METHODOLOGY AND FRAMEWORK OF THE SECONDARY INTEGRITY EVALUATION OF DETERIORATED CONCRETE STRUCTURES

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ABSTRACT

Grasping the deterioration of nuclear power plant concrete structures in use over time and accurately dealing with these by effective maintenance have been key challenges in recent years for ensuring a certain level of safety for nuclear power plants. Generally, deterioration evaluation of the reinforced concrete structure consists of two levels, the primary evaluation which evaluating the deterioration of materials and the secondary evaluation which is evaluating the integrity of the structural performance. This paper reorganizes the problems of conventional durability evaluation methods for reinforced concrete structures and proposes a framework on the evaluation of deteriorated material constitutive model in the secondary integrity evaluation of deteriorated concrete structure. Methodology on the integrity evaluation in the aging management and evaluation of reinforced concrete structures was investigated. Problems on the durability evaluation of reinforced concrete structures were pointed out. 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. Finally, the evaluation framework of the deteriorated material constitutive model which can be used for the numerical analysis of the integrity evaluation for the concrete structure was proposed.

INTRODUCTION

Generally, integrity evaluation of the deteriorated reinforced concrete structure in use over time consists of two levels, the primary evaluation which evaluates the deterioration of materials and the secondary evaluation which evaluates the integrity of the structures. In the primary evaluation, for instance, it evaluates the carbonation progress and chloride ion concentration around rebar, and then decides the necessity of the secondary evaluation by comparing the values with specification value. In the secondary evaluation, it evaluates the durability of the materials or the structures of the deteriorated parts or whether it fulfills the required functions. In order to implement the durability evaluation of the deteriorated parts or structures, it is necessary to evaluate and create constitutive model of the material property values of corroded rebar and deteriorated concrete. Abovementioned values of the properties are basically as same as the value to be used for the general numerical analysis, yet the evaluation framework considering the deteriorated materials is required.

This study states the secondary integrity evaluation method, the framework of the evaluation of deteriorated material property values as well as material constitutive model and the issues that come along so as to implement the integrity evaluation of the members.

OUTLINE OF THE EVALUATION METHOD

Fig. 1 shows an outline of the integrity evaluation method by extrapolation based on measurements. First, 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 α 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_{obs}, at certain points of time, t_{obs}, are determined by actual measurement and plotted. The coefficient, α, is then determined by extrapolating $v(t)$. This method provides evaluation values approximated to actual situations even when various deteriorative factors are involved. Also, α serves as an evaluation index characteristic of the structure. While a larger amount of V_{obs} data are preferable, evaluation is possible with only one piece of information. 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_{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.

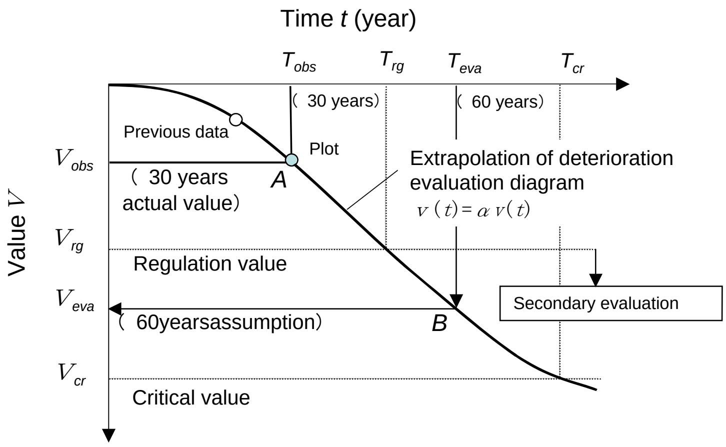

Fig.1: Outline of the integrity evaluation method by extrapolation

EVALUATION OF DETERIORATION EVALUATION DIAGRAMS FOR RC STRUCTURES

In order to obtain *P-t* diagram

If a *P-t* diagram of a reinforced concrete structure is directly obtained by plotting the deterioration evaluation diagram, $P(t)$, of its performance as the evaluation value, V, on the vertical axis of Fig. 1 in relation to the number of years elapsed, t, then an integrity evaluation can be carried out for the structure. This is difficult, however, because measurement of the performance of an actual structure is difficult and because the deterioration of concrete members develops as complex deterioration of multiple materials. For this reason, the following evaluation procedure is proposed:

Relationship between *t* and *F* (*F-t* diagram)

To begin with, the relationship between the amount of action of a deteriorative factor, F, and the number of years elapsed, t, is expressed as Eq. (2) using coefficient α and a basic evaluation equation, $f(t)$. This is referred to as an *F-t* diagram.

$$F(t)=\alpha f(t) \tag{2}$$

Coefficient α in this equation, which denotes the intensity of the action of the deteriorative factor, is referred to here as the deteriorative factor index. The amount of action of a deteriorative factor, F, represents such values as chloride ion concentration at the depth of reinforcement and carbonation depth (a substitute for the amount of action of carbonation concentration). These and other examples of factors are given in Table 1.

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	Constitutive law
F_4	Radiation	D_4	Sectional loss	P_4	Earthquake response
F_5	Aggregate reaction	D_5	Tensile strength	P_5	Adhesion strength of rebar
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	－	P_8	Permeability
F_9	－	D_9	－	P_9	－
F_0	Others	D_0	Others	P_0	Others

Relationship between *D* and *F* (*D-F* diagram)

The relationship between the deterioration degree of materials, *D*, and the amount of action of a deteriorative factor, *F*, is then expressed by coefficient β and a basic evaluation equation, $d(F)$. This is referred to as a *D-F* diagram.

$$D(F)=\beta\, d(F) \tag{3}$$

Coefficient β in this equation, which denotes the deterioration degree of materials under the effect of a deteriorative factor, is referred to here as the material deterioration index. When assuming a combined deteriorative factor to express various deteriorative factors affecting the deterioration of materials, the validity of the basic evaluation equation with such a deteriorative factor should be verified beforehand. When using an existing equation including time as a parameter, parameter *t* should be converted to parameter *F* by Eq. (2), for instance.

Relationship between *P* and *D* (*P-D* diagram)

The relationship between the performance of a structure, *P*, and the degree of material deterioration, *D* is formulated into a *P-D* diagram. Specification values related to secondary evaluation have to be determined by P_{rg}. The *P-D* diagram is directly determined by numerical analysis, design equations, or experiment equations based on the material properties after deterioration, as it is difficult to directly measure the performance of an actual structure, *P*, and as the *P-D* relationship is universal and independent of locality or affecting factors. Extrapolation will become applicable when sufficient data are accumulated.

Relationship between *t* and *P*

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 under items (1) to (3) as shown in Fig. 2. 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 Eqs. (2) and (3) and regarding its adequacy and accuracy.

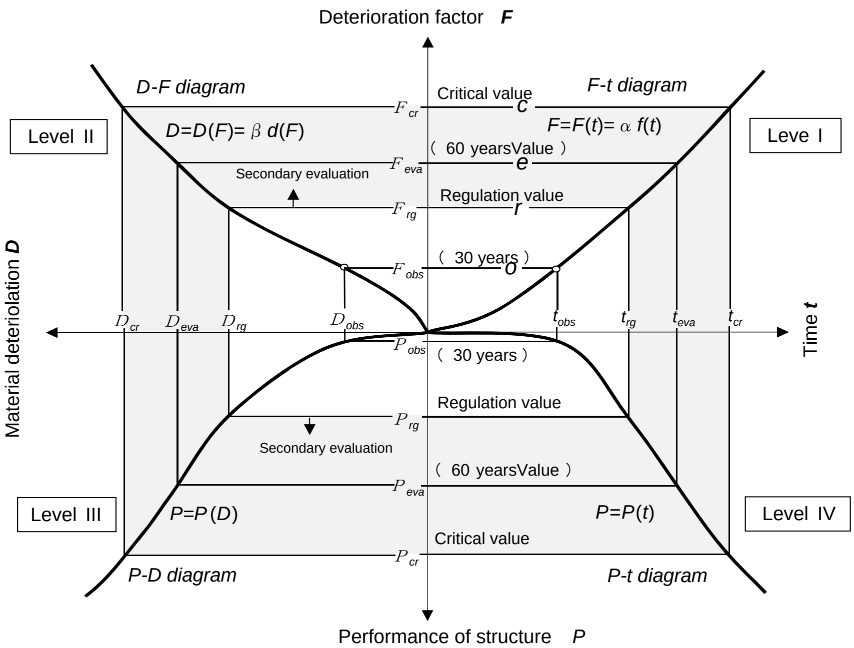

Fig.2: Integrity evaluation diagram of reinforced concrete structures （*PDFt diagram*）

INTEGRITY EVALUATION OF REINFORCED CONCRETE STRUCTURES USING A *PDFT* DIAGRAM

Integrity evaluation using a *PDFt* diagram (Fig. 2) is carried out as follows:

(1) Determination of the object of evaluation: Determine the deterioration of materials in focus, deteriorative factor, and the performance of the structure, P.

(2) Basic evaluation equations: Determine the basic evaluation equations, $f(t)$, and $d(F)$.

(3) Measurement of the degree of deterioration: Measure the F_{obs} and D_{obs} values of the actual structure at a time of evaluation, t_{obs} (30 years, for instance), by general destructive or nondestructive test methods.

(4) Evaluation of the deterioration index: Plot the obtained amount of action of the deteriorative factor, F_{obs}, in relation to the number of years elapsed, t, as well as the degrees of deterioration, D_{obs} in relation to F_{obs}, along with past data, if available, and extrapolate into $f(t)$ and $d(F)$, respectively, to determine coefficients α and β. These are deteriorative factor index, α_m, and material deterioration index, $\beta_m{}^n$, respectively, which are the evaluation values characteristic of the structure. Note that n and m match the item numbers of F and D in Table 1 (multiple numbers if multiple factors act). "$\beta_3{}^{12}$," for instance, denotes the material deterioration index for assessing the degree of reinforcement corrosion under the effects of two deteriorative factors: carbonation and chlorides.

(5) Determination of the deterioration evaluation diagrams: Establish the *F-t* and *D-F* diagrams using coefficients α and β. Determine the *P–D* diagram beforehand based on member conditions, etc., using empirical equations, analysis, and design equations.

(6) Establishment of the *P-t* diagram: Form the *PDFt* diagram from the established *F-t*, *D-F*, and *P-D* diagrams to establish the *P-t* diagram in level IV.

(7) Integrity evaluation: Determine the evaluation value, P_{eva}, at a desired year to be estimated, t_{eva}, using the *PDFt* diagram. Also determine the associated values of F_{eva} and D_{eva}.

(8) Secondary evaluation: Establish the specification value, P_{rg}, according to the performance of the structure. When it cannot be established, establish F_{rg} and D_{rg}. When the evaluated value exceeds the specification value, proceed to secondary evaluation for detailed investigation.

(9) Aging management: When the evaluated value does not exceed the specification value in item (8) above, carry out aging management, focusing on the time when it exceeds the specification value. Flow of integrity evaluation is shown in Fig. 3. Note that most conventional specification values related to the durability of reinforced concrete structures specify the amount of effect of deteriorative factors, F, and degree of material deterioration, D, but their validity is not clear in many cases. The evaluation of a *PDFt* diagram by the methodology proposed in the present study allows the establishment of specification values for the amount of effect of deteriorative factors, F, and degree of material deterioration, D, from the specification value based on the performance of the structure, P.

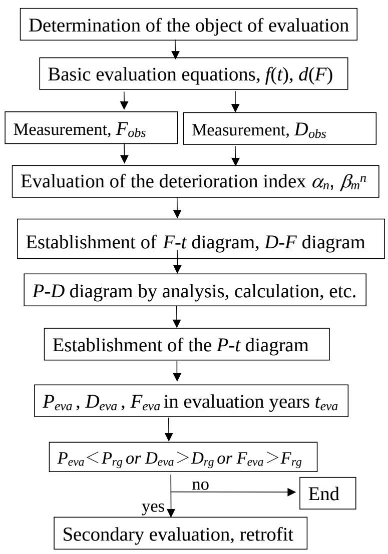

Fig.3: Flow of integrity evaluation

EVALUATION OF DETERIORATED MATERIAL PROPERTIES

Necessary material properties required for durability evaluations of RC members include concrete, rebar and mutual effect of both, meaning the property value of strength and initial stiffness as well as material constitutive model. Constitutive materials model represents relationship of stress and strain used for materials nonlinear numerical analysis such as finite element method. Property value of strength and initial stiffness can be obtained in the course of constitutive materials model evaluation. Important points to note for evaluation of constitutive materials model considering deterioration are stated as follows.

(1) To clarify the deterioration phenomenon and deterioration factors of the materials and grasp the mechanical damages.
(2) To extract the sample materials from actual deteriorated parts and create constitutive model on the basis of those properties.
(3) To assume materials model so as to result in conservative analytical results. Fig.4 shows framework of the secondary integrity evaluation.

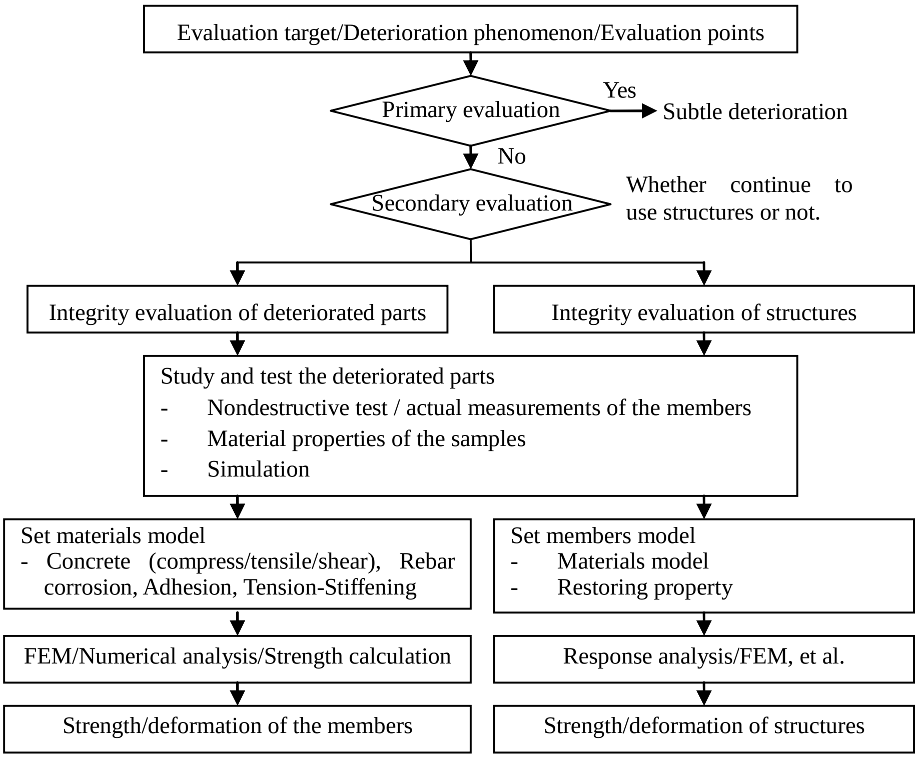

Fig.4: Framework of members/structures evaluation within secondary integrity evaluation

CONTSTITUTIVE MODEL OF CORRODED REBAR

It is preferred to extract the samples of corroded rebar from actual part and measure the amount eroded and obtain stress strain diagram from tensile test. In such case, evaluation of potential strain is also available. In case extraction of samples from rebar is difficult, expose the rebar and identify the diameter and type of the rebar so as to evaluate the extent of the corrosion. As corrosion of the rebar usually starts from the surface, that material deterioration due to corrosion of rebar can be regarded as erosion of cross sectional area. It is rational to evaluate appearing Young’s modulus instead of average cross sectional area and make a model by referring the largest erosion (the largest corroded amount) of the cross sectional area for yield value[1]（Fig.5）.

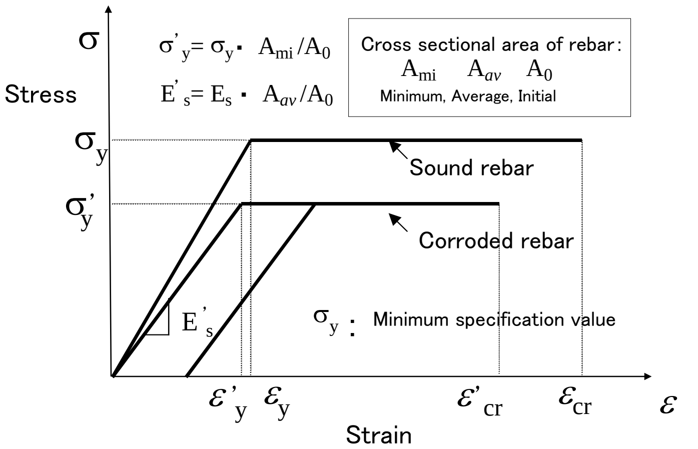

Fig.5: Model of stress strain diagram of corroded rebar

CONSTITUTIVE MODEL OF DETERIORATED CONCRETE

Compression stress strain relationship

Stress strain diagram is obtained by extracting the core parts from actual deteriorated parts and implementing the uniaxial compression test. In the course of obtaining the stress strain diagram, also evaluate the property value of compressive strength and Young's modulus. And make a model of stress strain relationship on the basis of the test results. Existing models are mostly approximated by function curve and poly-linear. Fig. 6 shows the evaluation example.

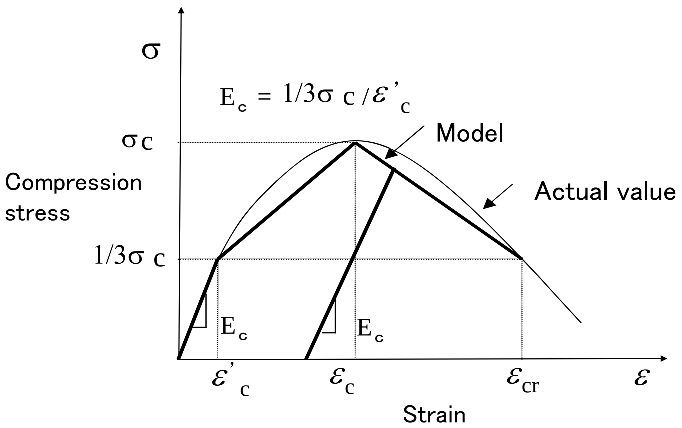

Fig.6: Model of stress strain diagram under compression stress

Tension softening diagram

When considering tensile strength by analysis, generally, the tension softening diagram is used. There are several types, one of which expresses the function, bilinear and poly-linear, yet the bilinear can be considered enough for normal concrete (Fig. 7). With CEB-FIB model code 1990[2], fracture energy G_F is calculated by (4) formula using compressive strength fc and largest diameter of aggregate d_{max}, and parameter of the bilinear model is evaluated by (5) formula using tensile strength F_t. These values can also be evaluated by core samples extracted from deteriorated parts. However, applicability to the deteriorated materials should require further verification. For further detailed evaluation, there are methods to decide parameter of bilinear model by evaluating[3] fracture energy G_F with three-point bending tests on notched beams specified in JCI standard and combining it with tensile strength F_t. There is also a report stating that a model making one fifth of a of Fig. 7 is appropriate[4]. JCI standard also proposes several evaluation methods for more detailed poly-linear model[3].

$$G_F=G_{F0}(f_c/10)^{0.7} \quad (G_{F0}\text{: Basic value determined by } d_{max}) \tag{4}$$

$$W_1=2G_F/F_t-0.15W_c, \quad W_c=\alpha_F \cdot G_F/F_t \tag{5}$$

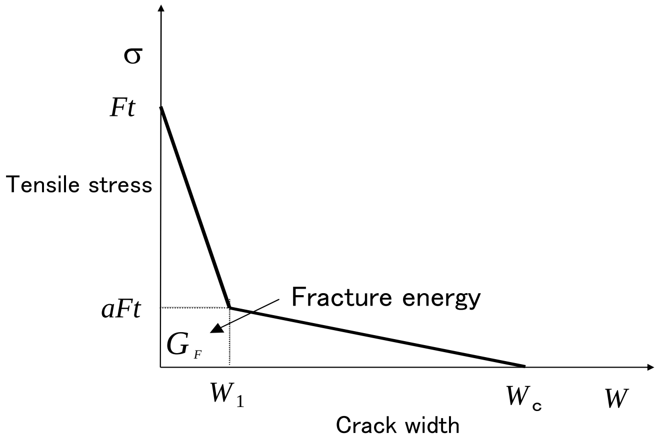

Fig.7: Tension softening model

MUTUAL EFFECT OF REBAR AND CONCRETE

Adhesion stress – slip relationship

The constitutive equation to evaluate adhesion of corroded rebar and concrete is related to the relationship between shear stress and slip amount of rebar (Fig. 8). As for such relationship, it is difficult to have direct evaluation from deteriorated parts, so that it requires the identification of the evaluation method which estimates the value from the extent of corrosion of rebar and properties of the concrete.

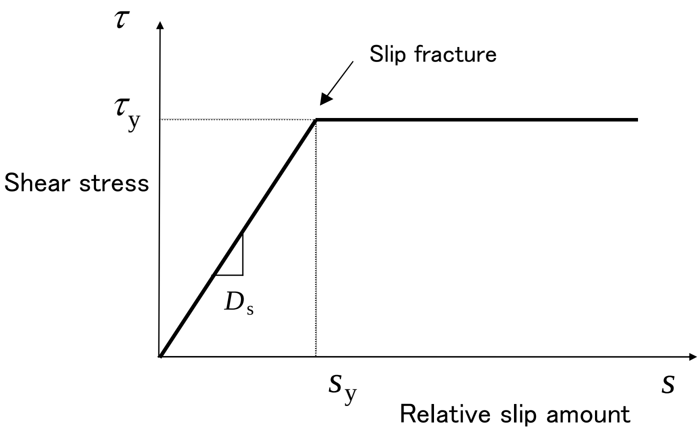

Fig.8: Model of shear slip of rebar and concrete

Tension stiffening

Adhesion characteristic of interface between rebar and concrete can be created as model for tension stiffening and can be regarded as constitutive law against tensile load of reinforced concrete. Generally, creating a model is available by combining the tensile strain relationship (Fig. 5) of rebar and tension softening property (Fig. 7), yet consideration is still required for combination in case of corroded rebar. There is an example of modeling of adhesion characteristic with corroded rebar by reducing the area of softened zone of tension softening diagram[1]. As for other material model, there are several types including shear stress – strain relationship, combination of each model and repeat/history model and grasping of following condition after deterioration of materials comes to as next issue.

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CONCLUSIONS

This report 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. In this method, basic evaluation equations of deterioration functions of a cumulative nature are determined by the minimum unit of one year to assume the uniformity of the deteriorative factor. Measurement data of the degree of deterioration are extrapolated into the equations to determine the evaluation diagram

(2) 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 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. Evaluation by *PDFt* diagrams combining these relationships is proven to be effective.

(3) For an enhanced accuracy of evaluation, it is necessary to investigate the validity of the evaluation equations and basic evaluation equations, as well as the validity of the basic evaluation equations for material deterioration with multiple deteriorative factors, based on experiments and accumulated measurement data on deterioration degrees.

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