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Corrosion of Reinforcement and Its Effect on Structural Performance in Marine Concrete Structures

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This paper discusses the chloride-induced corrosion of reinforcement in marine concrete structures focusing on the variability in the progress of deterioration. Through tests and analyses of reinforced concrete slabs taken out from existing open-pile structures that have been in service for 30 to 40 years, the following topics were particularly discussed: variation in chloride ion profiles of concrete, variation in corrosion properties of reinforcement embedded in concrete, and influence of the reinforcement corrosion on the load-carrying capacity of the concrete slabs. As a result, their variability was found to be very large even in one reinforced concrete slab with almost the same conditions. It was also discussed how to determine the calculation parameters for prediction of decreasing in load-carrying capacity of concrete members with chloride-induced corrosion of reinforcement.

Keywords *: chloride-induced corrosion, chloride ion concentration, slab of open-pile structure, variability, structural capacity.*

1. Introduction

When reinforced concrete structures are built in marine areas, an important deterioration phenomenon to be taken into account is corrosion of steel reinforcement embedded in concrete. Once the corrosion starts, cracks of concrete along the reinforcement can be initiated due to volume expansion of corrosion products. Such cracks may accelerate further corrosion, and subsequently structural performance will be degraded when corrosion progresses to a certain limit degree.

To realize rational and strategic maintenance with the concept of life-cycle management for existing reinforced concrete structures,[1)] it is necessary to carry out performance assessment of existing structures, prediction of future deterioration, and interventions to deteriorated structures based on the assessment and prediction. However, due to various reasons, deterioration phenomena generally show high diversity, which reveals various aspects even in one structure or in one structural member. This paper presents the results of investigation on the deterioration of reinforced concrete members to discuss the variability in structural performance assessment to deteriorated reinforced concrete structures in marine environment.

Through tests and analyses of reinforced concrete slabs taken out from existing open-pile structures which have been in service for 30 to 40 years, the following topics were particularly discussed in this paper such as variation in chloride ion profiles in concrete, variation in corrosion properties of reinforcement embedded in concrete, and influence of the variation of materials deterioration on the load-carrying capacities of the slabs. It was discussed quantitatively that the surface chloride ion concentration shows very wide variation even in one slab. The influence of corrosion properties of reinforcement on the load-carrying capacity of the slab was made clear by loading tests and analyses.

As a result, the variability of reinforcement corrosion was found to be very large even in one reinforced concrete slab with almost the same material, structural, and environmental conditions. It was also discussed how to determine the calculation parameters for prediction of deterioration and load-carrying capacity.

2. Experimental procedures

2.1 Description of test slab

Reinforced concrete slab of open-pile structure in port is focused in this paper as a typical marine concrete structure. The cross section of the pier in port H is shown in Fig. 1 for example. The slab of open-pile structure is one of the most vulnerable structural members subjected

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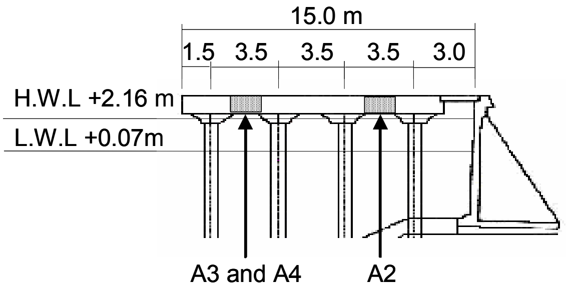


Fig. 1. Cross sectional view of open-pile structure in Port H

to chloride attack. A total of 12 slabs, either 30 or 40 years old, were taken out from the existing open-pile structures in 3 ports (ports H, Sa, and Sh), as shown in Fig. 1, for detailed investigations including loading tests to evaluate their residual load-carrying capacities. The configurations of these test slabs are listed in Table 1. All the slabs were located in the splash zone. Unfortunately the details of constituent materials and design calculations were not available.

2.2 Measurement of chloride ion concentration

To measure the chloride ion concentration in concrete, cylindrical specimens of 100 mm in diameter were cored from the parts without crack or delamination in the slabs after the loading test. The concrete core was milled into powder sample being cut into small pieces. Then, chloride ion concentration was measured with the dissolved powder samples according to the JCI Standard.[2)] The surface chloride ion concentration and the diffusion coefficient of chloride ion in concrete were obtained by curve fitting according to Fick's second law of diffusion as follows:

$$C(x,t) = C_0\left(1 - erf\frac{x}{2\sqrt{D_{ap}\cdot t}}\right) \tag{1}$$

where $C(x, t)$: chloride ion concentration (kg/m^3) at depth x (cm) in year t, C_0: surface chloride ion concentration (kg/m^3), D_{ap}: apparent diffusion coefficient of chloride ion in concrete (cm^2/year), and *erf*: error function.

2.3 Measurement of mass-loss of reinforcement

The upper and lower longitudinal reinforcement were taken out from the slab and visually observed. The mass-losses of the reinforcement were measured by the following procedures: at first, the reinforcement was cut into 100 mm long pieces each. The reinforcement piece was sand blasted to remove corrosion products and concrete sticking to the surface of reinforcement. Then, each piece was immersed in 10% diammonium hydrogen citrate solution at 60℃ for 1 day to completely remove the corrosion products. Finally by comparing the treated piece to the sound piece without any corrosion, the mass-loss was calculated. When corrosion was not observed, the mass-loss was set at 0.0 %.

2.4 Loading test

The slab taken out from the open-pile structure was experimentally load tested as a one-way slab.[3)] The slab was simply supported at its marginal regions having the loading span as listed in Table 1. A monotonically-increased concentrated load was applied at the midspan. Fig. 2 shows the test setup of Slabs A2-A4 for example. The supporting areas were reinforced by mortar in case that the cover

Table 1. Configurations of test slabs

	Port	Year	Max load (kN)	Width (mm)	Thick-ness (mm)	Loading span in the test (mm)	Tension reinforcement					
							Upper			Lower		
							Type	Qty	Depth (mm)	Type	Qty	Depth (mm)
A2	H	40	745	1520	270	1000	D13	4	92	D13	8	200
A3	H	40	869	1490	370	1000	D13	4	190	D13	8	290
A4	H	40	498	1500	310	1000	D13	4	190	D13	8	290
B1-1	Sa	40	252	699	300	1400	R13	3	140	R13	5	250
B1-2	Sa	40	221	732	310	1400	R13	3	150	R13	5	260
B1-3	Sa	40	196	798	300	1400	R13	3	140	R13	6	250
B2-1	Sa	40	281	812	310	1400	R13	3	150	R13	6	260
B2-2	Sa	40	261	535	300	1400	R13	4	140	R13	4	250
B2-3	Sa	40	212	569	310	1400	R13	3	150	R13	5	260
C1	Sh	30	-*	1010	350	2900	D16	2	165	D13	5	235
C2	Sh	30	139	1010	350	2900	D16	2	225	D13	5	280
C3	Sh	30	142	1010	350	2900	D16	2	220	D13	5	300

*) This was omitted for discussion because of showing an unfavorable failure mode.

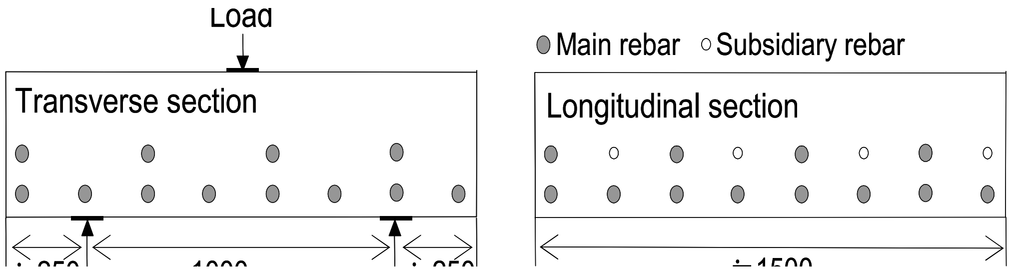


Fig. 2. Test setup and cross section of Slabs A2-A4

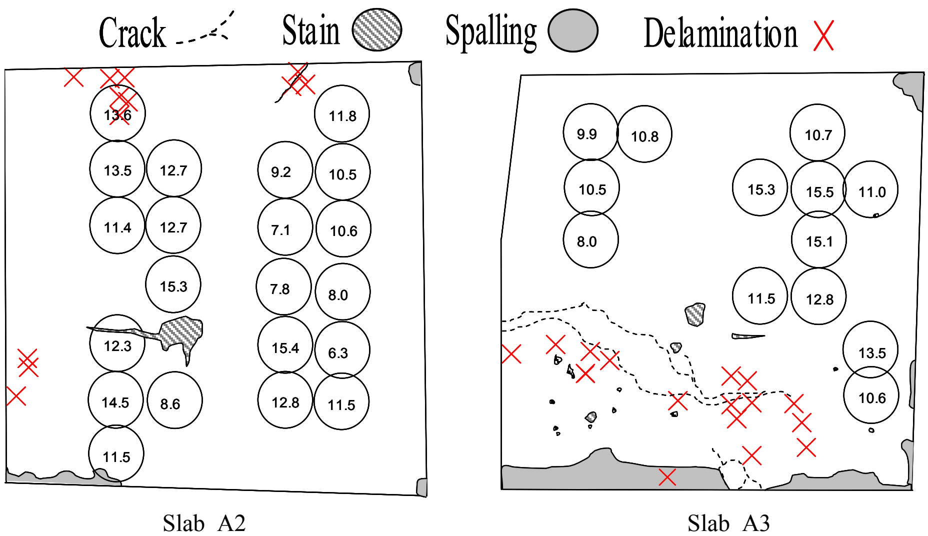


Fig. 3. Distribution of surface chloride ion concentration (kg/m^3)

concrete had been already spalled off. During the test, the applied load and deflection at the supporting points and at the midspan were measured and recorded.

3. Chloride ion concentration on the surface of slab

Fig. 3 shows the surface chloride ion concentration[4] measured in Slabs A2 and A3. Though the concrete cores were taken out from non-deteriorated parts of the slabs, the surface chloride ion concentration varied with location. The maximum differences of measured results between two adjacent points were more than double. Therefore, even in one structural member, variability in chloride ion profiles may exist significantly.

Fig. 4 shows the distribution of chloride ion concentrations based on the profile of normal distribution. They were measured with the concrete cores at the shallow part (denoted for “s”; 40-60 mm deep), which was inside the cover concrete of the transverse reinforcement. The chloride ion concentrations in Slab A2 were more widely distributed compared with those in Slab A3, though their

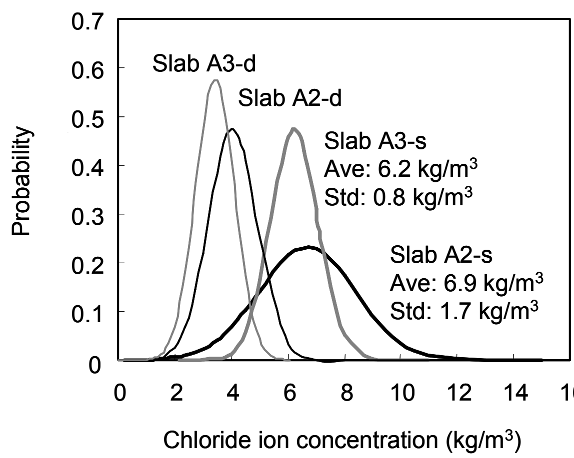


Fig. 4. Distribution of chloride ion concentration

averaged concentrations were almost the same. The difference in the sampling point of concrete was considered as one of the reason. Particularly in Slab A3, sampling was done after parts obviously deteriorated were removed. The measured chloride ion concentrations in the concrete at the deep part (denoted for “d”; 80-100 mm deep) are also plotted in Fig. 4. They showed less variation compared to those at the shallow part.

In the practical investigation of existing structures subjected to marine environment, chloride ion profile of concrete has generally been estimated according to one or a few sampled concrete. However, it seems that such a few numbers of cores cannot be representative.

4. Corrosion of steel reinforcement

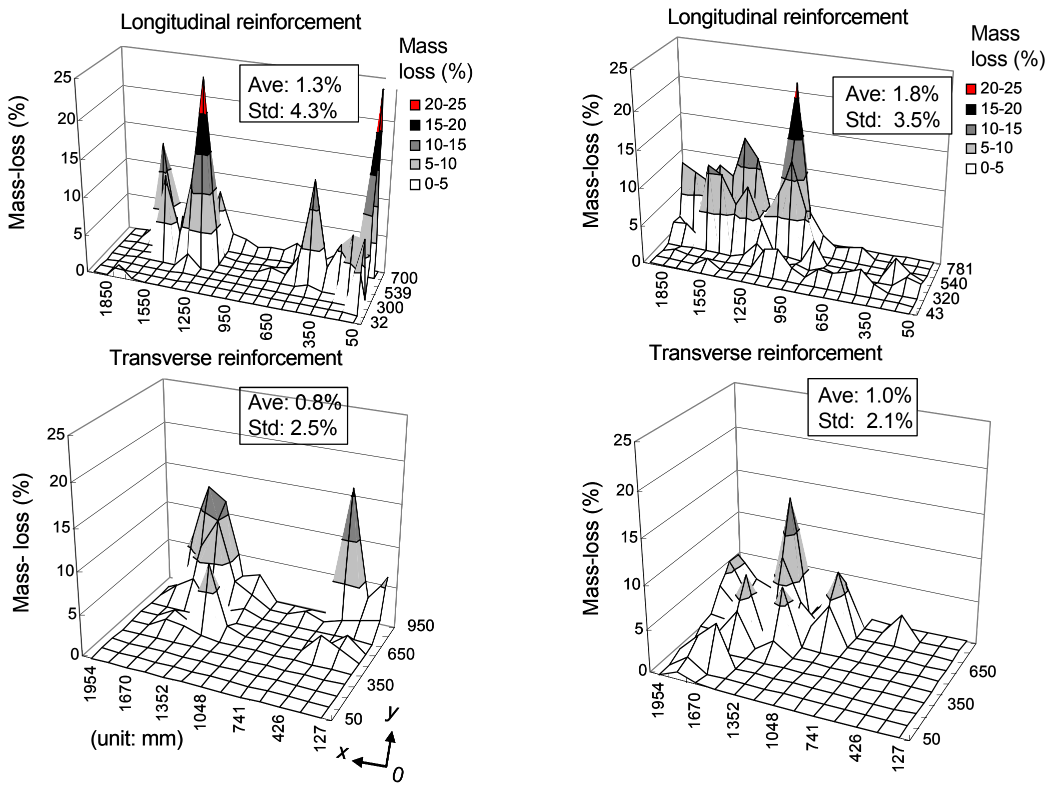
Corrosion of reinforcement was investigated in Slabs A and other two slabs B1-A and B2-A from Port Sa. They are not listed in Table 1 but their structural details are the same as those of Slabs B1 and B2, respectively. Many cracks were observed on the surface of Slab B1-A including cracks along the axis of reinforcement. In Slab B2-A, wide spread honeycomb was formed and cracks along the reinforcement and partial delamination of cover concrete were observed.

Distributions of mass-losses of reinforcement in Slabs B1-A and B2-A are shown in Fig. 5. The axis of x is the longitudinal direction and y is the transverse direction of the slab during the loading test. The parts containing cracks along the longitudinal reinforcement showed the largest mass-loss. These cracks may accelerate corrosion of transverse reinforcement. In Slab B2-A, heavy corrosion occurred in longitudinal and transverse reinforcement at the honeycomb forming parts.

Fig. 6 shows the relationship between the average and the maximum mass-losses of reinforcement. The maximum mass-loss was 2.3 times as large as the average one. Fig. 7 shows the frequency of mass-loss of reinforcement based on the normal distribution. In Slab A3, corrosion occurred only in the areas having delamination or cracks. Because of the localized corrosion, these distributions were considered not to be suitable for the normal distribution.

5. Structural performance of deteriorated slab

The maximum loads (ultimate loads) of the slabs obtained by the loading test are given in Table 1. All the slabs showed flexural failure at the ultimate state and sometimes accompanied with breakage of reinforcement. The load-deflection curves are shown in Fig. 8. Because of the different dimensions, materials properties, and posi-



Slab B1-A

Slab B2-A

Fig. 5. Distribution of mass-loss of reinforcement

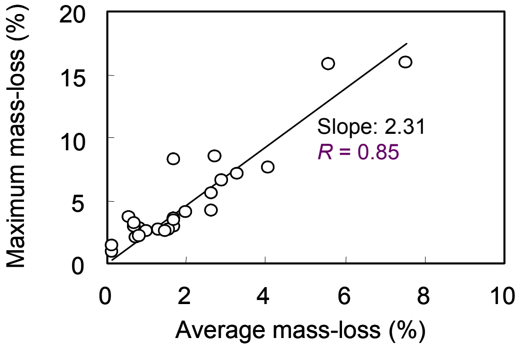


Fig. 6. Maximum and average mass-loss

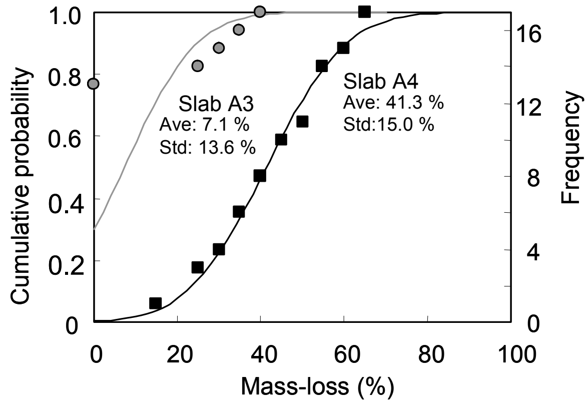


Fig. 7. Distribution of mass-loss

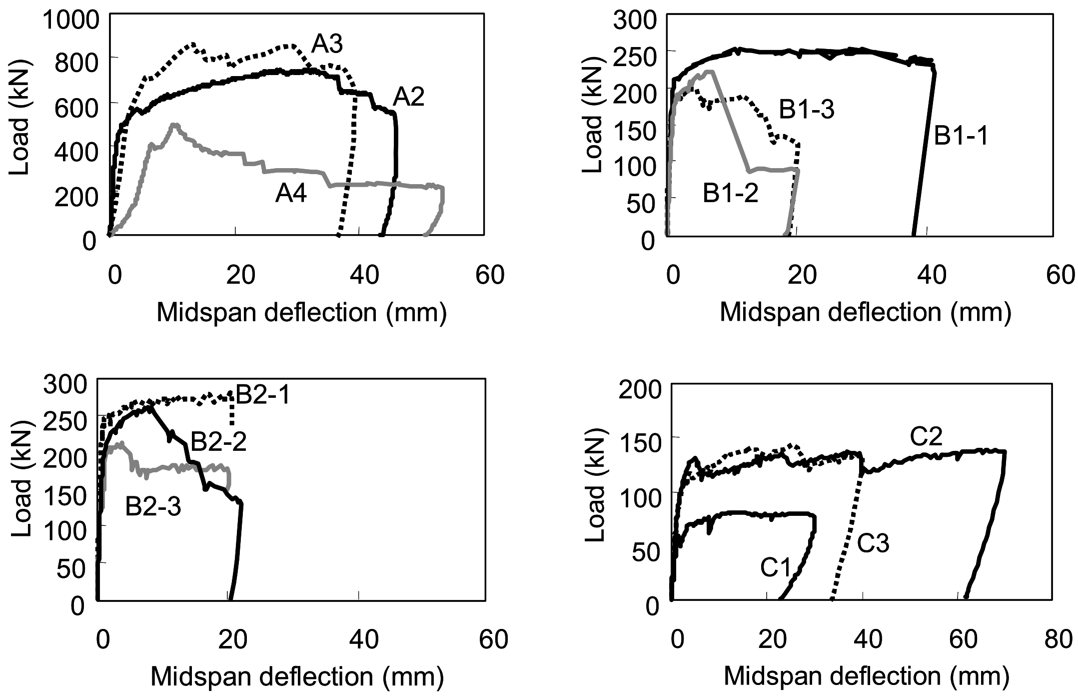


Fig. 8. Load-deflection curves of slabs

tions of reinforcement, load-deflection curves of the slabs cannot be directly compared with each other. In general, however, the apparent initial stiffness was smaller in case of a higher degree of deterioration. It is considered that this was due to the corrosion cracks and deterioration of bond property between reinforcement and concrete.[4)]

It is primarily concluded that heavily deteriorated slabs have small load-carrying capacity and ductility. Slab A3 showed a larger maximum load than Slab A4 regardless of their similar cross-sections of member and reinforcement. However, this primary conclusion was not true in some cases for example in Slab B1-2 and Slab B2-3, because the load-carrying capacity depends on localized corrosion of reinforcement. When the degree of deterioration was evaluated by the strictest judgment on the overall conditions of a structure, the position of heavily deteriorated parts should be inspected with much more attentions for an accurate evaluation of the structural performance.

Fig. 9 shows the relationship between ultimate load and mass-loss of reinforcement due to corrosion. The ultimate load was normalized by that of Slab A2. The ultimate load of each slab was modified with the dimensions of slab. In the same figure, the predicted ultimate load taking into account the cross-sectional loss (the same as the

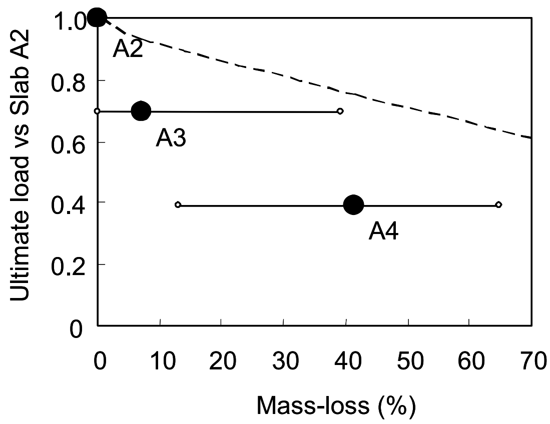


Fig. 9. Effect of variation of mass-loss on ultimate load

mass-loss in this paper) of reinforcement based on the conventional design theory is also plotted as a broken line. The experimental ultimate loads of Slabs A3 and A4 were smaller than the calculated ones. Horizontally straight lines in the same figure represent the maximum and minimum weight-losses of reinforcement. The ultimate loads of both slabs were not evaluated by the average mass-loss. In Slab A3, the ultimate load could be approximately calculated with considering the maximum mass-loss, but it was not true for the case of Slab A4. Therefore, the difference between the calculated and tested ultimate loads was considered to increase with the mass-loss.

Fig. 10 shows the relationships between the yield and the ultimate load ratios and the average mass-losses of reinforcement located near the midspan only. The ultimate load ratio was defined as the ratio of observed ultimate load to the predicted one. The predicted load was obtained using characteristic values of strengths of concrete and reinforcement. The cross-sectional loss (mass-loss) of reinforcement due to corrosion was taken into account. There is a clear tendency that the ultimate load ratio decreases as an increase of average mass-loss of reinforcement.

According to the past research,[5] the ultimate and yield loads can be predicted by considering the average mass-loss of reinforcement in the flexural span of a member. For Slab A4, however, members having relatively large mass-loss of reinforcement may be overestimated their ultimate loads. Therefore, it is required to take into account the localized corrosion, decreases in bond property and in elongation of reinforcement[6] for making accurate evaluation of the structural performance of heavily deteriorated members like Slab A4. Stress concentration due to pit corrosion or other reasons may cause localized deformation or failure in the member, resulting in much lower capacities than prediction. Therefore, it can be concluded that corrosion properties of reinforcement subjected to larger tensile forces should be further investigated in order to accurately evaluate the structural performance of deteriorated members.

6. Summary

The variability in chloride ion concentration causing deterioration, corrosion properties of reinforcement, and load-carrying capacity of deteriorated members was found to be very large even in one concrete deck with almost the same structural and environmental conditions. The following conclusions can be drawn based on the test results in this study:

1) Test pieces should be very carefully sampled to improve the reliability of evaluation results regarding the deterioration state of concrete members because the states of deterioration as well as properties of materials have wide variations.

2) The relationship between decrease in the load carrying capacity and the mass-loss of reinforcement due to

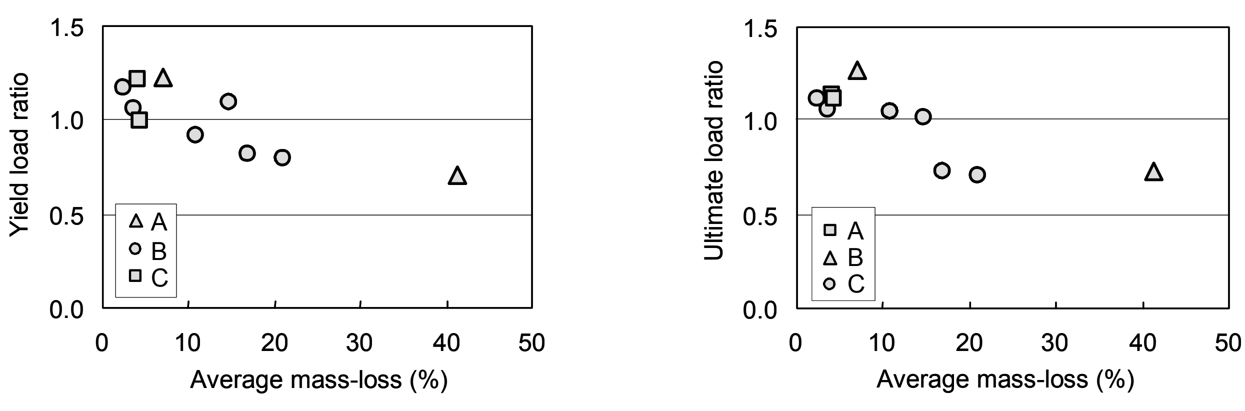


Fig. 10. Relationship between yield and ultimate load ratio and average mass-loss

corrosion was articulated, but needs to be further clarified. Consideration on variability in material properties and environmental conditions was necessary for evaluation and prediction of the present and future durability of concrete members. Moreover, information on the localized corrosion, the bond property and the mechanical properties of corroded reinforcement were necessary for evaluating the structural performance of deteriorated concrete members with improved accuracy, in particular, for those heavily deteriorated ones.

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