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CORROSION OF STEEL BRIDGES—ITS LONG-TERM PREDICTION AND EFFECT ON THE SAFETY

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Corrosion deterioration characteristics of the structural steel bridges, especially plate girder bridges are studied in this paper. The parts of bridges that are severely corroded are also investigated. Emphasis is placed on the prediction of corrosion (based on the steel exposure test, paint life, and corrosion ratio) of painted bridge members. The final aim is to find the effect of corrosion on the strength of painted bridge members.
Keywords : steel exposure test, paint life, corrosion ratio

1. INTRODUCTION

Corrosion damage at various parts of structural steel bridges has recently become conspicuous especially when the bridge is constructed in a severe environment. Therefore, diagnosis of existing bridges has become important to establish a rational maintenance or repair program, and has become an important topic among researchers;for example, Nowax[1),2)], who has studied the corrosion damage model for steel bridges (unpainted bridges). In this paper, corrosion of painted steel bridges will be predicted, and the effect of corrosion on the strength of the bridge members will be determined. Within the highway bridge grouping, the plate girder bridge is selected as a representative bridge type. The flowchart of the calculation procedure is shown in Fig. 1.

2. CORROSION OF BRIDGE MEMBERS

Previous investigations have shown that the rate of corrosion of bridge members is different depending on the positions in the bridge structure. The difference in the rate of corrosion depends on various factors such as moisture, dirt, and debris. Parts of bridges in which corrosion deterioration tend to occur are as follows[3)~5)] :

① End cross-girders and areas surrounding the expansion joints
② Lower surface at lower flange of both box girders and plate girders
③ Welded parts, bolt joints, and their surrounding area

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④ Lower surface at upper flange of external girders
⑤ Inner surface of box girders
⑥ Shoes, bearings, and their surrounding area
⑦ Areas of water leakage
⑧ Parts influenced by exhaust gas from vehicles
⑨ Parts subjected to impact and abrasion

In order to find the difference in the rate of corrosion among bridge members, an actual value of corrosion depth of bridge members should be measured. Here, corrosion depth for five plate girder bridges in a certain city are measured, and this data are used for evaluating corrosion ratio. These five bridges are classified into two groups. The first group is for bridges located in a rural environment while the other group is for bridges located in a marine environment. The rate of corrosion at the middle cross-girder of a lower flange of the external girder is considered to be a standard value. Therefore, the corrosion ratio of this part is set at 1.00, and the corrosion ratio of other parts is evaluated based on this standard part. Fig. 2 and Fig. 3 show the results of the evaluated corrosion ratio. Numbers in the figures are the corrosion ratios for total corrosion of both surfaces of the steel plate.

3. STEEL EXPOSURE EXPERIMENT

The rate of corrosion of steel materials in atmospheres depends on the environmental factors. Environmental factors that have great effect on the rate of corrosion deterioration of steel materials are humidity, temperature, precipitation, sulfur dioxide concentration, and sea-salt particle[6,7]. These factors vary greatly depending upon atmospheric conditions. Recognition of marked differences in the degree of corrosion has made it convenient to divide the atmospheres into several types. Based on the Japan National Railway[8], atmospheres are classified into four types, which are rural, moun-

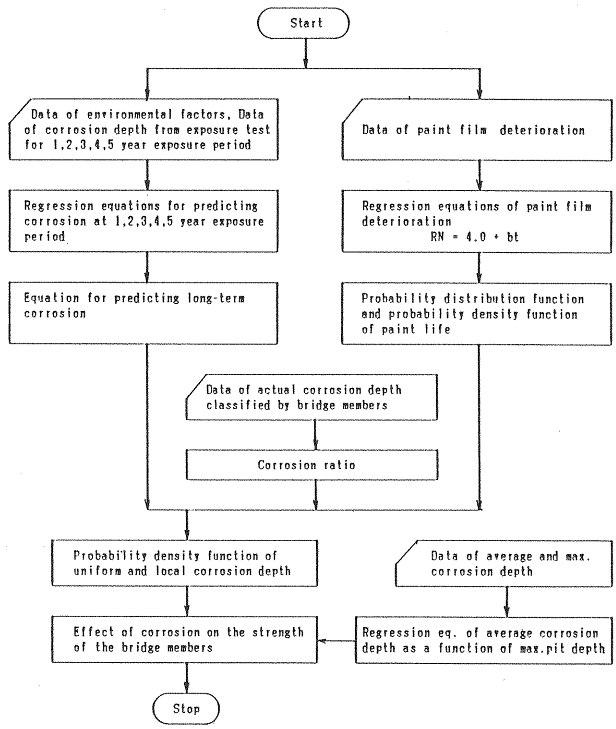


Fig. 1 Flowchart of the calculation procedure.

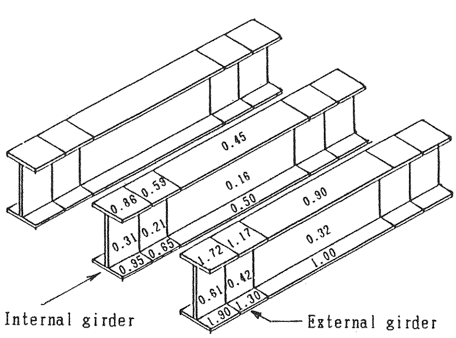


Fig. 2 Corrosion ratio (Rural environments).

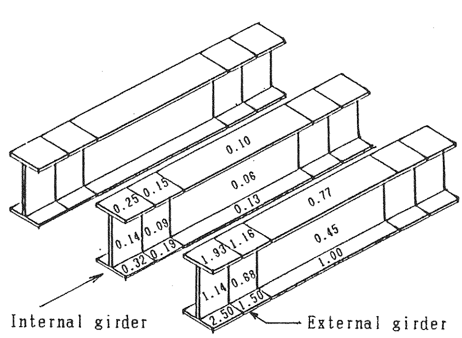


Fig. 3 Corrosion ratio (Marine environments).

tainous, industrial, and marine environments.

Horikawa et al.[9] have investigated long-term corrosion deterioration of bare steel. The results of the estimation of the corrosion rate of steel are consistent with the following relationship :

$$Y = AX^B \exp(C/X) \quad (1)$$

where Y is predicted long-term corrosion depth (mm). X is exposure time (year). A, B, and C are constants. Eq. (1) is readily convertible to a linear expression of the form

$$\ln Y = A' + B \ln X + C/X \quad (2)$$

where A' is $\ln A$.

The three parameters A', B, and C play a significant role in the characteristic of atmospheric corrosion. If these parameters are known, Eq. (2) can be used to predict the corrosion depth of bare steel at any exposure time. Two cases are considered in estimating these parameters.

[Case 1] This is the case when the results of a steel exposure test for the area under consideration can be obtained. This test should be placed at a different exposure times ; for instance, 1, 2, 3, 4, and 5 year-exposure times. The data of corrosion depth from exposure test are applied directly to Eq. (2) ; and by the least square method, parameters A', B, and C can be obtained. Based on the results of steel exposure test conducted by the Hanshin Expressway Public Corporation[10], parameters A', B, and C for 15 places in Japan are determined, and the results are shown in Table 1. Fig. 4 shows one example of predicting curve of corrosion depth together with the data from the steel exposure test for Shimizu.

[Case 2] This is the case when there is no data of corrosion depth from steel exposure test for the interested area. In this case, it is necessary to prepare the regression equations for predicting corrosion at each exposure time, i. e. at 1, 2, 3, 4, and 5 year-exposure time, as a function of environmental factors. From these regression equations, corrosion depths for exposure time of 1, 2, 3, 4, and 5 years can be predicted when data of environmental factors for interested area are obtained, and these expected corrosion dephts are applied to Eq. (2) in order to identify the parameters A', B, and C. Having investigated the data of environmental factors and corrosion depths from the steel exposure test conducted by the Hanshin Expressway Public Corporation, the same data is then applied to the SPSS Statistical Package. By the multiple linear regression analysis, regression equations for predicting corrosion at 1, 2, 3, 4, and 5 year-exposure time are obtained as follows :

$$Y_1 = 551.7 + 53.2\,X_1 - 15.4\,X_2 - 0.111\,X_3 + 33.9\,X_4 + 4.46\,X_5, \qquad \gamma = 0.65 \quad (3)$$

$$Y_2 = 878.3 + 75.1\,X_1 - 26.9\,X_2 + 0.021\,X_3 + 47.8\,X_4 + 5.99\,X_5, \qquad \gamma = 0.68 \quad (4)$$

$$Y_3 = 2\,001 + 101.3\,X_1 - 49.1\,X_2 + 0.120\,X_3 + 57.3\,X_4 + 6.83\,X_5, \qquad \gamma = 0.62 \quad (5)$$

$$Y_4 = 5\,289 + 118.3\,X_1 - 96.1\,X_2 + 0.333\,X_3 + 39.4\,X_4 + 7.29\,X_5, \qquad \gamma = 0.59 \quad (6)$$

$$Y_5 = 5\,793 + 131.5\,X_1 - 111.4\,X_2 + 0.503\,X_3 + 55.9\,X_4 + 7.57\,X_5, \qquad \gamma = 0.58 \quad (7)$$

Table 1 Estimated results of the parameters in the equation for predicting long-term corrosion.

Location	A'	B	C
Otaru	-3.002	0.293	-0.263
Sendai	-3.338	0.455	0.184
Niigata	-3.074	0.509	0.189
Nagano	-3.471	0.270	-0.188
Nagoya	-2.289	0.099	-0.432
Shimizu	-2.768	0.664	-0.345
Tokyo	-3.067	0.448	0.249
Kawasaki 1	-1.715	0.429	-0.262
Kawasaki 2	-2.206	0.785	0.459
Matsue	-3.132	0.429	-0.227
Amagasaki 1	-1.579	0.376	-0.635
Amagasaki 2	-2.646	0.280	-0.132
Wakayama	-2.451	0.138	-0.361
Shionomisaki	-2.977	0.725	0.052
Ashizurimisaki	-2.249	0.913	-0.176

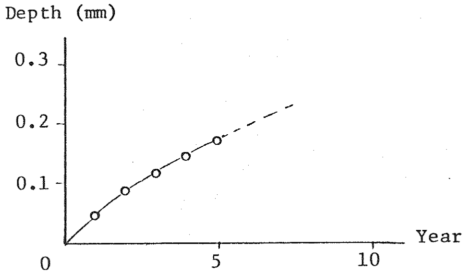


Fig. 4 An example of predicting curve of corrosion depth together with the data from the steel exposure test for Shimizu.

Condition (a) : $Y_5 > Y_4 > Y_3 > Y_2 > Y_1 > 0$
in which X_1 is temperature (°C). X_2 is humidity (%). X_3 is precipitation (mm/year). X_4 is sulfur dioxide concentration (10^{-3} ppm). X_5 is sea-salt particle (10^{-4} g/cm² year). X_1, X_2, and X_4 are average values in a year. Y predicts corrosion depth (10^{-4} mm), the subscript of Y expresses the time of exposure in years. γ is the multiple-correlation coefficient.

Table 2 Data of environmental factors in a certain city.

X1	X2	X3	X4	X5
16.2	67	1400	22.6	8.1

In these equations, humidity doesn't show the promotion of corrosion deterioration. This may be because the data of humidity used in this calculation is not so high (ranging from 66 % to 78 % with the average of 71 %), and is still lower than the critical value, in which humidity will not promote corrosion, that was reported as 75 % for mild steel[6]. Therefore, these regression equations are suitable for the areas in which humidity is not so high and condition (a) is still true. For areas of high humidity, difference regression equations should be determined.

An example of an application can be done using data in Table 2. Substituting this data into Eq. (3) to Eq. (7), predicted corrosion depths at 1, 2, 3, 4, and 5 year-exposure time are obtained. Applying these results to Eq. (2), and by the least square method, the parameters A', B, and C are obtained as −2.43, 0.627, and 0.157 respectively. Finally, the equation for predicting long-term corrosion in this case is Eq. (8). This equation will be used later for predicting corrosion depth of painted bridge girders :

$$\ln Y = -2.43 + 0.623 \ln X + 0.157/X \quad (8)$$

4. SERVICE LIFE OF PAINT

Since paint is applied to bridges for protecting against corrosion, the service life of paint must be taken into consideration for predicting corrosion of painted bridge members. There are many factors affecting the rate of paint film deterioration. However, main factors can be classified into three groups, which are atmospheric environments, types of paint, and parts of bridges to which paint is applied. The degree of deterioration of paint is represented by the rating number according to percentages of rust. The rating number system used by the Japan National Railway[8] consists of RN 1, RN 2, RN 3, and RN 4. The RN 4 expresses the state of no rust or new paint. Repainting should be done when the rating number of paint film is lower than two. Based on this rating number system, paint film deterioration of 270 railway steel bridges in Japan were investigated via the consideration of atmospheric environments and bridge members such as upper flange, web, and lower flange. Data for web and lower flange are used for determining the service life of paints. First of all, regression equations of paint film deterioration as a function of time are determined. These regression equations are assumed as a linear expression of the form

$$RN = \hat{a} + \hat{b}\, t \quad (9)$$

The least square method is used for estimating the parameters $\hat{a}$ and $\hat{b}$. The scattering (standard deviation) of the rating number is assumed to increase proportionally to time. The parameters $\hat{a}$ and $\hat{b}$ should satisfy the condition that the value of S in Eq. (10) is minimized.

$$S = \sum_{i=1}^{n} (RN_i - \hat{a} - \hat{b}\, t_i)^2 / t_i^2 \quad (10)$$

Because RN 4 expresses the state of new paint, the rating number estimated by Eq. (9) should be four at exposure time zero. Therefore, the value of the parameter $\hat{a}$ in Eq. (9) has to be four, and only the parameter $\hat{b}$ should be estimated. By the least square method, the differential product of Eq. (10) with $\hat{b}$ is set to zero.

$$\frac{\partial S}{\partial \hat{b}} = -2 \sum_{i=1}^{n} t_i\, (RN_i - \hat{a} - \hat{b}\, t_i) / t_i^2 = 0 \quad (11)$$

or

$$\sum_{i=1}^{n} RN_i / t_i = \hat{a} \sum_{i=1}^{n} 1/t_i + n\hat{b} \quad (12)$$

By substituting the value of $\hat{a}$ (4.0) into Eq. (12), parameter $\hat{b}$ can be easily estimated. In order to find the value of standard deviation as a function of time, the distribution of the rating number is changed into the standard form

$$Z_i=(RN_i-\widehat{RN}_i)/t_i \qquad (13)$$

where RN_i is the measured Rating Number, $\widehat{RN}_i$ is the expected rating number, and t is exposure time. Z is the standard normal distribution N $[0,\ c^2]$ in which c is the value used to estimate a standard deviation in the following equation :

$$\sigma=ct \qquad (14)$$

Estimated regression equations of the rating number and standard deviation are shown in Table 3. Fig. 5 shows a plot of one example of these regression equations together with the data of paint film deterioration for a web exposed in mountainous environment. Service life of paint is assumed to expire when the rating number is lower than two. This assumption is illustrated by Fig. 6. Shaded areas in this figure are the portions of paints of which service life has expired. By integrating the shaded areas in

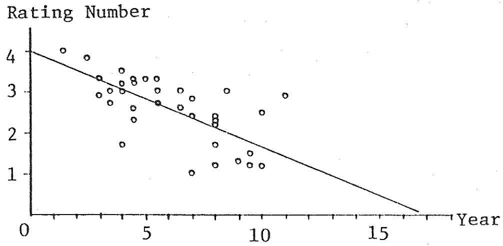


Fig. 5 Data of the rating number of paint film deterioration for a web exposed in mountainous environments.

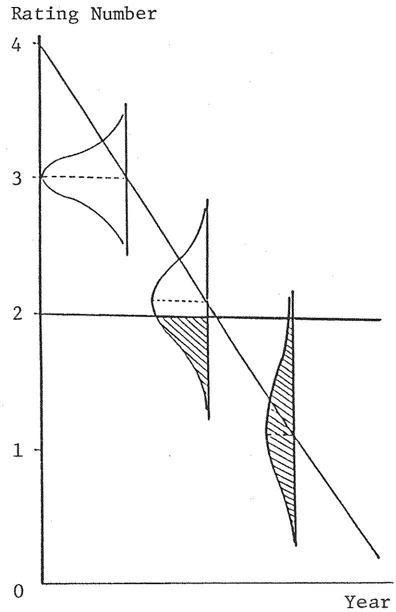


Fig. 6 Conceptual diagram of paint life.

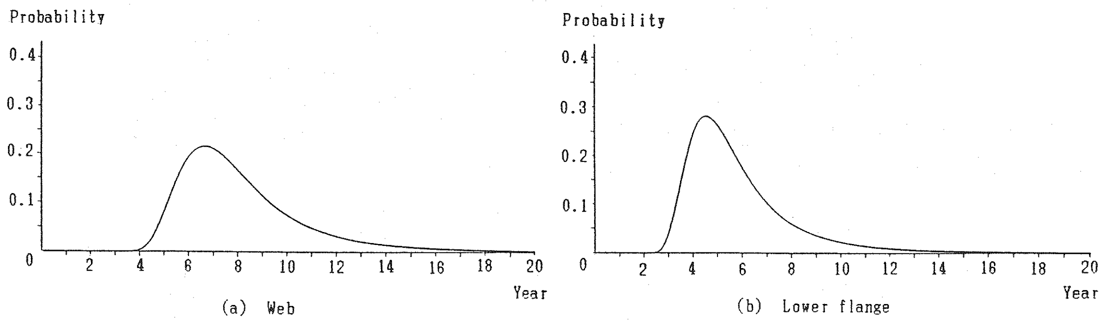


Fig. 7 Probability density of paint life, Rural environments.

Table 3 Regression equations of paint film deterioration.

Environments	Position in Bridge	Regression Equations	Standard Deviation	No. of Data
Rurral	Web Lower flange	RN=4.0-0.264t RN=4.0-0.377t	σ=0.0742t σ=0.1192t	55 55
Mountainous	Web Lower flange	RN=4.0-0.235t RN=4.0-0.317t	σ=0.0813t σ=0.0988t	37 37
Industrial	Web Lower flange	RN=4.0-0.382t RN=4.0-0.571t	σ=0.1697t σ=0.1728t	17 17
Marine	Web Lower flange	RN=4.0-0.282t RN=4.0-0.464t	σ=0.0760t σ=0.1581t	46 46

Table 4 Estimated service life of paint.

Environments	Position in Bridge	Mean Values (Years)	Standard Deviation
Rural	Web Lower flange	8.42 6.15	4.118 4.390
Mountainous	Web Lower flange	10.17 7.26	7.711 4.781
Industrial	Web Lower flange	7.15 4.00	4.599 2.836
Marine	Web Lower flange	7.80 5.18	3.457 4.711

Fig. 6, cumulative probability of paint life can be obtained. The differential product of this cumulative probability of paint life is then the expected probability density of paint life. Fig. 7 shows two examples of the estimated probability density of paint life. The mean value and standard deviation of these distributions are also obtained. They are illustrated in Table 4.

5. CORROSION OF BRIDGE MEMBERS

(1) Prediction of uniform corrosion

Uniform corrosion is the most common form of corrosion, where metal loss takes place uniformly over the entire exposed surface[1]. Uniform corrosion of painted bridge members is predicted based on the steel exposure test, paint life, and corrosion ratio. Corrosion of steel is assumed not to occur during the service life of paint, and after the expiration of paint life, corrosion mechanism of bridge members is the same as of bare steel in the steel exposure test multiplied by corrosion ratio.

Fig. 8 illustrates the concept of these assumptions. If $g\ (t)$ is a probability density function of paint life, then the conditional probability of t^*, which is the exposure time of the steel surface after the expiration of paint life, can be expressed as follow :

$$f_{t^*/T}(t^*/T)=g\,(T-t^*) \quad \cdots\cdots (15)$$

Here $f_{t^*/T}$ is the conditional probability density function of exposure time to the atmosphere of the steel surface. T is total time after construction. This exposure time of the steel surface is applied to Eq. (2), and by multiplying the result with the corrosion ratio, the predicted corrosion depth of painted bridge members will be obtained.

However, at any exposure time of steel surface t^*, there is a distribution (scattering) of corrosion depth as shown in Fig. 9. Estimated result of corrosion from Eq. (2) can represent only the mean value of this distribution. In calculation, the shape of distribution as well as the degree of scattering must be assumed. Because negative value of corrosion basically has no physical meaning, the distribution of corrosion depth is assumed to be a log-normal distribution. Consequently, the conditional probability of corrosion depth at any time T after construction, $P\ (Y_i/T)$, can be obtained by the following equation :

$$P\,(Y_i/T)=f_{Y_i/T}(Y_i/T)\,dY=\int_0^{\infty} f_{Y_i/t^*}(Y_i/t^*)\,f_{t^*/T}(t^*/T)\,dt^*dY \quad \cdots\cdots (16)$$

in which $f_{Y/t}$ is the conditional probability density function of corrosion depth of bare steel, $f_{Y/T}$ is the conditional probability density function of corrosion depth of painted steel.

Furthermore, the mean value and standard deviation of predicted corrosion depth can be estimated by Eq. (17) and Eq. (18). respectively.

$$\mu_Y=\int_0^{\infty} Yf\,(Y/T_i)\,dY \quad \cdots\cdots (17)$$

$$\sigma_Y^2=\int_0^{\infty} Y^2 f\,(Y/T_i)\,dY-\mu_Y^2 \quad \cdots\cdots (18)$$

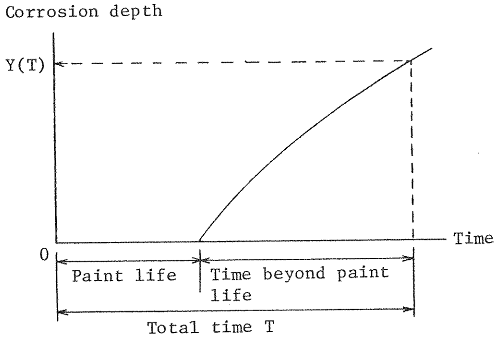


Fig. 8 Predicting model of corrosion depth.

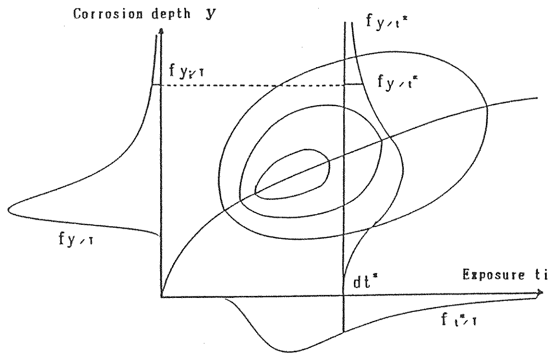


Fig. 9 Relationship among predicting corrosion depth, steel exposure test, and exposure time of steel.

(2) Prediction of maximum and/or local corrosion

Corrosion depth estimated in the previous section is the uniform corrosion. From this result, maximum value of corrosion depth is estimated based on the mean value and standard deviation of the distribution of this uniform corrosion by the following equation:

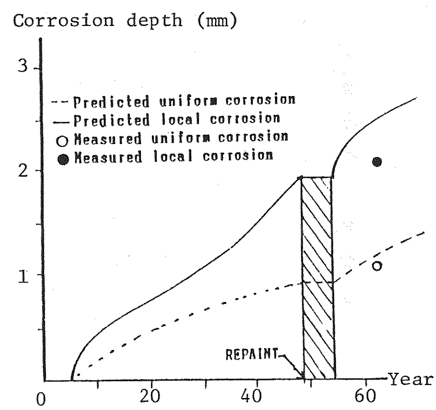
$$Y_{max}=\mu_y+3\,\sigma_y \quad \cdots\cdots (19)$$

However, past investigations showed that the rate of maximum pit depth changes rapidly when uniform corrosion depth reaches a certain value. This value may be called as "a triggered value". After that a state of maximum corrosion will change to local corrosion. Unfortunately, there were few investigations on local corrosion for steel bridges, but for a marine steel structure, this triggered value was reported as 0.7~1.3 mm[11]. After that, the local corrosion speed is about four times the uniform corrosion speed. Based on this corrosion property of marine steel structures, maximum and/or local corrosion is predicted based on the following assumptions:

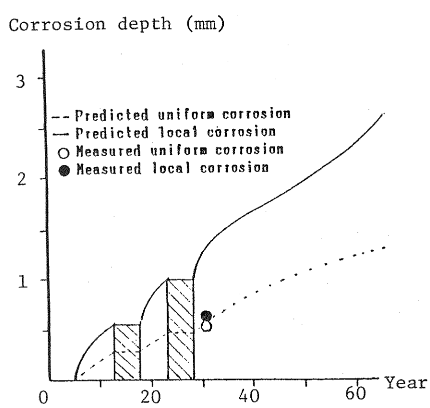
a) Local corrosion will develop when uniform corrosion depth reaches a triggered value. The distribution of this triggered value is a log-normal distribution of which its mean value is 0.7 mm, and the coefficient of variation is 0.15.

b) When uniform corrosion depth is less than the triggered value, maximum pit depth is estimated by Eq. (19); when uniform corrosion depth is greater than the triggered value, local corrosion speed is four times the uniform corrosion speed.

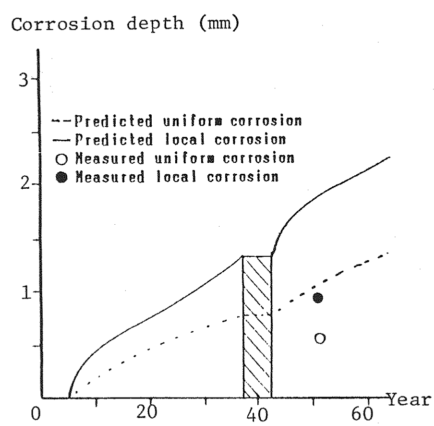
Results of the predicted corrosion depths for both local and uniform corrosion are compared with measured values shown in Fig. 10. The original thickness of materials is based on the design values of those bridges. The shaded parts in the figure represent the active life of paint resulting from repainting. From these results, predicted values of corrosion show an agreement with the measured values for both uniform and local corrosion for bridge A. For bridge B and C, predicted values of corrosion are a little bit overestimated. This may be the effect of a difference in environmental factors even though the bridges were constructed in the same city, but the precise data of



(a) Bridge A



(b) Bridge B



(c) Bridge C

Fig. 10 Comparison of corrosion depths, of bridges in a certain city, between predicted and measured values with the consideration of repainting.

environmental factors is not available.

6. EFFECT OF CORROSION DETERIORATION ON THE STRENGTH OF BRIDGE MEMBERS

Stress ratio, the ratio of the bending stress value of a corroded section to that of an uncorroded section, is introduced as a performance index to evaluate the effect of corrosion on the strength of bridge members. Fig. 11 shows the girder section used in the calculation.

For the effect of uniform corrosion, the calculation is performed by varying the fractile value of distribution of the corrosion depth in which each part of the girder is assumed to corrode at the same fractile value : and because corrosion depth has a linear relationship with the moment of inertia of girder cross section, and also with stress ratio, the distribution of estimated stress ratio also has the same fractile value as of the distribution of corrosion depth.

For the effect of maximum and/or local corrosion, because the tension test of corroded steel materials in the past has shown that the weakest section of materials is defined by the average corrosion depth, maximum and/or local corrosion depth is converted into average corrosion depth. Fig. 12 shows a plot of measured corrosion depths from investigation, indicating the relationship between maximum pit depth and average pit depth. From these data, by the least square method, regression equation of average corrosion depth as a function of maximum pit depth is obtained as follow :

$$Y_{ave} = -0.124 + 0.803\, Y_{max} \quad \cdots\cdots (20)$$

in which Y_{ave} is the average corrosion depth (mm), Y_{max} is the maximum pit depth (mm).

By using the above transformation equation, average corrosion depth can be obtained. Finally, the stress ratio can be estimated based on this average corrosion depth. Fig. 13 shows the estimated results of both the effect of uniform and local corrosion depth on the strength of bridge members by means of the stress ratio.

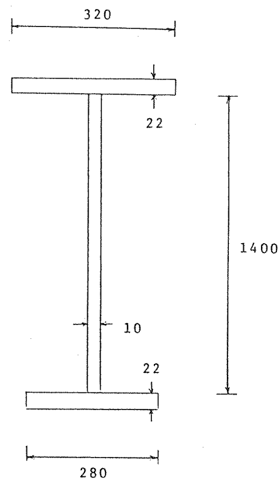


Fig. 11 Girder section for estimation of stress ratio.

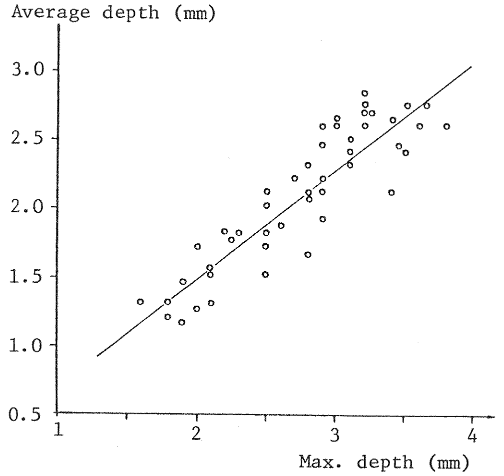


Fig. 12 Relationship between maximum and average corrosion depth.

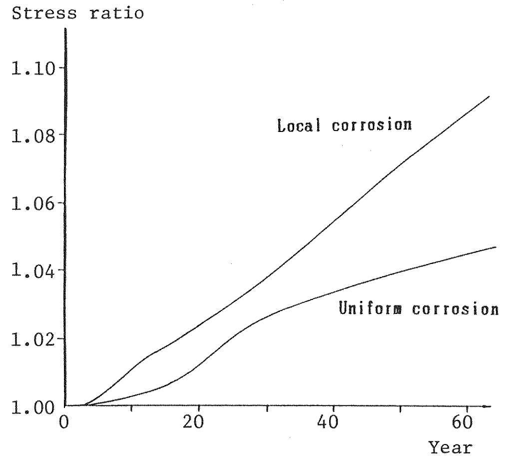


Fig. 13 Effect of corrosion on the strength of bridge members by means of stress ratio (Rural environments).

7. CONCLUSION

Evaluation of bridge deterioration is becoming important to establish rational bridge maintenance rules or to develop future code provisions for corroded steel bridges. This paper has introduced the model for predicting corrosion of painted steel bridges as well as the model for determining the effect of corrosion on the strength of steel girder bridges. Predicting corrosion of painted steel bridges is based on a steel exposure test, paint life, and corrosion ratio, which is the ratio of corrosion rate among bridge members. Evaluation of corroded steel bridges is determined in terms of stress ratio, which is the ratio of bending stress value of a corroded section to that of an uncorroded section.

The results have shown that bridge deterioration due to local corrosion is very important. This deterioration causes an increasing in stress level of the bridge sections due to section loss, and this deterioration might bring to the critical state of the structure if the stress level increases over the capacity of bridge sections.

It is apparent that bridge maintenance and inspections are especially important to ensure the safety of bridges. Repainting is one of the several possibilities for bridge maintenance in which the service life of paint obtained in this paper can be used as a guideline for the repainting period.

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