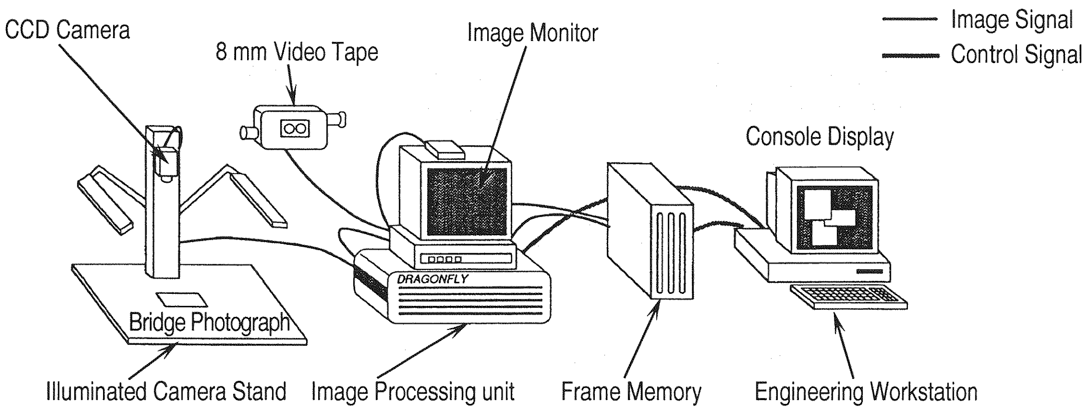


Fig. 1 Set-up of Paint Film Deterioration Diagnostic System

The on-site survey methods generally involve comparison of visual observation with some kind of standard chart (e.g., ASTM • D610/SSPC-Vis-2-68T)[5] in order to evaluate the degree of deterioration in terms of a percentage or rating number. However, while these methods may be carried out relatively easily, it has been pointed out by Kamiya et al.[6] that differences in individual experience or subjectivity are unavoidable in these judgements.

On the other hand, according to Yoshida[7, 8, 9], if the results of these observational surveys performed by paint film specialists are analyzed statistically, an S-curve similar to a logistic curve or Gompertz curve is obtained. Also, an investigation using the same methods was carried out on 254 bridges throughout Japan by Katawaki et al., and their research reported that deterioration of the paint film could be expressed by an S-curve, indicating the possibility of predicting the time for recoating[10, 11]. The same has also been reported by Kuriyama[12] and Nishimura[13].

However, as these results are all based on surveys using visual observation, the effects of differences due to individual judgement described above cannot be ruled out. Therefore, if this S-curve is actually to be applied, it is necessary to modify the ideal estimation curve by numerous values obtained by on-site survey.

Nishimura[13] stated the necessity of collecting data on not only verified paint film deterioration data, but also the reduction in section area of the steel member due to corrosion. Matsumoto et al.[14] carried out an investigation on the paint film deterioration of 152 road bridges and 33 railway bridges, and measured the thickness of steel plates of several bridges. They reported a relationship between the paint film deterioration and under-film corrosion and presented an evaluation method of corrosion .

A common feature of the above research is the fact that in all cases the findings are based on the results of paint film deterioration evaluated by comparing the results of observation with standard charts.

The authors carried out the current research with the aim of providing a highly practical means of evaluating paint film deterioration and determining the required time of recoating of steel bridge paint film. This was achieved by referring the investigation on the relationship between the paint film deterioration and the under-film corrosion based on objective data uninfluenced by subjective judgement through the development of a diagnostic system for evaluating deterioration of the paint film with image data of the painted surface.

2. OUTLINE OF THE PAINT FILM DETERIORATION DIAGNOSTIC SYSTEM

(1) System Outline

As the details of the diagnostic system have already been reported[1, 2], an outline of the system[15] will be described.

The set-up of the system, as shown in **Fig. 1**, can be broadly classified into the engineering workstation (hereinafter EWS) and the image processing equipment. The EWS is the host computer of the system, and the operation of the whole system is carried out while observing the EWS console display. The main roles of the EWS are:

i) Provide input guidance text - screen display, display of quantitative results

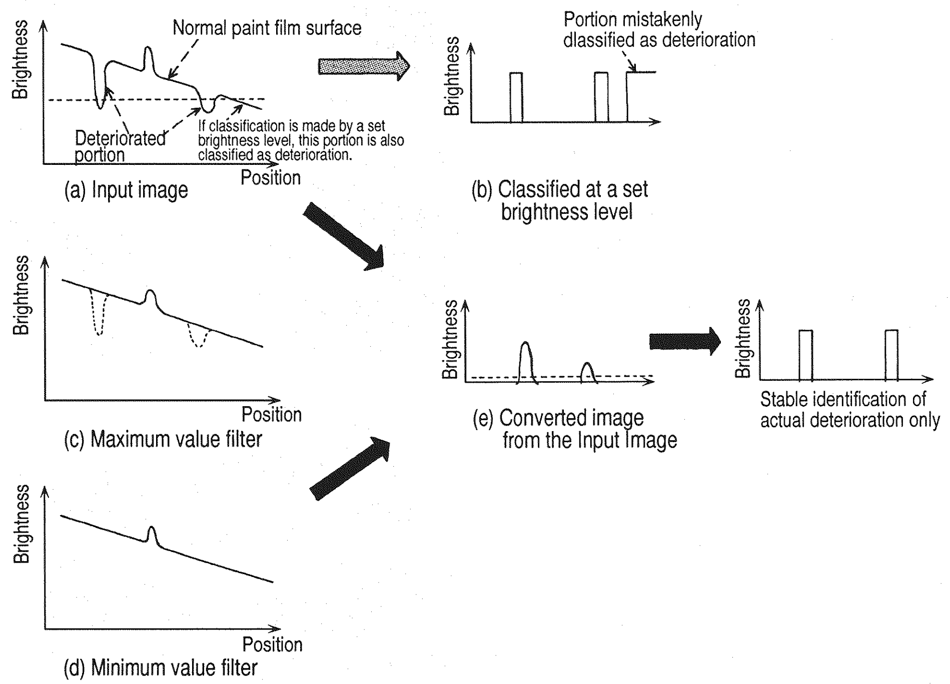


Fig. 2 Principle of Identifying Areas of Deterioration using Gradation Morphology Processing

ii) Receive operational commands and settings data via the mouse or touch panel
iii) Compute various physical characteristics and statistical values
iv) Control the peripheral equipment such as image processing unit and monitor

The image processing unit identifies the deteriorated portions of the paint film surface in images from the camera or VTR.

(2) System Structure

The functions and general processing procedure of the system are as follows:

i) The images are inputted from a CCD camera or 8mm video camera (image input).
ii) Areas of sudden change in gradation of color are identified (identification of deterioration).
iii) The image dimensions are then converted to actual dimensions (dimensional computation).
iv) Unwanted portions are then erased and the paint film surface to be processed is determined (determination of region).
v) The area, length of the periphery, circularity and other characteristic values and statistical values are computed (characteristic value computation).
vi) The various processing results and parameters are then saved in a file (data storage).

The entire process described above is carried out in dialogue form and the various results are indicated in the form of images, tables, and graphs on the EWS display. The original bridge image and the various results of the image processing are displayed sequentially on the image monitor.

(3) Principle of the Identification of Paint Film Deterioration

When photographing the deteriorated paint film on site, due to the structure of the bridge or the photographing environment, the brightness of the paint film, that is basically uniform, changes continuously due to the effects of sunlight, lights or flashlights used for photographing.

Usually, the region of deterioration such as corrosion or cracking (discolored region) is relatively darker than the surrounding paint film surface, and can be represented diagrammatically as shown in **Fig. 2(a)**.

If the method of determining the regions according to some predetermined brightness (a method in which the areas darker than the predetermined brightness are considered to be areas of deterioration) is used in order to identify the discolored region, the results will be no better than those obtained by human judgement. There will be cases where non-deteriorated regions are judged to be suffering deterioration because they have values of brightness less than the predetermined value (threshold value). On the other hand, there may be cases where regions suffering deterioration are judged to be normal, due to a high threshold value (**Fig. 2(b)**).

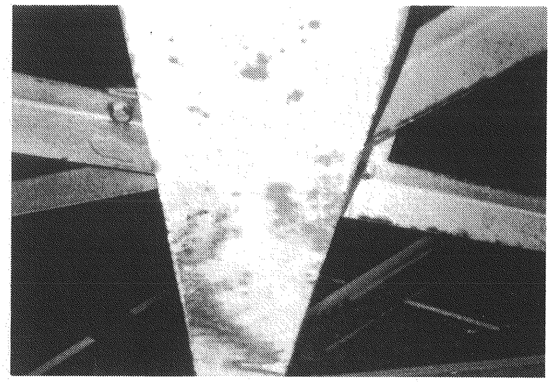
A main feature of the system is the method of identifying the areas of deterioration in cases where there are variations of illumination intensity in image and also where the regions relatively darker than the surrounding regions are identified and judged to be suffering deterioration at each location in image; in other words, "gradation morphology processing" is used. The basic procedure for gradation morphology processing is as follows:

i) At each point within the image, the value of brightness is replaced by the highest value of brightness (maximum value filter processing) within a fixed distance of the point (a region large enough to cover the size of the discolored area to be identified). By this process, the discolored region that is relatively darker than the surrounding region will be given the brightness of the normal paint film surface. However, by this process, the trend will be to increase the overall brightness (**Fig. 2 (c)**).

ii) To restore the condition of image, the points within the image are replaced by the darkest point within the same fixed distance described in i) above (minimum value filter processing). By this process, the overall brightness is returned to the original condition. However, as the brightness of the discolored portion was replaced with the brightness of the normal paint film surface in step i), this discolored portion will be made the same brightness as the surrounding normal paint film surface (**Fig. 2(d)**).

iii) The image obtained at ii) is then compared with the original to obtain the difference. As a result, the regions of normal paint film surface cancel each other out and the relatively darker regions only are identified (**Fig. 2(e)**). Using this difference image, and selecting the portions where the difference is greater than some fixed value, the discolored portions can be consistently identified.

The original image and the result of performing gradation morphology processing to identify the discolored portions can be seen in **Photo. 1**.



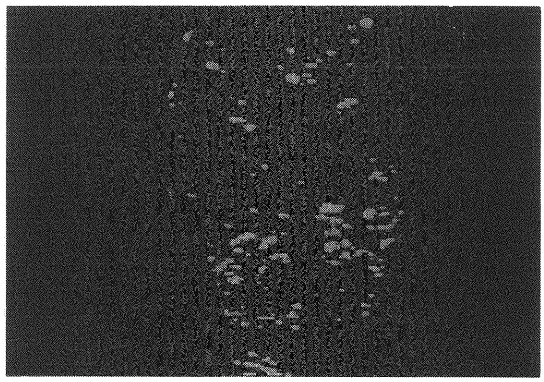


Photo. 1 Top: Original Image of Bridge Girder Paint Film Deterioration
Bottom: Result of Identification of Deterioration by Image Processing

3. PAINT FILM SURVEY OF BRIDGES

(1) The Choice of Bridges for the Survey

It has already been reported that the type of deterioration of paint film varies according to the environment in which the bridge is located[2]. With the additional aim of confirming this variation, three representative environments, namely rural regions, urban regions with heavy traffic, and coastal regions were decided upon. For each type of environment, two bridges were chosen that were due to be recoated in the current year, (see **Table 1**).

(2) Points to be Surveyed and Method

a) Identification of Samples

The bridges chosen for the survey, as was mentioned above, were all due to be recoated; therefore, they all exhibited a certain degree of deterioration. However, as the types and degree of deterioration were scattered, the following four grades were decided upon with regard to the degree of corrosion, and samples taken for each of these grades.

i) Extremely Light Corrosion - Corrosion specks only 1~2mm in diameter, with only one or two such specks existing within a 100×100mm area.

ii) Intermediate Level Corrosion - Locations with corrosion specks as described above but with several such specks existing.

Table 1 Bridges Investigated in the Survey

Environment at Bridge Location	Expressway	Bridge	Year of Completion	Type of Paint Used
Rural	Tohoku Expressway	Omoigawa Bridge	1972	Lead Primer + Phthalic Resin Coating (Recoated in 1985)
	Chuo Expressway	Sixth Ramp Bridge of Kofu South Interchange	1972	Lead Primer + Phthalic Resin Coating
Urban (High Traffic Volume)	Daisan Keihin Expressway	Shizakai Viaduct	1965	Lead Primer + Phthalic Resin Coating (Recoated in 1976)
	Yokohama - Yokosuka Expressway	Second Hino Interchange Bridge	1979	Lead Primer + Phthalic Resin Coating
Coastal	East Kanto Expressway	Futamata Viaduct	1981	Zinc Rich Primer + Chlorinated Rubber Paint
	Seisho Bypass Expressway	Banjoh Bridge	1985	Lead Primer + MIO + Chlorinated Rubber Paint

Table 2 Measurement Methods for Paint Film Deterioration and Under-film Corrosion Occurring on Bridges

Measured Item	Content
① Photographing of Corroded Portions	Photographed including a measuring rule to determine the actual measurements
② Removal of Paint Film	Paint removed by applying a paint removing solvent and removing with scraper and wire brush after the surface has lifted. This process is repeated until the bare surface is exposed.
③ Photographing of Steel Surface Revealed by Paint Removal	Photographed to reproduce the actual size of the under-film corrosion.
④ Preparation of Surface Replica	A silicon resin type mold agent to produce a male mold of the exposed surface (on-site work finishes with this operation).
⑤ Making of Plaster Mold	Plaster is poured into the mold to provide a reproduction of the surface of the bridge steel.
⑥ Measurement of Corrosion Depth	The plaster is then cut to produce a section of the average corrosion, which is then photographed using a visual microscope. From this photograph, based on the roughness measurement guidelines, the depth of corrosion is measured.
⑦ Measurement of Corrosion Area	Measurement of the corrosion surface of the plaster is performed using the image processing system.
⑧ Measurement of Percentage of Paint Film Surface Deterioration	Measurement of the photograph obtained in ¨ above is carried out using the image processing system.

iii) Considerable Corrosion - Locations where the corrosion has occurred to a greater degree than ii).

iv) Paint Film Lifting - Corrosion has exceeded the level mentioned in ii) above.

Ten sample areas were taken for each bridge with at least two samples for each of the grades i) ~ iv) above.

b) Points to be Surveyed and Method of Measurement

The following three points were surveyed for the sample regions of each bridge in accordance with the procedure indicated in **Table 2.**

Bridge Name : Omoigawa Bridge, Tohoku Expressway	Image Number : 001	Member : Plate Girder Web
Brightness Threshold Value : Set	Gradation Threshold Value :	Filter Size :
Darkness Threshold Value : Set	Gradation Threshold Value : 4	Filter Size : 0
Threshold Value Calculation Method : Regression Curve	Average : 1.9000	Dispersion : 15.81000
Magnification : 1.000	Distance Rectification : 0.022051 (cm/pixel)	
Subject Area : 53.103470 (cm^2)	Image Evaluation Value : B	
Number of Occurrences of Deterioration : 115	Percentage of Deterioration Area : 0.73894%	

Grain Size Distribution (mm)	Under 0.05	0.05–1.0	1.0–3.0	3.0–5.0	5.0–10	Over 10
Evaluation According to Grain Size	A	B	B	A	A	A
Percentage of Area According to Grain Size	0.00000	0.34429	0.39465	0.00000	0.00000	0.00000

Remarks : Condition of deterioration prior to paint film removal

Fig. 3 Example of Output from Image Processing System

i) Quantitative measurement of paint film deterioration: taking photographs of the paint film deterioration of bridges and inputting them into the image processing unit for quantitative measurement.

ii) Quantitative measurement of under-film corrosion: peeling off the paint film over the area for which the photograph was taken in i), taking photographs of the exposed corrosion and inputting them into the image processing unit, for quantitative measurement of the under-film corrosion is carried out.

iii) Measurement of Degree (Depth) of Under-film Corrosion: A silicon resin mold agent is applied to the peeled part exposed in ii) so as to make a convex, and plaster is poured to form a replica of the corrosion surface. This is then measured using an optical microscope with a 50 times magnification to determine the depth of corrosion beneath the paint film.

4. MEASURING RESULTS

(1) Proportion of Area and Number of Occurrences of both Paint Film Deterioration and Under-film Corrosion

The corrosion condition of paint film surface (hereinafter referred to as "visible deterioration"), and the condition of the corrosion on the steel surface exposed by removing the paint (hereinafter referred to as "hidden deterioration") were filmed in accordance with the procedure indicated in **Table 2**, and measurements were carried out using the image processing techniques described in Chapter 2 above.

The form of output from this system is indicated in the example for the Omoigawa Bridge, shown in **Fig. 3**. From the results of these measurements, the number of corroded regions (regions of deterioration) and the proportion of the surface area covered by the corrosion (percentage of the area of deterioration) for each bridge are given in **Table 3(1)~(3)**.

"Image evaluation" shown in these results (*evaluation* in **Table 3**) is the value obtained by referring to a deterioration criterion incorporated in the image processing system, and the details of this criterion are shown in **Table 4**.

The main feature of this standard is that, unlike the generally used standards that make use of the percentage of surface covered by corrosion, the evaluation of **Table 4** makes use of the area percentage weighted by the grain size of the corrosion.

The reason for considering the grain size is based on the fact that there is a strong correlation between the grain size of the corrosion appearing on the surface of the paint film and the degree of under-film corrosion, so that the larger the grain size, the greater the degree of under-film corrosion, and if recoating is carried out while the grain size is below about 5mm, the corrosion of the steel members can be kept to a minimum.

Table 3(1) Image Processing Results of the Paint Film Deterioration and Under-film Corrosion for each Bridge (I)

Bridge	Image Number		Number of Occurrences of Surface Deterioration	Deterioration Surface Area (%)	Distribution of Deterioration for each Grain Size (%)						Evaluation
					0.05mm<	~1.0mm	~3.0mm	~5.0mm	~10mm	10mm<	
Omoigawa Bridge	1	Before	115	0.739	0	0.344	0.395	0	0	0	B
		After	571	1.888	0	1.761	0.117	0	0	0	B
	2	Before	414	1.092	0	0.628	0.464	0	0	0	B
		After	628	2.218	0	2.049	0.170	0	0	0	B
	3	Before	762	5.888	0	2.938	3.494	0	0	0	D
		After	841	3.657	0	2.991	0.666	0	0	0	B
	4	Before	319	0.559	0	0.467	0.092	0	0	0	B
		After	401	1.079	0	1.079	0	0	0	0	B
	5	Before	468	1.076	0	0.921	0.155	0	0	0	B
		After	629	2.222	0	1.978	0.244	0	0	0	B
	6	Before	12	0.254	0	0.022	0.232	0	0	0	B
		After	357	0.895	0	0.895	0	0	0	0	B
	7	Before	44	0.570	0	0.132	0.137	0.300	0	0	C
		After	478	2.094	0	1.433	0.195	0.466	0	0	C
	8	Before	29	0.357	0	0.053	0.304	0	0	0	B
		After	227	0.746	0	0.679	0.067	0	0	0	B
	9	Before	22	0.353	0	0.036	0.077	0.240	0	0	C
		After	186	0.519	0	0.494	0.024	0	0	0	B
	10	Before	19	0.195	0	0.047	0.148	0	0	0	B
		After	239	0.821	0	0.700	0.121	0	0	0	B
Sixth Ramp Bridge of Kofu South Interchange	1	Before	69	0.314	0	0.142	0.172	0	0	0	B
		After	45	0.223	0	0.175	0.052	0	0	0	B
	2	Before	16	0.128	0	0.058	0.070	0	0	0	B
		After	115	0.640	0	0.501	0.138	0	0	0	B
	3	Before	135	0.674	0	0.321	0.353	0	0	0	B
		After	71	0.350	0	0.265	0.085	0	0	0	B
	4	Before	237	1.089	0	0.478	0.432	0.180	0	0	C
		After	115	0.643	0	0.485	0.159	0	0	0	B
	5	Before	118	0.523	0	0.278	0.245	0	0	0	B
		After	71	0.352	0	0.267	0.085	0	0	0	B
	6	Before	57	0.836	0	0.146	0.040	0	0.649	0	C
		After	51	0.284	0	0.201	0.083	0	0	0	B
	7	Before	75	0.869	0	0.195	0.472	0.202	0	0	C
		After	76	0.437	0	0.319	0.118	0	0	0	B
	8	Before	96	1.009	0	0.222	0.624	0.163	0	0	C
		After	76	0.437	0	0.319	0.118	0	0	0	B
	9	Before	296	6.711	0	1.382	3.259	1.458	0.612	0	D
		After	162	1.231	0	0.721	0.288	0.223	0	0	C
	10	Before	546	8.883	0	1.837	3.767	1.575	1.705	0	D
		After	59	0.334	0	0.247	0.087	0	0	0	B

(Note) The number of the image "before" and "after" refer to the visible deterioration and hidden deterioration exposed by paint removal, respectively.

Table 3(2) Image Processing Results of the Paint Film Deterioration and Under-film Corrosion for each Bridge (II)

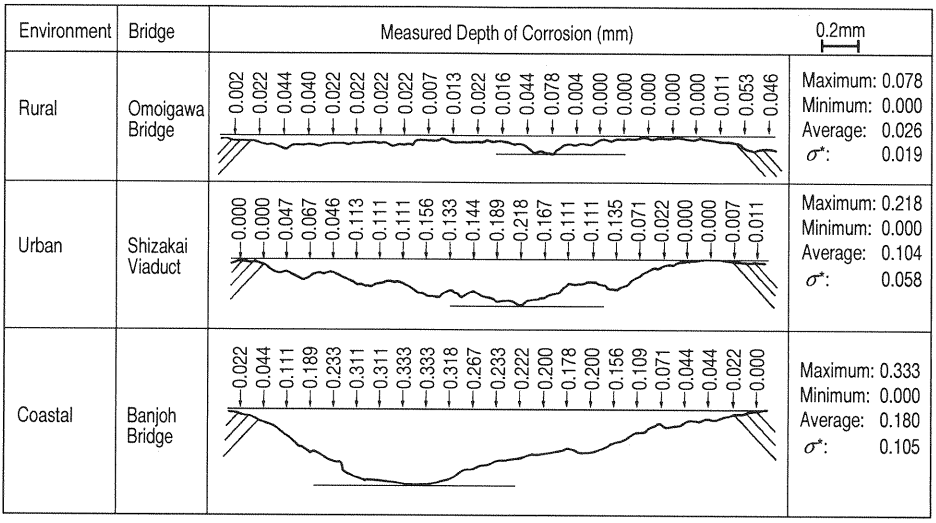
Bridge	Image Number		Number of Occurrences of Surface Deterioration	Deterioration Surface Area (%)	Distribution of Deterioration for each Grain Size (%)						Evaluation
					0.05mm<	~1.0mm	~3.0mm	~5.0mm	~10mm	10mm<	
Shizakai Viaduct	1	Before	36	0.557	0	0.121	0.264	0.172	0	0	C
		After	289	1.260	0	1.064	0.196	0	0	0	B
	2	Before	48	1.934	0	0.131	0.629	0.599	0.575	0	C
		After	347	1.681	0	1.412	0.268	0	0	0	B
	3	Before	69	2.069	0	0.216	0.669	0.491	0.693	0	C
		After	402	2.114	0	1.604	0.510	0	0	0	B
	4	Before	59	2.221	0	0.169	1.372	0.680	0	0	C
		After	400	2.115	0	1.576	0.540	0	0	0	B
	5	Before	72	4.789	0	0.249	0.686	0.791	3.063	0	E
		After	400	2.120	0	1.605	0.515	0	0	0	B
	6	Before	25	2.164	0	0.094	0.128	0.562	1.379	0	D
		After	288	1.250	0	1.084	0.166	0	0	0	B
	7	Before	19	1.143	0	0.074	0	0	1.069	0	D
		After	288	1.248	0	1.082	0.166	0	0	0	B
	8	Before	24	1.436	0	0.091	0	0.792	0.553	0	C
		After	401	2.124	0	1.555	0.569	0	0	0	B
	9	Before	42	2.758	0	0.170	0.142	0	0	2.446	D
		After	288	1.260	0	1.061	0.199	0	0	0	B
	10	Before	13	1.503	0	0.036	0	0	1.467	0	D
		After	192	0.742	0	0.621	0.122	0	0	0	B
Hino Viaduct	1	Before	12	0.466	0	0.051	0.153	0.263	0	0	C
		After	31	0.104	0	0.103	0	0	0	0	B
	2	Before	78	1.352	0	0.411	0.414	0.527	0	0	C
		After	152	1.141	0	0.589	0.136	0.417	0	0	C
	3	Before	376	15.07	0	1.659	3.146	0.609	0.553	9.107	E
		After	32	0.102	0	0.102	0	0	0	0	B
	4	Before	258	3.354	0	1.246	2.108	0	0	0	C
		After	204	1.647	0	0.672	0.337	0	0.638	0	C
	5	Before	600	8.934	0	2.747	4.374	0.196	1.617	0	D
		After	338	4.754	0	1.434	0.865	0	0	2.454	D
	6	Before	421	14.87	0	1.656	3.913	1.366	1.719	6.212	E
		After	205	1.646	0	0.671	0.337	0	0.638	0	C
	7	Before	252	1.365	0	1.023	0.342	0	0	0	B
		After	145	0.982	0	0.517	0.197	0.267	0	0	C
	8	Before	300	3.007	0	1.163	0.897	0	0.947	0	C
		After	113	0.759	0	0.417	0.343	0	0	0	B
	9	Before	577	3.361	0	2.228	1.133	0	0	0	C
		After	507	19.78	0	1.820	1.299	0.247	0	16.41	E
	10	Before	987	9.443	0	3.949	4.483	1.012	0	0	D
		After	233	1.313	0	0.888	0.425	0	0	0	B

(Note) The number of the image "before" and "after" refer to the visible deterioration and hidden deterioration exposed by paint removal, respectively.

Table 3(3) Image Processing Results of the Paint Film Deterioration and Under-film Corrosion for each Bridge (III)

Bridge	Image Number		Number of Occurrences of Surface Deterioration	Deterioration Surface Area (%)	Distribution of Deterioration for each Grain Size (%)						Evaluation
					0.05mm<	~1.0mm	~3.0mm	~5.0mm	~10mm	10mm<	
Futamata Viaduct	1	Before	7	0.110	0	0.032	0.078	0	0	0	B
		After	120	0.401	0	0.355	0.046	0	0	0	B
	2	Before	32	0.483	0	0.136	0.346	0	0	0	B
		After	308	1.517	0	1.037	0.243	0.236	0	0	C
	3	Before	31	0.771	0	0.155	0.322	0	0	0	B
		After	255	1.195	0	0.762	0.433	0	0	0	B
	4	Before	38	1.040	0	0.144	0.403	0.493	0	0	C
		After	377	1.995	0	1.328	0.394	0.273	0	0	C
	5	Before	51	0.747	0	0.289	0.240	0.219	0	0	C
		After	255	1.967	0	0.763	0.433	0	0	0	B
	6	Before	11	0.535	0	0.020	0.514	0	0	0	B
		After	289	1.238	0	1.077	0.162	0	0	0	B
	7	Before	97	2.917	0	0.365	0.870	1.112	0.570	0	C
		After	400	2.117	0	1.605	0.512	0	0	0	B
	8	Before	187	6.414	0	0.724	2.602	1.006	2.001	0	D
		After	808	8.080	0	3.596	2.886	1.598	0	0	C
	9	Before	412	6.936	0	1.666	3.329	1.246	0.695	0	D
		After	863	14.11	0	3.800	3.132	0.494	6.686	0	E
	10	Before	239	8.292	0	1.081	2.346	1.694	3.171	0	E
		After	836	14.37	0	3.880	3.030	0.812	3.362	3.288	E
Banjoh Bridge	1	Before	33	0.468	0	0.097	0.033	0	0.338	0	C
		After	720	3.427	0	2.487	0.656	0.248	0	0	C
	2	Before	42	0.513	0	0.126	0.195	0.191	0	0	C
		After	496	1.974	0	1.605	0.369	0	0	0	B
	3	Before	67	0.812	0	0.146	0.129	0.246	0.290	0	C
		After	533	2.083	0	1.717	0.366	0	0	0	B
	4	Before	239	1.986	0	0.648	1.203	0.135	0	0	C
		After	241	1.355	0	1.046	0.309	0	0	0	B
	5	Before	35	1.479	0	0.092	0.206	0.381	0.800	0	C
		After	243	1.356	0	1.051	0.305	0	0	0	B
	6	Before	285	11.95	0	0.568	3.624	3.252	4.502	0	E
		After	778	7.167	0	2.849	2.377	0.340	1.601	0	D
	7	Before	103	1.719	0	0.256	1.056	0.407	0	0	C
		After	783	7.162	0	2.884	2.364	0.337	1.577	0	D
	8	Before	696	15.646	0	1.988	6.970	4.148	2.539	0	D
		After	911	13.448	0	3.597	3.933	2.396	3.522	0	E
	9	Before	12	2.708	0	0.031	0.147	0	0	2.529	D
		After	243	1.355	0	1.050	0.305	0	0	0	B
	10	Before	246	3.286	0	4.292	0.606	0	0	2.251	D
		After	178	0.853	0	0.698	0.155	0	0	0	B

(Note) The number of the image "before" and "after" refer to the visible deterioration and hidden deterioration exposed by paint removal, respectively.



(Note) σ^* : Standard Deviation

Fig. 4 Measurements of Degree of Under-film Corrosion (Representative Values for Each Type of Environment)

(2) Measurement of the Degree of Under-film Corrosion

The degree of under-film corrosion refers to the depth of corrosion of the steel under the visible deterioration of the paint film. Measurement of this depth was made using the replicas taken from the sample areas (10 for each bridge × 6 bridges = 60) and taking a 50 times magnification photograph using a microscope of the representative corrosion region from each sample. From these images the depth of corrosion was found for 23 points at 0.12mm intervals as shown in **Fig. 4**. From these results, the maximum, minimum, and average depths and the standard deviation were obtained. The results thus obtained are shown in **Table 5**.

While it is difficult to discuss the form of corrosion of each sample on the basis of these results alone, if a comparison of all the specimens for the corrosion cross section for each bridge is made, there is a commonality in the form of corrosion according to the bridge environment as can be seen in **Fig. 4**. To be more explicit, in rural regions, the corrosion tends to occur at isolated points and is shallow, whereas in urban regions the corrosion tends to be deeper and occur more continuously over the surface, while in coastal regions, deep conical pitting occurs.

From the overall averages of **Table 5**, the maximum and average values for each bridge are shown in **Fig. 5**. It can be seen that the values are maximum for the urban region, followed by the coastal and rural regions in order, indicating a connection with the form of the corrosion mentioned above.

Table 4 Paint Film Evaluation Standard by Corrosion Grain Size and Percentage Area

Grain Size (mm)	e	d	c	b	a	a
Corrosion Surface Area %	10 and Above	10~5	5~3	3~1	1~0.05	0.05 and Below
10 and Above l	E	E	E	E	D	C
3 ~ Less than 10 m	E	E	D	D	C	C
1 ~ Less than 3 n	D	D	C	C	B	B
0.1 ~ Less than 1 o	D	C	C	B	B	B
Less than 0.1 p	D	C	B	B	B	A

(Note)
The evaluation grades appearing in the table are as follows:
A: Good Paint Film B: Fairly Good Paint Film
C: Requiring Observation D: Continue observation on the premise of recoating E: Recoating is necessary

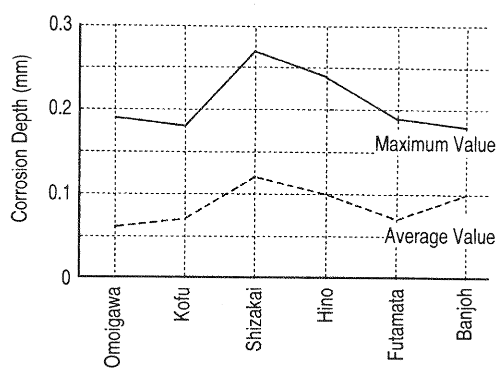


Fig. 5 Average Depth of Under-film Corrosion for each Bridge

Table 5 Measured Depth of Under-film Corrosion

	Environment	Rural Region		Urban Region		Coastal Region	
	Measurement Items \ Bridge	Omoigawa Bridge	Kofu South*	Shizakai Viaduct	Hino Interchange**	Futamata Viaduct	Banjoh Bridge
1	Maximum Value (mm)	0.078	0.089	0.218	0.251	0.178	0.160
	Minimum Value (mm)	0.000	0.000	0.000	0.000	0.000	0.022
	Average Value (mm)	0.026	0.054	0.104	0.110	0.058	0.071
	Standard Deviation	0.019	0.027	0.058	0.050	0.047	0.045
2	Maximum Value (mm)	0.133	0.178	0.140	0.178	0.200	0.144
	Minimum Value (mm)	0.000	0.000	0.000	0.000	0.004	0.000
	Average Value (mm)	0.042	0.062	0.059	0.088	0.077	0.115
	Standard Deviation	0.039	0.057	0.043	0.049	0.063	0.181
3	Maximum Value (mm)	0.156	0.289	0.356	0.211	0.133	0.133
	Minimum Value (mm)	0.000	0.000	0.000	0.000	0.000	0.011
	Average Value (mm)	0.041	0.076	0.120	0.082	0.052	0.065
	Standard Deviation	0.041	0.080	0.114	0.073	0.043	0.035
4	Maximum Value (mm)	0.356	0.133	0.233	0.267	0.338	0.264
	Minimum Value (mm)	0.000	0.000	0.000	0.011	0.011	0.000
	Average Value (mm)	0.112	0.054	0.130	0.072	0.177	0.146
	Standard Deviation	0.106	0.042	0.072	0.071	0.114	0.087
5	Maximum Value (mm)	0.156	0.133	0.467	0.156	0.178	0.100
	Minimum Value (mm)	0.000	0.000	0.011	0.000	0.000	0.004
	Average Value (mm)	0.132	0.047	0.167	0.081	0.079	0.047
	Standard Deviation	0.160	0.038	0.167	0.049	0.053	0.035
6	Maximum Value (mm)	0.133	0.091	0.356	0.467	0.224	0.333
	Minimum Value (mm)	0.000	0.000	0.000	0.000	0.002	0.000
	Average Value (mm)	0.043	0.037	0.112	0.153	0.108	0.180
	Standard Deviation	0.041	0.027	0.098	0.168	0.072	0.105
7	Maximum Value (mm)	0.062	0.144	0.111	0.267	0.100	0.133
	Minimum Value (mm)	0.000	0.000	0.000	0.000	0.000	0.000
	Average Value (mm)	0.021	0.041	0.064	0.065	0.037	0.083
	Standard Deviation	0.014	0.036	0.033	0.077	0.024	0.036
8	Maximum Value (mm)	0.467	0.078	0.356	0.197	0.294	0.189
	Minimum Value (mm)	0.000	0.000	0.000	0.000	0.000	0.000
	Average Value (mm)	0.116	0.029	0.250	0.059	0.059	0.082
	Standard Deviation	0.156	0.017	0.093	0.542	0.075	0.064
9	Maximum Value (mm)	0.111	0.200	0.200	0.189	0.204	0.200
	Minimum Value (mm)	0.000	0.000	0.000	0.000	0.000	0.000
	Average Value (mm)	0.029	0.110	0.062	0.111	0.047	0.093
	Standard Deviation	0.026	0.069	0.062	0.140	0.060	0.062
10	Maximum Value (mm)	0.289	0.556	0.244	0.256	0.131	0.156
	Minimum Value (mm)	0.000	0.000	0.000	0.000	0.000	0.000
	Average Value (mm)	0.059	0.193	0.099	0.134	0.033	0.069
	Standard Deviation	0.086	0.212	0.076	0.094	0.038	0.047
Overall Average	Maximum Value (mm)	0.1941	0.1891	0.2681	0.2439	0.1935	0.1812
	Minimum Value (mm)	0.0000	0.0000	0.0011	0.0011	0.0017	0.0037
	Average Value (mm)	0.0621	0.0703	0.1167	0.0955	0.0727	0.0951

* Kofu South → Abbr. for Sixth Bridge of the Kofu South Interchange
** Hino Interchange → Abbr. for the Second Hino Interchange Bridge

5. CONSIDERATIONS

(1) Regarding the Relationship between Visible and Hidden Deterioration

The relationship between the corrosion occurring on the paint film surface, referred to as "visible deterioration", and that occurring beneath the paint film on the steel surface, referred to as "hidden deterioration", is described below.

The average visible deterioration and hidden deterioration of the samples, from the results of the image processing measurements indicated in **Table 3**, are shown in **Fig. 6**.

From these results, with the exception of the sixth ramp bridge of the Kofu South Interchange, and the second bridge of the Hino Interchange, it can be seen that the number of occurrences of hidden deterioration are higher. This implies the fact that, on these bridges that have been in service for over ten years or so, there is not only the visible corrosion that can be seen on the paint film surface, but also considerable corrosion existing beneath the paint film. However, comparison of the percentage of surface area covered by corrosion shows less difference than the number of occurrences. From the average values shown in **Fig. 7**, it can be seen that the corrosion area in the case of visible deterioration is either greater than or the same as that of the hidden deterioration.

In other words, this result means that the grain size of the hidden corrosion is smaller than the grain size of the corrosion of the visible deterioration that can be seen on the paint film surface. As this small grain size corrosion beneath the paint film surface will, under the satisfied conditions, emerge on the paint film surface, it is necessary to carefully observe the hidden deterioration (under-film corrosion) for the diagnosis of paint film deterioration.

Hidden deterioration was considerable in Shizakai Viaduct, where traffic is heavy, and the two bridges located in coastal regions. The extent of the deterioration in these high corrosion environments indicates the strong need for paint film management in these regions.

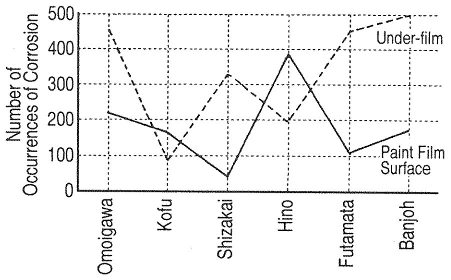


Fig. 6 Average Number of Occurrences of Corrosion for each Bridge

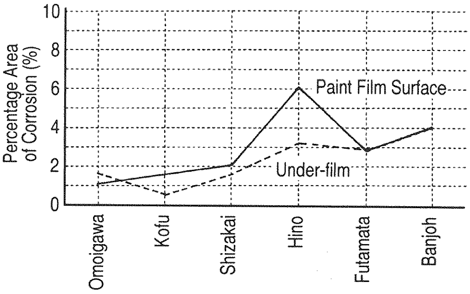


Fig. 7 Average Percentage Area of Corrosion for each Bridge

(2) Investigation of the Correlation between Visible and Hidden Deterioration

A simple regression analysis[16), 17)] was performed based on the measured values shown in **Table 3** to determine the correlation between visible and hidden deterioration.

Equation (1) was assumed for the model for the simple regression, and the parameters α and β were determined by the least squares method.

$$Y_i=\alpha+\beta X_i+u_i, \qquad i=1,2\cdots n \tag{1}$$
$$H_0:\beta=0, \qquad H_1:\beta>0$$

The values of α and β determined by the least squares method were a and b. In this equation, Y represents the corrosion hidden below the paint film (number of occurrences of corrosion and percentage of area covered), and X represents the visible deterioration on the paint film surface (number of occurrences of corrosion and percentage of area covered).

From Equation (1) it can be seen that the only factor having any real decisive influence on Y is X. Although there are many other factors besides X that have influence, rather than a systematic influence, they may be considered to represent chance variations (error terms) and are represented collectively by the term u.

The parameters a and b were obtained as follows:

$$S^2x=\Sigma(X_i-\overline{X})^2=\Sigma X^2-n\overline{X}^2 \tag{2}$$
$$S^2y=\Sigma(Y_i-\overline{Y})^2=\Sigma Y^2-n\overline{Y}^2 \tag{3}$$
$$S_{XY}=\Sigma(X_i-\overline{X})(Y_i-\overline{Y})=\Sigma_{XY}-n\overline{X}\overline{Y} \tag{4}$$
$$\therefore b=S_{XY}/S^2x, \quad a=\overline{Y}-b\overline{X} \tag{5}$$

From the above, the regression curve is given by:

$$\hat{Y}i=a+bX_i,\ i=1,2\cdots n \tag{6}$$

The coefficient of determination R^2 was found as the degree of representation of this parameter:

$R^2=S^2\hat{Y}/S^2Y$ therefore, the coefficient of correlation $r=\sqrt{R}^2$

In other words, when $R^2=1$, $S^2\hat{Y}=S^2Y$ and $\Sigma e^2i=0$.

$$\Sigma e^2i=e^2{}_1+e^2{}_2\ldots e^2{}_n=0$$

This is limited to the case where all of the values of e_i are zero, i.e., $e_1=e_2\ldots e_n=0$.

Therefore, from the relationship $Y_i=\hat{Y}_i+e_i$, $\hat{Y}_1=Y_1,\ \hat{Y}_2=Y_2\cdots\ \hat{Y}_n=Y_n$

Table 6 Results of Simple Regression Analysis for Visible and Hidden Deterioration

Environment / Bridge (Statistical Value)		Number of Occurrences of Visible and Hidden Deterioration: Regression Formula	Coefficient of Determination R^2	Coefficient of Correlation r	Number of Occurrences of Visible Deterioration and Area of Hidden Deterioration: Regression Formula	Coefficient of Determination R^2	Coefficient of Correlation r	Areas of Visible and Hidden Deterioration: Regression Formula	Coefficient of Determination R^2	Coefficient of Correlation r
Rural	Omoigawa Bridge	Y=300.7 +0.704 X	0.735	0.857 ✻	Y=0.921 +0.003 X	0.697	0.834 ✻	Y=1.087 +0.475 X	0.690	0.831 ✻
Rural	Kofu South Interchange Bridge	Y=78.37 +0.035 X	0.023	0.153	Y=0.425 +0.0004 X	0.047	0.218	Y=0.414 +0.038 X	0.155	0.394
Urban	Shizakai Viaduct	Y=224.2 +2.513 X	0.503	0.709 ✻	Y=0.868 +0.018 X	0.543	0.737 ✻	Y=0.206 +0.187 X	0.180	0.425
Urban	Hino Interchange Bridge	Y=87.77 +0.280 X	0.308	0.555 ✻	Y=0.632 +0.007 X	0.101	0.319	Y=4.09 –0.14 X	–0.017	–0.13
Coastal	Futamata Viaduct	Y=240.6 +1.905 X	0.821	0.906 ✻✻	Y=0.399 +0.039 X	0.880	0.938 ✻✻	Y=0.022 +1.656 X	0.916	0.957 ✻✻
Coastal	Banjoh Bridge	Y=410.6 +0.580 X	0.195	0.442	Y=1.334 +0.015 X	0.619	0.787 ✻	Y=1.422 +0.640 X	0.694	0.833 ✻

(Note) Where there is no value indicated for the coefficient of correlation r, there is no correlation. Cases where there is a coefficient of correlation of 0.5 or more, are marked with ✻. Cases where there is a strong coefficient of correlation of 0.9 or more, are marked with ✻✻.
The areas of visible and hidden deterioration are indicated as %.

This means that the variations of Y can be completely represented in the simple regression model. On the other hand, when R^2=0, this indicates that X is not a statistical factor of Y. In other words, the size of R^2 or r can be seen as a measure of the degree of representation of the regression model..

In **Table 6** is shown the correlation of the visible and hidden deterioration and the results obtained as the following procedure, using a computer for the regression analysis based on the measured values of **Table 3**.

As can be seen from this result, the items investigated by the regression analysis were as follows:

1) The relationship between the number of occurrences of corrosion for the visible and hidden deterioration.
2) The relationship between the number of occurrences of visible corrosion and the percentage of area covered by the hidden deterioration.
3) The relationship between the percentage of area covered by the visible deterioration and the area covered by the hidden deterioration.

In other words, in order to predict the under-film corrosion, in this research, whether to use the number of corrosion occurrences as a parameter or to use the percentage of area covered by corrosion as a parameter, was examined.

From **Table 6**, regarding the relationship to the number of occurrences of corrosion, except for the cases of the Kofu South Interchange Ramp 6 Bridge and the Banjoh Bridge, there are a correlation between the surface of paint film and the back side of paint film. In particular, in the Omoigawa Bridge and the Futamata Viaduct, a correlation coefficient of 0.9 was obtained which is a fairly determinative result.

Although these results indicate the fact that the greater the number of occurrences of visible deterioration, the greater the number of occurrences of deterioration below the paint film, as the coefficient X varies considerably between bridges, it can be assumed that the number of occurrences of deterioration below the paint film is largely influenced by the history of the painting work and the environment in which the bridge is located.

With regard to the relationship between the number of occurrences of visible corrosion and the percentage of area covered by hidden deterioration, with the exception of the sixth ramp bridge of the Kofu South Interchange and the Hino Interchange Bridge, a correlation could be seen in all cases. In a trial calculation using the regression formula, based on the assumption that 1000 occurrences of corrosion are observed on a section of bridge, the area of hidden deterioration becomes 3~20%. This corresponds to the deterioration rate of over 3% used by JH as the guideline, and therefore can be used as a guide in the recoating of bridges.

The relationship between the percentage of area covered by the visible deterioration and the area covered by the hidden deterioration can be divided into cases where a distinct correlative relationship can be seen, and cases where it cannot be seen. This is an indication of the fact that the type of deterioration depends on the environment, and it is therefore difficult to consider all these cases together. However, in the cases of the Omoigawa Bridge, Futamata Bridge, and Banjoh Bridge, for which a high correlation exists, the area of the corrosion beneath the paint film corresponded to between 0.5 and 1.6 times the area of the visible deterioration. This result implies the necessity to consider the condition of the corrosion beneath the paint film surface when deciding on the time for recoating.

From the above results, when estimating the under-film corrosion using the simple regression formula, either the number of occurrences of corrosion on the paint film, or the percentage of area covered, may be used as parameters. However, if all cases are considered without taking into account the particular environmental conditions, it can be said that estimation of the area of hidden deterioration using the number of occurrences of corrosion on the paint film surface gives results in closest agreement with actual conditions. It was demonstrated, however, that in highly corrosive environments, such as coastal regions, the under-film corrosion can be estimated from the percentage area covered by the visible paint film deterioration.

(3) The Degree of Under-film Corrosion (Corrosion Depth)

A feature of the current research is the measurement of the degree (depth) of under-film corrosion and the study of the relationship between the degree of corrosion and the grain size of the corrosion appearing on the paint film surface.

The reason for this study was the fact that the standard for the evaluation of the paint film deterioration incorporated in the image processing system involves a weighting for the grain size of the surface corrosion. This is based on the idea that the larger the grain size of the corrosion on the paint film surface, the greater the degree of under-film corrosion. In order to corroborate this idea, multiple regression analysis was performed to investigate the relationship between the measured values of corrosion depth mentioned in *4 (2)*, and the results of the percentage of area obtained by image processing for each different grain size, as described in *4 (1)*.

In this analysis, as the factor *X* that represents the under-film corrosion *Y*, is the corrosion grain size, only actually measured grain sizes were chosen as parameters.

- *X*1: Grain size from 0.05~1.0mm (percentage of corrosion area; %)
- *X*2: Grain size from 1.1~3.0mm (percentage of corrosion area; %)
- *X*3: Grain size from 3.1~5.0mm (percentage of corrosion area; %)
- *X*4: Grain size from 5.1~10mm (percentage of corrosion area; %)
- *X*5: Grain size more than 10.1mm (percentage of corrosion area; %)

Taking *Y* as the depth of steel corrosion, the following multiple regression model is assumed:

$$Y_i=\beta_0+\beta_1X_1+\beta_2X_2\cdots\beta_5X_5+u \qquad (7)$$

Assuming that b_0, b_1, b_2, ... b_5 are the values calculated from the unknown parameters β_0, β_1, β_2, ... β_5 by the least squares method, then:

$$b_0=\overline{Y}-b_1\overline{X}_1-b_2\overline{X}_2-b_3\overline{X}_3-b_4\overline{X}_4-b_5\overline{X}_5$$

$$b_1=1/D(S_5^2S_{1y}-S_{1,2}\cdots{}_5S_{5y})$$

$$b_2=1/D(S_4^2S_{2y}-S_{1,2}\cdots{}_5S_{4y})$$

$$b_3=1/D(S_3^2S_{3y}-S_{1,2}\cdots{}_5S_{3y})$$

$$b_4=1/D(S_2^2S_{4y}-S_{1,2}\cdots{}_5S_{2y})$$

$$b_5=1/D(S_1^2S_{5y}-S_{1,2}\cdots{}_5S_{1y})$$

where,

$$S_1{}^2=\sum_{i=1}^{n}(X_{1i}-\overline{X}_1)^2=\Sigma X_1{}^2-n\overline{X}^2{}_1$$

$$S_2{}^2=\sum_{i=1}^{n}(X_{2i}-\overline{X}_2)^2=\Sigma X_2{}^2-n\overline{X}^2{}_2$$

$$\vdots$$

$$S_5{}^2=\sum_{i=1}^{n}(X_{5i}-\overline{X}_5)^2=\Sigma X_5{}^2-n\overline{X}^2{}_5$$

$$S_{1,2\cdots5}=\sum_{i=1}^{n}(X_{1i}-\overline{X}_1)(X_{2i}-\overline{X}_2)(X_{3i}-\overline{X}_3)$$
$$(X_{4i}-\overline{X}_4)(X_{5i}-\overline{X}_5)$$
$$=\Sigma X_1X_2X_3X_4X_5-n\overline{X}_1\overline{X}_2\overline{X}_3\overline{X}_4\overline{X}_5$$

$$S_{1y}=\sum_{i=1}^{n}(X_{1i}-\overline{X}_1)(Y_i-\overline{Y})=\Sigma X_1Y-n\overline{X}_1\overline{Y}$$

$$S_{2y}=\sum_{i=1}^{n}(X_{2i}-\overline{X}_2)(Y_i-\overline{Y})=\Sigma X_2Y-n\overline{X}_2\overline{Y}$$

$$\vdots$$

$$S_{5y}=\sum_{i=1}^{n}(X_{5i}-\overline{X}_5)(Y_i-\overline{Y})=\Sigma X_5Y-n\overline{X}_5\overline{Y}$$

$$D=S_1^2S_2^2\cdots S_5{}^2-S_1{}^2{}_{,2\cdots5}$$

All the above were calculated by a computer. The multiple regression formula obtained by the calculation is shown in **Table 7**.

Following this result, in the case of the Omoigawa Bridge for example, from the fact that the coefficients X_2 and X_3 that give rise to large values of rust diameter are both negative imaginary numbers, this percentage of area can be considered

Table 7 Results of Multiple Regression Analysis Between Under-film Corrosion (Corrosion Depth) and Percentage Areas of Deterioration for each Grain Size

Environment • Bridge		Multiple Regression Formula	R^2	Coefficient of Correlation (R)
Rural	Omoigawa Bridge	$Y=0.0672+0.046X_1-0.047X_2-0.152X_3$	0.53 ✻	0.73 ✻
	Kofu South Interchange Bridge	$Y=0.025+0.082X_1+0.044X_2-0.122X_3+0.022X_4$	0.90 ✻✻	0.95 ✻
Urban	Shizakai Viaduct	$Y=0.072+0.11X_1-0.073X_2+0.157X_3-0.007X_4-0.008X_5$	0.61 ✻	0.79 ✻
	Hino Interchange Bridge	$Y=0.071+0.009X_1-0.007X_2+0.065X_3+0.001X_4-0.002X_5$	0.72 ✻	0.85 ✻✻
Coastal	Futamata Viaduct	$Y=0.087-0.009X_1-0.009X_2+0.017X_3-0.01X_4$	0.15	0.39
	Banjoh Bridge	$Y=0.077-0.013X_1+0.064X_2-0.14X_3+0.07X_4+0.003X_5$	0.55 ✻	0.74 ✻

(Note) The ✻ symbol indicates correlation, and the symbol ✻✻ indicates strong correlation.

as discoloration due to the spread of fluid corrosion products rather than actual corrosion, and can be discarded. Therefore, the actual grain size which influences Y is restricted to the extremely small point corrosion X_1 of grain size 0.05~1.0mm.

Furthermore, as the value of the coefficient β_1 is only 0.046, the degree of corrosion is only of the order of 0.5mm, which is quite small, even if the percentage of corrosion area on the paint film surface is 10%. Therefore, if recoating of the paint film is carried out at this time, the recoating will be achieved at a time when corrosion of the steel can still be considered negligible. This reasoning is based on a value of R^2=0.53 (R=0.73) which, while being a little weak, is considered to provide a reliable representation.

In the case of the sixth ramp bridge of the Kofu South Interchange, which has the highest coefficient of correlation (R=0.95), only for the corrosion grain size of 0.3~5.0mm, β_3 is given a minus coefficient. In the case of the other grain sizes, while being small, all values are real numbers, indicating that the corrosion can be predicted for the various grain sizes.

If the bridges in the urban and coastal areas where paint film deterioration was more pronounced are considered; firstly, in the case of the urban area, i.e., the second Hino Interchange Bridge and the Shizakai Bridge, as R=0.80 or more, the multiple regression formula for both cases is seen to be significant.

However, in both cases, the values of β_2 and β_5 are minus, and in the case of Shizakai Viaduct, β_4 is also minus. Minus coefficients were discarded for the same reasons as in the case of the Omoigawa Bridge. If β_1 and β_3 are compared for both bridges, the coefficient for the Shizakai Viaduct is found to be an order of magnitude greater than that of the second Hino Interchange Bridge. Although this result is natural when considering the larger average values for the Shizakai Viaduct in **Table 5** and **Fig. 5**, this can also be seen to indicate the fact that the degree (depth) of under-film corrosion has greater correspondence to the corrosion grain size in the Shizakai Viaduct.

On the other hand, in the case of the second Hino Interchange Bridge, despite the fact that large values for localized corrosion can be seen in **Table 5** in the same way as for Shizakai Bridge, the average value becomes small as the number of cases of deep corrosion is small (there is localized bias).

Considering the Futamata and Banjoh Bridges that are located in coastal regions; in the case of the Futaba Bridge, the multiple correlation factor for the percentage of area and the degree of under-film corrosion (corrosion depth) yielded the small values of R^2=0.15, R=0.39. On the other hand, in the case of the Banjoh Bridge, although weak, multiple correlation can be seen (R^2=0.55, R=0.74).

However, in the multiple regression formula for the Banjoh Bridge, the coefficient for the small range of corrosion grain size between 0.05~1.0mm, and for the relatively large group of point corrosion is minus, and over 10mm, the rather small coefficient of 0.003 for the area percentage can be observed. This is because there are only two values above 10mm within the values i_1~i_{10} in the Banjoh Bridge. To summarize, the degree of corrosion at the Banjoh Bridge is statistically related to the area percentage of corrosion size within 1~3mm, and the way that the small grain size of corrosion influences the degree of corrosion under the paint film at the Banjoh Bridge is different from that of the Omoigawa Bridge which is located in a rural region and is greatly influenced by the small grain size.

In other words, it is evident that the relationship between the paint film deterioration and the corrosion of the bridge steel varies according to environment, and it is therefore difficult to deal with bridges of all environments collectively.

6. CONCLUSIONS

The research described in this paper was carried out in order to provide a means of determining the correct time for recoating the paint film on steel bridges. The method involves using an image processing system to evaluate the paint film deterioration from image data obtained by filming the paint film. The system provides an objective evaluation by comparison with a predetermined evaluation standard to remove the subjectivity that inevitably occurs when the evaluation is carried out by conventional observation.

Firstly, the most suitable way of evaluating the deterioration was studied. This study involved measuring the grain size of corrosion and the number of occurrences and the area occupied by the corrosion on the paint film surface and studying the relationship between these factors and the degree of under-film corrosion of the steel members (depth of corrosion). Data was obtained for bridges located in six regions having different environmental conditions and analyzed using statistical methods. The following conclusions can be drawn as a result of these investigations:

i) Using the image processing system developed for this research, it was possible to determine the number of occurrences and grain size of corrosion quantitatively and with accuracy.

ii) As a result of performing both simple and multiple regression analyses on the various items of data obtained in i), it was found that, although there were some differences due to environment, there was a correlation between the condition of the paint surface and the degree of under-film corrosion (depth of corrosion). Using a regression formula with a large coefficient of correlation, and from the fact that it is possible to estimate the degree of under-surface corrosion from the number of occurrences and percentage of area occupied by the deterioration on the paint film surface, it was found that an effective determination of the time for recoating could be achieved if the recoating was planned to be carried out while the depth of steel corrosion was minimal.

iii) The standard for the evaluation of deterioration incorporated in the image processing system shown in **Table 4** including weighting for the grain size and surface area occupied by the corrosion was proposed. The applicability of this concept was corroborated by the results of the multiple regression analysis.

iv) Differences in the form of under-film corrosion occurring in each environments was verified. In corrosive environments, considerable deep pitting corrosion was found to have occurred, while in the less severe rural environments, the grain size and depth of the corrosion were found to be relatively small.

v) It was verified that the recoating of the deteriorated paint film should be planned while the under-surface corrosion is only light and a regression formula was proposed for predicting the degree of under-surface corrosion. The reliability of this formula will be increased with the accumulation of actual measured data, so it is planned to systematically add to the database while improving the image processing system.

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