CORROSION MODEL FOR PAINTED STEEL EXPOSED TO ATMOSPHERE

Dr. Somkiat RUNGTHONGBAISUREE
Department of Civil Engineering
King Mongkut's Institute of Technology Thonburi
Bangkok, THAILAND

ABSTRACT

The objective of this paper is to establish the model for prediction of corrosion of painted steel materials exposed to atmosphere. Corrosion depth of painted steel materials is determined based on corrosion behavior of bare steel and service life of paint. Corrosion behavior of bare steel is determined based on the results of steel exposure test. Service life of paint is determined based on the data of paint film deterioration.

INTRODUCTION

Corrosion of steel occurs whenever it is exposed to atmospheres. Because steel is not stable in nature, it tends to change to a stable form of oxide. Consequently if steel is used as a structural members, it is necessary to apply any methods to protect steel from corrosion in order to achieve long service life of the structures. The most common method for protecting steel materials against corrosion in atmosphere is to apply paints to the steel surface. During service life of paint, corrosion of steel will not occur. Whenever paint is no longer active, corrosion occurs. The corrosion behavior of painted steel materials can be determined based on corrosion behavior of bare steel and service life of paint.

CORROSION BEHAVIOR OF BARE STEEL

There are many factors influencing the rate of steel corrosion. These factors can be classified into two groups. Group one is inner factors such as steel components, while the other group is outer factors such as environmental factors. Only environmental factors will be discussed in this paper.

Factors influencing corrosivity of the atmosphere

Environmental factors influencing the corrosivity of the atmosphere were reported as temperature, humidity, precipitation, sulfur-dioxide, sea-salt particles, wind direction, wind velocity, shining hours etc..[1)-9)] Among these, factors which greater influence the rate of steel corrosion are temperature, humidity, precipitation, sulfur-dioxide, and sea-salt particles.

Temperature: As for reaction velocity of the corrosion process, in general, increase in temperature will increase the reaction velocity. Consequently, corrosion rate of steel in high temperature atmospheres is higher than corrosion rate of steel in low temperature atmospheres. It is reported that each centigrade rise of temperature increase the rate of steel corrosion by 2.5 %.[1)]

Humidity: Humidity is a very important factor influencing the rate of steel corrosion. The rate of steel corrosion increases with increasing humidity. However, Vernon discovered that a critical humidity exists below which corrosion is negligible.[10)] Experimental values for the critical humidity are found to fall in general between 50 and 80 % for steel.[1),2),4)] Furthermore if the atmosphere is purified of substances such as sulfur dioxide concentration, sea-salt particles, and dust, critical value of humidity may reach some values such as 99 %.[5)] It was reported that when humidity is higher than critical value, the rate of corrosion will increase around 20 % by 1 % of the increment in humidity.[11)]

Precipitation: In general, precipitation is one of the most important factors influencing the rate of steel corrosion as it makes the steel surface wet. Moreover, precipitation can make the atmosphere more corrosive by increasing in humidity.

Sulfur-dioxide: The most important corrosive constituent of industrial atmospheres is sulfur-dioxide, which originates predominantly from the burning of coal, oil, and gasoline.

Sea-salt particles: Sea-salt particles are the most important corrosive constituent of especially marine atmospheres. The sea-salt particles in the atmosphere are produced on the sea surface, as a result of the direct interaction between the atmosphere and the ocean, and are carried over land by turbulence and wind. The rate of steel corrosion is high in the areas of high concentration of sea-salt particles.

<u>Corrosion of bare steel at certain exposure times</u>

As mentioned above that the rate of steel corrosion depends mainly on environmental factors such as temperature, humidity, precipitation, sulfur-dioxide, and sea-salt particles. The regression equations for predicting corrosion at certain exposure times, i.e. at 1,2,3,4, and 5 year-exposure times, as a function of environmental factors are determined. From these regression equations, corrosion depths for certain exposure times can be predicted when the data of environmental factors for the interested area are obtained. These regression equations are divided into two groups. The first one is for the members exposed to rain, and the other one is for the members underneath bridges.

For the members exposed to rain, the data of environmental factors and corrosion depth from the steel exposure test conducted by the Hanshin Expressway Public Corporation are used. These data are applied to the SPSS Statistical Package, and by the multiple linear regression analysis, regression equations for predicting corrosion at 1,2,3,4, and 5 year-exposure times are obtained. These regression equations are as follows:

$$Y_1 = 551.7 + 53.2X_1 - 15.4X_2 - 0.111X_3 + 33.9X_4 + 4.46X_5 \qquad \gamma = 0.65 \qquad (1)$$

$$Y_2 = 878.3 + 75.1X_1 - 26.9X_2 + 0.021X_3 + 47.8X_4 + 5.99X_5 \qquad \gamma = 0.68 \qquad (2)$$

$$Y_3 = 2001 + 101.3X_1 - 49.1X_2 + 0.120X_3 + 57.3X_4 + 6.83X_5 \qquad \gamma = 0.62 \qquad (3)$$

$$Y_4 = 5289 + 118.3X_1 - 96.1X_2 + 0.333X_3 + 39.4X_4 + 7.29X_5 \qquad \gamma = 0.59 \qquad (4)$$

$$Y_5 = 5793 + 131.5X_1 - 111.4X_2 + 0.503X_3 + 55.9X_4 + 7.57X_5 \qquad \gamma = 0.58 \qquad (5)$$

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 particles (10^{-4}g/cm^{2}year). Y is predicting corrosion depth (10^{-4}mm), the subscript of Y expresses the time of exposure in a year.

In these equations, humidity does not show the promotion of corrosion deterioration. This behavior also has been reported by the former researches.[3),12)] This may be because the data of humidity used in this calculation is not so high (ranging from 66% to 78% with the average at 71%), and is still lower than the critical value, in which humidity will not promote corrosion. Therefore, these regression equations are suitable for 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.

For members underneath bridges, the data of environmental factors and corrosion depth from the steel exposure test underneath bridges conducted by the Public Work Research Institute are used. By the multiple linear regression analysis, regression equations for predicting corrosion at 1, 2, and 3 year-exposure times are obtained. These regression equations are as follows:

$$Y_1 = 47.29 + 1.83X_1 - 1.47X_2 + 0.07X_3 - 0.53X_4 + 27.21X_5 \qquad \gamma = 0.92 \qquad (6)$$

$$Y_2 = -416.63 + 5.06X_1 + 4.72X_2 + 0.09X_3 - 1.10X_4 + 51.16X_5 \qquad \gamma = 0.93 \qquad (7)$$

$$Y_3 = -973.27 + 8.54X_1 + 11.70X_2 + 0.11X_3 - 1.59X_4 + 73.64X_5 \qquad \gamma = 0.92 \qquad (8)$$

Condition (b): $Y_3 > Y_2 > Y_1 > 0$

In these equations, sulfur-dioxide does not show the promotion of corrosion deterioration. The same behavior also has been reported by the Public Works Research Institute.[13)] This may be because the number of data used in the analysis is too small and the data of corrosion deterioration in the areas of low concentration of sulfur-dioxide are high due to the other factors that may effect the rate of corrosion deterioration. Therefore the sense that sulfur-dioxide should promote corrosion deterioration is not observed in this analysis. For the real behavior of sulfur-dioxide, the future investigation is required.

Long-term corrosion of bare steel

Relationship between corrosion depth and exposure time is assumed as an exponential expression of the form

$$Y = k\,t^{m} \qquad (9)$$

where Y represents predicting long-term corrosion of bare steel, t represents exposure time. k and m are constants. This equation is readily convertible to a linear expression of the form

$$\ln Y = k' + m \ln t \qquad (10)$$

where k' represents lnk.

The parameters k and m can be determined based on corrosion depth at certain exposure time from Eq.1 to Eq.5 or Eq.6 to Eq.8.

SERVICE LIFE OF PAINT

Factors influencing service life of paint

There are many factors influencing the rate of paint film deterioration. For structural steelwork exposed to the atmosphere, however, main factors that influence the rate of paint film deterioration are atmospheric environments, types of paint, thickness of paint film, and steel surface preparation.[14)-21)]

Atmospheric Environments: Service life of paint is greatly different according to atmospheric environments. The main factors that affect the rate of paint film deterioration are environmental factors such as temperature, humidity, precipitation, sulfur dioxide concentration, and sea-salt particles; which are widely different in each atmospheric environment.

Types of Paint: The service life of paints for the same atmospheric environment is also different depending on the type of paint. Paints can be classified by their main component; so-called "binder". Binder is the predominant factor in determining the characteristic of paints. The function of the binder is to give a permanently continuous film which is responsible for adhesion to the surface, resistance to climatic conditions, and mechanical resistance. More details can be found from Ref. No. 22.

Thickness of paint film: Thickness of paint film also plays a significant role in its service life, the greater the thickness of paint film, the longer the service life.

Steel surface preparation: Good surface preparation before painting is essential to obtain maximum service life of paint. A high quality paint may provide poor performance because of a lack of adherence. Two main elements relevant to a proper surface preparation are surface cleanliness and surface roughness. Grease, oil, dirt and rust must be removed to permit good adherence of paint. The roughness of the surface to be painted should be as low as practicable.

Service life of paint

Service life of paint can be determined from data of paint film deterioration. The degree of paint film deterioration is represented by the rating number according to percentages of rust, and consists of RN1, RN2, RN3, and RN4. RN4 expresses a state of no rust or new paint. Repainting should be done when the rating number of paint film is lower than two. RN2 is considered as a termination of service life of paint. Regression equations of paint film deterioration is assumed as a linear expression of the form

$$RN = a + bt \tag{11}$$

where RN is rating number, t is exposure time in year. a and b are constants.

The least square method is used for estimating the parameters a and b. Because RN4 expresses the state of new paint. This requires that rating number estimated by Eq.11 must be four at exposure time zero. Thus, the value of the parameter a in Eq.11 has to be four. There is left only the parameter b which should be estimated.

Next, the scattering (standard deviation) of the rating number is assumed to increase proportionally to time. The distribution of rating number is changed into the standard form

$$Z_i = (RN_i - \hat{RN}_i)/t_i \tag{12}$$

where RN_i is measured Rating Number. $\hat{RN}_i$ is the expecting rating number. Z is the standard normal distribution $N[0,c^2]$ in which c is the parameter used to estimate a standard deviation in the following equation:

$$\sigma = c\ t \tag{13}$$

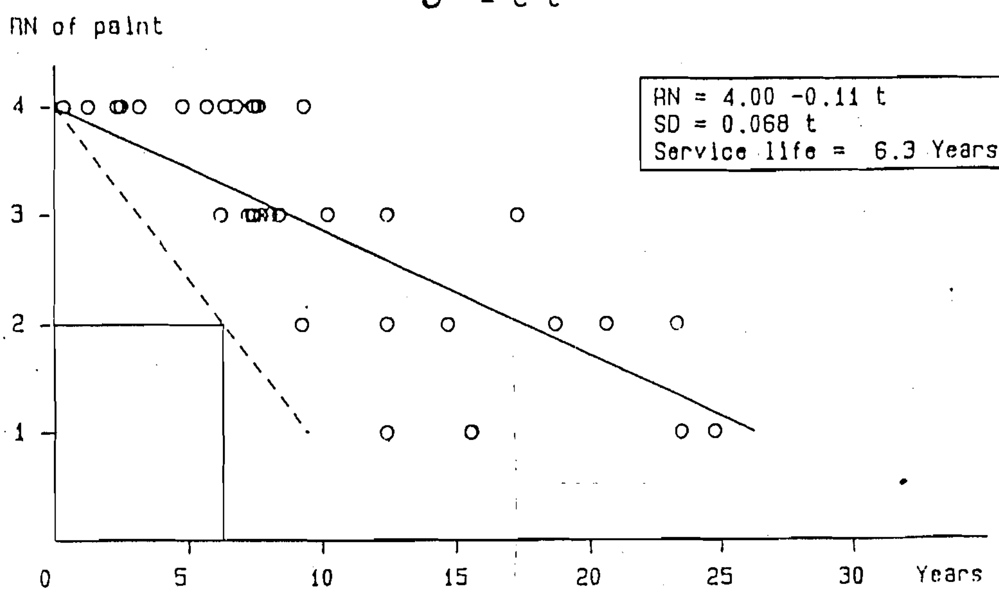

Fig. 1 Relation between RN of paint film deterioration and exposure time
P15 Middle part of span of main girder (External girder)
Lower surface of upper flange - Outer side (City A, Rural envi.).
Paint type = Alkyd resins (N=35)

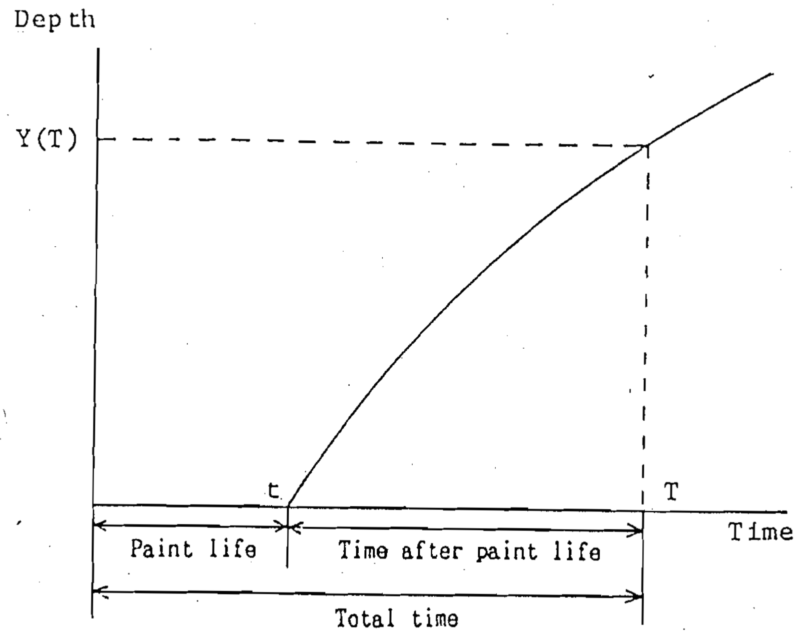

Fig. 2 Conceptual diagram of corrosion behavior of painted steel materials

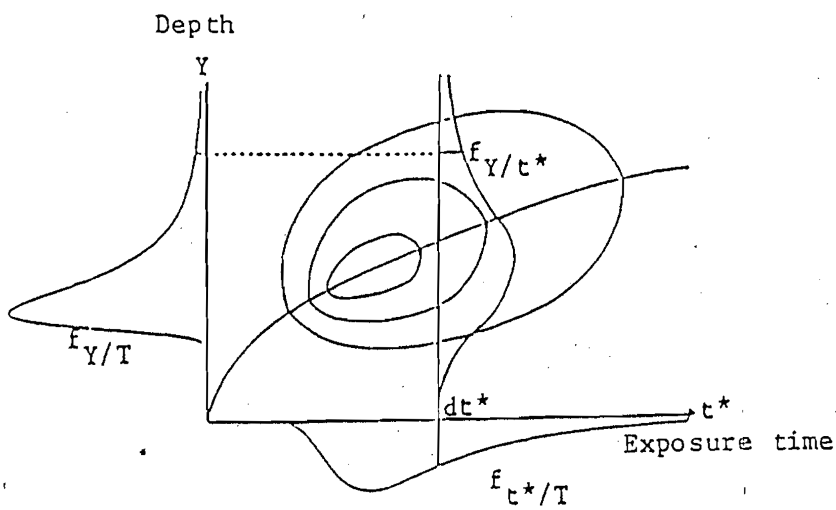

Fig. 3 Conceptual diagram for predicting uniform corrosion depth

Fig.1 shows an example of the plot indicating the relationship between rating number of paint film deterioration and exposure time for a certain environment. Circles in the figure represent data of paint film deterioration. Solid line represents a predicting line of rating number from determined regression equation. The dotted line represents the line of $\mu - 3\sigma$ of which 99.87 % of the data are located above this line (minimum boundary). From the dotted line in Fig.1 exposure time that makes rating number of paint film deterioration equal to two is defined as service life of paint.

CORROSION OF PAINTED STEEL MATERIALS

Corrosion depth of painted steel materials is determined based on the following assumptions;

1. Corrosion of steel will not occur during the active life of paint.
2. After the expiration of paint life, corrosion behavior of painted steel materials is assumed to be the same as of bare steel exposed to atmospheres.

Fig.2 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 follows:

$$f_{t^*/T}(t^*/T) = g(T-t^*) \tag{14}$$

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 painted. The exposure time of the steel surface to the atmosphere is applied to Eq.9 in order to determine corrosion of painted steel materials.

However, at any exposure time of steel surface t^*, there is a distribution (scattering) of corrosion depth as shown in Fig.3. The estimated result of corrosion from Eq.9 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 the 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 determined by the following equation:

$$\begin{aligned} P(Y_i/T) &= f_{Y_i/T}(Y_i/T)\,dY \\ &= \int_0^{\infty} f_{Y_i/t^*}(Y_i/t^*)\, f_{t^*/T}(t^*/T)\, dt^* dY \end{aligned} \tag{15}$$

in which $f_{Y/t}$ represents the conditional probability density function of corrosion depth of bare steel. $f_{Y/T}$ represents 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.16 and Eq.17 respectively.

$$\mu_Y = \int_0^\infty Y\, f(Y/T_i)\, dY \tag{16}$$

$$\sigma_Y^2 = \int_0^\infty Y^2 f(Y/T_i)\, dY - \mu_Y^2 \tag{17}$$

CONCLUSIONS

The model for predicting corrosion of painted steel materials exposed to atmospheres was introduced in this paper. Corrosion of painted steel materials can determined based on corrosion behavior of bare steel and service life of paint. Corrosion of painted steel materials is assumed not to occur during the service life of paint. After the expiration of paint life, corrosion behavior of painted steel materials is assumed to be the same as of bare steel exposed to atmospheres.

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