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Evaluation and prediction on performance degradation of marine concrete structures

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ABSTRACT

Typical deterioration of concrete structures in marine environments is chloride-induced corrosion of rebar. After starting corrosion, it progresses rapidly and loss in structural performance or even structural collapse may be consequences. To meet these facts, it is extremely important to coordinate durability design and strategic maintenance and essential to establish life-cycle management strategies. The authors have been conducting several research programs for the core parts of the life cycle management system of marine concrete structures. In this paper, the results and discussions are introduced how deterioration of concrete members and structural performance degradation should be evaluated and assessed. In addition, the effect of marine fouling organisms attaching the surface of concrete is experimentally discussed. Finally, prediction with the Markov-chain is proposed in the life-cycle management. Some of the practical considerations have been introduced in the design and maintenance standards for port and harbor structures.

Keywords. Marine concrete, Chloride-induced deterioration, Markov-chain, Structural performance, Marine fouling organism

INTRODUCTION

Civil infrastructure has a long lifetime and must be expected to meet demands during its lifetime that cannot be foreseen. Marine areas are very severe for them from the viewpoints not only of mechanical actions but also of environmental actions. Marine concrete structures are exposed to severe environments compared to land structures, where performance degradation is often observed due to materials deterioration, particularly corrosion of rebar, caused by chloride ion supplied from seawater splashing and sea breeze.

Reinforced and prestressed concrete members have been widely used in port and harbor structures. Among them, many examples of heavy deterioration and degradation have been collected, particularly due to chloride attack caused by severe seawater splashing or sea breezing. To ensure the reliability of existing structures for a certain period of service life, a rational maintenance system should be established. In the maintenance system, evaluation of deteriorated structures, particularly structural assessment is very important. Reliable service life predictions can also be made by measuring the durability performance of the materials in that environment. However, the effect of the deterioration condition, such as crack formation and corrosion of rebar, to the load-bearing capacity of deteriorated members has not been made clear.

The authors have carried out several series of exposure tests in marine environments and field investigations on marine structures. The results are presented in this paper focusing on prediction and assessment of structural performance and tendency of deterioration. Firstly, based on the investigation, tendency of deterioration and the prediction model with the Markov-chain are discussed. Marine fouling organisms attaching on concrete surfaces are focused and their effect on durability enhancement is examined. Furthermore, the effect of rebar corrosion on structural performance including load-bearing capacity and ductility is experimentally investigated. Lastly, change in the transition probability in the Markov-chain is discussed after intervention is taken.

PERFORMANCE OF STRUCTURES IN MARINE ENVIRONMENT

Deterioration of RC decks of wharf. A reinforced concrete (RC) deck of open-piled wharf may have been seriously damaged by chloride ion. Field investigation was carried out in 18 wharf decks in 11 ports covering various environmental features (Komure, et al. 2002, Yokota, et al. 2003). Beams and slabs of the decks were visually investigated and the deterioration degree of each member was judged according to the criterion given in Table 1. Figure 1 shows an example of the distributions of deterioration degree of a deck. The figure clearly indicates that the deterioration degrees of members are widely varied even in one block of the deck. Moreover, the variation is random and not related to the position of members. Figure 2 shows the distributions of deterioration degree of three decks. These results clearly indicate that each distribution has a peak on a certain deterioration degree. The deterioration degree for each member forwards as time goes; subsequently the peak of deterioration gradually shifts to the forward direction.

To express the tendency of deterioration progress, the Markov-chain has been applied. In this principle, the state and the transition are main components, and a probability from a certain state to its next state is expressed by using a transition probability. The characteristics of the Markov-chain are (1) a structural member belongs to a certain deterioration degree; (2) the deterioration degree shifts to the next degree in a time step with a certain transition probability, while the other structural members remain in the present deterioration degree; (3) at the commencement of calculation, the deterioration degrees of all structural members are set at degree O; and (4) degree V is the final stage of deterioration. The transition probability for each deterioration degree is assumed at a constant value in this paper, because Table 1 is probably determined to have almost the same time span (Yokota, et al. 2006). The application of the Markov-chain to the investigation results was done by seeking the most suitable transition probability to agree well with the result of investigation. Examples of the results are shown in Figure 3. It can be clearly seen that calculation results represent the widely ranged actual investigation results.

The progress of deterioration is closely related to the environmental and structural conditions. As a structural condition, the height of a deck above the seawater is considered. Figure 4 shows the relationship between height of decks and the transition probability. The approximate equation is proposed to estimate an approximate transition probability depending on the position of a member.

Table 1. Deterioration degree judgment

Deterioration degree	0	I	II	III	IV	V
Crack	None	- Hair cracks in one direction (for a slab) - Hair cracks perpendicular to rebar (for a beam)	- Crack width over 0.3 mm - Cracks in two directions (for a slab) - Cracks parallel to main rebar (for a beam)	- Crack width over 1.0 mm - Crack with rust stain	- Crack width over 3.0 mm	
Peeling and spalling	None		- Delamination without peeling - A few steel rebars without enough cover are exposed	- Some delamination - Small peeling/spalling for a steel rebar - Many steel rebars without enough cover are exposed	- Many peeling/spalling (over 10% of 1 block) - Peeling/spalling over two or more steel rebars	- Many peeling/spalling (over 40% of 1 block)
Corrosion of rebar	None	- Spots of rust stain on concrete surface	- Trace of rust stain flows	- Lump of rust stain	- Small loss in cross-sectional area of rebar	- Large-scale loss in cross-sectional area of rebar

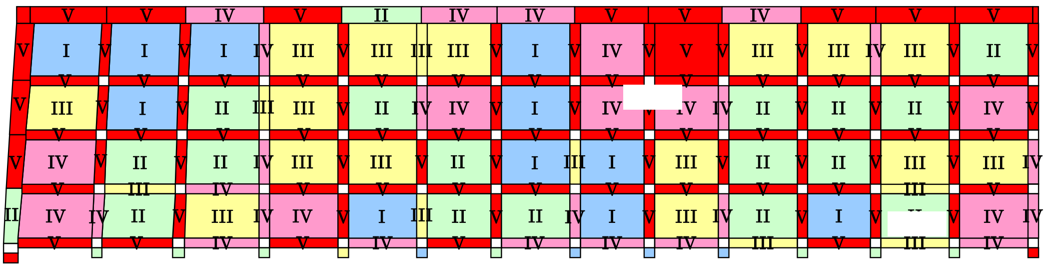


Figure 1. Example of investigation result (plan view)

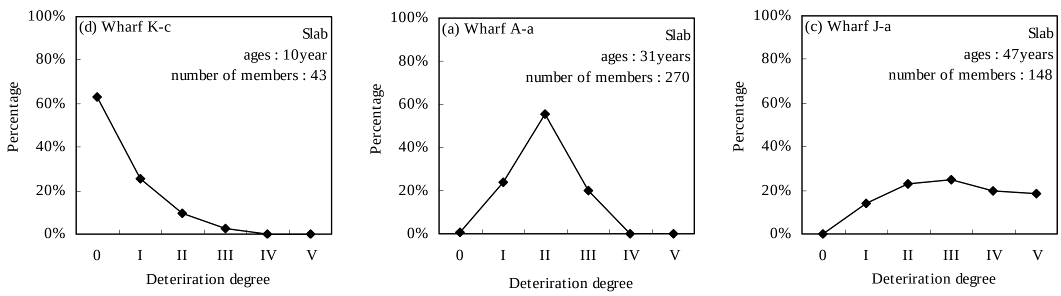


Figure 2. Distributions of deterioration degree

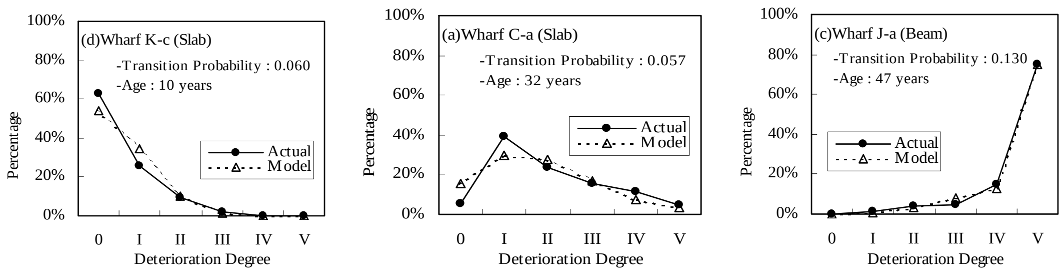


Figure 3. Actual and calculated distributions of deterioration degree

PERFORMACE DEGRADATION MODEL

The deterioration progress can be roughly divided into two stages such as the initiation stage and the propagation stage. The boundary of these stages is corrosion initiation of rebar. The main factor governing the period of the initiation stage is a chloride diffusivity of concrete, while the main factor governing the period of propagation stage is corrosion rate of rebar. The corrosion rate of rebar is mainly determined by the diffusivity of the oxygen. Structural performance is gradually degraded as deterioration progress, which is shown in Figure 5 as a conceptual illustration depending on durability of concrete. Durability of concrete can be clearly defined as the curve shifts to the right hand side for high durability concrete, and the curve shifts to the left hand side for low durability concrete.

Rebar corrosion is initiated with high concentration of chloride ions existing around the rebar. On the other hand, progress of corrosion depends on the oxygen supply to the rebar surface. Therefore, in the splash zone in which much oxygen is supplied to concrete, the corrosion rate becomes larger, whereas in the submerged zone in which little oxygen is supplied to the concrete, corrosion rate becomes very small. As the corrosion loss of rebar increases, structural performance degrades more. Accordingly, it is necessary to find the relationship between structural performance and rebar corrosion.

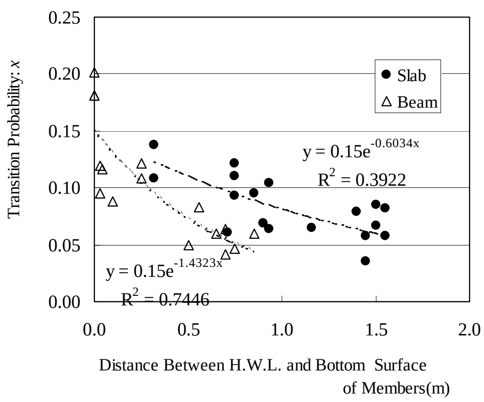


Figure 4. Height of deck vs. transition probability

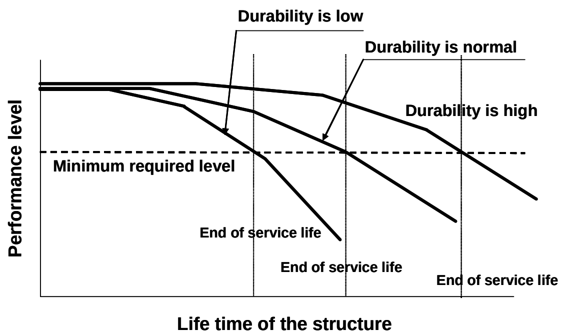


Figure 5. Structural performance degradation

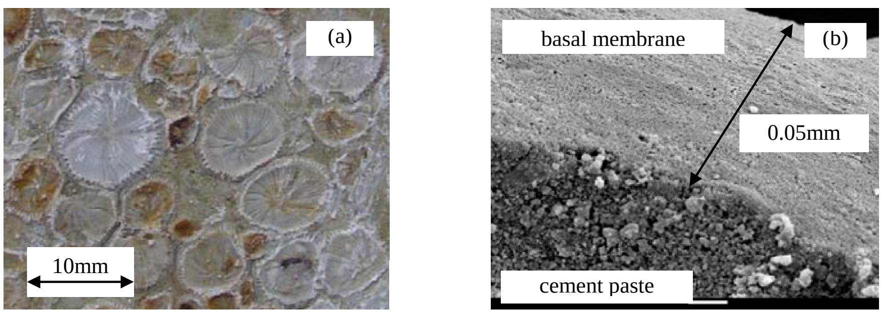


Figure 6. Basal membranes of barnacles; (a) Residual membranes on concrete surface; (b) A cross-section of basal membrane

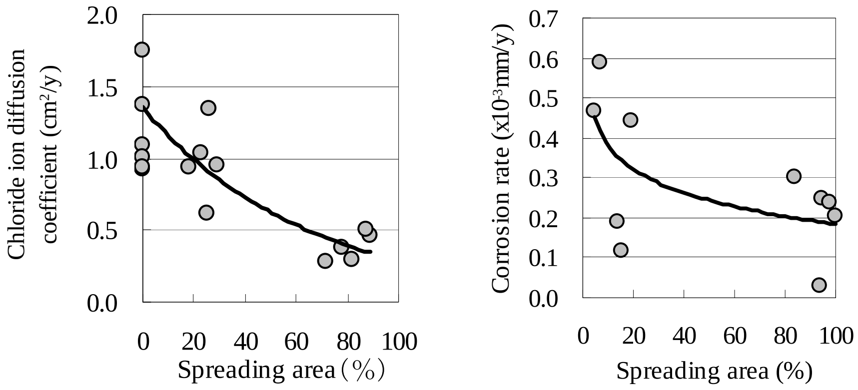


Figure 7. Influence of attached organisms on durability of concrete

EFFECT OF MARINE FOULING ORGANISMS

Attachment of marine fouling organisms. Tidal and submerged zones of marine concrete structures are generally covered with marine fouling organisms. It can be presumed that layers of such organisms may inhibit penetration of deterioration agents such as chloride ion and oxygen into concrete. Types of marine fouling organisms attached to concrete surface are generally identified as several kinds of barnacles and oysters.

To carefully observe the condition of concrete surfaces after attachment of marine fouling organisms, shell parts of the organisms were removed by a scraper, leaving a basal membrane layer of the organisms (Iwanami, et al. 2002). Figure 6 (a) shows the residual basal membrane layer on the concrete surface after removing the shell part. Since the layer seemed to be strongly attached to concrete surface, an SEM analysis was conducted on cross-section of the basal membrane layer. The SEM image obtained is shown in Figure 6 (b), indicating that the basal membrane is considerably denser than cement paste matrix. The X-ray diffraction analysis revealed that major component of the layer was identified as calcium carbonates: aragonite and calcite. Consequently, from the viewpoint of deterioration agents penetration, concrete surface is supposed to be considerably improved by this dense basal membrane layer. In the experiment, several types of mix proportion of concrete were prepared, but the influence of mix proportion on the amount of organisms attached on the concrete surface is not observed clearly.

Effects of marine fouling organisms on durability. Figure 7 shows influences of the amount of attached organisms on chloride ion diffusion coefficient of concrete and corrosion rate of rebar. The amount of attached organisms is quantified by an index of the spreading area of organisms, which is defined as the ratio of the total area of residual basal membrane layer to the total area of concrete surfaces. The chloride ion diffusion coefficient was obtained from an accelerated migration test. From this figure, it is found that both chloride ion coefficients and corrosion rate of rebar decrease with an increase in the amount of attached organisms. As explained earlier, the basal membrane layer attached to concrete surface is much denser than cement paste matrix. Therefore, it becomes difficult for harmful substances such as chloride ion and oxygen to penetrate into inside of concrete. Consequently, corrosion rate of rebar is reduced with an increase in the amount of attached organisms, resulting in longer service life.

LOAD-CARRYING CAPACITY OF DETERIORATED MEMBER

Structural performance degradation due to rebar corrosion. It is of great importance to evaluate safety and serviceability of deteriorated RC members. Structural performance, such as load bearing capacity and ductility, would be degraded due to corrosion of rebar (Yokota, et al. 1998, 1999).

Figure 8 shows the results of flexural loading tests on RC beams damaged by rebar corrosion. The straight line in the figure is calculated load bearing capacity with the beam theory using an average cross-sectional loss of longitudinal rebar due to corrosion. Most of the experimental results scattered below this line, indicating that it is essential to fully evaluate influence of rebar corrosion on structural performance of RC members. Corrosion of rebar would cause not only loss in cross-section, but also deterioration in bond property between concrete and rebar. Also, rebar corrosion would affect ductility of RC members under earthquake forces as well as static load bearing capacity. As shown in the figure, local corrosion has great influences on load bearing capacity even with the same average cross-sectional area loss. Those influences are discussed by Kato et al (2008).

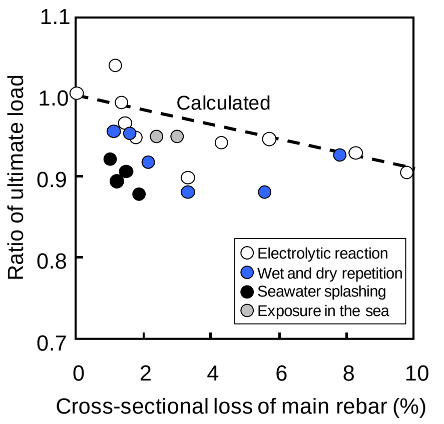


Figure 8. Load bearing capacity vs. corrosion loss of rebar

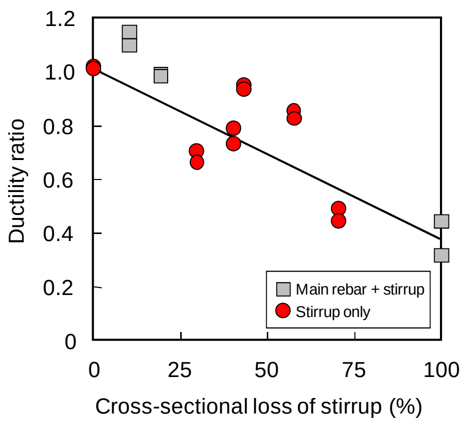


Figure 10. Ductility vs. corrosion loss of rebar

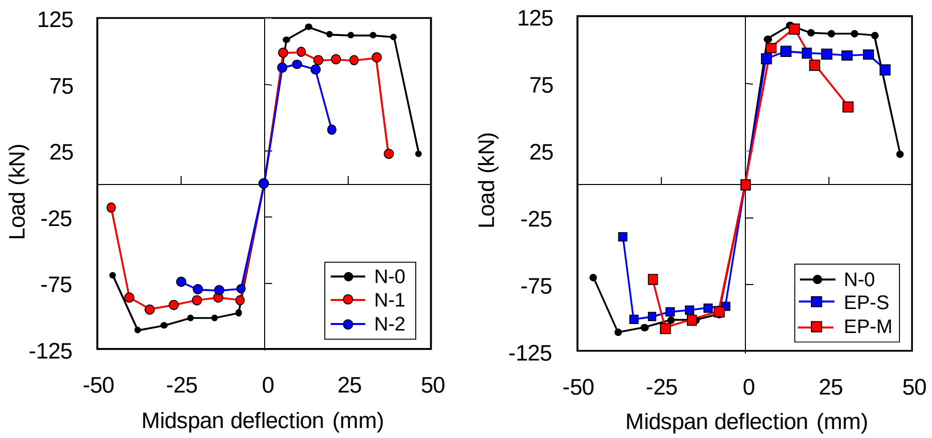
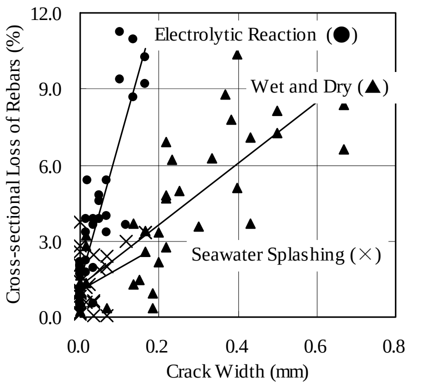


Figure 9 Result of reversed cyclic loading tests



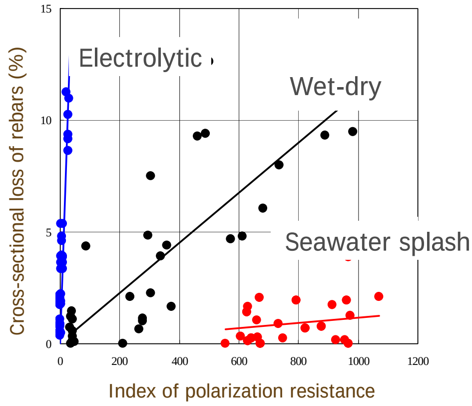


Figure 11. Crack width vs. corrosion loss of rebar

Figure 12. Polarization resistance vs. corrosion loss of rebar

Figure 9 shows the results of reversed cyclic loading tests. N-0 is a sound beam, while N-1 and N-2 are deteriorated beams. Corrosion of steel rebar in N-2 was more serious than that in N-1. It is found that the maximum load and the ultimate deflection decreased with progress in corrosion of rebar. In EP-S and EP-M, epoxy-coated rebar is used for stirrup and main rebar, respectively. By using the epoxy-coated rebar, corrosion could be prevented completely, even after completion of electrolytic procedure. As shown in the envelop curve of EP-S, load bearing capacity is smaller than that of sound one, although the ultimate deflection is similar.

On the other hand, in case of EP-M, the ultimate deflection is much smaller than that of sound one, while the maximum load is almost the same. Therefore, ductility of RC members depends on the degrees of corrosion of stirrup. Those degradation in structural performance might be caused by loss in cross-section and bond deterioration between concrete and rebar. Figure 10 shows the relationship between ductility of RC beams and cross-sectional loss of stirrups. From this figure, the ductility could be evaluated accurately by estimating the degrees of corrosion in stirrups.

Quantitative evaluation on rebar corrosion. To evaluate structural performance of RC members with rebar corrosion, the state of rebar corrosion should be estimated appropriately, if possible, quantitatively, in terms of location, degree, and rate. Nondestructive evaluation methods could be promising. The simplest method to nondestructively estimate the degree of rebar corrosion is to measure the width of a corrosion crack. An example of the relationship between crack width and corrosion loss (mass loss or cross-sectional area loss) of rebar is shown in Figure 11. The wider a crack, the more severe rebar corrosion. However, the relationship between crack width and corrosion amount depends on the method to corrode rebar; that is, environmental conditions. If the environmental condition seems to be identical, this method could be applicable to estimate the degree of corrosion relatively.

It would be another problem that the estimation by corrosion crack width could not provide any information on rebar corrosion before crack initiation. It is well known that corrosion of steel is caused by chemical reaction based on electrochemistry. Therefore, it is expected that electrochemical parameters, such as half-cell potential and polarization resistance, would be suitable to estimate the corrosion state of rebar. Figure 12 shows the relationship between the index of polarization resistance and corrosion loss of rebar. The corrosion amount could be estimated by measuring polarization resistance. However, the relationship is not identical, but it depends on the environmental conditions. Therefore, when using this parameter, it is required to pay attention to environmental conditions.

PREDICTION WITH MARKOV-CHAIN

Accuracy of Markov-chain. A deck of open-piled wharf was inspected two times in 2000 and 2003 and some RC beams were experimentally repaired in 2002 based on the deterioration degree judged by investigation (Yokota, et al. 2003, 2005). That is, three RC beams having deterioration degrees II, III and IV were repaired by section repair. Concrete of 150 mm thick from the bottom surface of each beam was removed, and the removed part was filled with non-shrinkage mortar after applying rust-proof coating to the rebar. Two RC beams with the deterioration degrees III and IV were repaired by cathodic protection. In the beam having deterioration degree III, concrete of 150 mm thick was removed in which titan ribbon mesh anodes were then installed. The removed part was filled with non-shrinkage mortar. Almost the same technique was applied to that of degree IV except being covered by FRP panels. The current densities of the both repaired beams were approximately 25 mA/m^2.

The applicability of the Markov-chain to the prediction of deterioration degrees of existing pier is evaluated. Figure 13 shows the distributions of deterioration degrees obtained by investigation and prediction. The most reliable transition probabilities are found to be 0.113 and 0.213 for RC slabs and RC beams respectively. The predicted results agree well with the investigated results from the viewpoints of their peaks and tendencies. Therefore, the prediction method based on Markov-chain is confirmed to its applicability with reasonable accuracy to the existing marine concrete structures.

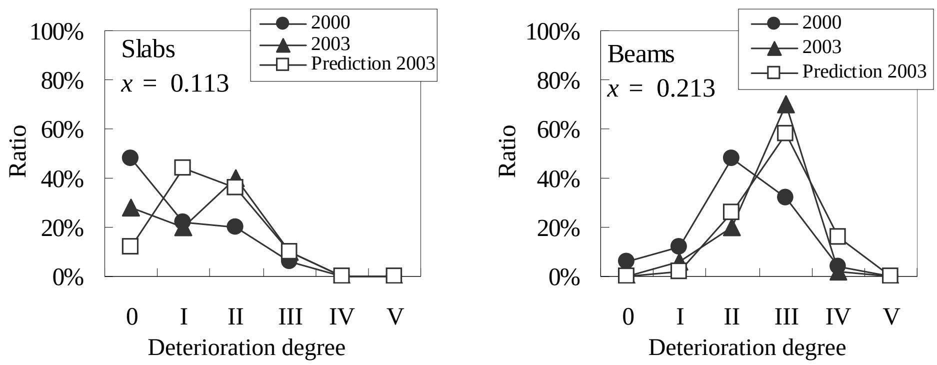


Figure 13. Deterioration degree of investigation and prediction

Effects of intervention. When the safety and the serviceability are presumed to fall below their required levels because of deterioration during the service periods, intervention should be implemented. To predict the future progress of deterioration after intervention is taken, the deterioration degree, the transition probability, and design service life are required to quantify as precisely as possible. The effect of intervention to recover or to improve structural performance can be estimated depending on the kind of intervention.

The polarization resistance was measured by the AC impedance method at the timings of before the experimental repair and 6 months after the repair. The results are summarized in

Table 2. The corrosion currents compared before and after repair, which is relating to the corrosion rate of rebar, are decreased to less than 40 % for section repair and less than 10 % for cathodic protection. These results indicate that the section repair is effective to reduce the rate of rebar corrosion. In the prediction, the transition probabilities are assumed to be reduced to 50 % for section repair and 10 % for cathodic protection.

Based on the measurement, the effect of intervention on the transition probability is summarized in Table 3. The section repair is applicable when the deterioration degree is III or higher. After doing section repair, degree II is recovered to degree I and degree III or higher are to degree II by removing chloride contaminated concrete and heavily corroded part of rebar. The transition probability after section repair is reduced to 50% of its original value before repair is taken. The cathodic protection is applicable to all deterioration degrees. By taking cathodic protection, the deterioration degree is recovered as listed in Table 3. In case that the cathodic protection is effectively used, the transition probability is changed to 10 % of its value before the repair is taken. The partial replacement will be done when the deterioration degree becomes III or higher. It should be most effective to draw back the structural performance to the almost initial stage; thus the deterioration degree returns to 0, but the transition probability does not change because of the same materials as original ones.

Table 2. Measured results of polarization resistance

Kind	Degree before repair	R_p, kΩcm^2		I_c, μA/cm^2		$I_{c,before}/I_{c,after}$
		Before	After	Before	After	
Section repair	II	91.7	237.0	0.284	0.110	0.387
	III	180.3	1251.9	0.144	0.021	0.144
	IV	135.7	360.6	0.192	0.072	0.376
Cathodic protection	III	42.6	487.9	0.611	0.053	0.087
	IV	261.7	10655.7	0.099	0.002	0.025

R_p: Polarization resistance and I_c: Corrosion current

Table 3. Effects of repair on the transition probability

Repair \ Deterioration degree before repair		0	I	II	III	IV	V	Transition probability after repair
Deterioration degree after repair	Section repair	-	-	I	II	II	II	Reduced to 50%
	Cathodic protection	0	0	I	II	II	II	Reduced to 10%
	Partial replacement	-	-	-	0	0	0	Not changed

CONCLUSIONS

Concrete and rebar in marine environments should be durable during the design life of structure. Maintenance work after building the structure is also important. To coordinate design and maintenance, the life-cycle management system including assessment of structural performance and prediction of the progress of deterioration has been developed and being implemented. The authors expect that rational and effective link between design and maintenance is realized so that the life-cycle cost reduction and performance maximization can be attained. This may make it possible to realize sustainability of concrete structures.

Research projects summarized in this paper was introduced in the current design standard of marine concrete structures (PHAJ, 2007) and has contributed to develop the life-cycle management system. Further research is of course needed to realize full coordination between design and maintenance including development of performance assessment methodologies and prediction procedures with theoretical models and stochastic mathematical models.

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