QUANTITATIVE ANALYSIS ON DETERIORATION AND REMAINING LIFE OF STEEL BRIDGE PAINTING BASED ON FIELD DATA

Hiroshi FUJIWARA¹ and Masaru MIYAKE²

¹ Tokorozawa Operation Office, Tokyo Operation Bureau, Japan Highway Public Corporation
(761-1, Sakanoshita, Tokorozawa-shi, Saitama, 359-0012, Japan)

² Second Construction Division, Hokkaido Regional Bureau, Japan Highway Public Corporation
(5-12-30, Ohyachi-Nishi, Atsubetsu-Ward, Sapporo, 004-8512, Japan)

With the results of field investigations and outdoor exposure experiments of painted specimens, time-lapse deterioration of paintings was statistically analyzed by using "Automatic Evaluation System for Paint Film Deterioration" in order to establish deterioration curves logically. Quadratic curves were found to be well fitted to the paint film deterioration within the practical period of 10 to 20 years. Estimation curves were established for three corrosive environments such as mild environment, seashore environment, and tropical environment (hot and highly humid).

Key Words : *steel bridge, paint film deterioration ratio, image processing system, estimating remaining life, deterioration model, corrosion depth*

1. INTRODUCTION

Although paintings are widely used for corrosion protection of steel bridges, periodical repainting is required throughout bridge's lifespan to maintain its performance. The painting area of the steel bridge in our country is about 40,000,000 sq. m and about 3,000,000 sq. m is repainted among these every year.¹⁾ The steel bridge repainting is repeated in about 10 years in a mild environment on the average.²⁾ Moreover, the repainting area and the repainting cost keep increasing every year because steel bridge asset increases.¹⁾

The remaining life estimation of the paint film is important to execute repainting of the steel bridge efficiently. Though visual observation is mainly applied for current inspection of steel bridge paintings, quantitative evaluation on paint film deterioration is quite difficult due to individual errors occurred from each inspector. A quantitative evaluation of the paint film deterioration by a

scientific technique is necessary and indispensable to improve the accuracy of the longevity forecast. Therefore, "Paint film deterioration degree diagnosis system" was developed, which evaluates the degree of paint film deterioration quantitatively by photos with applying the image processing technology.³⁾

Feasibility studies have been conducted by using "Paint film deterioration degree diagnosis system". Results of field investigations for 624 steel bridges and results of exposure tests for painted specimens at Tokyo, Hokuriku, and Okinawa have been analyzed by the diagnosis system. Paint film deteriorations were quantitatively analyzed and closely resembled to logistic curves on several corrosive environments, and finally, remaining life of paint film on each steel bridges is estimated.

2. DETERIORATION TENDENCY OF STEEL BRIDGE PAINT FILM BY THE FIELD INVESTIGATION DATA

(1) Field investigation

Seven environments (the Rural, the ravine, mountains, the residential quarter, the intersection

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Table 1 Details of investigated bridge

Expressway	Number of investigated bridge	Main environment at Bridge location					Bridge type					Coating System			Number of investigated data					
		Country, Residential quarter	Mountains, Ravine	Sea and Coast	River, Lakes and Marshes	Urban , Road, Railroad	Factory	Plate girder	Box girder	Truss	Plate girder + Box girder	Plate girder + Truss	A	B	C	Number of investigation span	Evaluation by Aismel oqsaarajou (km)	Tape flakingoff test (point)	Cross cut tape test (point)	Analysis of the test (point)
Douo	65	28	5	24		8		50	8	1	5	1	41	24		5	10.803	1178	120	6
Sapporo	9		4	2		3		8				1	8	1		1	1.784	77	76	3
Tohoku	62	25	17		19	1		51	10		1		55	7		3	8.001	484	132	6
Jouban	14	5	2		7			14					9	5		1	3.898	388	40	2
Tomei	59	16	17	1	20	5		59					56	1	2	4	7.979	1859	431	21
Higashi Kanto	9	6			2	1		7	1		1		9			1	2.922	322	52	2
Chuo	80	24	18		24	14		72	3		5		78	2	7	7	11.539	1490	210	10
Kanetu	7	2			4	1		6	1				4	3			1.612	146		
Hokuriku	48	18	1		28	1		45	3				41	6	1	3	8.158	751	176	8
Meishin	18	5			9	4		13	4		1		15		3		1.790	272	56	2
Higashi Maihan	8	4			4			8					8				1.381	348	64	1
Ise	3	3						3					3				0.221	48	24	1
Tokai-Hokuriku	4	1			3			2	2				4				0.342	56	40	2
Kinki	5						5	5							5		0.353	64	24	1
Nishi Meihan	6	4				2		6					6				0.297	48	8	4
Hanwa	2	1	1					1	1				2				0.158	16		6
Maizuru	2		1		1			2					2				0.279	32		
Chugoku	40	2	9		24	5		39	1				40			2	4.727	500	116	58
Sanyo	18	2	4		9	3		17	1				18				2.151	208	88	42
Santo Kurashik	1					1		1					1				0.036	4	4	2
Hiroshima	3				3			3					3				0.511	48	12	6
Kyusyu	17	4	2		11			16	1				17				1.332	160	24	12
Miyazaki	8	2	1		5			6	2				8				0.832	84	26	18
Nagasaki	7	3	2	1	1			6	1				6	1			0.729	64	24	12
Okinawa	2		2						2					2			0.350	44	12	6
Keiyo	6					6		6					4	2		1	2.724	344	32	16
Chiba Togane	2	1				1		2					2				0.424	52		
Nikkou Utsunomiya	2		2					1	1				2				0.258	28	8	4
Shin Tone	2	1			1				1		1		2				1.103	68		
Kainan Yuasa	2				2			1	1				2				0.178	20	8	4
Keiji	2		1		1			1	1				2				0.486	36		
Oinosaka Kameoka	1	1						1					1				0.116	12		
Daini Shinmei	3	1	1			1		3					3				0.261	32	4	2
Himeji	1					1		1					1				0.085	12		
Taishi Tathuno	1	1							1				1				0.095	12		
Hiroshima Kure	1			1					1					1			1.015	44		
Kanmon	13	1	2	2		7	1	13					9	4		1	2.398	399	39	20
Daisan Keihin	14					14		12	1		1		13	1	1	1	2.880	316	312	157
Yokahama Shindo	11					11		6	2		3		8	3			1.422	24	24	12
Yokohama Yokosuka	21	12	6			3		18	2		1		21			1	3.512	104	56	28
Odawara Athugi	19	12	7					18			1		19			2	3.014	426	57	25
Seishou	8	1		6		1		4	2		2			8		1	2.343	223	209	110
Manazuru	1		1					1					1				0.020			
Fujimiya	1	1						1					1				0.031	4	4	2
Nishi Fuji	1	1						1					1				0.089			
Fujieda	4	4						4					4				0.489	11		
Kakegawa	2	2						2					2				0.066			
Iwata	9	9						9					9				0.252			
Total	624	203	104	39	178	94	6	545	54	1	22	2	542	61	21	49	95.446	10858	2512	1248

(※) A coating syst :lead tictorrosive paint / kyd resin paint , B coating system:lead anticorrosive paint / chlorinated rubber paint , C coating system :zinc rich aint / chlorinated rubber paint

Table 2 Investigation location, investigation item, and investigation frequency

Bridge form	Investigation location and investigation frequency	○ : Enforcement of the investigated		
		Exvaluation by visual observation	Adhesion test (※)	Analysis of Paint film adhesion material
Plate girder	Web plate	Outside of outside girder	○	○
		Inside of outside girder, Inside girder (Edge : 2 point, Center : 1 point)		
	Flange plate	Lower side of lower flange	○	○
		Lower side of upper flange (Edge : 2 point, Center : 1 point)		
	Stringer (Plate)	Edge : 2 point, Center : 1 point	○	
Box girder	Cross-frame, Lateral	Supporting point : 1point, Center : 1 point	○	
	Web plate, Lower flange plate	Edge : 2 point, Center : 1 point	○	○
	Inside in box girder bridge	Upper side of lower flange : 2 point	○	
		Web plate : 1 point		
	Stringer, Cross beam, Bracket	Edge : 2 point, Center : 1 point	○	

(※) The adhesion test means the tape flaking off test and cross-cut tape test.

road, Public road adjacent, the river, lakes and marshes, the factory, and the sea and coast) were specified to cover all environments of steel bridge locations and 624 bridges from Hokkaido to Okinawa were selected as shown in **Table 1**.

Three investigations were conducted, such as visual observations, adhesion examinations, and analyze of the paint film adhesion material by using "Steel bridge paint film investigation indicator" of "JH maintenance standard" ⁴⁾ and Japanese Steel Structural Societies.⁵⁾ Because the content of these investigation results was huge, the visual observation results are mainly analyzed in this paper. The investigation was conducted by the inspectors belonged to 93 Operation Offices of JH (Japan Highway). Afterward, other engineers, specialized in investigating painting by using the diagnosis system, took pictures and analyzed the pictures by the diagnosis system in order to cancel the individual errors occurred from inspectors' individual subjectivities and different experiences. The investigation location, the investigation item, and the investigation frequency are shown in **Table 2**.

Deterioration degrees are determined by chart 3 to chart 6 indicated below following 4 deterioration phenomenon; total area of the rust, peeling off, crack, chalking. Definition of each deterioration phenomena and meaning of evaluation rate are described as follows ⁶⁾ :

① Evaluation rate of rust

Because the rust seen on the surface of the paint film means the steel material corrodes under the paint film, this phenomena means crucial and fatal defect. JH judges repainting time of steel bridges when rust area reaches about 3%.

Table 3 Evaluation Grades for rust ⁴⁾

Points	State of paint film
40	Rust is seen in 3% or more of the investigation area.
30	Rust is seen from 1 to less than 3% of the investigation area.
20	Rust is seen from 0.3 to less than 1% of the investigation area.
10	Rust is seen from 0.1 to less than 0.3% of the investigation area.
0	Abnormality is not seen in the paint film.

Table 4 Evaluation Grades for peeling off ⁴⁾

Points	State of paint film
30	Peeling off is seen in 33% or more of the investigation area.
24	Peeling off is seen from 16 to less than 33% of the investigation area.
18	Peeling off is seen from 10 to less than 16% of the investigation area.
12	Peeling off is seen from 3 to less than 10% of the investigation area.
6	Peeling off is seen in less than 3% of the investigation area.
0	Abnormality is not seen in the paint film.

Table 5 Evaluation Grades for crack ⁴⁾

Points	State of paint film
10	The crack is remarkable.
5	The crack occurs.
0	Abnormality is not seen in the paint film.

Table 6 Evaluation Grades for chalking ⁴⁾

Points	State of paint film
10	An initial painting color cannot be remarkably presumed like white compared with initial
5	Most is considerably changeless though an initial painting color can be presumed compared with initial as white.
0	Abnormality is not seen in the paint film.

Table 7 Composition of the investigation data according to environment

Environments at bridge location	Total of data		Data breakdown according to coating system					
	Total	Ratio (%)	A	Ratio (%)	B	Ratio (%)	C	Ratio (%)
Rural, Ravine	21930	30.4	19701	31.0	1370	22.6	462	17.6
Residential quarter	7990	11.1	6773	10.7	0	—	0	—
Intersection road	8170	11.3	7358	11.6	87	1.4	22	0.8
Public road adjacent	12069	16.7	11419	18.0	411	6.8	1787	67.9
River	20016	27.8	18182	28.7	815	13.4	0	—
Factory	885	1.2	0	—	0	—	361	13.7
Sea and Coast	1066	1.5	0	—	3378	55.8	0	—
Total	72126	100	63433	100	6061	100	2632	100

Note) Besides, the data of the unmeasurement is 3455.

Therefore, after inspection, all steel bridges maintained by JH are divided into 5 groups described in table 3 and this categorization contributes to determine long-term repainting plan for huge number of steel bridge assets.

② Evaluation rate of peeling off (flaking off)

Peeling off of the paint film means the decrease of paint film thickness or even disappearance of paint film. Moreover, peeling off has huge influence on external appearance of bridges. Thus, peeling off sometimes requires immediate repainting. According to the Repainting Standard of JH, steel bridges are repainted when more than 1/3 (33%) of their external surfaces are found to be peeling off.

③ Evaluation rate of crack

Paint film crack easily deteriorates into flaking off or rust though the crack itself is not a serious defect. Therefore, the crack must not be ignored as paint film defect. The crack of the paint film progresses from surface crack to deep one, and deep crack usually accompanies peeling off and rust. Therefore, surface crack is counted as beginning of other deterioration phenomenon.

④ Evaluation rate of chalking

Top coating of paint film has an important role on resisting atmospheric materials of penetrating into under coating. However, chalking of top coating reduces its chemical performance as a steel coating. As a result, moisture such as rain water and acid stuffs such as SO_x and NO_x infiltrate the paint film easily and accelerate the paint film on deteriorating. Therefore, the paint film chalking is also evaluated.

(2) Investigation data

There are 542 bridges applying “A coating system” by which a mild corrosion environment is targeted and this accounts for 86.9% in 624 bridges of the total of the investigation bridge ac-

Fig. 1 Average Evaluation points according to the environment until 14 years.

Fig. 2 Average Evaluation points according to environment (all period)

cording to **Table 1**. Moreover, B coating system for factory zones and seashores is applied by 61 bridges (9.8%) and C coating system exists by 21 bridges (3.3%). These numbers are listed in **Table 7**.

As for the numbers of field investigation data, number of data inspecting “A coating system bridge” accounts for 63433, which becomes 87.9% of whole inspection data (72126) as shown in **Table 7**. 8693 (12.1%) of the remainder are the inspection for B or C coating system. The compo-

sition of this coating system is almost corresponding to current composition ⁷⁾ of the steel bridge painting in Japan based on the research by Public Works Research Institute, Ministry of Public Works, Japan. In this paper, analyses are carried out mainly by the majority inspection data from A Coating System bridges. 63433 A coating system data shown in **Table 7** is evaluated by four evaluation rates shown in **Table 3** to **Table 6** respectively and average rate and time from repainting was obtained in **Fig. 1**. The curve was an approximation one obtained by the following equation.

$$Y = a_2 X^2 + a_1 X \quad (1)$$

The approximation curve indicates the increasing rate of deterioration with respect to time from repainting throughout all environment. Correlation coefficient of **Fig. 1** is computed as 0.962, which is considered to be very high because this data include all environments. However, evaluation results seem to disperse when inspection interval after repainting becomes long, especially after 15 years as shown in **Fig. 2**. Therefore, in this paper, inspection data up to the evaluation rate of 20 points (**Fig. 1**) and the data of the year up to 14 years are dealt.

(3) Relationship between Paint film deterioration and repainting time

According to the investigation of repainting cycles for steel girder bridges, first repainting for newly constructed bridge is executed about 10 years after construction for all environments as shown in **Fig. 3**. Girder type steel bridge is the majority type of rating 87.3% in all types of steel bridges. According to the report published by Japan Railway Corporation ⁸⁾ inspecting about 100 railway steel bridges, the repainting cycles of the paint film corresponding to A coating system of JH are about 10 years on the average.

In comparison with highway steel bridge and railway steel bridge, deteriorating process and characteristics are quite different even at the same corrosive environment due to their structural differences. Because highway steel bridges generally apply upper-deck type structure, steel members are covered by deck slabs. Therefore, ultraviolet rays are intercepted by deck, and internal girders are seldom affected by rain and snow falling from the air. Oppositely, a lot of pollution things such as dusts and salt adhere to the surface of inside girders because permeability worsens, and dewdrops are hard to evaporate. On the other hand, most of the railway steel bridges apply open floor type

Enviroments at bridge location	Data Number				
	1st	2nd	3rd	4th	Total
Rural, Ravine	114	25	2	1	142
Residential quarter	43	19	4	—	66
Intersection road	53	10	—	—	63
Public road adjacent	36	6	—	—	42
River	124	33	5	1	163
Total	370	93	11	2	476

Fig. 3 Average repainting period in terms of environment

Table 8 Correlation between each evaluation points

	Three det- eriation	Rust	Peeling	Crack	Chalking
For det- eriation	0.997	0.991	0.928	0.367 (0.866)	0.953
Three det- eriation	—	0.993	0.938	0.354 (0.886)	0.926
Rust	—	—	0.894	0.288 (0.858)	0.926
Peeling	—	—	—	0.370 (0.864)	0.837
Crack	—	—	—	—	0.397 (0.735)

Note) The total evaluation point of rust, peeling off, the crack, and the chalking is called four deterioration phenomenon. In ( ) is a correlation coefficient by the data until year 10.

structure. Because of their porous and breathable structure, deterioration process and characteristics of railway steel bridges are quite different from those of highway steel bridges.

In spite of characteristic differences mentioned above, repainting cycles of highway steel bridges and railway steel bridges coincide around 10 years. Thus, atmospheric environment is thought to influence much more on repainting cycles than structural difference.

Moreover, repainting cycles of all environments

tend to become shorter when the number of repainting increases as shown in **Fig. 3**. Defect of quality control concerning the foundation cleaning when repainting is found as a main cause of reducing repainting cycles according to our other study. Perfect extraction of deterioration area when inspection is impossible due to technical difficulties and inspection expenses. Certain rate of deteriorated paint film remains under the repainted coating. Thus, remaining pollutants and adhesive shortage accelerate the deterioration process.

(4) Correlation coefficient between evaluation rates of four deterioration phenomenon

The correlation coefficient between each paint film deterioration phenomena was shown in **Table 8**. Correlation between four deterioration phenomenon is found to be relatively high, and thus, each deterioration is found to influence each other closely as a result.

In this paper, “Paint film deterioration diagnostic system” is used to identify the deterioration degree of paint film as described in Chapter 1. This system can compute the area of three deterioration phenomenon such as rust, peeling off, and crack. As for the visual inspection, deterioration of the paint film is evaluated by four deteriorations (rust, peeling off, crack, and chalking) as described in Chapter 2.(1). However, the distinction between the chalking and the paint film deterioration is difficult in the image processing system. Therefore, the degree of paint film deterioration is evaluated by using three deterioration phenomenon (rusts, peels off, and crack) to exclude the chalking in “Paint film deterioration diagnostic system”.

The correlation coefficient between the evaluation rate sum of four deteriorations and that of three deteriorations is $r=0.997$ which is comparatively high as indicated in **Table 8**. Therefore, the inspection with the sum of three deteriorations evaluation rates was found to be valid.

(5) Characteristic of paint film deterioration with respect to bridge types and locations

From **Fig. 4** to **Fig. 7**, the relation between average evaluation point by three deterioration phenomenon and bridge age are plotted with respect to bridge types and locations.

From **Fig. 4** and **Fig. 5**, a comparatively good correlation is found between the paint film deterioration and bridge age at the web member and at the bottom flange of the plate girder bridge. However, a remarkable disperse is found in the river environment.

This reason is not clarified completely, but following reasons are thought. The snow accumulated on the bridge is occasionally removed by simply pushed down to the river or by carried to thrown away with dump truck. Pushing down is the common removal method because of its efficiency and economy. Dump truck sometimes applied when water of the river is utilized for drink. Accumulated snow usually contains a lot of salt included in snow-melting agent, and this salt adheres to the girders and promotes paint film deterioration. Thus, the difference of snow removal methods influences on paint film deterioration.

Moreover, the bridge on the river tends to receive influence of moisture compared with other environments. The alkyd resin coating used for A coating system is soft and easily dissolved up by moisture. Therefore, the paint films swell by sucking dews. The paint films of bottom flange members are affected much more by dews than those of web members. However, even for the paint films of same lower flange members, influences are slightly different depending on heights from rivers and width of rivers. Thus, deterioration rate varies even at paint film of same lower flanges and tends to disperse.

Fig. 6 and **Fig. 7** shows the relation between the paint film deterioration and bridge age at web members and bottom flange members of box girder bridges. As for the data of the rural environment and the intersection road and the public road adjacent environment, weak correlation is found. However, correlation cannot be found for river environment due to remarkable disperse. The cause of this disperse is thought to be induced by influence of the salt and dews as described in the example of plate girder bridges. The characteristics of deterioration for both bridge types might be obtained by evaluating the paint film deterioration as each bridge unit because the area ratio of web and bottom flange is structurally different for plate girder bridge and box girder bridge. However, further data accumulation is necessary because the data of the box girder bridge is about 10% compared with the data of plate girder bridge.

Plate girder bridges consist of webs, flanges, cross-frames and laterals. Moreover, these members are set up horizontally, vertically, diagonally and inclined. **Fig. 8** shows the relationship between members of plate girder bridges and their repainting cycles with respect to surrounding environments. According to this figure, horizontal mem-

Fig. 4 Relationships between paint film deterioration and passing year (Plate girder bridge — Web plate)

Fig. 5 Relationships between paint film deterioration and passing year (Plate girder bridge — Lower flange plate)

Fig. 6 Relationships between paint film deterioration and passing year (Box girder bridge — Web plate)

Fig. 7 Relationships between paint film deterioration and passing year (Box girder bridge — Lower flange plate)

bers such as bottom flanges, laterals, and cross-frame deteriorate faster in each environment. On the contrary, the deterioration speed of the vertical members such as web is slow. In these horizontal materials, adhesions tend to accumulate such as chlorine from the sea, the sulfuric acid oxide and nitrogen oxide from automotive exhaust gas etc. Moreover, because the adhesions are located inside girders, rain cannot directly infiltrate and wash them. Moreover, the air located inside of the girders are not well ventilated and adhesion salinity is deliquescent, wet time of paint film surfaces lengthen and deterioration rate are accelerated compared with that of vertical members. Because lower flanges deteriorate quite faster than other members, one paint layer of the bottom flange is recently increased and repainting cycles are intended to be uniform within whole members of plate girder bridges.

(6) Relation between deterioration area and average deterioration grade

Fig. 9 shows the relation between average deterioration grade evaluating three deterioration

Fig. 8 Average repainting period of members (Plate girder bridge)

phenomenon (rust, peels, and cracks) and their deterioration area. Thus, very high correlation is confirmed in this graph. In the same manner, a good correlation is confirmed between average deterior-

ration grade evaluating four deterioration phenomenon (rusts, peels off, cracks, and chalking) and their deterioration area from **Fig. 10**. Though steel bridge paintings are currently inspected by average deterioration grade evaluating four deterioration phenomenon (rusts, peels off, cracks, and chalking), inspection by deterioration area can substitute the former inspection method. Thus, was shown to have practical use that “Paint film deterioration degree diagnostic system” was confirmed to have practical ability to evaluate paint film deterioration by which the paint film deterioration degree is evaluated from total area of three deterioration phenomenon.

3. RELATION BETWEEN EXTERNAL DETERIORATION AREA AND CORROSION DEPTH UNDER PAINT FILM

Repainting the steel bridge paint film is executed by estimating the corrosion size and depth under the paint film (loss of steel cross section) from the external deterioration (deterioration on the paint film surface) on an experimental basis. However, the relation between external deterioration and corrosion under the paint film has not been clarified yet. Therefore, the relation was investigated with inspection data of actual bridges, the possibility to judge the repainting time adequately by estimating the steel corrosion under the paint film by heavy recurrence type was shown in 9).

The outline was described in this chapter and the relation between the external deterioration area rate and the corrosion depth was examined according to the data in 9).

(1) The examined data

a) Investigated bridges

Two bridges were selected from rural, urban, and coastal environment shown in **Table 9**.

b) Extraction of sample

From each bridge, 10 places were selected as samples. As for analysis, four grades established to divide deterioration degree. For each bridge, more than 2 samples were selected for each grade.

- ① Very slight deterioration: 1-2 point rust of about 1-2mm ϕ exists within every 100 $\times$ 100mm
- ② Medium deterioration: 1-3 point rusts of more than 1-2mm ϕ exist in above-mentioned ① condition

Fig. 9 Relationship between Average deterioration grade evaluating three deterioration phenomenon (rust, peels, and cracks) and their deterioration area

Fig. 10 Relationship between Average deterioration grade evaluating four deterioration phenomenon (rust, peels, cracks, and chalking) and their deterioration area

Table 9 Characteristics of investigated bridges

Environment at Bridge location	Express -way	Bridge	Year of completion	Type of paint used
Rural	Tohoku	Omokawa	1985	A
	Chuo	Kofu Minami	1972	A
Urban (H h traffic volum	Daisan Kreihin	Shisakai	1976	A
	Yokohama Yo	Hino I.C.	1979	A
	-kosuka			
Coastal	Higashi Kanto	Futamata	1981	C
Seisho	Seishyo	Manhoh	1985	B

- A) lead anticorrosive paint + alkyd resin paint
 B) zinc-rich primer + chlorinated rubber paints
 C) lead anticorrosive paint + phenolic resin type
 Micaceous Oxide paints + chlorinated rubber paints

- ③ Considerable deterioration: 4-10 point rusts of more than 1-2mm ϕ exist in above-mentioned ① condition
- ④ Severe deterioration: Peeling off exist within above-mentioned ③ condition

c) Investigation item and measuring method

The following three items of the extracted sample location on each bridge were measured.

- ① Measurement of paint film deterioration degree: Take a picture of the deterioration of the paint film and evaluate by “Paint film deterioration degree diagnostic system”³⁾.
- ② Measurement of corrosion under paint film: After the stage of ①, paint film is removed. Then, a picture of corrosion under the paint film is taken and evaluated by the system.
- ③ Measurement of corrosion depth under paint film: After the ② stage, Silicon Resin is poured on steel surface and removed. Then, plaster is poured on the convex surface of Silicon Resin and removed. This plaster is the stuffing of corrosion surface. The corrosion section part of this stuffing is measured with an optical microscope (50 times) and the corrosion depth under the paint film is obtained.

d) Comparison

As for both external deteriorations and steel corrosion under paint film, the number of deteriorations, each size (diameter) of deteriorations, and total area of deteriorations were computed.

(2) Relation between deterioration of being area rate and corrosion depth

Fig. 11 shows the relation between the area of external deteriorations and area of steel corrosion beneath the paint film for 60-sample data. Regardless of bridge environment, the correlation was found to be very high as reported in Ref.9). Thus, corrosion under paint film can be well estimated by measuring external deterioration.

Fig. 12 shows the relation between passing year and the corrosion depth for each selected bridge. According to **Fig. 12**, the relation between passing year and the corrosion depth is not especially recognized and the maximum value of the corrosion depth is 0.25mm. The relation between the corrosion environment and the corrosion depth is not especially found. As for this reason, the corrosion depth of steel bridge was thought not to increase more than some amount regardless of the corrosion environment and passing year when inspection is conducted regularly based on the manual and regular repainting are repeated.

Fig. 13 shows the relation between corrosion depth and external deterioration area. Most of the

Fig. 11 Area rate of external deteriorations and corrossions

9 year : KofuMinami (Rural), Manjoh (Coastal)
 13 year : Futamata (Coastal)
 15 year : Omokawa (Rural), Hino I.C. (Urban)
 29 year : Shisakai (Urban)

Fig. 12 Corrosion depth and time from construction

Fig. 13 Relation between corrosion depth and externals deterioration area rate

plotted data is located within the range of 0.2mm of corrosion depth and 3% of deterioration area. Therefore, when repainting is conducted regularly within less than 3% of external deterioration area, corrosion depth is thought to reaches as much as about 0.20mm.

Table 10 Outline of the examined data

Kind of data	Outdoor exposure test and Date number	Environment at the Bridge location	Exposure period (Years)	Measurement method Area rate of deterioration
Inspection	624Bridge (63433 date)	Mild	1 ~ 18	visual comparison with SSPC Standard Charts
Painting test panel	Tokyo (Machida) Hokuriku (Oyashirazu) Okinawa (Kyoda) (Each 1 date)	Mild Salinity coming flying High temperature humidity	1 ~ 6	Fixed quantity by using the grayscale morphology method
Specific Inspection	Jobandou expressway 21Bridge (239 date)	Mild	4 ~ 15	

4. LIFE CYCLE ESTIMATION OF PAINT FILM

Energy of ultraviolet rays decomposes paint film and promotes deterioration. Thus, layer of paint film is consumed.¹⁰⁾ Therefore, if the surface fracture velocity of paint film caused by optical oxidation and the diffusion speed of water and oxygen into paint film are obtained, life cycle estimation of paint film could be possible. However, because steel bridge paintings are exposed in the air and wet and dry conditions are repeated irregularly due to rain and dew, deterioration process is quite difficult to be approximated by ideal expression. Therefore, life cycle of paint film is investigated by analyzing actual bridge deterioration statistically. In this chapter, estimation curve of paint film deterioration is assumed from actual inspection data statistically, and practical use of the estimation curve is studied.

(1) The examination data of paint film deterioration curve

Three data were applied to obtain approximation curve such as (a) inspection data of actual bridges, (b) exposure test data by painted steel specimen, and (c) specific investigation data of actual bridges. Outlines of these data are described in **Table 10**.

a) Inspection data of actual bridges

63433 data inspected for steel bridges of A coating system was computed among the whole field inspection data shown in Chapter 2. The deterioration area rate was obtained by inspection experts comparing photos and the standard chart⁶⁾.

b) Exposure test data by painted steel specimen

Painting methods and exposure methods for steel specimens were already reported in another

Table 11 Real bridge for paint film deterioration measurement

No	Bridge	Interchange	Bridge type	Passing year
1	Soka	Soka ~ Misato Nishi	P.G.	9 months, 4
2	Nakathuma	Kita Ibaragi	P.G.	4 months, 8
3	Kanazonogawa	~ Iwaki	B.G.	6 months, 8
4	Satonegawa		P.G.	6 months, 9
5	Hananuki	Hitathi Kita ~ Takahagi	P.G.	9 months, 9
6	Nakagou	Takahagu	P.G.	9 months, 9
7	Okitagara	~ Kita Ibaragi	P.G.	9 months, 9
8	Tajiri	Hitachi Minami	P.G.	10 months, 11
9	Omori Va. (B)	Ota	P.G.	11 months, 11
10	Miyatagawa	~ Hitachi Kita Tuss	P.G.	8 months, 11
11	Edogawa	Misato T.B.	B.G.	12
12	Imajohgawa	~ Nagareyama	P.G.	12
13	Momiyagawa	Hitachi Minami Ota ~ Hitachi Kita	P.G.	12
14	Obagawa	Misato T.B. ~ Nagareyama	P.G.	13
15	Misato	Misato	P.G.	13
16	Misato I.C.	~ Misato T.B.	P.G.	13
17	Omori (A)	Hitachi Minami	P.G.	11 months, 13
18	Omori (B)	Ota ~ Hitachi Kita	P.G.	11 months, 13
19	Kujigawa	Naka ~ Hitachi Minami Ota	P.G.	14
20	Omori Va. (A)	Hitachi Minami Ota ~ Hitachi Kita	P.G.	4 months, 14
21	Nakagawa	Mito ~ Naka	P.G.	15

note) Investigated points are web surface.

P.G. Means Plate Girder, B.G. means Box Girder and T means Truss.

paper¹¹⁾. The data of painted specimens was decided to be handled as that of bottom flange because they were exposed horizontally.

c) Specific investigation data of actual bridges

21 bridges of A-type coating system located in the Joban Expressway were selected. These bridges

shown in **Table 11** have not received repainting from construction. Because investigation of paint film deterioration on the same bridge needs quite long years, bridge investigation data from same environment are considered as that of same bridge.

Though painting methods and exposure conditions are not exactly same even in the same environment, investigation data are considered same for statistical computation.

(2) Examination of paint film deterioration curve

In order to estimate life cycle of paint film, the recurrence type and the growth curve, etc. have been studied ^{12) ~ 15)}. Both of the estimation curves were studied to estimate deterioration from beginning of deterioration until complete deterioration. Complete deterioration means the state that whole of steel surface is covered by corrosion. However, the bridge is actually repainted with the deterioration area rate of about 0.2-5%. Therefore, in order to judge adequate time of repainting for bridge safety and economically, deterioration curve of the deterioration beginning should be clarified specifically. Moreover, in order to obtain deterioration curve until repainting, complex recurrence type and growth line estimation are not necessary which requires a lot of parameters and complex analysis. Therefore, the deterioration curve of the paint film decided to be obtained by using the second curve in this research.

Inspection data shown in **Table 10** was examined its adaptability to be approximated by second curve and verified for each environment and each members. Though second curve cannot represent S-shape curve which gradient is plus at the beginning and then gradient becomes minus, exposure time of 10 to 20 years for repainting is considered short enough to be approximated by second curves.

(3) Remaining Life Estimation Curve for paint film

In order to estimate remaining life of paint film, it must be defined clearly. However, range of remaining life of paint film is difficult to define clearly. Deterioration condition to be repainted is different according to road administrations. Moreover, deterioration condition of painting differs depend on environment and maintenance. Therefore, judgment of repaint has left to painting experts. In this paper, following definitions are assumed considering repainting execution in JH.

① A-Coating System is selected for this study.

(rust resisting paint/oily alkyd resin coating system) A-Coating System is mainly used in a mild environment.

② Total deterioration area of three phenomenon (rusts, peels off, and cracks) are used for estimating life cycle of paint film

③ Life cycle estimation is conducted for each environment

④ Life cycle is estimated based on deterioration estimation curve obtained from actual inspection data

All the paint film deterioration curves obtained by 4.(2) are shown in **Fig. 14**. The deterioration curves can be roughly divided into three (① salinity adhering environment (Hokuriku), ② high temperature humidity environment (Okinawa), and other ③ mild environments) according to **Fig. 14**.

Eight paint film deterioration curves classified as a mild environment (**Fig. 14**) are enlarged in **Fig. 15**. At the deterioration area rate of year 15, a minimum value is about 0.5% in the web (intersection road etc.) and the maximum value is about 7% in the bottom flange (intersection road etc.). However, the deterioration tendency of these eight curves is almost corresponding. Moreover, the deterioration area rate of the bottom flange (all environments) and the painting test panels (Tokyo) is large and the deterioration area rate of the web (all environments) is small.

As described in Chapter 2 (5), this is caused by structural difference between horizontal members and vertical members.

As for mild environment, deterioration estimation curve for bottom flange and web might be considered separately. However, influence on deterioration rate of environment was confirmed to be much larger than bridge type and bridge members in 2. (5). In addition, considering data deviation caused by visual observation, estimating remaining life separately in mild environment is thought not to be rational at present stage. In the future, after the accumulation of the quantitative data by the image processing system, reexamination of estimation curves can be possible. In addition, 20% of the bridges used in this analysis have already received repainting of more than 2 times. Therefore, quality control in repainting works should also be clarified before exact estimation.

3 deterioration estimation curves classified by environment are drawn on **Fig. 16** and the parameters of each curve are shown in **Table 12**. 95% trust threshold value curve of an upper and lower limit is shown in each curve.

Fig. 14 Paint film deterioration curve (each part and each environment)

Fig. 15 Paint film deterioration curve (display of logarithm of Fig. 14)

Table 12 Parameters for Life Cycle estimation curves

Exposure condition		Quadratic	regression formula ($Y=a X^2$)	Environment
Inspection	Web	$Y=0.008X^2$	$Y=0.004X^2$ ($r=0.839$)	Mild
	Rural, Mountains, Residential quarter		$Y=0.001X^2$ ($r=0.644$)	
	Intersection road, Public road adjacent		$Y=0.011X^2$ ($r=0.621$)	
	River	$(r=0.978)$	$Y=0.013X^2$ ($r=0.846$)	
	Lower flange		$Y=0.041X^2$ ($r=0.790$)	
	Intersection road, Public road adjacent		$Y=0.011X^2$ ($r=0.570$)	
Specific Inspection			$Y=0.003X^2$ ($r=0.829$)	
			$Y=0.005X^2$ ($r=0.954$)	
Painting test panel	Hokuriku	$Y=0.206X^2$	$(r=0.999)$	Salinity coming flying
	Okinawa	$Y=0.109X^2$	$(r=0.986)$	High temperature humidity

note) Y: Deterioration area rate and X: Passing year's r: Correlation coefficient with measurement value

5. JUDGMENT OF REPAINTING TIME

As mentioned before, definition of paint film life cycle is vague. As for this reason, Yoshida¹²⁾ enumerates three following reasons, that is ① There are a lot of causes accelerating deterioration. ② Environment and quality control of painting

work is not uniform. ③ Limit state of paint film (the end of paint film life cycle) is not clear. In order to define life cycle of paint film, these problems must be clarified clearly.

In chapter 2, ① and ② has already been investigated by analyzing huge field inspection data statistically. However, there is no concrete solution

Fig. 16 Life Cycle estimation curves

Table 13 Parameter of straight line recurrence type

Bridge (Passing year)	Mode (λ)	Average value (μ)	Standard Deviation (σ)
Kofu minami Manjoh (9year)	0.133	0.150	0.160
Futamata (13year)	0.178	0.189	0.200
HinoI.C. Omokawa (15year)	0.156	0.193	0.211
Shisakai (29year)	0.218	0.239	0.275

for ③. Thus, even if paint film deterioration area ratio can be estimated by statistic curves, suitable (economical and safe) repainting time cannot be obtained. Therefore, in this research, life cycle of paint film was assumed as practical result of repainted cycles conducted for steel bridges in JH. Estimation of paint film life cycle was investigated by analyzing the relation between deterioration area ratio on the surface and corrosion depth under the paint film described in chapter 3.

(1) Distribution of the maximum corrosion depth

The 60 data of six bridges shown in Table 9 in Chapter 3 was used for the examination. Here, the maximum values of corrosion depth were selected and cumulative probability of maximum corrosion depth was drawn on Fig. 17. Frequency value (λ), average value (μ), and standard deviation (σ) obtained from each recurrence curve are shown in Table 13.

Nextly, estimation line of the maximum corrosion depth with respect to time was drawn on Fig. 18 from the distribution of the maximum corrosion depth.

Fig. 17 Distribution of the maximum depth

Fig. 18 Forecast of the maximum depth

Fig. 19 Life Cycle Estimation curves
(Enlarged Figure of Fig. 16)

The maximum corrosion depth was found to increase linearly by 0.02mm/year according to Fig. 18. (straight line recurrence type $Y=0.0164X$, Y: maximum corrosion depth and X: passing year). This result coincided with common idea that the corrosion speed of the steel material was generally 0.02mm/year. In Fig.18, maximum corrosion depth was found as 0.2mm after ten years from painting (Average repainting time for A painting system).

(2) Life cycle and repainting time of paint film

95% of the whole data is included within the range of the external deterioration area rate 3% and corrosion depth of 0.20mm according to Fig. 13 in Chapter 3. Moreover, the relation between passing year and the corrosion depth is not especially found according to Fig. 12 and the highest value of the corrosion depth is 0.25mm. The relation between the corrosion environment and the corrosion depth is also not especially admitted as described in 2(2). Therefore, deterioration area ratio of 3% is estimated to correspond to corrosion depth of 0.20mm under the paint film.

Fig. 19 is an enlarged figure of Fig. 16 from the deterioration area rate of 0% to 5%. The repainting time in each environment corresponding to deterioration area of 3% is presumed from Fig. 9 as follows, mild environment: 15 years, high temperature humidity environment: 6 years, salinity adhering environment: 4 years. This result had just corresponded to the past investigation results²⁾.

6. TO THE END

After the current technical problems of steel bridge (steel highway bridge) painting were clarified, a quantitative evaluation of the paint film deterioration and the possibility of the life cycle estimation of paint film were examined in Ref.16).

This paper focused on estimating the deterioration process and speed by analyzing field inspection data statistically, and final target was to obtain life cycle of paint film. Physical and chemical mechanism of paint film deterioration was not specifically described in this paper. However, because chemical clarification of deterioration process cannot be ignored for effective maintenance of steel bridges, development of diagnosis system for paint film deterioration is urgently required. Therefore, future subject must be to carry out rational analysis of huge inspection data and to find parameters for life cycle estimation.

In this paper, only A coating system applied for mild corrosion environment has been investigated.

Heavy-duty coating system has not been investigated because example bridges and painted specimens were too young to deteriorate and number of examples was few. Data accumulation and widening investigation on other coating systems must be required in the future.

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