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# Simulation and Evaluation of Deterioration of Reinforced Concrete Structures

Simulation et évaluation de la détérioration des structures en béton armé

Simulation und Auswertung der Schädigung von Stahlbetonkonstruktionen

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**SUMMARY**

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 were analyzed.

**RÉSUMÉ**

Le but de cette étude est d'évaluer la détérioration des structures en béton armé dans la phase du projet. L'article examine les bases permettant d'évaluer la durabilité des structures. Des prévisions sont faites pour l'évaluation de la détérioration des structures en béton armé.

**ZUSAMMENFASSUNG**

Das Ziel dieser Studie ist es, die Schädigung von Stahlbetonkonstruktionen im Planungs- und Entwurfsstadium zu bewerten. Der Beitrag befasst sich mit möglichen quantitativen Erfassungsmethoden.

## 1. INTRODUCTION

Recently, calculation of life cycle cost and quantifying of service life for concrete structures have been of concern, and establishment of rational and objective techniques for quantifying the durability of new structures at planning are in demand. The technique for quantifying durability of concrete structures are distinguished between evaluating the degree of health for existing structures and the techniques of quantifying for planning structures by purpose. This paper examines the basis of quantifying for structures at planning at the design stage and the prediction of concrete deterioration change in time by analyzing and choosing of concrete durability data. One of the latest studies are the projects of synthetic developing techniques of the Building Research Institute of the Ministry of Construction. Some of the purposes are development of synthetic techniques for research and improvement of durability, and preparing of criterion for judgment of structures. At the present, the techniques for judging the degree of deterioration of existing structures for maintenance and the technical skill has been given in the project. On the other hand, the test method or construction materials and quantifying durability and the prediction of service life are given at ASTM E-632. The development of the technique of quantifying for planning structures at the design stage would be an advance.

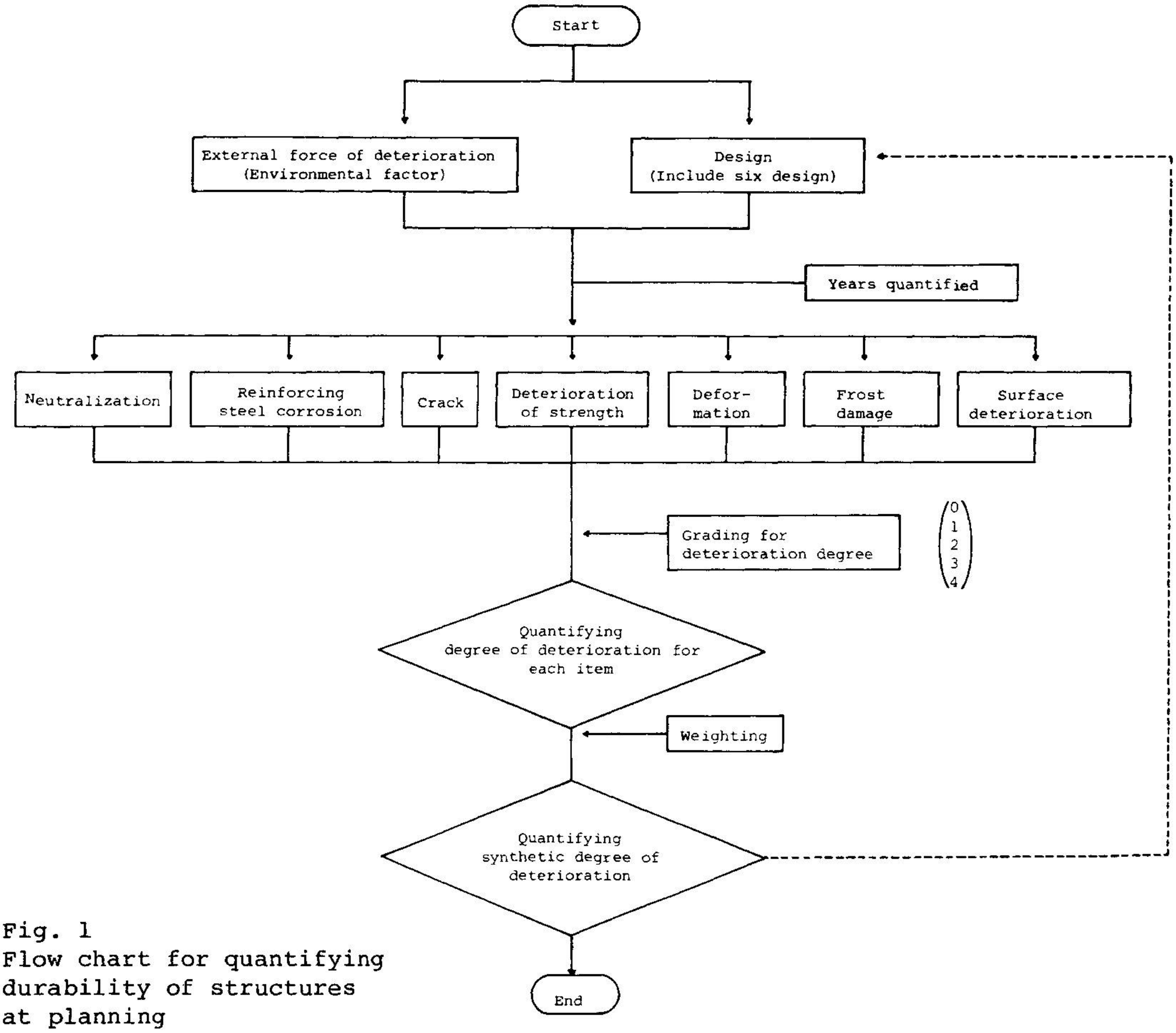



Fig. 1
Flow chart for quantifying durability of structures at planning

## 2. INVESTIGATION OF TECHNIQUE FOR QUANTIFYING DURABILITY

### 2.1 Investigation of Flow for Quantifying Durability of Structure at Planning

The Flow chart for quantifying durability of structures at planning is shown in Fig. 1. In this flow chart, the initial data of temperature, humidity, the distance from the sea, the result of water analysis and so on, which are external forces of degradation of external factors, and environmental factors around the structure, are imputted. 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 imputted too. Further, years of quantifying are imputted. Next, the degree of deterioration for year for each item are calculated, graded, and weighted with capability demanded in each item. Lastly, the synthetic degree of deterioration are quantified with calculation results.

### 2.2 Choice of Items for Quantifying Durability

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

### 2.3 Choice of Deterioration Indicator

In choosing a deterioration indicator, the possibility of quantifying deterioration change in time and much existing data supported with enough 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 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 permi 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 Deflection | Deterioration due to deflecting 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 lossing concrete surface by scaling and popout |

Table 2(a) Deterioration indicator, factor, calculation and grading for each item quantified

| Quantifying Item | Selected Indicator | | Factor (1): valuable) | | Calculation of Deterioration Indicator (durability) at Lapse of Year | Grading |
|---|---|---|---|---|---|---|
| | Indicator | Phenomenon | External Factor | Inner Factor | | |
| a. Neutralization | Depth of neutralization X (mm) | ① Neutralization | [t: Service life (year)] | W/C: Water cement ratio (%)<br>R: Type of cement<br>Type of AE agent<br>Type of aggregate | W/C≧60%: $x=10\times\sqrt{\frac{R^2(0.01W/C-0.25)^2}{0.3(1.15\cdot 0.01W/C)}t}$<br>W/C<60%: $x=10\times\sqrt{\frac{R^2(0.046W/C-1.76)^2}{7.2}t}$ 4) | 1: 20≦X<40<br>2: 40≦X<80<br>3: 80≦X<100<br>4: 100≦X<br>X: $\frac{\text{Depth of neutralization}}{\text{Depth of cover}}$% |
| b. Reinforcing steel corrosion | Ratio of corrosion surface P (%) | ① Corrosion of penetrating chloride | [t: Service life (year)]<br>L: Distance from sea (m)<br>Co: Amount of chloride from sea (wt%) | Dc: Diffusivities of concrete ($cm^2$)<br>D: Depth of cover (mm)<br>UC: Unit weight of cement ($kg/m^2$)<br>W/C: Water cement ratio (%)<br>γ: Index of workability: γ=1 | Co=0.48-0.07ln L (Pacific side)<br>Co=0.45-0.06ln L (Japan sea side)<br>$C=Co\left(1-erf\frac{D/10}{2\sqrt{Dc\cdot t\cdot 3.1536\times10^7}}\right)$ 5)<br>$erfx=\int_0^1 cxp(-\mu^2)d\mu\, m\cdot 0.094t+0.245-0.029D$ 6)<br>$P=\gamma\frac{2000}{UC}\cdot\frac{C}{2}\cdot(0.01W/C-0.3)\cdot 10^n$ 7) | 0: P<10<br>1: 10≦P<20<br>2: 20≦P<30<br>3: 30≦P<50<br>4: 50≦P |
| | | ② Corrosion of neutralization | | D: Depth of cover (mm)<br>X: Depth of neutralization (mm) | $P=(1-\phi(d-X/0.41X))\times100$ 8)<br>where; $\phi(a)$: Normal distribution function | |
| | | ③ Corrosion of crack | | D: Depth of cover (mm)<br>Wmax.: Maximum width of crack (mm) | $Wmean=\frac{Wmax+0.03}{1.91}$ 9)<br>where; Wmean: Average width of crack<br>$P=0.167(Wmean/D^2\times10^6-20)$ 10) | |
| c. Crack | Maximum width of crack (mm) | ① Crack of steel stress | | fs: Stress of reinforcing steel ($kgf/cm^2$)<br>D: Depth of cover (mm)<br>β: Note 1)<br>A: Note 2) | $Wmax=0.0108\,\beta\cdot fs\sqrt[3]{D/10\times A}\times10^{-3}$ 11) | 0: Wmax<0.05<br>1: 0.05≦Wmax<0.2<br>2: 0.2 ≦Wmax<0.3<br>3: 0.3 ≦Wmax<0.5<br>4: 0.5 ≦Wmax |
| | | ② Crack of dry and temperature shrinkage | TC: Change of temperature (°C) | b: (m)<br>h: (m)<br>NH:<br>fct: (kgf/cm )<br>fb: (kgf/cm )<br>φ: (m)<br>cs:<br>te:<br>Show in Table 4 | $Wmax=\frac{2b\cdot h\cdot fct}{\pi\cdot NH\cdot\phi\cdot 1b}(\varepsilon cs+\varepsilon te-100\times10^{-6})\times1000$ 12) | |
| | | ③ Crack of alkali silica reaction | | RG: Content of reactionable aggregate (%)<br>Ru: Amount of $Na_2O$ in aggregate by cement (%) | The expansion (EX) is estimated by RG and RU 13) | |

Table 2(b)

| Quantifying Item | Selected Indicator | | Factor (1): valuable) | | Calculation of Deterioration Indicator (durability) at Lapse of Year | Grading |
|---|---|---|---|---|---|---|
| | Indicator | Phenomenon | External Factor | Inner Factor | | |
| d. Deterioration of strength | Notes 2)<br>Ratio of compressive strength SN(%) | ① Deterioration of penetrating sulfate | [t: Service life (year)] | W/C: Water/cement ratio | Linear Regression of experimental data 14)<br>W/C=55%<br>$H_2SO_4$: 0.3%, SN=-40.15t+100<br>$H_2SO_4$: 2.0%, SN=-233.6t+100<br>$H_2SO_4$: 5.0%, SN=-244.55t+100 | 0: $95<SN$<br>1: $90<SN\leq 95$<br>2: $80<SN\leq 90$<br>3: $70<SN\leq 80$<br>4: $SN\leq 70$ |
| | | ② Deterioration of frost damage | [t: Service life (year)]<br>M: Cycles of freeze-thaw a year | W/C: Water/cement ratio<br>AE or NonAE: Whether the there is AE agent | DN of f ① is converted to by the equation<br>$SN=\frac{DN-25}{0.75}$<br>AE: W/C=40% SN=-0.04 N·t+100 15)<br>W/C=50% SN=-0.07 N.t+100<br>W/C=55% SN=-0.11 N.t+100<br>W/C=60% SN=-0.12 N.t+100<br>NonAE: W/C=40% SN=-0.49 N·t+100 16)<br>W/C=60% SN=-0.69 N·t+100 | |
| | | ③ Deterioration of alkali silica reaction aggregate | | RG: Content of reactionable aggregate<br>RU: Amount of $Na_2O$ in aggregate (%) | SN(f(EX)) is estimated with the expansion EX of c ③ 17) | |
| e. Deformation | Strain ε (%) | ① Deformation of creep strain | σ: Stress of concrete loading ($kgf/cm^2$) | Ec: Youngs modulus<br>φ: Coefficient of creep | $\varepsilon=\frac{\sigma}{Ec}\cdot\phi$ (outdoor φ=2.0) 18) | 0: $\varepsilon<420$<br>1: $420\leq\varepsilon<670$<br>2: $670\leq\varepsilon<1033$<br>3: $1033\leq\varepsilon<2290$<br>4: $2290\leq\varepsilon$ |
| | | ② Deformation of dry and temperature | Tc: Change of temperature (°C) | Uc: Unit weight of cement<br>W/C: Water cement ratio | $\varepsilon cs=0.00148W/C+0.000301UC-0.131$ 19)<br>$\varepsilon te=10\times10^{-4}\times IC$ | |
| f. Frost damage | Change rate in relative dynamic modulus of elasticity DN (%) | ① Frost damage | [t: Service life (year)]<br>N: Cycles of freeze-thaw a year | W/C: Water cement ratio (%)<br>AE or NonAE: Whether there is AE agent | Linear Regression of experimental data 15)<br>AE: W/C=40% DN=-0.026N·t+100<br>W/C=50% DN=-0.053N·t+100<br>W/C=55% DN=-0.080N·t+100<br>W/C=60% DN=-0.085N·t+100<br>NonAE: W/C=40% DN=-0.36 N·t+100<br>W/C=60% DN=-0.51 N·t+100 | 0: $96<DN$<br>1: $93<DN\leq 96$<br>2: $85<DN\leq 93$<br>3: $78<DN\leq 85$<br>4: $DN\leq 78$ |
| g. Surface deterioration | Average depth of damage H(mm) | ① Surface deterioration of frost damage | [t: Service life (year)]<br>N: Cycles of freeze-thaw year<br>W: Coefficient of supplying seawater | W/C: Water cement ratio (%)<br>α: Coefficient of type of cement and curing condition<br>fc: Compressive strength of concrete<br>K: Construction | $H=W\cdot\alpha(N^{(\frac{W/C}{55})^3}-(0.001195k^2\cdot fc^2)^{(\frac{W/C}{55})^3})$ 20)<br>W=0.5 where; α=0.0129 21) | 0: $H<1$<br>1: $1\leq H<2$<br>2: $2\leq H<3$<br>3: $3\leq H<4$<br>4: $4\leq H$ |

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

Note 2) Superpose the development strength at the age {SN=-55.32+16.60ln(365t); DN=-41.49+12.45ln(365t)}

## 2.4 Quantifying Change of Deterioration in Time by Deterioration Indicator

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

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) | | | | | | ■ | ○ | | | | | | |

Table 3 Note 1) ●: Deterioration phenomenon which vary deterioration indicator and are converted to the indicator.
○: Deterioration phenomenon which subordinate other deterioration phenomenon and are not converted to deterioration indicator.
■: Deterioration phenomenon which subordinate other quantifying item and are converted to deterioration indicator.
△: Deterioration phenomenon which are subordinated the Case (3) and are not converted to deterioration indicator.

## 2.5 Investigation of Grading for Degree of Deterioration

The maximum values of the varying indicators are assumed. They are divided with proportion and so on, 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 are calculated by equation (1). The number of items quantifying are seven.

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

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

## 3. APPLICABLE INVESTIGATION FOR EXISTING STRUCTURES

The external forces of deterioration of existing structures, the value of design and the number of years at the 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 in time of the item quantifying were calculated and shown in Fig. 2 from 1 to 7 , but the calculation was done without considering crack because cracks occurred at the early stage and was maintained at the beginning. The rate of the depth of neutralization and the corrosion of reinforcing steel of the actual data were very much faster than the calculation showed. The reason seemed to be the effect of crack 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 were assumed to be 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 (unit) | Actual Structure | |
|---|---|---|---|---|
| | | | Wharf (A) | 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 | 0.50 |
| | | h: Depth of the member (m) | 1.30 | 0.60 |
| | | WH: Number of steel members | 4 | 4 |
| | | ø: 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 |
| | | fb: Average bond strength of concrete and steel ($kgf/cm^2$) | * 54.0 | * 68.9 |

| Factor | | Mark: Parameter (unit) | Actual Structure | |
|---|---|---|---|---|
| | | | Wharf (A) | Wharf (B) |
| Inner factor | Material | Ec: Youngs modulus ($kgf/cm^2$) | $2.58 \times 10^5$ | $3.29 \times 10^5$ |
| | | ø: 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 ($cm^2$) | $1.6 \times 10^{-8}$ | $0.44 \times 10^{-8}$ |
| | Construction | α: Coefficient of type of cement and curing condition | 0.0129 | 0.0129 |
| | | K: Ratio of decreasing surface strength | | |
| | | γ: Index of workability: γ=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 |

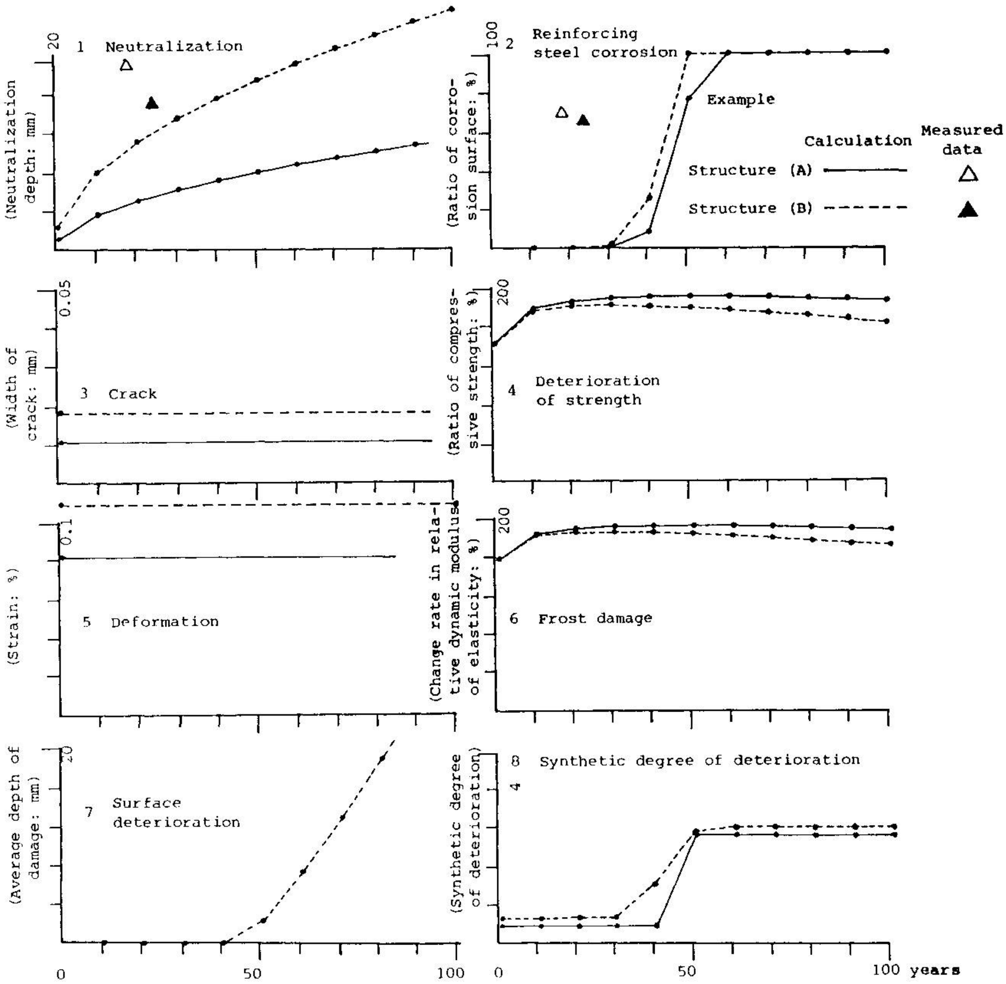
Note (1) β: The ratio of distance from axial of neuturality to center of reinforcing steel to distance from axial of neuturality to tensile side in the case of beam 1.2

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 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) The measuring and understanding of the rate of damage occurrence, and the 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 practice for many years.

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

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