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# Durability Evaluation Method on Rebar Corrosion of Reinforced Concrete

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**ABSTRACT**

In this paper, method on the durability evaluation in nuclear power plant concrete structures was investigated. In view of the importance of evaluating the degree of deterioration of reinforced concrete structures, relationships should be formulated among the number of years elapsed, *t*, the amount of action of a deteriorative factor, *F*, the degree of material deterioration, *D*, and the performance of the structure, *P*. Evaluation by *PDFt* diagrams combining these relationships may be effective. A detailed procedure of durability evaluation for a reinforced concrete structure using *PDFt* concept is presented for the deterioration of rebar corrosion caused by neutralization and penetration of salinity by referring to the recent papers.

**KEYWORDS**

concrete, rebar, corrosion, durability, aging management

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## 1. Introduction

Important reinforced concrete structures in nuclear power plant require aging management and evaluation. There has been an enormous accumulation of study results regarding the durability evaluation and deterioration prediction of reinforced concrete structures. However, durability evaluation of reinforced concrete structures generally involves the problems of a wide variety of external factors and a combination of reinforcing steel and concrete. Evaluation on the aging of nuclear power plants, "Review Manual for Age-Related Technical Assessment in Japan " [2] is generally used, but more accurate evaluation will be needed. The problems involved in these studies or evaluations are the relations between time changes, deteriorative factors, material deteriorations and performances of structure are not clearly indicated. If these relations are cleared and combined, the evaluation method can be more accurate. In view of the importance of evaluating not only each material but also the composite body for evaluating the degree of deterioration of reinforced concrete structures, relationships should be formulated among the number of years elapsed, *t*, the amount of action of a deteriorative factor, *F*, the degree of material deterioration, *D*, and the performance of the structure, *P*. Evaluation by *PDFt* diagrams combining these relationships may be effective [1].

In this paper, a detailed procedure of durability evaluation for a reinforced concrete structure using *PDFt* concept is presented for the deterioration of rebar corrosion caused by neutralization and penetration of salinity by referring to the recent papers.

## 2. Deterioration evaluation based on PDFt diagrams [1]

### 2.1. Concept

In this method, problems on the durability evaluation of reinforced concrete structures were considered. Durability evaluation of reinforced concrete structures generally involves the following problems:

(1) A wide variety of external factors: Reinforced concrete structures are placed in natural environments involving external factors that vary from one place to another and over a long time

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span.

(2) Combined materials: In order to evaluate the performance of reinforced concrete structural bodies, which are a combination of reinforcing steel and concrete, not only the acting factors and deterioration degrees of individual materials but also the combined action of factors on the combined material should be considered.

One solution to problem (1) above is the assumption of the uniformity of deteriorative action. Despite the wide variety of deteriorative factors acting on a structure, uniformity may be assumed for their action when considering long-term changes on one year-unit basis at a certain place, as each structure is fixed to a location for a long time. In other words, evaluation may be carried out by continuous deterioration functions based on changes on a scale of a minimum unit of one year. Also, since physical changes can be regarded as increasing functions generally having a cumulative property, the following estimation method may be considered simpler and more accurate than deductive evaluation using a number of parameters: Determine a basic form of the deterioration function using only time or a deteriorative factor as the parameter, and extrapolate actual measurement data of deterioration degrees into the function to determine the coefficient in an inductive manner. This coefficient allows the evaluation of properties related to the durability of various structures on a universal scale.

As to the combined action stated in item (2) above, it is necessary to clarify the relationships among the time, the effect of deteriorative factors, the degree of material deterioration, and the performance degradation of the structure.

## 2.2. Integrity evaluation method by *PDFt* curve

A deterioration evaluation diagram, $V(t)$, expressing time-related changes in an evaluation value, $V$, is assumed as follows,

$$V(t) = \alpha\, v(t) \tag{1}$$

where $\alpha$ is the coefficient, $t$ is time (years), and $v(t)$ is a basic evaluation equation having no parameters other than $t$. "$v(t)$" is determined beforehand based on past experiment data and analysis results. Evaluation values, $V_{\mathrm{obs}}$, at certain points of time, $t_{\mathrm{obs}}$, are determined by actual measurement and plotted. The coefficient, $\alpha$, is then determined by extrapolating $v(t)$. This method provides evaluation values approximated to actual situations even when various deteriorative factors are involved. Also, $\alpha$ serves as an evaluation index characteristic of the structure. While a larger amount of $V_{\mathrm{obs}}$ data are preferable.

Evaluation is carried out by determining the evaluation value, $V_{eva}$, at a desired year, $t_{eva}$, using the established deterioration evaluation diagram, $V(t)$, and comparing the result with the predetermined specification values ($V_{\mathrm{rg}}$: regulation value, $V_{cr}$: critical value, etc.). When $V_{eva}$ exceeds $V_{rg}$, a necessary step may be taken, such as to proceed to the secondary evaluation.

In order to obtain a rational evaluation, the relationships of the deterioration factor and year (*F-t* diagram), the material deterioration and deterioration factor (*D-F* diagram) and the structural performance and material deterioration (*P-D* diagram) should be cleared. Examples of parameters are given in Table 1. A diagram of the evaluation of the deterioration degree of reinforced concrete structures (hereafter referred to as a *PDFt* diagram) is obtained by integrating the above-mentioned evaluation diagrams as shown in Fig. 1. The diagram in the right lower quadrant (level IV), which is determined by plotting several values of $t$ and $P$ in the right upper (level I) and left lower (level III) quadrants, respectively, forms a *P-t* diagram for assessing the time-related changes in the structural performance. This diagram also clarifies the relationships among the physical quantities. Thorough

preliminary investigation of the basic evaluation equation for each diagram is necessary as to whether it can be expressed by coefficients given in Fig. 1 as $\alpha$ and $\beta$ regarding its adequacy and accuracy. There are many factors rerating *F-t* relation and *D-F* relation, but these relations can be easily evaluated by fitting the actual measured data to the basic equations and deciding the $\alpha$ and $\beta$ values by extrapolation technique.

**Table 1 Example of parameters**

| Deterioration factor $F$ | | Material deterioration $D$ | | Performance of structure $P$ | |
|---|---|---|---|---|---|
| $F_1$ | Carbonation(depth) | $D_1$ | Compressive strength | $P_1$ | Stiffness |
| $F_2$ | Chloride ion | $D_2$ | Young's modulus | $P_2$ | Bearing capacity |
| $F_3$ | Heating | $D_3$ | Rebar corrosion | $P_3$ | Earthquake response |
| $F_4$ | Radiation | $D_4$ | Rebar strength | $P_4$ | Constitutive law |
| $F_5$ | Alcali aggregate reaction | $D_5$ | Tensile strength | $P_5$ | Crack |
| $F_6$ | Vibration | $D_6$ | Crack resistance | $P_6$ | Bolt strength |
| $F_7$ | Freeze-thaw | $D_7$ | Bolt corrosion | $P_7$ | Airtightness |
| $F_8$ | Chemical attack | $D_8$ | Water content | $P_8$ | Permeability |
| $F_9$ | – | $D_9$ | – | $P_9$ | – |
| $F_0$ | Others | $D_0$ | Others | $P_0$ | Others |

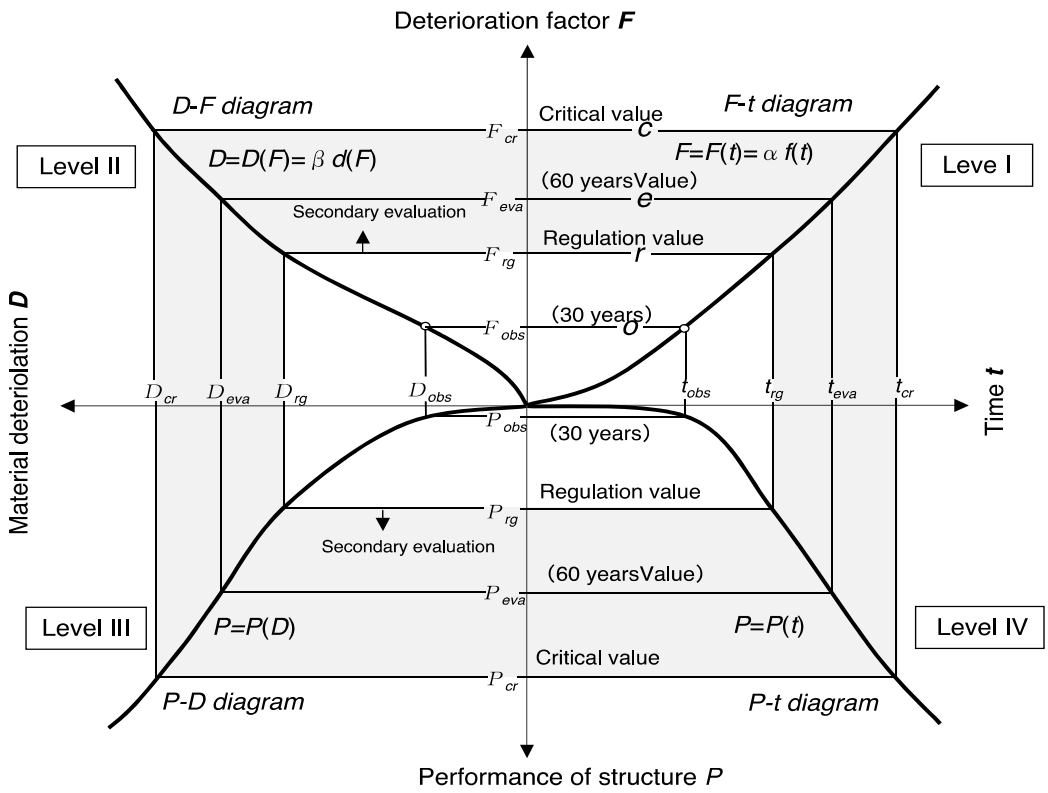


**Fig. 1. Integrity evaluation diagram of reinforced concrete structures (*PDFt* diagram)[1]**

### 2.3. Current evaluation method of aging management for NPP concrete structures

In the current evaluation method on the neutralization and penetration of salinity contained in the "Review Manual for Age-Related Technical Assessment in Japan " [2] is as follows.

***Neutralization:*** The degradation of concrete is evaluated according to whether or not the depth of concrete neutralization over the life span of the structure is less than reference levels, and whether or not neutralization reached to rebar.

***Penetration of salinity:*** The deterioration of reinforced concrete due to penetration of salinity is evaluated according to whether or not the chloride concentration over the life span of the structure is less than reference levels, and whether or not cracks occur in the concrete.

## 3. Evaluation formula for integrity evaluation of reinforced concrete structures

### 3.1. Neutralization

#### 3.1.1. *F-t* diagram, relation between a deteriorative factor and the number of years elapsed

The amount of action of Oxygen as it affects the corrosion of reinforcing steel. However, it is difficult to measure this value, so the neutralization depth is used as an alternate value. The neutralization depth is represented as $F_1$, (subscript “1” represents the neutralization of concrete) which is the evaluation physical property. Generically, the neutralization depth can be expressed by the square root t theory as follows [3, 4] ,

$$F_1 = a_1\sqrt{t} \tag{2}$$

where, $F_1$ is neutralization depth (mm), $\alpha_1$ is neutralization rate coefficient (mm/$\sqrt{}$ year) and $t$ is time (year).

#### 3.1.2. *D-F* diagram, relation between the material deterioration and the deteriorative factor

The rate of loss of steel reinforcing bars, $D_3$ (subscript “3” represents the corrosion of steel reinforcing bars), is the amount of corrosion of steel reinforcing bars as compared to their condition at the time of construction. Based on the corrosion experiments of Tomosawa et al. the Eq. (3) is proposed [5].

$$W_c = \frac{1}{38.1}(1.35T + 2.76H + 1.800O_2 - 163)\cdot\sqrt{t} \tag{3}$$

where, $W_C$ is rate of loss of steel reinforcing bars by corrosion ($10^{-4}$g/cm$^2$), $T$ is temperature (°C), $H$ is relative humidity (%), $O_2$ is concentration of oxygen (%) and $t$ is elapsed time after neutralization reaches the steel reinforcing bars (day). The corrosion loss of steel reinforcing bars, $W_c$, and the square root $t$ show a linear relationship. So the rate of corrosion loss of steel reinforcing bars, $D_3$, could be expressed by simple basic equation and extrapolating coefficient $\beta_3$ as Eq. (4).

$$D_3 = \beta_3 \cdot \sqrt{{F_1}^2 - {F_0}^2} \tag{4}$$

where, $D_3$ is rate of corrosion loss of steel reinforcing bars (-), $\beta_3$ is environmental condition (temperature, relative humidity, concentration of oxygen et al.) and material (steel reinforcing bars, concrete) constant, $F_0$ is concrete cover depth (mm). Real phenomena on rebar corrosion will be so complicated and be including many factors, but we may evaluate the rebar corrosion by using the basic equation Eq.(4) according to the obtained some actual data of the rebar corrosion on the site and deciding the $\beta_3$ by using extrapolation technique.

### 3.2. Penetration of salinity

### 3.2.1. *F-t* diagram, relation between the deteriorative factor and the number of years elapsed

For the action of the chloride ion $F_2$ (subscript "2" represents the penetration of salinity) , we propose the value of chloride concentration as show in Fig. 2. This evaluation uses the integrated value per annum in practice.

$$F_2 = \int_0^{t_n} C_t \, dt, \quad C_t \geq C_{cr} \tag{5}$$

where, $F_2$ is amount of action of chloride ion (kg/m$^3$ year), $C_t$ is chloride concentration (kg/m$^3$), $t$ is time (year), $t_n$ is evaluation period (year) and $C_{cr}$ is critical chloride concentration of stainless steel corrosion (=1.2kg/m$^3$).

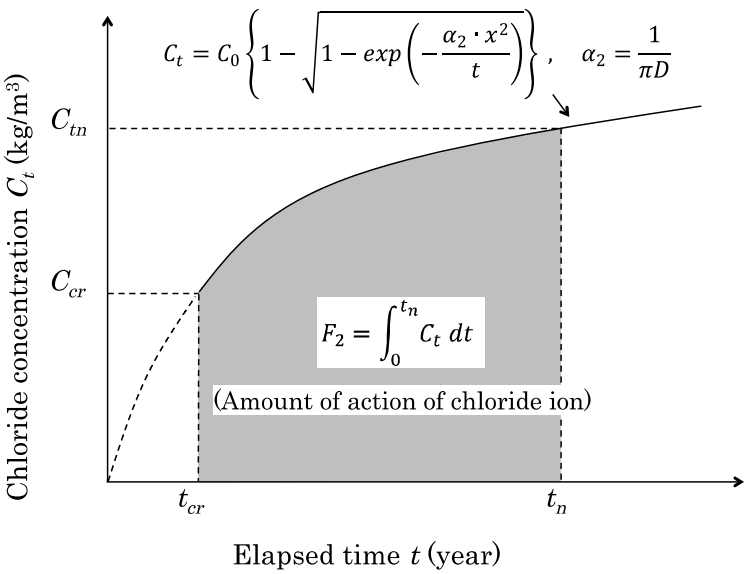


**Fig. 2. The conceptual diagram of integrated value of chloride concentration $F_2$**

The normally used equation for the prediction of the distribution of chloride concentration in concrete is Eq. (6), which is based on the diffusion equation [6, 7].

$$C_t = C_0\left(1 - erf\left(\frac{x}{2\sqrt{D \cdot t}}\right)\right) \tag{6}$$

where, $C_0$ is chloride concentration at surface of concrete (kg/m$^3$), x is thickness of concrete cover (mm) and $D$ is apparent diffusion coefficient (mm2/year). In Eq. (7) an approximation formula [8] is applied in place of the error function "*erf*" found in Eq. (6).

$$C_t = C_0\left\{1 - \sqrt{1 - exp\left(-\frac{\alpha_2 \cdot x^2}{t}\right)}\right\}, \quad \alpha_2 = \frac{1}{\pi D} \tag{7}$$

where, $\alpha_2$ is constant of the amount of action of degradation factor as related to the material properties. $C_0$ and $\alpha_2$ are calculated using the distribution of chloride concentration values as measured at the determined evaluation periods.

### 3.2.2. *D-F* diagram, relation between the material deterioration and the deteriorative factor

The amount of action of degradation factor, $F_2$, which represents the integrated value of chloride

concentration around steel reinforcing bars, is expressed as Eq. (8),

$$F_2 = \int_0^t C_t \, dt \quad \left( = \sum_{t=0}^{n} C_t \, \Delta t \right) \tag{8}$$

where, $F_2$ is amount of action of chloride ion around steel reinforcing bars, $C_t$ is amount of chloride ion around steel reinforcing bars at evaluation time t (kg/m$^3$), $t$ is time (year) and $\Delta t$ is unit time (1year).

The rate of deterioration of material is $D_3$ (subscript "3" represents the corrosion loss of steel reinforcing bars) and is assumed to be the rate of corrosion loss of carbon steel reinforcing bars. $D_3$ is the amount of corrosion of steel reinforcing bars as compared to their condition at the time of construction. $D_3$ can represent as follows,

$$D_3 = \int_0^{t_n} V_t \, dt \tag{9}$$

where, $D_3$ is the corrosion loss of steel reinforcing bars (mg/cm$^2$), $V_t$ is corrosion rate (mg/cm$^2$/year), $V_t$ can be represented as Eq. (10).

$$V_t = \frac{1}{\sqrt{x}} (a \, C_t + b) \tag{10}$$

where, $a$ and $b$ is constants. By substituting the Eq. (10) into the Eq. (9), the Eq. (11) is obtained, which is the relational expression of *D-F*. An example of the determination of the value of the constants $a$, $b$ is as follows [9],

$$D_3 = \frac{1}{\sqrt{x}} (a \, F_2 + b t_n) \qquad a = 6.0, b = 0.4W/C - 31.7 \tag{11}$$

where, *W/C* is water to cement ratio (%). If the diagram is to be determined by the measurement value, then the corrosion loss of steel reinforcing bars should use a multi-year measurement.

## 3.3. Concrete surface cracking by rebar corrosion

### 3.3.1. *P-D* diagram, relation of the material deterioration and the performance of structure

By the evaluation of salinity indicated in "Review Manual for Age-Related Technical Assessment in Japan " [2], the deterioration of reinforced concrete is evaluated according to whether or not the chloride concentration over the life span of the structure is less than reference levels, and whether or not cracks occur in the concrete. So in this study, the performance of the structure, $P$ is set to the width of cracks in the concrete surface.

The relation between when cracks will occur in the concrete and the corrosion loss of steel reinforcing bars which diameter is used as stirrup or tye is shown as follows [10] ,

$$D_u = -(0.19d + 0.06x + 2.0) \cdot ln(F_c) + 0.1d + 47 \tag{12}$$

where $D_u$ is critical corrosion loss of steel reinforcing bars to affect a crack in the concrete at a width of 0.1mm by FEM analysis (mg/cm$^2$), $d$ : diameter of steel reinforcing bars (mm) which size is assuming the use of stirrup or hoop, $x$ : thickness of concrete cover (mm), $F_c$ : compressive strength of concrete (N/mm$^2$) which represents the crack resistance of concrete. There exists a linear relationship between the corrosion loss of steel reinforcing bars and width of cracks in the concrete [11]. The relation between the corrosion loss of steel reinforcing bars, $D_3$, and width of cracks in the concrete, $P_8$ (subscript "8" represents the crack of concrete) is expressed as follows:

$$P_8 = 0.1\frac{D_3}{D_u} \tag{13}$$

### 3.3.2. *PDFt* diagram, relation of the number of years elapsed, the deteriorative factor, the material deterioration and the performance of structure

An example of the integrity evaluation diagram (*PDFt* diagram) in the case of time changes ($t$) and concrete surface cracking ($P$) caused by the penetration of salinity ($F$) and rebar corrosion ($D$) by using formulas mentioned above is shown in Fig. 3.

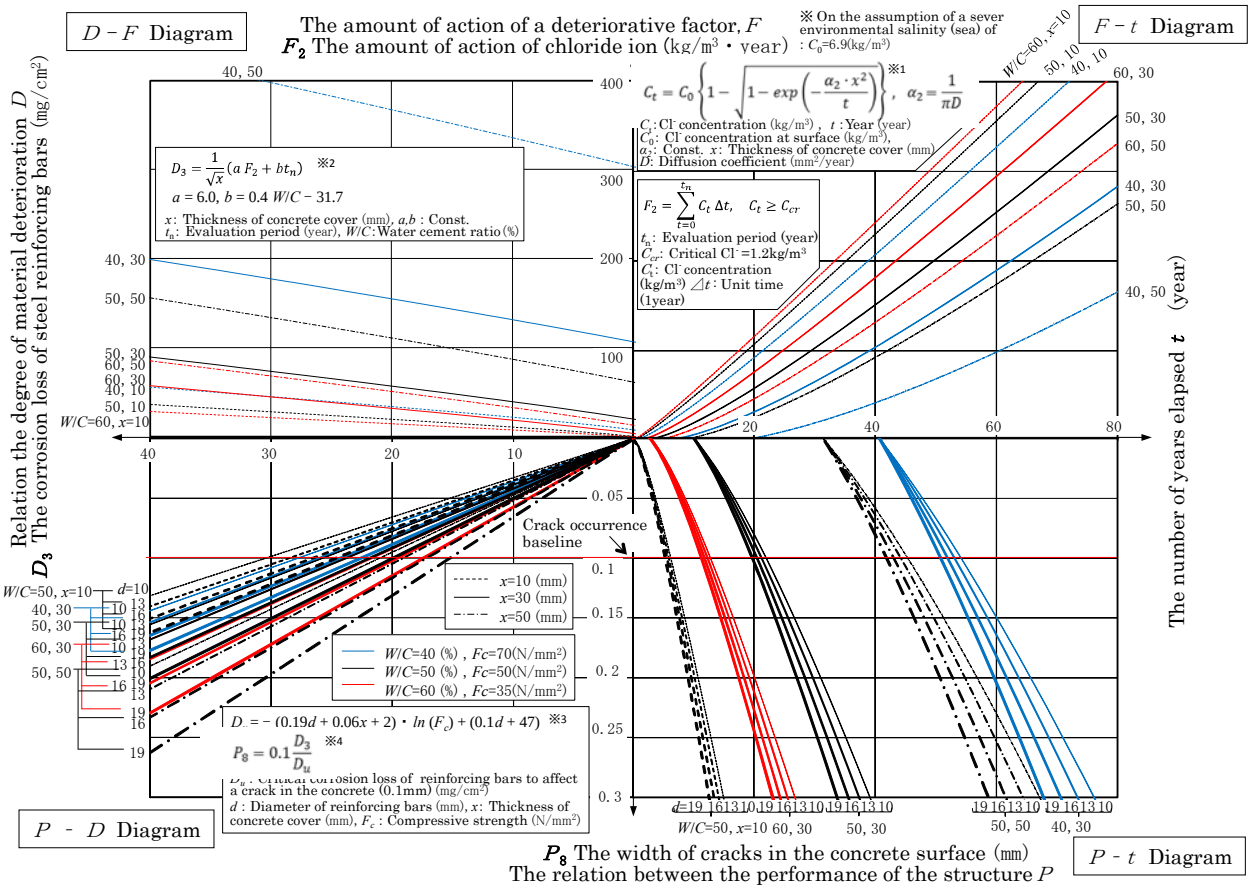


**Fig.3 *PDFt* diagram – time changes, chloride ion, rebar corrosion and concrete surface cracking**

## 4. CONCLUSIONS

Conclusions obtaind from this study is summarized as follows:

1. A method of inductively determining a deterioration index and evaluation diagram is proposed for evaluating the integrity of reinforced concrete structures subjected to multiple deteriorative external factors.
2. Relationships are formulated among the number of years elapsed $t$, the amount of action of a deteriorative factor $F$, the degree of material deterioration $D$, and the performance of the structure $P$ and these relationships are conbined as a *PDFt* diagram.

3. Detailed procedure of durability evaluation for a reinforced concrete structure using *PDFt* concept is proposed by referring to the recent papers for the deterioration of rebar corrosion caused by neutralization and penetration of salinity.

## Acknowledgement

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