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Experimental Study for Simulation of the Deterioration of Concrete Structures*

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Abstract

The purpose of this study is to evaluate the deterioration of reinforced concrete structures at the planning and design stages.

This paper examines the basis for quantifying the durability of structures. In addition, reinforced concrete structure (kaleidoscopic change) deterioration predictions are analyzed. The steps are as follows:

1) Various concrete durability calculation formulae were selected by ourselves, from previously published file data.
2) Next we designed a series of formulae with the purpose of calculating the synthetic degree of deterioration.
3) Finally the synthetic degree of deterioration was calculated and understood.

1. Introduction

Recently, calculation of life cycle cost and quantifying of the service life of concrete structures have been of concern, and establishment of rational and objective techniques for quantifying the durability of new structures at the planning stage are in demand. The techniques for quantifying the durability of concrete structures are distinguished between evaluating the degree of health for existing structures and the techniques for quantifying for planning structures by purpose. This paper examines the basis of quantifying for structures at the design stage and the prediction of concrete deterioration change in time by analyzing and choosing concrete durability data. One of the latest studies is the project of synthetic developing techniques of the Building Research Institute of the Ministry of Construction. Some of the purposes are the development of synthetic techniques for research and the improvement of durability, and the preparation of criterion for judgment of structures. At present, techniques for judging the degree of deterioration of existing structures for maintenance and the technical skills have been considered in the project. On the other hand, a test

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method for construction materials quantifying durability and the prediction of service life are given at ASTM E-632. The development of a technique for quantifying for planning structures at the design stage would be an advance.

2. Investigation of the Technique for Quantifying Durability

2.1 Investigation of Flow for Quantifying the Durability of Structures at Planning

The flow chart for quantifying the durability of structures at planning is shown in Fig. 1. In this flow chart, the initial data of the temperature, the humidity, the distance from the sea, the result of water analysis and so on, which are external forces of degradation by external factors, and environmental factors around the structure, are inputted. The strength of concrete, its stress, the strength of its reinforcing steel, mix proportion of concrete (w/c, type of cement, water amount, content of air, material and so on), which are the value of design and inner factors, are inputted too. Further, years of quantifying are inputted.

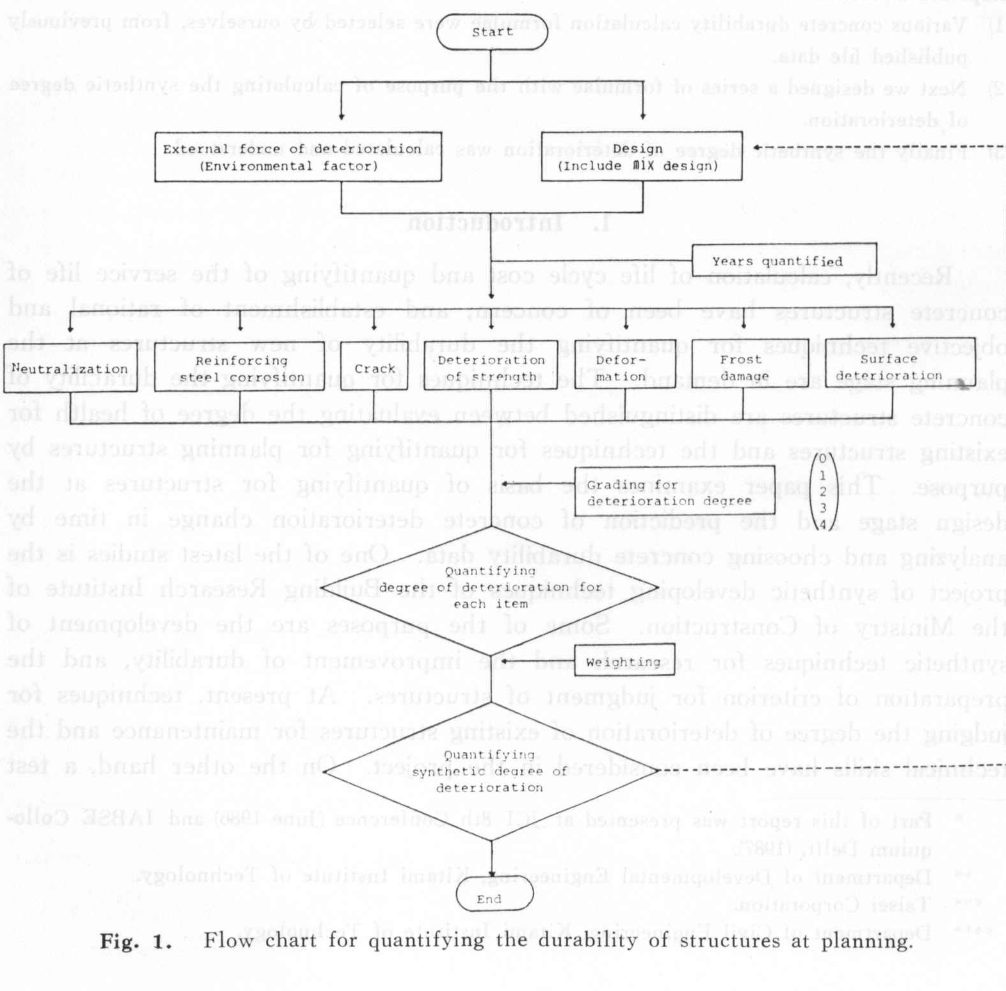

Fig. 1. Flow chart for quantifying the durability of structures at planning.

Next, the degree of deterioration each year for each item is calculated, graded, and weighted with the capability demanded from each item. Lastly, the synthetic degree of deterioration is quantified with the calculation results.

2.2 Choice of Items for Quantifying Durability

Seven items for quantifying the durability of civil structures were chosen, which are neutralization, reinforcing steel corrosion, crack, deterioration of strength, deformation, frost damage and surface deterioration. The definition of these is shown in Table 1. The reason why surface deterioration is chosen is that fine sight and adequate cover of reinforcing steel are demanded for bridges and civil structures. However, the deterioration phenomenon of each item's quantified durability is regarded as independent of their dependence on each other.

Table 1. Definition of deterioration for each item quantified

Item of quantifying	Definition
a Neutralization	Deterioration due to declining alkalinity of concrete with carbonic acid gas in air and sodium carbonate in water (pH<10)
b Reinforcing steel corrosion	Deterioration due to corroding reinforcing steel by oxidation and deoxidation with neutralization of concrete around it, water from cracks and corrosion (Cl^-, SO_4^{2-})
c Crack	Deterioration due to growing macro and scopic failure of concrete by over permitted stress (major stress over tensile strength) of concrete
d Deterioration of strength	Deterioration due to decreasing strength of concrete with material, environment in service, thermal action and chemical action
e Deformation	Deterioration due to deformating horizontal members by structural external force action and dry shrinkage (excepting short term load)
f Frost damage	Deterioration due to decreasing strength proper ties of concrete by freezing and thawing water in concrete
g Surface deterioration	Deterioration of concrete surface by scaling and popout

2.3 Choice of Deterioration Indicator

In choosing a deterioration indicator, the possibility of quantifying deterioration change over a period of time and much existing data supported by the sufficient experiments are to be taken into account. As the indicator, neutralization depth, ratio of corrosion, change rate in relative dynamic modulus of elasticity and average depth of damage are selected for each item to be quantified, as shown in Table 2.

Table 2 (a). Deterioration indicator, factor,

Quantifying Item	Selected Indicator		Factor ([ ]
	Indicator	Phenomenon	External Factor
a. Neutralization	Depth of neutralization ×(mm)	① Neutralization	[t: Service life (year)]
b. Reinforcing steel corrosion	Ratio of corrosion surface P (%)	① Corrosion of penetrating chloride	[t: Service life (year)] L: Distance from sea (m) Co: Amount of chloride from sea (wt%)
		② Corrosion of neutralization	
		③ Corrosion of crack	
c. Crack	Maximum width of crack (mm)	① Crack of steel stress	
		② Crack of dry and temperature shrinkage	TC: Change of temperature (℃)
		③ Crack of alkali silica reaction	

calculation and grading for each item quantified

variable) Inner Factor	Calculation of Deterioration Indicator (durability) at Lapse of Year	Grading
W/C: Water cement ratio (%) R: [Type of cement, Type of AE agent, Type of aggregate]	$W/C \geqq 60\%$: $x=10\times\sqrt{\frac{R^2(0.01W/C-0.25)^2}{0.3(1.15\cdot 0.01W/C)}t}$ 4) $W/C<60\%$: $x=10\times\sqrt{\frac{R^2(0.046W/C-1.76)^2}{7.2}t}$	1: $20\leqq X<40$ 2: $40\leqq X<80$ 3: $80\leqq X<100$ 4: $100\leqq X$ X: $\frac{\text{Depth of neutralization}}{\text{Depth of cover}}\%$
Dc: Diffusivities of concrete (cm²/s) D: Depth of cover (mm) UF: Unit weight of cement (kg/m³) W/C: Water cement ratio (%) γ: Index of workability: $\gamma=1$	$Co=0.48-0.07\ln L$ (Pacific side) $Co=0.45-0.06\ln L$ (Japan sea side) $C=Co\left(1-erf\frac{D/10}{2\sqrt{Dc\cdot t\cdot 3.1536\times10^7}}\right)$ 5) $erfx=\int_0^x \exp(-\mu^2)\,d\mu,\ m=0.094t+0.245-0.029D$ 6) $P=\gamma\frac{2000}{UC}\cdot\frac{C}{2}\cdot(0.01W/C-0.3)\cdot10^m$ 7)	0: $P<10$ 1: $10\leqq P<20$ 2: $20\leqq P<30$ 3: $30\leqq P<50$ 4: $50\leqq P$
D: Depth of cover (mm) X: Depth of neutralization (mm)	$P=(1-\phi(d-X/0.41X))\times100$ 8) where; ϕ (a): Normal distribution function	
D: Depth of cover (mm) W_{max}: Maximum width of crack (mm)	$W_{mean}=\frac{W_{max}+0.03}{1.91}$ 9) where; W_{mean}: Average width of crack $P=0.167(W_{mean}/D^2\times10^6-20)$ 10)	
f_s: Stress of reinforcing steel (kgf/cm²) D: Depth of cover (mm) β: Note 1) A: Note 2)	$W_{max}=0.0108\beta f_s\sqrt[3]{D/10\times A}\times10^{-3}$ 11)	0: $W_{max}<0.05$ 1: $0.05\leqq W_{max}<0.2$ 2: $0.2\leqq W_{max}<0.3$ 3: $0.3\leqq W_{max}<0.5$ 4: $0.5\leqq W_{max}$
b: (m) h: (m) NH: fct: (kgf/cm) fb: (kgf/cm) ϕ: (m) ε_{cs}: shrinkage stralm ε_{te}: Note 3) Show in Table 4	$W_{max}=\frac{2b\cdot h\cdot fct}{\pi\cdot NH\cdot\phi\cdot 1b}$ $(\varepsilon_{cs}+\varepsilon_{te}-100\times{}^{-6})\times1000$ 12)	
RG: Content of reactionable aggregate (%) Ru: Amount of Na_2O in aggregate by cement (%)	The expansion (EX) is estimated by RG and RU 13)	

Note 1) β: The ratio of distance from axial of neutrality to center of reinforcing steel to distance from axial of neutrality to tensile side in the case of beam L.

A: The area of tensile side concrete of symmetry with steel number of reinforcing steel.

Table 2 (b).

Quantifying Item	Selected Indicator		Factor [ ]
	Indicator	Phenomenon	External Factor
d. Deterioration of strength	Notes 2) Ratio of compressive strength *SN* (%)	① Deterioration of penetrating sulfate	[*t*: Service life (year)]
		② Deterioration of frost damage	[*t*: Service life (year)] *M*: Cycles of freeze-thaw a year
		③ Deterioration of alkali silica reaction aggregate	
e. Deformation	Strain ε (%)	① Deformation of creep strain	σ: Stress of concrete loading (kgf/cm^2)
		② Deformation of dry and temperature	*Tc*: Change of temperature (℃)
f. Frost damage	Change rate in relative dynamic modulus of elasticity *DN* (%)	① Frost damage	[*t*: Service life (year)] *N*: Cycles of freezethaw a year
g. Surface deterioration	Average depth of damage *H* (mm)	① Surface deterioration of frost damage	[*t*: Service life (year)] *N*: Cycles of freeze-thaw year *W*: Coefficient of supplying seawater

Note 1) β: The ratio of distance from axial of neuturality to center of reinforcing steel to distance from axial of neuturality to tensile side in the case of beam 1.2.

A: The area of tensile side concrete of symmetry with steel number of reinforcing steel.

Continued

variable) Inner Factor	Calculation of Deterioration Indicator (durability) at Lapse of Year	Grading
W/C: Water/cement ratio	Linear Regression of experimental data 14) $W/C=55\%$ H_2SO_4: 0.3%, $SN=-40.15t+100$ H_2SO_4: 2.0%, $SN=-233.6t+100$ H_2SO_4: 5.0%, $SN=-244.55t+100$	0: $95<SN$ 1: $90<SN\leqq95$ 2: $80<SN\leqq90$ 3: $70<SN\leqq80$ 4: $SN\leqq70$
W/C: Water/cement ratio AE or Non AE: Whether the there is AE agent	DN of f. ① is converted to by the equation $SN=\dfrac{DN-25}{0.75}$ AE $W/C=40\%$ $SN=-0.04N\cdot t+100$ 15) $W/C=50\%$ $SN=-0.07N\cdot t+100$ $W/C=55\%$ $SN=-0.11N\cdot t+100$ $W/C=60\%$ $SN=-0.12N\cdot t+100$ Non AE $W/C=30\%$ $SN=-0.49N\cdot t+100$ 16) $W/C=60\%$ $SN=-0.69N\cdot t+100$	
RG: Content of reactionable aggregate RU: Amount of Na_2O in aggregate (%)	$SN(f(EX)$ is estimated with the expansion EX of c ③ 17)	
Ec: Youngs modulus ϕ: Coefficient of creep	$\varepsilon=\dfrac{\sigma}{Ec}\cdot\phi$ (outdoor $\phi=2.0$) 18)	0: $\varepsilon<420$ $(\times10^{-6})$
Uc: Unit weight of cement W/C: Water cement ratio	$\varepsilon_{cs}=0.00148W/C+0.000301UC-0.131$ 19) $\varepsilon_{te}=10\times10^{-4}\times TC$	1: $420\leqq\varepsilon<670$ 2: $670\leqq\varepsilon<1033$ 3: $1033\leqq\varepsilon<2290$ 4: $2290\leqq\varepsilon$
W/C: Water cement ratio (%) AE or NonAE: Whether there is AE agent	Linear Regression of experimental data 15) AE $W/C=40\%$ $DN=-0.028N\cdot t+100$ $W/C=50\%$ $DN=-0.053N\cdot t+100$ $W/C=55\%$ $DN=-0.080N\cdot t+100$ $W/C=60\%$ $DN=-0.085N\cdot t+100$ Non AE $W/C=40\%$ $DN=-0.36$ $N\cdot t+100$ $W/C=60\%$ $DN=-0.51$ $N\cdot t+100$	0: $96<DN$ 1: $93<DN\leqq96$ 2: $85<DN\leqq93$ 3: $78<DN\leqq85$ 4: $DN\leqq78$
W/C: Water cement ratio (%) α: Coefficient of type of cement and curing condition fc: Compressive strength of concrete K: Rate of decreasing surface strength	$H=W\cdot\alpha(N^{\left(\frac{W/C}{55}\right)^3}-(0.001195k^2\cdot fc^{2)})^{\left(\frac{W/C}{55}\right)^3})$ 20) $W=0.5$ where; $\alpha=0.0129$ 21)	0: $H<1$ 1: $1\leqq H<2$ 2: $2\leqq H<3$ 3: $3\leqq H<4$ 4: $4\leqq H$

Note 2) Superpose the development strength at the age

$$\begin{bmatrix} SN=-55.32+16.60\ln(365t) \\ DN=-41.49+12.54\ln(365t) \end{bmatrix}$$

Note 3) ε_{te}: Total contraction after peak temperature due to heat of hydration

Table 3. Relation between quantifying item (deterioration indicator) and deterioration phenomenon

Item	Deterioration Phenomenon												
	Neutralization	Reinforcing Steel Corrosion	Crack	Deterioration of Strength	Deformation	Frost Damage	Surface Deterioration	Dry Shrinkage and Thermal Shrinkage	Alkali-Aggregate Damage	Strain of Creep	Diffusion of Chloride	Crack of Steel Stress	Diffusion of Sulfate
Neutralization (Neutralization depth: mm)	●												
Reinforcing steel corrosion (Ratio of corrosion surface: %)	■	○	■					△	△		●	△	
Crack (Width of crack: mm)			○					●	●			●	
Deterioration of strength (Ratio of compressive strength: %)				○		■			●				●
Deformation (Strain: %)					○			●		●			
Frost damage (Change rate in relative dynamic modulus of elasticity: %)						●							
Surface deterioration (Average depth of damage: mm)						■	○						

Note ●: Deterioration phenomenon varies deterioration indicator and is converted to the indicator.
○: Deterioration phenomenon subordinates other deterioration phenomenon and is not converted to deterioration indicator.
■: Deterioration phenomenon subordinates other quantifying item and is converted to deterioration indicator.
△: Deterioration phenomenon is subondinated Case (3) and is not converted to deterioration indicator.

2.4 Quantifying Change of Deterioration in Time by Deterioration Indicator

In the case when the deterioration indicators are varied by plural deterioration which are shown in Table 3. The equation and data to quantify the change of indicator over a period of time correspond to the deterioration phenomenon distinguished. In the case that the progress of deterioration was not described by a general equation, the data was analyzed and adjusted by regression analysis statistically. The increase of the indicator of each deterioration phenomenon is calculated by the equation and they are added according to their relation as shown in Table 3. The indicators of each quantifying item are made with the sum. However, crack and deformation are assumed to occur at an early stage because the setting up of the condition to calculate their occurrence and the change in time are complex.

2.5 Investigation of Grading for Degree of Deterioration

The maximum values of the varying indicators are assumed. They are proportionally divided and made to grade from 0 to 4. The grading is shown in Table 2.

2.6 Calculation of Synthetic Degree of Deterioration

The synthetic degree of deterioration is calculated by equation (1). The number of quantifying items is seven.

$$\text{SYNTHETIC DEGREE OF DETERIORATION} = \sqrt{\sum_{i=1}^{7}\left(Ai^2 \cdot \frac{\alpha i}{100}\right)} \qquad (1)$$

Where Ai is the average degree of deterioration and αi is the weight of deterioration for each item $\left(\sum_{i=1}^{7} \alpha i = 100\right)$.

3. Applicable Investigation for Existing Structures

The external forces of deterioration of existing structures, the value of the design and the age the time of investigation were inputted and calculated. The results were compared to the actual deterioration, and those applicable for existing structures were examined. The conditions of the existing structure, which was a wharf and shown in Table 4, were inputted. The change over a period of time of the quantifying items were calculated and shown in Fig. 2 from 1 to 7, but the calculation was done without considering cracks, because cracks occurred at the early stage and were repaired at the beginning. The rate of the depth of neutralization and the corrosion of the reinforcing steel of the actual data were very much faster than the calculation showed. The reason seemed to be the effect of the cracks which occurred at an early stage. The structural safety and fire proof capability were assumed to be the capability of the structures, and the weight of capability was assumed to be as shown in Table 5. The synthetic degree of deterioration was calculated and shown in Fig. 2.

Table 4. Data of actual structures for examination

Factor		Mark : Parameter (nuit)	Actual Structure Wharf (A)	Actual Structure Wharf (B)
External factor	External factor of deterioration	t: Service life (year)	18	24
		L: Distance from sea (m)	1	1
		Co: Amount of chloride from sea (Wt%)	1.3	0.33
		Ic: Change of temperature (°C)	30.3	33.3
		S: Concentration of sulfate of water contacted surface (Wt%)	—	—
		M: Cycles of freeze-thaw a year	5	5
		W: Coefficient of supplying seawater	0.5	0.5
Inner factor	Design	D: Depth of cover (mm)	75	50
		fs: Stress of reinforcing steel (kgf/cm^2)	816	1,400
		α: Stress of concrete (kgf/cm^2)	17.4	50.0
		β: Note 1	1.2	1.2
		A: Note 2 (cm)	260	62.5
		b: Width of the section (m)	0.80	0.05
		h: Depth of the member (m)	1.30	0.60
		NH: Number of steel members	4	4
		ϕ: Diameter of the steel (m)	0.029	0.019
	Material	fc: Compressive strength of concrete (kgf/cm^2)	271	344
		fct: Tensile strength of concrete (kgf/cm^2)	27.1*	34.4*

Factor		Mark : Parameter unit	Actual Structure Wharf (A)	Actual Structure Wharf (B)
Inner factor	Material	fb: Average bond strength of concrete and steel (kgf/cm^2)	54.0*	68.9*
		Ec: Youngs modulus (kgf/cm^2)	2.58×10^5	3.29×10^5
		φ: Coefficient of creep	2.0	2.0
		W/C: Water cement ratio (%)	49.1	62.0
		Uc: Unit weight of cement (kg/m^2)	320	282
		Uw: Unit weight of water (kg/m^2)	157	174
		R: Type of cement, Type of AE agent, Type of aggregate	0.6	0.6
		Ru: Amount of Na_2O in aggregate by cement (%)	—	
		RG: Content of reactionable aggregate (%)	—	—
		AE or Non AE: Whether there is AE agent	AE	AE
		Dc: Diffusivities of concrete (cm^2)	1.6×10^{-8}	0.44×10^{-8}
	Construction	α: Coefficient of type of cement and curing condition	0.0129	0.0129
		K: Ratio of decreasing surface strength		—
		γ: Index of workability : $\gamma=1$	1.0	1.0
Result of investigation		x: Depth of neutralization (mm)	19.0	15.1
		p: Corrosion surface	70	65
		Crack etc.	Loss of cover	Loss of cover

Note (1) β: The ratio of distance from axial of neuturality to center of reinforcing steel to distance from axial of neuturality to tensile side in the case of beam 1.2.

Note (2) A: The area of tensile side concrete of symmetry with steel number of reinforcing steel.

Table 5. Assumption of weight for capability demanded in each item quantified

Capability of structure	Structure safety (%)	Fire proof capability (%)	Factor of weight (%)
Weight of capability	80	20	
Neutralization	4	7	5
Reinforcing steel corrosion	58	20	50
Crack	8	20	10
Deterioration of strength	20	20	20
Deformation	4	7	5
Frost damage	3	13	5
Surface deterioration	3	13	5
Total	100	100	100

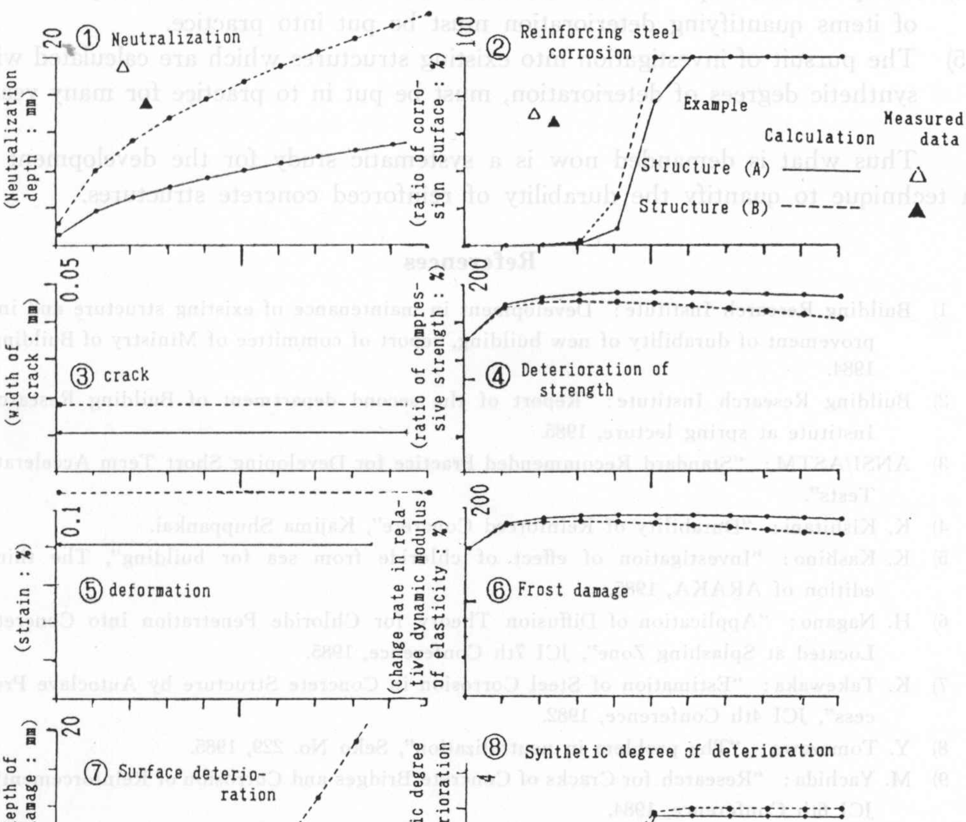

Fig. 2. Example of calculation for actual structure.

4. Future Problems

For developing the technique for quantifying the durability of reinforced concrete structures, the following studies are needed for further application of the technique.

1) The mechanisms and the factors of deterioration must be understood and readjusted. F. T. A. (Fault Tree Analysis) and so on must be put into practice.
2) Measurement and understanding of the rate of damage occurrence, and its grading must be studied.
3) The capability and the weight of capability must be examined using many cases of deterioration in existing structures and items of quantified deterioration should be weighted to each of them.
4) Many detailed experiments combined with accelerated tests and exposed tests of items quantifying deterioration must be put into practice.
5) The pursuit of investigation into existing structures which are calculated with synthetic degrees of deterioration, must be put in to practice for many years.

Thus what is demanded now is a systematic study for the development of a technique to quantify the durability of reinforced concrete structures.

References

1) Building Research Institute: Development in maintenance of existing structure and improvement of durability of new building, report of committee of Ministry of Building, 1984.
2) Building Research Institute: Report of the second department of Building Research Institute at spring lecture, 1985.
3) ANSI/ASTM: "Standard Recommended Practice for Developing Short Term Accelerate Tests".
4) K. Kishitani: "Durability of Reinforced Concrete", Kajima Shuppankai.
5) K. Kashino: "Investigation of effect of chloride from sea for building", The third edition of ARAKA, 1985.
6) H. Nagano: "Application of Diffusion Theory for Chloride Penetration into Concrete Located at Splashing Zone", JCI 7th Conference, 1985.
7) K. Takewaka: "Estimation of Steel Corrosion in Concrete Structure by Autoclave Process", JCI 4th Conference, 1982.
8) Y. Tomozawa: "The problem in neutralization", Seko No. 229, 1985.
9) M. Yachida: "Research for Cracks of Concrete Bridges and Corrosion of Reinforcement", JCI 6th Conference, 1984.
10) H. Kamiyama: "Crack of Concrete and Corrosion of Steel", CAJ REVIEW of The 31 GENERAL MEETING, 1977.
11) ACI 224 Committee: "ACI standard of structural design (ACI 318-77)", ACI, 1977.
12) BSI: BS5337 "The Structural use of concrete for retaining aqueous liquids", 1976.
13) The Society of Material Science Japan: "Symposium about Alkali-Silica Reaction, 1985.
14) H. Ikenaga: "The deteriorarion of concrete soaked in water which are different kind and concentration of acid and chloride", 1976.

15) K. Ayuta: "The Effect of Aggregate in duaability of freeze and thaw", Hokkaido branch of JSCE Conference, 1976.
16) S. Ito: "New edition of Concrete Engineering", Morikita Shuppan.
17) H. Yamashita: "Basic Experiment of reaction aggregate (No. 1)", JSCE Conference, 1985.
18) JSCE: "Specification of Reinforced Concrete", 1980.
19) JCI: "Point of Concrete technique '82", JCI, 1982.
20) H. Sakurai: "Progress Degree of Scaling on Concrete Surface", Hokkaido branch of JSCE Conference, 1980.
21) H. Sakurai: "Some Experiments of Progress Degree of Scaling on Concrete Surface", JSCE Conference, 1980.