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# Simplified assessment on structural performance of deteriorated concrete members

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ABSTRACT: This paper discusses how we could understand the structural performance of a deteriorated reinforced concrete (RC) member only based on the visual investigation data of its surface appearance. The authors have proposed a simplified assessment system of RC member suffered from chloride-induced corrosion as the deterioration grading system. The deterioration grading system is a kind of condition assessment which will be judged by the appearance of RC members such as crack geometries, rust stain, delamination, spalling of cover concrete, corrosion state of reinforcement if it is directly visible, and so on. This system is simple and more or less subjective but will be a very efficient tool if it is linked to structural performance. A total of 30 reinforced concrete slabs extracted from superstructures of open-type wharves aged 30 to 44 years was experimentally load tested to examine the load-carrying capacities after corrosion of reinforcement occurred. The relationship was found between the deterioration grade judged only by visual inspection and the load-carrying capacity. It was concluded that the load-carrying capacity becomes smaller than the calculated prediction when the symptom of deterioration appears on the surface of RC members. It was possible to estimate the load-carrying capacity based on the visually judged deterioration grade but large variations were observed. As a result, a simplified evaluation procedure is proposed for estimating structural performance of a corroded RC member based on the deterioration grade as well as the positions of significantly deteriorated part.

## 1 INTRODUCTION

### 1.1 *Background*

When reinforced concrete (RC) structures are located in coastal and offshore areas, the most important deterioration phenomenon to which attention should be paid in design and maintenance is chloride-induced corrosion of reinforcement. Corrosion of reinforcement can initiate a crack of concrete due to the volume expansion of corrosion products. Such a crack may accelerate further progress of corrosion, delamination and spalling of cover concrete, and eventually structural performance such as load-carrying capacity and ductility will be deteriorated (Kato et al. 2006). To keep structural performance of RC structures over the required levels during the service life, it is necessary to implement a strategic maintenance plan and to carry out suitable maintenance work according to the degree of deterioration.

Life-cycle management system

The authors have been making efforts to establish the strategic maintenance methodology for RC harbor structures based on the concept of life-cycle management, as shown in Figure 1 (Yokota et al. 2008). The life-cycle management system is constituted by a series of procedures including evaluation of the deterioration grade by periodic inspection, assessment of structural performance, prediction of the future progress of performance degradation, and proposal of alternatives of appropriate interventions from the viewpoints of life-cycle cost minimization or performance maximization under budget capping.

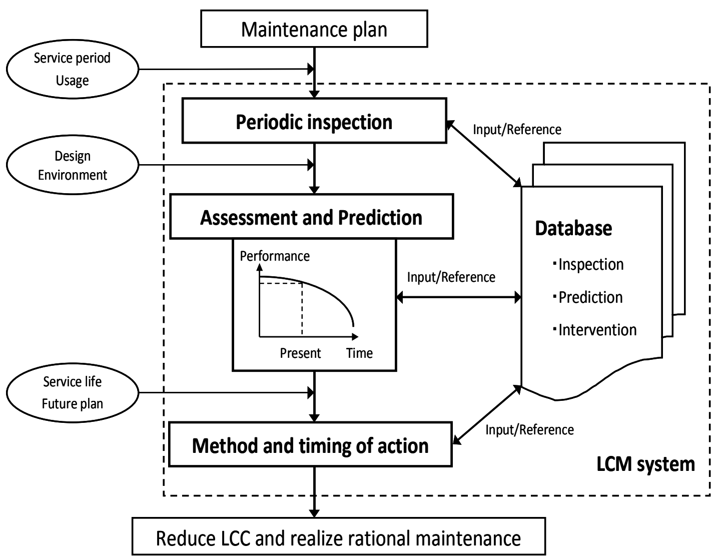

Figure 1. Life-cycle management system.

Table 1. Configuration and deterioration grade of tested slabs.

| Slab No. | ID | Year | Grade | Min. side length (mm) | Ave. thickness (mm) | Tensile reinforcement Upper | Tensile reinforcement Lower | Shear span (mm) | Exp. ultimate load (kN) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Ha-1 | 40 | *c* | 1520 | 270 | 4 - D13 | 8 - D13 | 400 | 745 |
| 2 | Ha-2 | 40 | *b* | 1490 | 370 | 4 - D13 | 8 - D13 | 400 | 869 |
| 3 | Ha-3 | 40 | *a* | 1500 | 310 | 4 - D13 | 8 - D13 | 400 | 498 |
| 4 | Ha-4 | 40 | *b* | 532 | 255 | 3 - D13 | 3 - D13 | 450 | 147 |
| 5 | Ha-5 | 40 | *c* | 389 | 255 | 2 - D13 | 2 - D13 | 450 | 94 |
| 6 | Ha-6 | 40 | *d* | 575 | 261 | 3 - D13 | 3 - D13 | 450 | 159 |
| 7 | Ha-7 | 40 | *a* | 492 | 178 | 3 - D13 | 3 - D13 | 450 | 128 |
| 8 | Ha-8 | 40 | *a* | 408 | 170 | 2 - D13 | 2 - D13 | 450 | 86 |
| 9 | Ha-9 | 40 | *a* | 585 | 172 | 3 - D13 | 3 - D13 | 450 | 105 |
| 10 | Sa-1 | 40 | *d* | 699 | 300 | 3 - R13 | 5 - R13 | 700 | 252 |
| 11 | Sa-2 | 40 | *b* | 535 | 300 | 4 - R13 | 4 - R13 | 700 | 221 |
| 12 | Sa-3 | 40 | *c* | 798 | 300 | 3 - R13 | 6 - R13 | 700 | 196 |
| 13 | Sa-4 | 40 | *c* | 732 | 310 | 3 - R13 | 5 - R13 | 700 | 281 |
| 14 | Sa-5 | 40 | *b* | 569 | 310 | 3 - R13 | 5 - R13 | 700 | 261 |
| 15 | Sa-6 | 40 | *c* | 812 | 310 | 3 - R13 | 6 - R13 | 700 | 212 |
| 16 | Sa-7 | 40 | *b* | 1940 | 253 | 13 - D16 | 5 - D16 | 750 | 384 |
| 17 | Sa-8 | 40 | *a* | 1987 | 226 | 13 - D16 | 5 - D16 | 750 | 224 |
| 18 | Sa-9 | 40 | *a* | 1984 | 275 | 13 - D16 | 5 - D16 | 750 | 267 |
| 19 | Sa-10 | 40 | *a* | 1964 | 262 | 13 - D16 | 5 - D16 | 750 | 243 |
| 20 | Shi-1 | 30 | *c* | 1010 | 350 | 2 - D16 | 5 - D13 | 1450 | 139 |
| 21 | Shi-2 | 30 | *b* | 1010 | 350 | 2 - D16 | 5 - D13 | 1450 | 142 |
| 22 | Shi-3 | 30 | *d* | 1010 | 350 | 2 - D16 | 5 - D13 | 1450 | 80 |
| 23 | Ka-1 | 44 | *b* | 600 | 215 | 2 - R13 | 3 - R13 | 800 | 101 |
| 24 | Ka-2 | 44 | *c* | 595 | 210 | 2 - R13 | 3 - R13 | 800 | 103 |
| 25 | Ka-3 | 44 | *a* | 595 | 205 | 2 - R13 | 3 - R13 | 980 | 68 |
| 26 | Ka-4 | 44 | *c* | 590 | 210 | 2 - R13 | 3 - R13 | 755 | 58 |
| 27 | Ka-5 | 44 | *b* | 590 | 205 | 2 - R13 | 3 - R13 | 755 | 45 |
| 28 | YH-1 | 41 | *c* | 1518 | 266 | 14 - D13 | 7 - D13 | 1000 | 247 |
| 29 | YH-2 | 41 | *c* | 1508 | 242 | 14 - D13 | 7 - D13 | 1000 | 201 |
| 30 | Ma-1 | 32 | *c* | 1561 | 280 | 8 - D16 | 8 - D19 | 1000 | 379 |

### 1.2 *Research objectives*

In general, visual inspection has been often, widely applied to the maintenance work for evaluating the present condition of infrastructure. In the maintenance for harbor RC structures, the result of visual inspection is represented by using the deterioration grade according to the surface condition of structural members (Port and Airport Research Institute 2007). This procedure may conclude more or less subjective and inconsistent evaluation among inspectors. To realize the life-cycle management concept, a structure should be assessed its structural performance rather than its surface appearance or symptom of deterioration.

For these objectives, the relationship between the deterioration grade and load-carrying capacity of RC members is investigated in this paper. Also, a simplified assessment method of performance of RC members is proposed focusing on the relationship between the deterioration grade and structural performance. A total of 30 RC slabs extracted from real superstructures of open-type wharves was experimentally tested after visual inspection.

## 2 INVESTIGATION PROCEDURE

### 2.1 *Tested slab*

An open-type wharf is one of the most typical mooring facilities in harbors as shown in Figure 2. Its concrete superstructure (beams and slabs) is the most vulnerable structural member subjected to chloride attack. RC slabs were extracted from superstructure in existing open-type wharves that have been in service over a period of 30-40 years in 6 ports as shown in Figure 3. The configurations of these test slabs and the quantities of reinforcement are listed in Table 1. Unfortunately the details of constituent materials and design calculations were not available. All the tested slabs were located in the splash zone and the deterioration grades almost covered their variations.

### 2.2 *Visual inspection*

Before the load application, the slabs were visually inspected on their bottom surfaces, of which degrees of deterioration were judged by the grading system, grades *a*, *b*, *c*, and *d*. Grade *d* refers to a sound condition without any signs of deterioration, while grade *a* is the most severe deterioration state. The criterion of judgment is summarized in Table 2 (Port and Airport Research Institute, 2007). Visual inspection was carried out by focusing on cracks and their directions, spalling of cover concrete, rust stain, and corrosion appearances. The deterioration grades of all the slabs are given in Table 1.

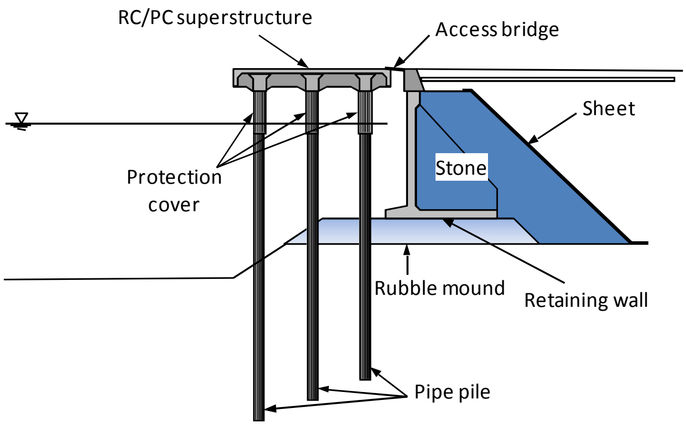


Figure 2. Typical cross-section of open-type wharf.

Figure 3. Slab extraction.

Table 2. Grading criteria for RC slab of open-type wharf.

| Deterioration grade | Criteria |
|---|---|
| *A* | Map cracking (over 50%)<br>Spalling off of concrete cover<br>Heavy rust stain |
| *B* | Map cracking (less than 50%)<br>Much rust stain |
| *C* | One directional crack or gel extraction<br>Partial rust stain |
| *D* | None |

### 2.3 *Loading test*

After the visual inspection and judgment, the slab was experimentally load tested as a one-way slab. They were simply supported at their marginal regions having loading spans as listed in Table 1 and a monotonically-increased three-point (Slabs Nos. 1 through 15) or four-point (Slabs Nos. 16 through 30) bending load was applied at the midspan. The supporting areas were repaired by mortar in case that the cover 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. Since no strain gauges were glued on the surface of reinforcement, the first yield load was determined when the midspan deflection showed a sharp increase.

## 3 LOAD CARRYING CAPACITIES OF TESTED SLABS

The load-deflection relationships of tested slabs are shown in Figure 4. Because of the different dimensions, materials properties, and positions of reinforcement, the load-deflection curves of the slabs cannot be directly compared with each other.

In Slabs Ha-2 and Ha-3, breakage of main tensile reinforcement occurred before crushing of concrete and the applied load was rapidly decreased due to the breakage of reinforcement. The load was carried even after crushing of concrete near the loading plate in Slab Ha-1. Since the failure mode of Slab Ha-1 was different from those of the others, the slab was omitted from the following discussion.

Slabs Ha-4~9 were sampled from the same wharf as Slabs Ha-1~3, where their each shear span was shorter than that of Slabs Ha-1~3. Slabs Ha-4 and Ha-5 showed bending failures without breakage of reinforcement occurred. In Slab Ha-8, breakage of main tensile reinforcement occurred and the applied load was rapidly decreased. In Slabs Ha-7 and Ha-9, after the yielding, the applied load was gradually decreased due to the crack progressing in their shear span. On the other hand, in Slab Ha-6, the load was rapidly decreased due to shear crack occurring.

Slabs Sa-1~9 showed flexural failure after yielding of main tensile reinforcement. Breakage of reinforcement occurred in Slabs Sa-2, Sa-3, Sa-5 and Sa-6, which caused rapid loss in load carried, and in Slabs Sa-8~10, which caused gradually loss in those. Sa-7 showed the different failure from the other Slab Sa-series. In Slab Sa-7, the load was carried with deformation concentration at the bending crack.

Slabs Shi-1 and Shi-2 showed the flexure-tension failure mode. On the other hand, separation between the slab and the pavement parts became distinct due to shear in Slab Shi-3. Because of the different failure condition from the other slabs, the slab should be omitted from the following discussion.

In Slabs Ka-1 and -2, though the load was slightly decreased after yielding of tensile reinforcement, applied load carried with concentration of the deformation at the bending crack. The same tendency was observed in load-deflection relationship in Slab Ka-3, however, the load was decreased due to the breakage of the tensile reinforcement after keeping the

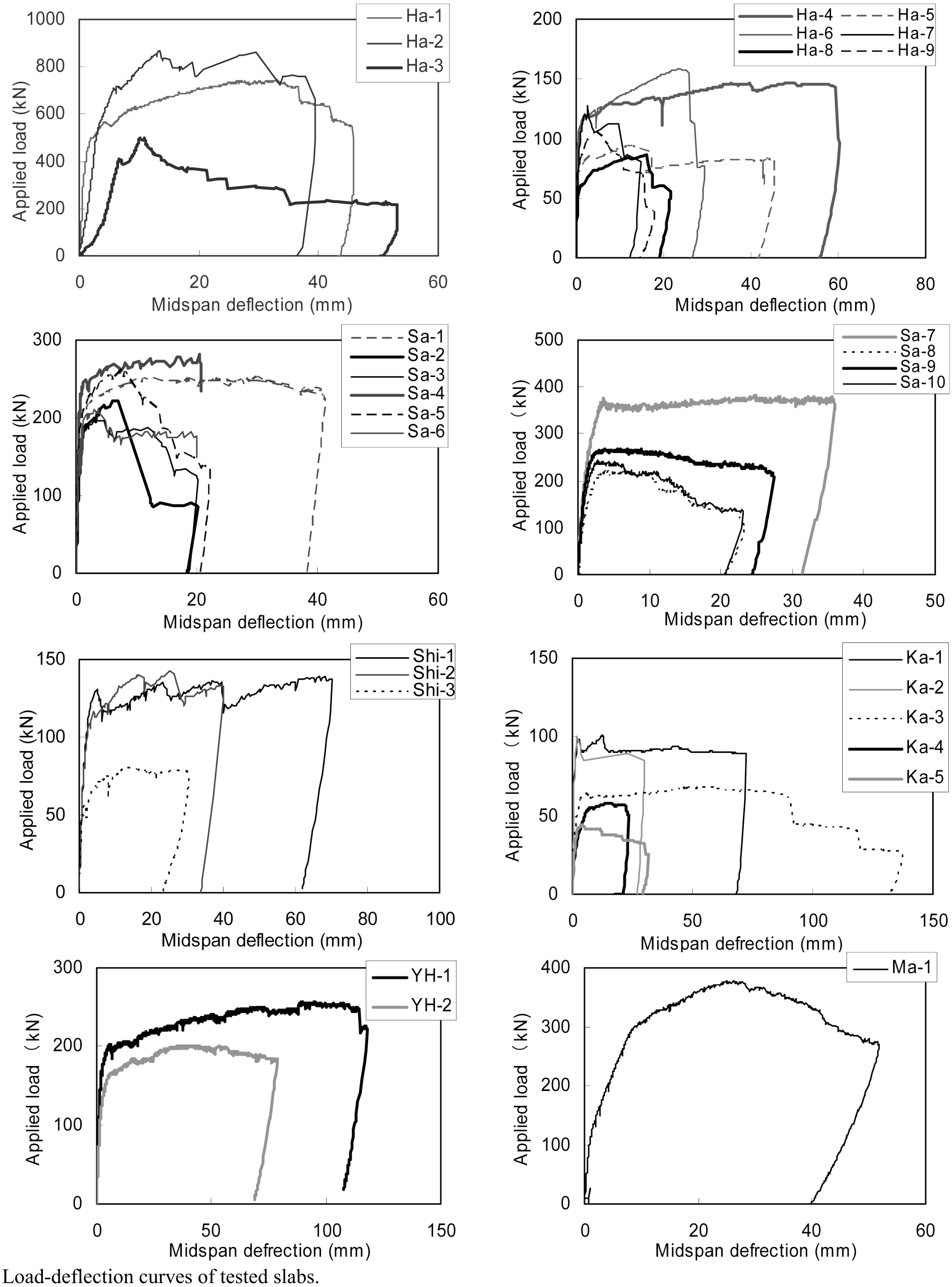

Figure 4. Load-deflection curves of tested slabs.

load carried. Slabs Ka-4 and Ka-5 showed flexural failure after yielding of the main tensile reinforcement. In Slab Ka-5, breakage of tensile reinforcement was observed in the bending span.

Slabs YH-1, YH-2 and Ma-1 showed the typical flexure-tension failure mode. Bending cracks were observed to distribute widely through the side surface of the beam within longitudinal spans.

# 4 SIMPLIFIED ASSESSMENT OF STRUCTURAL PERFORMANCE

## 4.1 *Relationship between deterioration grade and structural performance*

To compare the load carrying capacities of tested slabs with various structural details, the loads were normalized by corresponding calculated predictions based on the beam theory by using designed values of strengths, dimensions, and the initial cross-sectional areas of reinforcement (Yokota et al. 2007). The design values of compressive strength of concrete and yield strength of reinforcement were assumed at 24 $N/mm^2$ and 345 $N/mm^2$, respectively. Their Young's moduli were also assumed at 25 $kN/mm^2$ and 200 $kN/mm^2$.

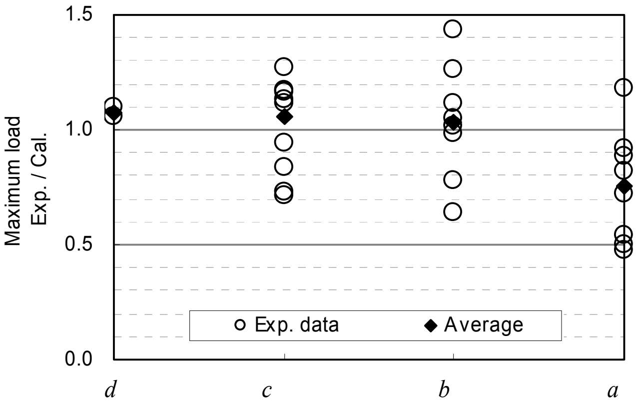


Figure 5. Structural capacity vs. deterioration grade.

Figure 5 shows the relationships between the deterioration grades and the maximum (ultimate) loads of tested slabs. In the slabs judged as grade *c*, *b* or *a*, there were large variations in their load-carrying capacities. There existed the cases of which the maximum load ratios are smaller than 1.0 in grade *c*, *b*, or *a*. In case of slabs judged as grade *a*, in particular, their load-carrying capacities dropped to around 0.7 times as large as the calculated predictions. These were observed in Slabs Ha-3 (delamination on all the bottom surfaces) and Sa-8 through Sa-10 (breakage of reinforcement). Some of the load-carrying capacities of slabs judged as grade *c* were reduced to the same level as that of slab judged as grade *a*.

The average load-carrying capacities of each deterioration grade are also plotted in Figure 5. The average load-carrying capacities become smaller than 1.0 when the deterioration reaches grade *a*. However, for a safe-side evaluation, when deterioration reaches grade *c* or *b*, in other words, symptom of deterioration appeared on the surface of an RC member, the member may not be expected to have adequate structural performance.

## 4.2 *Cause of variation*

Large variations in the load carrying capacity in deterioration grades *c* and *b* were considered to be influenced by two factors as follows: 1) mislead of the deterioration grades judgment and 2) deteriorated area in the tested slab.

1) Delamination of cover concrete was detected by hammering test at the midspan area of some tested slabs. However, the delamination was not directly related to the judgment on the deterioration grades as listed in Table 1. Furthermore, in some tested slabs, many small cracks and honeycomb existing on the surface layer of concrete disturbed the change in appearance due to corrosion, which may mislead the healthier deterioration grade. The degree of corrosion of reinforcement was considered to not always contribute to the surface appearance of slab; that is, judgment of the deterioration grade.

2) One deterioration grade is judged for one slab. In some slabs, corrosion cracks and delamiation of cover concrete were observed in a small part of their surface. According to Table 2, those slabs were judged as deterioration grade *c*. However, some of those slabs showed the different failure mode from the uniformly deteriorated slabs. In the range of this research, not uniformly deteriorated slabs showed a tendency to loss in load carrying capacity due to the shear crack progress. From these results, there is a possibility that the failure mode changes according to the deterioration parts and their states. Moreover, in the previous research (Hamada et al. 2008), it was found that the decrease in the load carrying capacities is remarkable in locally corroded RC beams compared with uniformly corroded RC beams. It can be considered that the load-carrying capacities of tested slabs were easy to be influenced by localized corrosion of reinforcement.

## 4.3 *Cause of variation*

To accurately estimate the load-carrying capacity of deteriorated RC members, it is necessary to obtain an actual cross-sectional area of corroded reinforcement and their positions. Moreover, to develop a structural performance evaluation method having reasonable accuracy, it is necessary to discuss the corrosion characteristics of reinforcement, which has a large effect on the structural performance of RC members. However, inspecting the corrosion state requires not only experience and special techniques, but also a certain amount of money. Development of a simplified and cost-effective assessment method without any special techniques becomes important in the strategic maintenance to prioritize the alternatives of interventions.

In the meantime, a simplified assessment flow of structural performance of RC concrete slab is proposed based on the deterioration grade and the position of deteriorated area. These may be obtained only by visual inspection. The proposed flow of simplified structural performance evaluation is shown in Figure 6. At first, the deterioration grade is judged visually over an entire surface of RC member. In case of deterioration grade *b* or *c*, the deterioration position is also investigated such as the deterioration occurs either near the span center, near the span end and uneven or localized. After that, depending on the ratio of deteriorated area to the entire surface of member, the probability of performance degradation

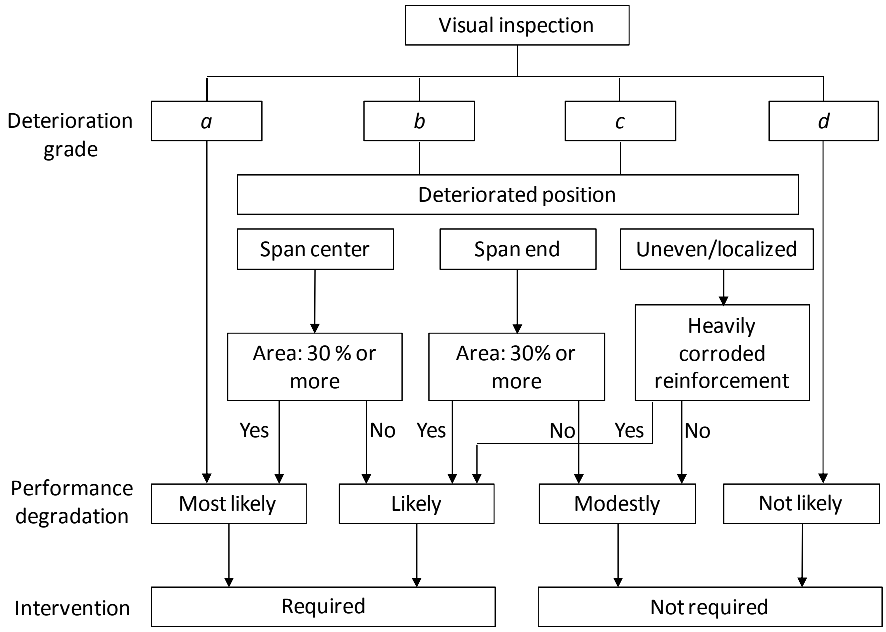


Figure 6. Flow of simplified structural performance evaluation.

can be evaluated. This flow may not be perfect, but may be of great help to discuss whether intervention is required or not.

The result of this research could help us understanding the degradation tendency of load-carrying capacity due to corrosion of reinforcement, which has not been evaluated quantitatively. However, data of experimental load-carrying capacities in each deterioration grade were insufficient to develop a statistical assessment method. The accuracy of this simplified assessment is expected to be improved by accumulating further experimental data.

## 5 CONCLUSIONS

The following conclusions are drawn based on the experimental relationship between the degree of deterioration and structural performance of RC members:

1) When the symptom of deterioration appears on the surface of concrete members, the load-carrying capacity may become smaller than the calculated predictions.

2) Large variations in the load-carrying capacities in deterioration grades *c* and *b* are considered to be influenced by mislead of the deterioration grade judgment and deteriorated area in a tested slab.

3) A flow of simplified assessment on structural performance of deteriorated RC member is proposed in this study. The accuracy of the assessment method is expected to be improved by accumulating further experimental data.

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