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Experimental Study for the Weighting of Deterioration Phenomenon on the Performance of Concrete Structures*

by Hiroshi SAKURAI**, Koich AYUTA**, Aketo SUZUKI*** and Kazuhiro MOMOZAKI***

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Abstract

This paper deals especially with the modeling of the deterioration process of concrete structures by arranging and clarifying the formation of the deterioration phenomenon. The method of weighting is considered and examined for the performance of a structure during deterioration. Furthermore, as a model, the deterioration of a structure is simulated with the result of weight calculated from the data of existing structures, and the results are then compared and considered in relation to data from actual structures.

1. Introduction

The authors studied a method to simulate deterioration in concrete structures for design with durability and service year.[1,2] In those studies, the following problems arose. The first was how to model the deterioration phenomenon properly by arranging and analyzing the deterioration factors. The second was how to grade deterioration. The third was how to weight the deterioration phenomenon so as to obtain the performance of concrete structures in order to quantify the decrease synthetically.

In modeling the deterioration phenomenon, as the calculated value of neutralization depth tends to be smaller than the value of existing structures. It is the same with steel corrosion. In the case of frost damage, it tends to be larger, the cause being that the rate of change in the relative dynamic modulus of elasticity and the increasing ratio of compressive strength are calculated as higher. The model obtained from laboratory experimental data must approach that of existing structures.

In grading deterioration, objective standards are necessary. For buildings, this has been shown as a guide in the projects of synthetic developing techniques of the Ministry of Construction.[3] But some points require further consideration, because it is difficult to judge the grading of frost damage and surface deterioration in terms of the rate of growth of the damage area on the whole area of a structure, and the margin of the calculated synthetic degree of deterioration may not be

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** Faculty of Engineering, Kitami Institute of Technology.
*** Technical Research of Taisei Corporation.

the same because of personal differences of assessment when the degree of deterioration is being quantified. Accordingly, the grading corresponds to numerical indicators of the deterioration phenomenon and equations for calculating these must be defined. These must be made more objective through further research by various institutes and laboratories.

In weighting, because each quantifying item consists of some part of the deterioration phenomenon, it is necessary that deterioration phenomenon develop according to a Fault Tree Analysis[4], which is called F. T. A.; to arrange and clarify the relation of each step. It is also necessary that the stochastic matrix and M-matrix are produced to study how to calculate the weight of deterioration on each performance aspect of the structure.

2. Investigation Method

2.1 Assumptions for Producing the Stochastic Matrix from Deterioration Phenomenon

The process from the normal state to the abolition (absorbing) state is modeled in order to arrange the deterioration phenomenon and to evaluate each quantifying item for the very complicated deterioration of real concrete structures. In this investigation, it is assumed that the progression from the normal state (mark: O) caused by the deterioration phenomena of neutralization (N), reinforced steel corrosion (SC), crack (C), deterioration of strength (DS), deformation (D), frost damage (F) and surface deterioration (SD) to the absorbing state (E), in which the performance of the structure deteriorates, can be arranged and simplified by the Markov process.

2.2 The Process of Investigation

The investigation proceeds according to the following steps.

(1) The deterioration phenomenon of each quantification item is arranged by F. T. A.

(2) The group of the mini-path which is linked to each deterioration phenomenon is chosen. At this time, normal state (O) and absorbing state (E) are included in the event.

(3) The path, in which deterioration phenomena and the occurance corresponds a event, is chosen.

(4) It is assumed that the probability of changing from one event to another is in direct proportion to the number of paths and the probability is calculated on that basis.

(5) The figure of the Shanon path is drawn up by the probability calculated for events.

(6) The stochastic matrix (P-matrix) is produced from the preceding calculations.

(7) The matrix just before the absorbing state (E), which is the Q-matrix, is taken from the P-matrix.

(8) The M-matrix, which is the average frequency and the average time

of occurrence of each event of deterioration phenomenon from the normal state (O) to the absorbing state (E), is calculated by the following equation.

$$M=(I-Q)^{-1} \cdots\cdots\cdots\cdots\cdots\cdots \text{Equation (1)},$$

where I is a unit matrix.

(9) The total number of deterioration phenomena in each state is summed up using the average frequency number in the M-matrix and divided by the number of all deterioration phenomena without the number of the normal state. The quotient, expressed as a percentage is defined to weight each quantifying item of deterioration.

(10) The simulation is carried out using the data of existing structures.

3. The Caluclation of Weight of the Performance of Structures and the Result

3.1 Development of F. T. A. for Deterioration Phenomena

The relationship between a quantifying item and deterioration phenomenon is shown in Table 1. Furthermore the relations are expressed by the first branches of F. T. A. in order to arrange the correlations of deterioration of

Table 1. The relationship between quantitying items and deterioration phenomena

Item	Deterioration phenomenon						
	Neutral-ization	Rein-forcing Steel Corrosion	Crack	Deteri oration of Strength	Defor mation	Frost Damage	Surface Deteri-oration
Neutralization (Neutralization depth : mm)	●		●				●
Reinforcing steel corrosion (Ratio of corro-sion 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 : %)						●	
Srface deterioration (Average depth of damage : mm)						●	●

Note ● : Deterioration phenomenon varies deterioration indicator and is converted to indicator.

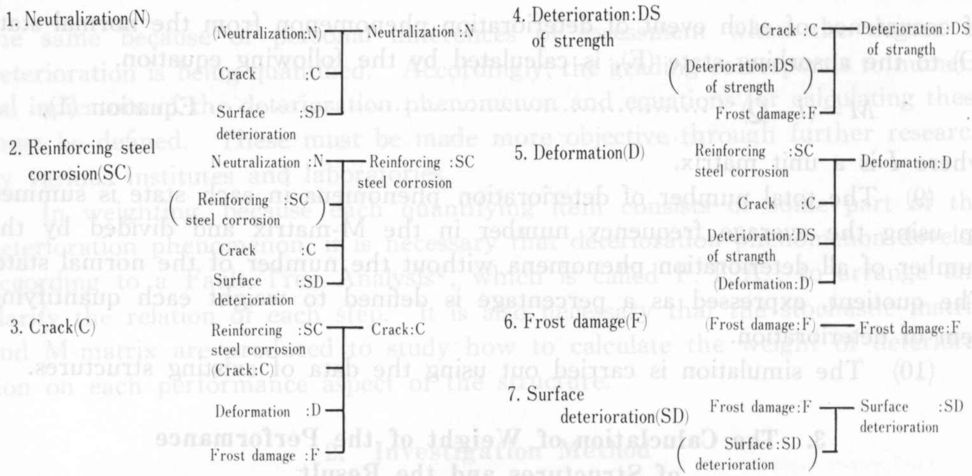

Fig. 1. The Fault Tree's first branch in each deterioration phenomenon (the basic relationship).

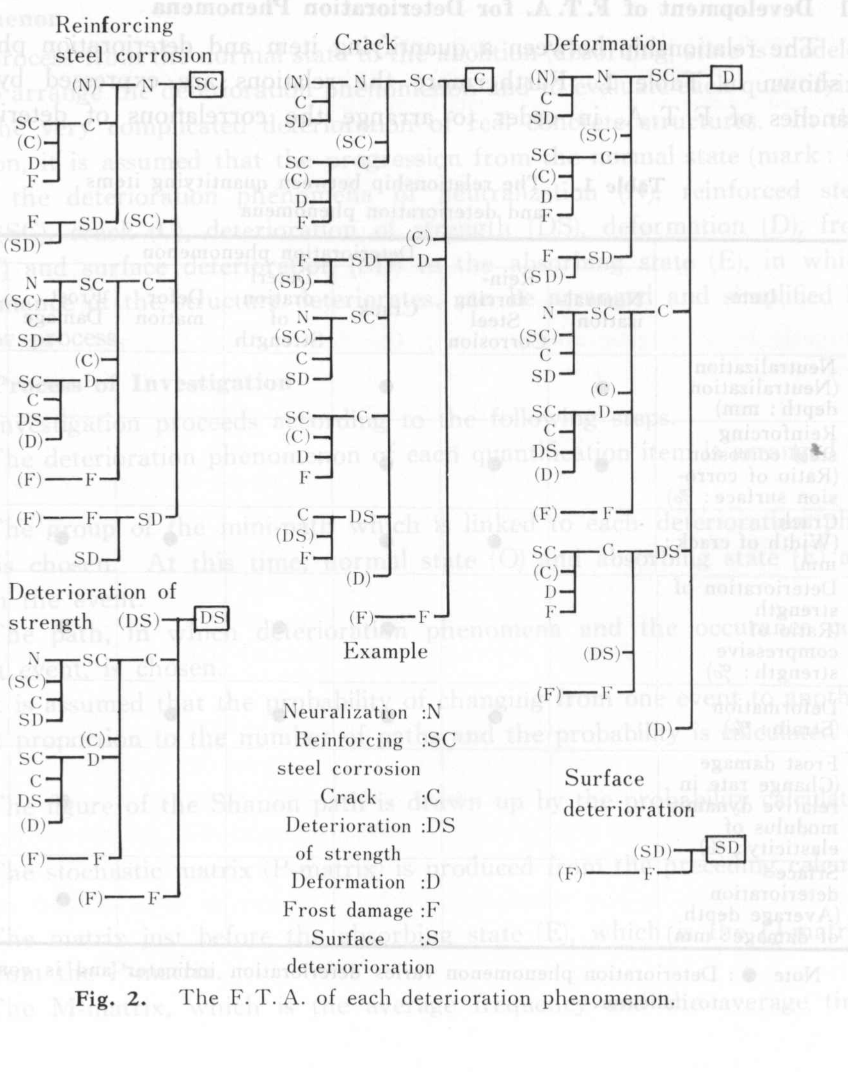

Fig. 2. The F.T.A. of each deterioration phenomenon.

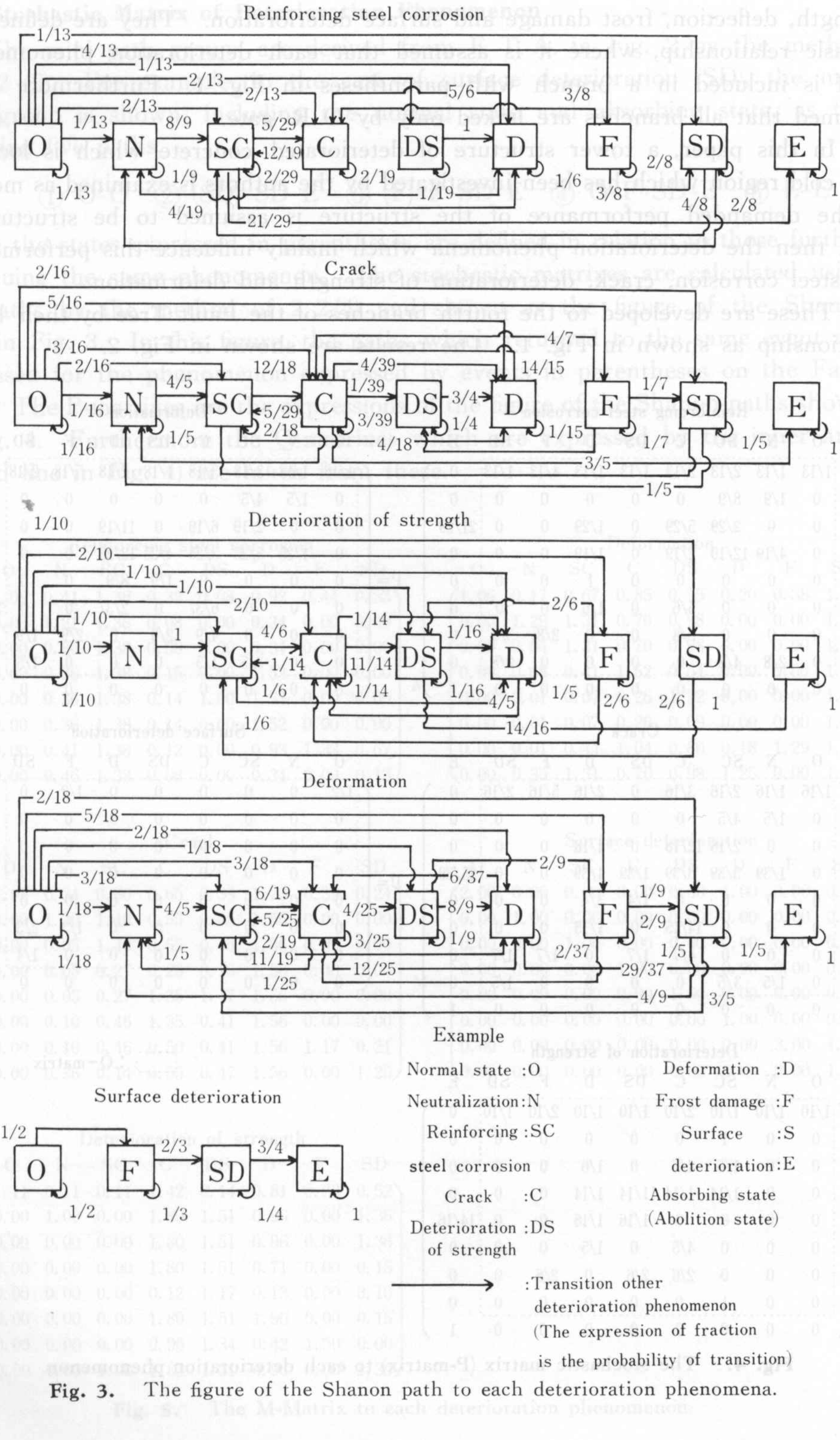

Fig. 3. The figure of the Shanon path to each deterioration phenomena.

strength, deflection, frost damage and surface deterioration. They are defined as a basic relationship, where it is assumed that each deterioration phenomenon itself is included in a branch with parentheses in Fig. 1. Furthermore it is assumed that all branches are linked only by O.R. gate.

In this paper, a tower structure of deteriorated concrete which is located in a cold region which has been investigated by the authors is examined as model. If the demanded performance of the structure is assumed to be structurally safe, then the deterioration phenomena which mainly influence this performance are steel corrosion, crack, deterioration of strength and deformation.

These are developed to the fourth branches of the Fault Tree by their basic relationship as shown in Fig. 1. The results are shown in Fig. 2.

Reinforcing steel corrosion

P=

O	N	SC	C	DS	D	F	SD	E
1/13	1/13	2/13	2/13	1/13	1/13	4/13	1/13	0
0	1/9	8/9	0	0	0	0	0	0
0	0	2/29	5/29	0	1/29	0	0	21/29
0	4/19	12/19	2/19	0	1/19	0	0	0
0	0	0	0	0	1	0	0	0
0	0	0	5/6	0	1/6	0	0	0
0	0	0	3/8	0	0	2/8	3/8	0
0	2/8	4/8	0	0	0	0	2/8	0
0	0	0	0	0	0	0	0	1

Deformation

P=

O	N	SC	C	DS	D	F	SD	E
1/18	1/18	3/18	3/18	1/18	2/18	5/18	2/18	0
0	1/5	4/5	0	0	0	0	0	0
0	0	2/19	6/19	0	11/19	0	0	0
0	1/25	5/25	3/25	4/25	12/25	0	0	0
0	0	0	0	1/9	8/9	0	0	0
0	0	0	6/37	0	2/37	0	0	29/37
0	0	0	4/9	2/9	0	2/9	1/9	0
0	0	3/5	1/5	0	0	0	1/5	0
0	0	0	0	0	0	0	0	1

Crack

P=

O	N	SC	C	DS	D	F	SD	E
1/16	1/16	2/16	3/16	0	2/16	5/16	2/16	0
0	1/5	4/5	0	0	0	0	0	0
0	0	2/18	12/18	0	4/18	0	0	0
0	1/39	5/39	3/39	1/39	4/39	0	0	25/39
0	0	0	0	1/4	3/4	0	0	0
0	0	0	14/15	0	1/15	0	0	0
0	0	0	4/7	1/7	0	1/7	1/7	0
0	1/5	3/5	0	0	0	0	1/5	0
0	0	0	0	0	0	0	0	1

Surface deterioration

P=

O	N	SC	C	DS	D	F	SD	E
1/2	0	0	0	0	0	1/2	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1/3	2/3	0
0	0	0	0	0	0	0	1/4	3/4
0	0	0	0	0	0	0	0	1

Deterioration of strength

P=

O	N	SC	C	DS	D	F	SD	E
1/10	1/10	1/10	2/10	1/10	1/10	2/10	1/10	0
0	0	1	0	0	0	0	0	0
0	0	1/6	4/6	0	1/6	0	0	0
0	0	1/14	1/14	11/14	1/14	0	0	0
0	0	0	0	1/16	1/16	0	0	14/16
0	0	0	4/5	0	1/5	0	0	0
0	0	0	2/6	2/6	0	2/6	0	0
0	0	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	1

[dashed box] : Q-matrix

Fig. 4. The stochastic matrix (P-matrix) to each deterioration phenomenon.

3.2 Stochastic Matrix of Deterioration Phenomenon

The mini path groups are derived from F. T. A. in Fig. 2 by the method of 2.2 (2). For example, in the case of surface deterioration (SD), the mini path group is shown, including the normal state and absorbing state, as the following five paths.

① O-O ② (SD)-SD-E ③ (F)-F-SD-E ④ O-F-SD-E ⑤ E-E

where the states expressed in parentheses are defined in relation to those further continuing the same phenomenon. The stochastic matrixes are calculated using the paths by the method of 2.2(4) and shown as the figure of the Shanon path in Fig. 3. In this figure, the paths which returned to the same event are expressed for the phenomenon expressed by events in parentheses on the Fault Tree. The P-matrixes are the expressions of the figure of the Shanon paths shown in Fig. 4. Furthermore the Q-matrixes which are expressed by the inner area (dotted line in Fig. 4) are taken from these.

Reinforcing steel corrosion

M=

O	N	SC	C	DS	D	F	SD
1.08	0.41	1.38	0.32	0.08	0.92	0.44	0.33
0.00	1.21	1.38	0.08	0.00	0.34	0.00	0.00
0.00	0.80	1.38	0.08	0.00	0.34	0.00	0.00
0.00	0.36	1.38	0.15	0.00	1.53	0.00	0.00
0.00	0.36	1.38	0.14	1.00	1.53	0.00	0.00
0.00	0.36	1.38	0.14	0.00	1.52	0.00	0.00
0.00	0.41	1.38	0.12	0.00	0.93	1.33	0.67
0.00	0.46	1.38	0.08	0.00	0.34	0.00	0.13

Deformation

M=

O	N	SC	C	DS	D	F	SD
1.06	0.17	0.67	0.85	0.75	0.20	0.38	1.20
0.00	1.29	1.31	0.70	0.98	0.00	0.00	1.28
0.00	0.04	1.31	0.70	0.98	0.00	0.00	1.28
0.00	0.08	0.41	1.52	0.54	0.00	0.00	1.28
0.00	0.01	0.07	0.26	1.22	0.00	0.00	1.28
0.00	0.01	0.07	0.26	0.09	0.00	0.00	1.28
0.00	0.01	0.44	1.04	0.80	0.18	1.29	1.28
0.00	0.35	1.31	0.70	0.98	1.25	0.00	1.28

Crack

M=

O	N	SC	C	DS	D	F	SD
1.07	0.34	0.86	0.65	0.39	1.73	0.39	0.24
0.00	1.30	1.40	0.55	0.45	1.56	0.00	0.00
0.00	0.05	1.40	0.55	0.45	1.56	0.00	0.00
0.00	0.05	0.27	0.28	0.13	1.56	0.00	0.00
0.00	0.05	0.27	1.35	1.47	1.56	0.00	0.00
0.00	0.10	0.46	1.35	0.41	1.56	0.00	0.00
0.00	0.10	0.46	0.50	0.41	1.56	1.17	0.21
0.00	0.36	0.14	0.55	0.47	1.56	0.00	1.25

Surface deterioration

M=

O	N	SC	C	DS	D	F	SD
2.00	0.00	0.00	0.00	0.00	1.00	3.00	0.00
0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	3.00	1.33
0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.33

Deterioration of strength

M=

O	N	SC	C	DS	D	F	SD
1.11	0.11	0.11	1.42	0.14	0.81	0.33	0.52
0.00	1.00	0.00	1.80	1.51	0.96	0.00	1.36
0.00	0.00	0.00	1.80	1.51	0.96	0.00	1.36
0.00	0.00	0.00	1.80	1.51	0.71	0.00	0.15
0.00	0.00	0.00	0.12	1.17	0.13	0.00	0.10
0.00	0.00	0.00	1.80	1.51	1.96	0.00	0.15
0.00	0.00	0.00	0.96	1.34	0.42	1.50	0.00
0.00	0.00	1.00	1.82	1.51	0.96	0.00	1.35

Fig. 5. The M-Matrix to each deterioration phenomenon.

3.3 The Calculation on Weight on Performance of Structures for Deterioration Phenomenon

The M-matrixes are calculated from the Q-matrix by equation (1) in method 2.2 (8) and shown in Fig. 5. These are expressed for the frequency of phenomena occurring at each stage of the phenomenon.

The ingredients of the file of the matrix are summed up. The sum, which is expressed for frequencies, is considered to reveal the weight of a phenomenon on the other increases. The weights of each deterioration phenomenon on steel corrosion, crack, deterioration of strength and deformation are shown in Table 2.

The weights of each phenomenon on structural safety are calculated by summing up the weights of each stage of deterioration and are shown in Table 2. The result shows that the weight of deformation, steel corrosion and cracks are larger than the others. Furthermore the more correct weight can be calculated by assuming proper Fault Tree Analysis.

Table 2. The weight of deterioration phenomena that exert an influence on structural safety

Quantifying Item	Weight of each deterioration to each structural safety					To weight of structural safety (%)
	Reinforcing steel corrosion (%)	Crack (%)	Deterioration of strength (%)	Deformation (%)	Total (%)	
Naturalization	15.6	7.0	2.9	5.8	31.3	7.9
Reinforcing steel corrosion	39.4	15.7	2.9	16.8	74.8	18.7
Crack	3.9	17.2	30.6	18.2	69.9	17.5
Deterioration of strength	3.9	12.5	27.0	19.0	62.4	15.6
Deformation	26.7	37.8	18.4	4.9	87.8	21.8
Frost damage	6.4	4.7	4.8	4.9	20.8	5.2
Surface deterioration(s)	4.1	5.1	13.4	30.4	53.0	13.3
Total	100.0	100.0	100.0	100.0	100.0	100.0

3.4 Simulation with Data of Existing Structures

The inputted data which the authors have investigated comes from a structure located in an inland area in a cold region which was built 30 years ago and used as a fire lookout. The data were taken from the platform of the structure and are shown in Table 3. The methods of calculation and grading are based on our paper of 1986[1]. The results of simulation for the data are shown in Fig. 6.

Table 3. The input data of the actual structure in an inland area of a cold region for simulating deterioration

Factor		Mark	Parameter	Unit	Data
External factor	External tactor of deterioration	t :	Service life	(year)	31
		L :	Distance from sea	(m)	39,000
		Co :	Amount of chloride from sea	(wt%)	0
		Ic :	Change of temperature	(℃)	65.2
		S :	Concentration of sulfate of water contacted surface	(wt%)	0
		M :	Cycles of freeze-thaw a year		50
		W :	Coefficient of supplying seawater		note (4)
Inner factor	Design	D :	Depth of cover	(mm)	64.5
		fs :	Stress of reinforcing steel	(kgf/cm^2)	1,200(3)
		α :	Stress of concrete	(kgf/cm^2)	50(3)
		β :	Note 1		2.45
		A :	Note 2	(cm)	91.3
		b :	Width of the section	(m)	1.42
		h :	Depth of the member	(m)	0.218
		NH :	Number of steel members		11
		ϕ :	Diameter of the steel	(m)	0.0125
	Material	fc :	Compressive strength of concrete	(kgf/cm^2)	272
		fct :	Tensile strength of concrete	(kgf/cm^2)	2.72
		fb :	Average bond strength of concrete and steel	(kgf/cm^2)	58
		Ec :	Yonug's modulus	(kgf/cm^2)	2.24×10^5
		ϕ :	Coefficient of creep		2.0
		W/C :	Water cement ratio	(%)	68.5(3)
		Uc :	Unit weight of cement	(kg/m^3)	366(3)
		Uw :	Unit weight of water	(kg/m^3)	250(3)
		R :	Type of cement, type of AE agent, type of aggregate		1.0
		Ru :	Amount of Na_2O in aggregate by cement	(%)	
		RG :	Content of reactionable aggregate	(%)	
		AE or Non-AE :	Whether there is AE agent		None
		Dc :	Diffusivities of concrete	(cm^2)	1.7×10^{-8}
	Construction	α :	Coefficient of type of cement and curing condition		0.0129
		K :	Ratio ofdecreasing surface of strength		—
		γ :	Index of workability $\gamma=1$		1.0
Result of investigation		x :	Depth of neutralization	(mm)	14.7
		p :	Corrosion surface		0
		Crack, etc.			0.55 mm

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 : 1.2.

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

Note (3) : Reference material are the Specification of Building in 1953.

Note (4) : W = 0.00028

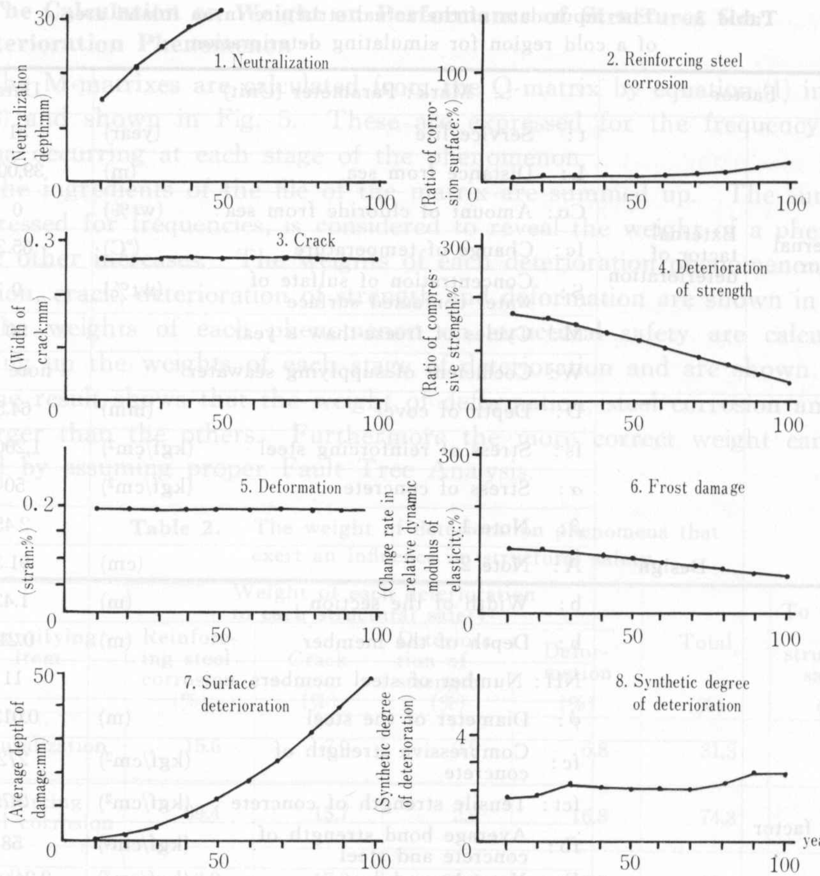

Fig. 6. The result of simulation for the actual structure in an inland area of a cold region.

The synthetic degree of deterioration was calculated and shown in Fig. 6-8. The result is that the synthetic degree of deterioration seems to be larger than previously because of large deformations that occurred at an early stage. Besides, the synthetic degree of the structure is 1.7 with the guide and explanation of it in terms of techniques for evaluation of deterioration for reinforced building structures illuminated by our investigation.

4. Conclusion

The results may be summarized as follows:

(1) The deterioration of concrete structures can be systemized and arranged by F.T.A. (Fault Tree Analysis).

(2) The progress of concrete deterioration can be developed by the stochastic matrix and arranged by assuming an F.T.A. for it.

(3) The consideration criteria for the weight of deterioration phenomenon influencing the performance of a structure can be given by the stochastic matrix.

(4) As for future directions, studies are needed to clarify the definition of the performance of a structure, the expression of performance function, and the evaluation the deterioration of a concrete structure for its quantitative performance changing over time by arranging and studying the relationship between these and the deterioration phenomenon.

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