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EVALUATION OF THE DURABILITY OF TECHNICALLY REPRESENTATIVE PRESTRESSED CONCRETE RAILWAY BRIDGES

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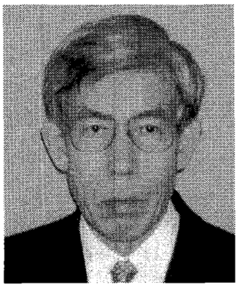

Yukio MIYAMOTO

The history of prestressed concrete railway bridges in Japan began with construction of the Daiichi Daidogawa Bridge on the former JNR Shigaraki Line (now the Shigaraki Kogen Railway Company), which was completed in 1954. Since then, many prestressed concrete bridge projects have broken new ground in the areas of additions to track structures, river improvement, grade-separated railway crossings in urban areas, the "Shinkansen" bullet train projects, and more.
This paper discusses durability evaluations on twenty-eight prestressed concrete railway bridges selected as representative of their various types and that have all been in service for twenty years or longer. The focus of the evaluations is structural durability, the significance of which appears likely to increase in the future. Based on the results of visual inspections, the soundness of these twenty-eight bridges is evaluated in terms of a "soundness score" assigned according to the type of deterioration, how far it had progressed, and repair records. It is found that this soundness score for expressing the durability of actual bridges generally agrees well with evaluation based on the "Proposed Recommendation on Durability Design for Concrete Structures" made by the Japan Society of Civil Engineers.

Keywords: *prestressed concrete railway bridge, evaluation of durability, durability design, deterioration, repair and reinforcement*

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1. INTRODUCTION

There are two primary situations in which an evaluation of the durability of a prestressed concrete railway bridge (PC railway bridge) is required. One is the obvious need when designing a new PC railway bridge, while the other is when improvements need to be made to an existing bridge, including repair and reinforcement projects.

Current durability studies related to the design of new PC railway bridges involve individual checks on specific structural items such as cracking at the service limit, concrete cover, the construction profile of steel members, and protection of anchors for prestressing steel members. They tend not to involve any special studies or checks on overall durability.

On the other hand, the durability of existing PC railway bridges needs to be checked when local agencies responsible for maintenance are required to judge whether or not repair or reinforcement is required, and this entails inspections of those portions of the subject structure in question. The types of checks carried out by such responsible agencies are typically visual inspections or deflection measurements under loading with moving trains, and these are the basis for determining how and when repair or reinforcement work should be implemented.

In either case, PC railway bridge design is not based on evaluations of durability that include a future component. This may be because there are only a few actual cases in which comprehensive investigations of long-term durability have been carried out for in-service PC railway bridges. The lack of knowledge hinders the establishment of an appropriate technique for durability evaluation, and further there is little serious demand for such comprehensive evaluations in practice.

Considering the present state of society and anticipating a need for greater precision in the evaluation of PC railway bridge durability in the near future, this paper attempts to evaluate durability based on data from actual PC railway bridges. The study investigates twenty-eight PC railway bridges, each with a defining technological feature related to structure, materials, or construction method, chosen from among bridges in service for twenty years or more. The author attempts to establish an evaluation of durability from a technological standpoint and based on the results of visual inspections, all of which were performed by the same person. The results are verified against durability as assessed according to the durability index defined in the "Proposed Recommendation on Durability Design for Concrete Structures" [1] (the "Proposed Recommendation") published by the Japan Society of Civil Engineers. Environmental indexes are obtained from actual environmental conditions.

This paper is a summary of some selected sections of a dissertation for a degree submitted to the University of Tokyo in December 1998.

2. OVERVIEW OF THE SURVEY

2.1 Selection of Bridges

Table 1 [2]–[34] lists the adopted as the subject of this survey. All selected bridges satisfy the following criteria:

1) In service for twenty years or longer, and suitable for assessment of durability. Priority was given to those with longer in-service periods.

2) Bridges (or groups of bridges) that represent the pioneering days of PC railway bridges

3) Bridges with notable technical characteristics in terms of structure, materials, or construction methods

4) Simple T- and I-girder bridges, as examples representing a large number of bridges of this structural type constructed prior to building of the Tokaido Shinkansen. Viaduct O was selected from the Kansai region and viaduct N from the Kanto region.

Table 1 Surveyed Bridges

No.	Bridge name	Year constructed	In-service period *	Environment	Noteworthy characteristics
1	Bridge D	1954	44	Temperate lowland	The first long-span PC railway bridge, simple T-girder carrying single track
2	Up-line bridge Y	1959	39	Cold area	Early simple T-girder carrying single track
3	Viaduct O	1959	39	Temperate lowland	Twin simple T-girders carrying parallel single-tracks, the first such massive work in the Kansai region
4	Bridge O1	1960	38	Temperate coastal area	Simple box-girder carrying single track, massive live line work
5	Bridge H	1961	37	Cold area	Early simple through-girder carrying single track
6	Bridge K	1961	37	Cold area	3-span continuous box-girder, erection on fixed staging, concrete cast in place
7	Bridge W	1962	36	Cold mountainous area	3-span continuous box-girder, cantilever erection, concrete cast in place
8	Viaduct N	1962	36	Temperate lowland	Twin simple T-girders carrying parallel single-tracks, the first such massive work in the Kanto region
9	Shinkansen bridge Y	1963	35	Temperate lowland	The only 3-span continuous bridge on the Tokaido Shikansen line, Leonhardt system
10	Bridge T	1963	35	Cold mountainous area	Early PC rigid frame bridge
11	Road overbridge K	1965	33	Temperate lowland	The first lightweight concrete girder, twin simple I-girders carrying parallel single-tracks
12	Bridge A1	1965	33	Temperate lowland	The first single through-girder carrying double track, 24 separate spans
13	Bridge S	1967	31	Temperate lowland	5-span continuous box-girder with bearings distributing seismic forces, concrete cast in place
14	Down-line bridge Y	1969	29	Cold area	3-span continuous box-girder, precast block erection on fixed staging
15	Shinkansen bridge H	1970	28	Temperate lowland	3-span and 2-span continuous box-girder, erection on fixed staging, concrete cast in place
16	Shinkansen bridge A1	1970	28	Temperate lowland	5-span continuous box-girder, cantilever erection, concrete cast in place
17	Shinkansen bridge K1	1971	27	Temperate lowland	3-span continuous box-girder, precast block cantilever erection
18	Shinkansen bridge Y	1971	27	Temperate lowland	2-span continuous box-girder, 4 separate spans, Leonhardt system, concrete cast in place
19	Shinkansen bridge A2	1973	25	Temperate lowland	High-strength concrete I-girder, erection by track cranes
20	Shinkansen bridge K2	1973	25	Temperate lowland	4-span continuous box-girder, cantilever erection, concrete cast in place
21	Shinkansen road overbridge I	1973	25	Temperate lowland	The only through truss bridge of Warren type on the Shikansen lines
22	Shinkansen bridge O	1974	24	Temperate lowland	7-span continuous box-girder, cantilever erection, concrete cast in place
23	Shinkansen road overbridge N	1974	24	Temperate lowland	3-span continuous box-girder, cantilever erection, concrete cast in place. PC bridge with the longest span on the Sanyo Shinkansen line
24	Shinkansen road overbridge O	1976	22	Cold area	Simple through girder with the longest span, VSL system
25	Bridge O2	1973	25	Cold area	The first deck truss bridge of Howe type
26	Bridge A2	1975	23	Cold coastal area	Deck truss bridge of Howe type, 5 separate spans
27	Bridge M	1977	21	Cold mountainous area	The first continuous through truss bridge of Warren type
28	Bridge O3	1979	19	Cold area	The first PC cable stayed bridge, concrete cast in place

* No. of years since construction as of 1998

As to the environmental conditions at the respective bridge sites, sixteen are located on temperate plains, one in a temperate coastal area, ten in cold or mountainous areas, and one in a cold coastal area. They therefore encompass a variety of environmental conditions.

2.2 Survey Method

A number of methods were used to complete the survey, including the study of magazines, journals, and work reports, data recorded at the time of construction (such as the Reports of JNR Annual Conferences on Civil Engineering Works), records of deterioration maintained by local agencies, visual inspections on site, and photography.

Since the bridges surveyed have particular technical points of interest, there is some published literature available for each of them. However, such documents are frequently lacking in such areas as accurate records of cement types and concrete mixtures used in the project. Furthermore, many do not offer information collected at the time of construction, such as methods of concrete placement and number of curing days. Such information is important in evaluating durability.

The author referred to "structural check record ledgers", which are records kept by local government agencies during maintenance. Of the bridges discussed here, only a few were actually subjected to individual inspection by such agencies, so the structure deterioration reports that should have been prepared were not available in a large number of cases.

The visual inspections carried out by the author followed in outline the general inspection method used by maintenance agencies. It should be noted, however, that in this study the same person (the author) assessed the state of deteriorations for all the inspection items listed below [35].

1) Status of cracking
2) Detachment and honeycombing of concrete
3) Status of exposed reinforcing bars and prestressing steel
4) Discoloration and precipitated free lime (efflorescence)
5) Status of aging and frost damage
6) Status of water drainage and leakage
7) Status of bearings
8) Girder warp

Table 2 Number of Cases of Deterioration Found for Each Structural Type

	Cracking	Detachment, Honeycombing of concrete	Discoloration, Precipitated free lime	Exposed steel	Aging, Frost damage	Defective drainage, Water leak	Defect around bearing	Girder warp	Total cases of deteriorations A	No. of bridges B	A/B
T(I)-girder	3	3	4	2	1	3	4	1	21	6	3.5
Box-girder	9	6	14	9	7	2	6	0	53	15	3.5
Through-girder	2	1	3	2	2	0	1	0	11	3	3.7
Truss	3	2	4	2	2	1	0	0	14	4	3.5
Total	17	12	25	15	12	6	11	1	99	28	3.5

Note) Rigid frame bridge and cable-stayed bridge are included as box-girders.

The survey results were compiled into survey sheets. In addition, photos of different portions of the bridges were taken and used as inspection data.

3. EVALUATION OF DURABILITY OF SURVEYED BRIDGES

3.1 Survey Results

(1) Summary of deterioration

Table 2 shows the frequency of various types of deterioration for each bridge type. The inspection items in this table are the "general inspection items" provided in "Standards for Maintenance of Railway Civil Engineering Structures, and Commentaries (Concrete Structures)" [35].

The following overall observations can be made with respect to deterioration of the surveyed bridges:

1) Discoloration or precipitated free lime is the most frequent type of deterioration, followed by cracking and exposure of steel. These three phenomena were observed in more than half of the twenty-eight bridges inspected. The frequency of the eight types of deterioration described in reference [35] is 3.5 per bridge on average. This frequency distribution does not vary significantly with structure type (Table 2).

2) Discoloration and precipitated free lime are changes that usually take place with aging. These phenomena were observed in twenty-five of the twenty-eight bridges. Free lime appears on the concrete surface in the form of calcium oxide, as a consequence of the reaction of water with calcium from the concrete. The presence of this substance, therefore, means that water has seeped into cracks in the concrete where it reacts with cement components. If the volume of such precipitation is large and indicating a tendency to increase, it may have an impact on the durability of the concrete. However, in the case of bridge D (No. 1) and most of the continuous box-girders for the Shinkansen lines, only a little free lime was observed, so generally the presence of free lime does not indicate an immediate effect on durability. Nevertheless, the presence of large quantities of precipitated free lime and ongoing precipitation, as in evidence at bridge T (No. 10), mean that continuous observations are required to determine its impact.

3) Unsatisfactory drainage and water leakage is a type of deterioration whose effect appears with aging. Unsatisfactory drainage was often found, particularly where drainage gutters had been laid along the track axis in the infill between twin T-(or I-) girder assemblies where a pair of single tracks run in parallel, such as viaduct O (No.3) and viaduct N (No.8). This type of structure is now obsolete, as double-track girders have come into common use. Consequently, such cases of unsatisfactory drainage will not increase further.

Water leakage occurs in the joint between precast and cast-in-place sections in the case of a T-girder, whereas in the case of a box-girder, it appears at the joint between the main girder and post-cast sections carrying the sidewalk in a cantilevered slab or the curb with a handrail. These are weak points in the work, and rainwater tends to flow in those areas, so they are prone to water leakage. However, given that some bridges that have been in service for more than 30 years are free of such defects, it can be concluded that the quality of workmanship to some extent determines whether a bridge deteriorates as it ages. No unsatisfactory drainage or water leakage was observed in the three cases of through-girders investigated.

4) Cracking, detachment and honeycombing, and exposure of reinforcing steel, are defects often found in cases where the concrete workmanship was poor. About half of the surveyed bridges exhibited such forms of deterioration. Of these three types of deterioration, cracking was the most frequent. Cracks typically occur along the sheath of the main girder web, on the side of the girder end in the vicinity of the bearing, at the corner of the diaphragm inside a box-girder, and on the lower face of a box-girder. There are many variations in crack width and orientation, as well as in the trends of crack development.

5) In cold regions, aging and frost damage appear in structures that have been in operation for long periods. These types of deterioration are attributable to aging effects where workmanship was poor or to the impact of environmental on elements affecting the poor drainage or waterproofing work. Such deterioration can be

delayed by improving workmanship and developing more effective drainage paths to avoid frost damage.

6) The deterioration seen at bearings is cracking. Cracks can arise in the concrete of the girder end if steel in the bearing corrodes or if a sliding bearing malfunctions. Among the bridges surveyed, almost all steel line bearings of simple T-girders were corroded. In contrast, the roller bearings of continuous box-girders were satisfactorily maintained in general, and little corrosion was in evidence. The rubber bearings currently in use are inherently free of such problems.

7) Among the surveyed bridges, warping was found in only one case, that is the up-line bridge Y (No.2). It appears that warping does not occur very frequently.

(2) Progress of deterioration and implementation of repairs

One of the key points to consider in the evaluation of bridges is whether or not the deterioration is ongoing. Among the forms of deterioration given in Table 2, the discussion in this section focuses on cracking, because it is easy to quantitatively evaluate crack development with the elapse of time. Typical cases of cracking among the bridges surveyed are: cracks in the girder end at the bearing of bridge O1 (No.4); cracks in the web and bottom face of the lower flange of Shinkansen bridge A2 (No.19); and cracks along the track axis in the lower slab and upper surface of the main girder of Shinkansen road overbridge O (No.24). These cracks are not likely to have an immediate effect on durability, but under some circumstances they may influence the soundness of the entire girder or induce corrosion of the reinforcing steel. They are therefore a major consideration in evaluating long-term durability.

Some form of deterioration was found in all twenty-eight bridges surveyed. The survey also indicated that some of these forms of deterioration, such as cracking and seepage of free lime, may be of a progressive nature. Appropriate repairs are implemented on the basis of judgments made by the maintenance agencies concerned, taking into account the significance of the observed deterioration.

Of the bridges surveyed, eleven bridges had not undergone repairs, while seventeen had already been repaired in some way. Length of service was not a factor in whether a bridge had been repaired or not. The bridges not repaired included a simple T-girder constructed very early on, girders constructed with artificial lightweight aggregate, some continuous box-girders and cable-stayed bridges and truss girders. There was no noticeable tendency for a particular structure type to have undergone repairs, except that the number of repairs to truss girders made with precast members was small.

3.2 Evaluation of Durability

In this section, the durability of the twenty-eight bridges is first evaluated on the basis of visual inspections. Next, durability indexes are calculated by applying the Proposed Recommendation [1] by the Japan Society of Civil Engineers as a general standard for the durability design of concrete structures. These indexes based on the Proposed Recommendation are then compared with the durability evaluations based on visual inspections.

(1) Evaluation of durability and analysis based on inspection results

In the Proposed Recommendation on Maintenance of Concrete Structures [36] by the Japan Society of Civil Engineers, a method of evaluating degree of deterioration is described. The commentaries to the method state that, "it is preferable that the degree of deterioration should be evaluated theoretically and quantitatively by assessing the impact of the state of deterioration and the development of the deterioration mechanism on performance of the structures concerned. However, such an evaluation method is difficult to establish, and so, it is generally recommended that a system of grading deterioration conditions and deterioration mechanism development be established".

In this paper, visual inspections of the selected bridges are used as the basis for proposing the concept of soundness scoring. This system defines a soundness index derived from the major types of deterioration whose severity can be judged in terms of the following three factors: impact on durability (excluding progression of the deterioration), progressiveness of the deterioration involved, and records of repairs.

Table 3 Evaluation of Durability of the Bridges Surveyed

No	Bridge name	Environmental index Sp	No. of cases of deterioration	Point deduction for significant deterioration	Point deduction for progressive deterioration	Deduction for repairs	Soundness score	Durability index Tp	Tp/Sp	Major deteriorations
1	Bridge D	100	1	−1	0	0	9	105	1.05	Precipitated free lime
2	Up-line bridge Y	130	4	−1	0	0	9	121	0.93	Frost damage
3	Viaduct O	100	6	−2	0	−1	7	98	0.98	Discoloration due to defective drainage
4	Bridge O1	130	5	−2	−2	−2	4	63	0.48	Cracking in the girder end surface near the bearing support
5	Bridge H	130	5	−2	−1	−2	5	106	0.82	Aging, rust on steel
6	Bridge K	110	5	0	0	−2	8	105	0.95	Cracking in the corner of diaphragm concrete
7	Bridge W	130	5	−2	0	0	8	121	0.93	Cracking in the girder end surface near the bearing support
8	Viaduct N	100	6	−2	0	−1	7	106	1.06	Discoloration due to defective drainage
9	Shinkansen bridge Y	100	6	−2	0	−1	7	114	1.14	Aging, rust on steel
10	Bridge T	120	5	−2	−1	−2	5	105	0.88	Aging, rust on steel
11	Road overbridge K	100	1	−1	0	0	9	108	1.08	Cracking in the girder end surface near the bearing support
12	Bridge A1	100	2	−1	0	−1	8	119	1.19	Precipitated free lime on girder end surface
13	Bridge S	100	6	−2	0	−1	7	102	1.02	Rust on reinforcing bars
14	Down-line bridge Y	130	3	−2	0	−1	7	111	0.85	Aging
15	Shinkansen bridge H	100	2	0	0	0	10	99	0.99	no deterioration
16	Shinkansen bridge A1	100	1	0	0	0	10	115	1.15	no deterioration
17	Shinkansen bridge K1	100	1	0	0	−1	9	125	1.25	no deterioration
18	Shinkansen bridge Y	100	1	0	0	−1	9	102	1.02	no deterioration
19	Shinkansen bridge A2	100	3	−2	−2	−2	4	132	1.32	Cracking on the surface of lower flange of girders
20	Shinkansen bridge K2	100	3	−2	0	−1	7	81	0.81	Cracking in the bottom surface of box-girder
21	Shinkansen road overbridge I	100	2	−2	0	0	8	144	1.44	Precipitated free lime in post-filled portion at panel point structure
22	Shinkansen bridge O	100	1	0	0	0	10	102	1.02	no deterioration
23	Shinkansen road overbridge N	100	4	−2	−1	−2	5	65	0.65	Aging, cracking in the bottom surface of box-girder
24	Shinkansen road overbridge O	110	4	−2	−2	−2	4	93	0.85	Cracking in the side surface of main girder and lower surface of slab concrete
25	Bridge O2	130	4	−2	0	0	8	146	1.12	Cracking in the panel point structure
26	Bridge A2	160	5	−2	−1	−2	5	148	0.93	Rust on reinforcing bars
27	Bridge M	130	3	−2	0	0	8	135	1.04	Cracking in the panel point structure
28	Bridge O3	130	5	−2	0	0	8	130	1.00	Cracking in the upper surface of cantilevered slab concrete

The purpose of this scheme is to quantify the qualitative evaluations made in general inspections; that is, to translate the primary inspections conventionally conducted by agencies responsible for maintenance into a quantitative yardstick. Of the three factors involved, the first two are the basis of the soundness judgment described in references [35] and [36]. The first is used to determine whether any deterioration noted in the visual inspection has any potential adverse effect on the function of the subject structure without considering the potential of the deterioration to progress. The second is used to determine whether or not the deterioration is of a progressive nature. Thus, these two factors can be used in combination to judge any deterioration detected in an inspected bridge as of inspection day. The third factor is included on the assumption that any past repair instances or lack of them can be effectively used to determine present durability. It is included here because any repair work aimed at recovering functionality leaves a trace of the original defect, so the possibility of recurrence cannot be disregarded. Further, there is always uncertainty as to whether the repair work was performed satisfactorily.

The author makes the assumption that these three factors can be used to evaluate the durability of PC railway bridges. In the soundness scoring approach described here, each bridge is initially scored at 10 points, and points are deducted for each factor depending on the degree to which, in the author's subjective judgment, it affects durability. That is, one point is deducted if the effect is deemed insignificant, and two points if it is deemed more significant. The number of points remaining after the evaluation is the soundness score of the bridge concerned.

As an example of this, viaduct O (No. 3) received seven points as its final soundness score. The calculation was carried out as follows. Two points were deducted for the deterioration factor, because a large number of traces of water leakage were seen at joints between precast PC girders and cast-in-place concrete filling the inter-girder gaps. No points were deducted for the progressiveness factor, because it was judged that the deterioration was not progressive, and one point was deducted on the repair record because a simple lining repair had been made in some locations.

Table 3 shows the judgment criteria and the evaluations for each of the bridges, as well as the final soundness scores. Also given in Table 3 are calculated values of the environmental index (Sp), the durability index (Tp), and the value of Tp/Sp. The environmental and durability indexes are defined in the Proposed Recommendation, and this is discussed in article (3) of this section. Table 4 provides a soundness ranking (the number preceding the bridge name) within each of three groups classified by soundness score, based on comprehensive judgment from visual inspection results.

The first group consists of bridges given soundness scores of eight to ten points (Group A). In this group, the subgroup with the lowest soundness score of eight points consists of bridges given minus two (-2) points on one of the three factors and those given minus one (-1) point on two of the three factors. Of the total of seven bridges with a soundness score totaling eight points, soundness has been checked with general inspections only throughout their in-service periods of twenty years or more. This indicates that a satisfactory soundness level has been maintained among all bridges in Group A. For this group, biennial inspections are sufficient, as stipulated in the relevant ordinances, requiring no additional maintenance work.

Table 4 Classification of Soundness of the Surveyed Bridges

Soundness group	Soundness score	Bridge name and soundness ranking in group
A	10	(1) Shinkansen A1 (2) Shinkansen O (3) Shinkansen H
	9	(1) Shinkansen K1 (2) Shinkansen Y (3) Road overbridge K (4) Up-line Y (5) D
	8	(1) K (2) W (3) A1 (4) O3 (5) Shinkansen road overbridge I (6) M (7) O2
B	7	(1) Shinkansen Y (2) Shinkansen K2 (3) S (4) Down-line Y (5) Viaduct N (6) viaduct O
	6	---
C	5	(1) H (2) T (3) A2 (4) Shinkansen road overbridge N
	4	(1) Shinkansen road overbridge O (2) Shinkansen A2 (3) O1

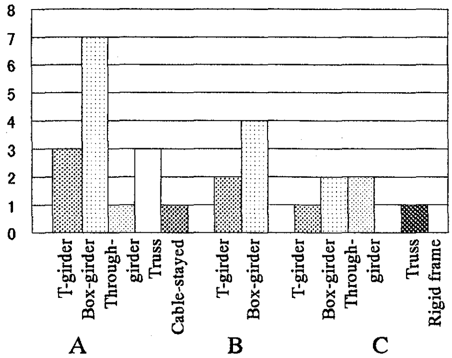

Fig. 1 Soundness of Bridges by Structure Type

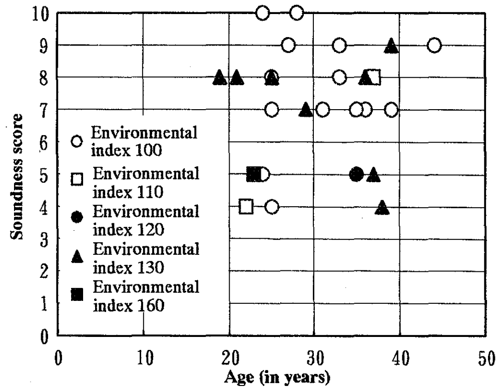

Fig. 2 Relationship between Soundness Score and Age

The second group consists of bridges with soundness scores of six to seven points (Group B). For the bridges in this group, the pattern of point deduction is either one of the four cases: for a score of seven points, a case of -1-1-1 or a case of -2-1, and for a score of six points, a case of -2-1-1 or a case of -2-2. In other words, for the bridges in this group, one point was deducted on all of the three factors or deduction was made on two to three factors with minus two points on one or two factors. Based on this distribution of points, it was judged that bridges classified under this group require greater care for maintenance than the bridges in Group A. Thus, the Group B bridges are considered to be maintaining average (medium-level) soundness but deterioration occurring on them may affect their durability. This group of bridges requires more care than group A, and general inspections should focus particular attention on sections with observed deterioration.

The third group includes bridges with soundness scores of four and five points (Group C). The pattern of point deduction for the bridges in this group is either a case of -2-2-2 or a case of -2-2-1. Since these bridges have points deducted for two or more factors, they are judged to be requiring particular caution with respect to durability. In fact, all of the bridges in this group had been individually inspected by the relevant maintenance agencies and repaired according to the inspection results.

Some of the deteriorations observed in this group may be progressively aggravated. The condition of bridges in this group is such that their function and load-carrying capacity may be affected over time, if not immediately, unless appropriate measures are taken. It is suggested that regular, semi-annual checks should be performed with particular attention to sections where deterioration is occurring, so that individual inspections may lead up to any repair measures required.

Figure 1 shows the numbers of bridges in each soundness group by structural system. Of the bridges studied, about half of the T-girder or box-girder structures belong to Group A. Further, over 80% of all bridges in Groups A and B are either T-girder or box-girder structures. Three out of the four truss bridges also belong to Group A. In contrast, two out of the three through-girder bridges belong to Group C. Although the sample is too small to draw accurate conclusions, it appears that T-girder and box-girder structures have generally maintained satisfactory soundness. It can also be concluded that since truss bridges comprise an assembly of precast concrete members, the cast-in-place joints are prone to defects even though the precast members themselves may present no problems. Since through-girder bridges have complex sectional geometries as well as a mass of steel members (main cable, transverse and vertical prestressing steel members, and reinforcing bars), construction of these bridges is considered difficult, and this kind of structure appears prone to deterioration.

(2) Relationship between soundness score and age

Figure 2 shows the relationship between soundness score and the number of years the bridge has been in service. In this figure, bridges located in areas with the same environmental index are marked with the same symbol. Figure 2 does not indicate a tendency for older bridges to have a lower soundness score. The reason for this may be that the in-service periods are still short at present. In particular, bridges constructed in locations with an average environmental index of 100 show no effects of aging. However, some of those bridges constructed

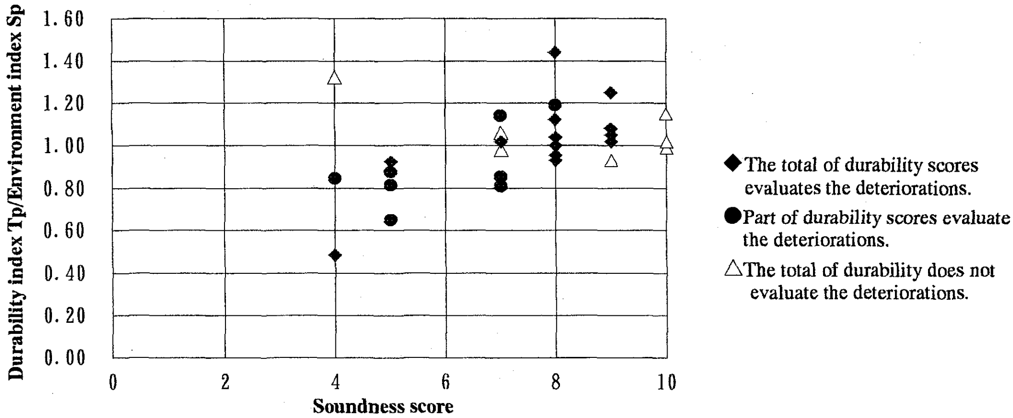

Fig. 3 Relationship between Tp/Sp and Soundness Score

in areas with more severe environmental conditions exhibit lower soundness scores nearly forty years after construction. With these bridges, it is possible that rust on steel members or honeycombing of concrete resulting from initial defects such as improper concrete compaction or insufficient cover have further accelerated deterioration due to aging and environmental effects. It can be concluded therefore that no aging phenomena such as carbonation that may appear over time under normal environmental conditions, are observed on PC railway bridges in service for thirty to forty years. However, where environmental conditions are more severe, bridges are prone to greater damage if there are any initial defects in the workmanship.

(3) Discussion according to the Proposed Recommendation from the Japan Society of Civil Engineers

The Proposed Recommendation [1] is a 1995 revision of the "Recommendation on Durability Design for Concrete Structures (Tentative Proposal)" [37], [38], [39] published in 1989. The recommendations made in the document feature in a durability design approach based on techniques similar to those used for structural safety checks. In other words, values of environmental and durability indexes are compared to check the durability of the respective sections of the relevant members. The environmental index is determined according to environmental conditions in the vicinity of the structure as well as the required length of maintenance-free service. If the target is construction of a concrete structure requiring 50 years of maintenance-free service, the environmental index under average environmental conditions is assumed to be 100. For a structure placed where environmental conditions are severer than average, it is specified in the Proposed Recommendation that the environmental index should be increased by 10 to 70, depending on the effects of salt and freeze-thaw cycles. As for the durability index, it is obtained by adding 30 points to the total of durability score calculated from various factors pertaining to the design, materials, and construction method.

The Proposed Recommendation aims to facilitate durability design in the case of new construction. As such, its relevance to the evaluation of existing PC structures can be questioned. The recommendation does, however, provide the only standards available for the academic-level quantitative evaluation of PC structures. Also, if sufficient design and construction data are available, it should be possible to calculate durability index values even for existing PC structures. It is for this reason that the author opted to make use of the Proposed Recommendation.

The calculation of durability points was based on data taken from construction work reports, the Report of JNR Annual Conferences on Civil Engineering Works, various magazines and journals, and as-built drawings. However, these materials often failed to provide detailed data on dimensions (missing relevant drawings), materials initially used, or information on construction methods employed. For those items, values were estimated by reference to available design/construction examples for similar structures. The sections studied include the main girder for T-, box-, and through-girder bridges, the span section for rigid-frame bridges, the diagonal member for cable-stayed bridges, and the lower chord member for truss bridges.

Summarizing the breakdown of durability index values for the twenty-eight bridges listed in Table 3, significant variances in scores are seen with respect to the following three items: Tp (1, J) (design work, geometry of members, types of reinforcing members, details of reinforcing members, and design drawings), Tp (5, J) (concrete specifications and quality), and Tp (6, J) (concrete work performance). In contrast, there were no significant variances among the other items including Tp (2, J) (cracks permitted in design), Tp (3, J) (special formwork, surface protection work), Tp (4, J) (materials of concrete), Tp (7, J) (reinforcing work, formwork installation, support work), and Tp (8, J) (items complementary to PC work).

For the twenty-eight bridges surveyed, Fig. 3 shows the relationship between the soundness score and the (durability index)/(environmental index) ratio (Tp/Sp) as listed in Table 3.

A general tendency can be seen in Fig. 3, although there is some variance. That is, a greater Tp/Sp value is generally associated with a higher soundness score. In this figure, different symbols are assigned depending on the relevance of the evaluation to the actual state of deterioration represented by the durability score based on the Proposed Recommendation.

According to Fig. 3, the Proposed Recommendation-based durability score substantially reflects the actual deterioration status of twenty-one of the twenty-eight bridges. The bridges to which the Proposed Recommendation were effectively applied to evaluation of the actual deterioration status include four bridges (Nos. 9, 13, 20 and 24) with rusted reinforcing bars or cracks due to insufficient cover, one bridge (No. 10) in which the design-related score is involved, two bridges (Nos. 14 and 23) involving the concrete-related score, one bridge (No. 4) involving a score pertaining to design and concrete, and thirteen bridges with a relatively prominent relationship to the magnitude of the total durability score, totaling twenty-one bridges.

Those bridges for which the Proposed Recommendation failed to provide relevant evaluation of the deterioration status included three (Nos. 2, 3, and 8) with no case found in the Proposed Recommendation for evaluation of drainage work, three (Nos. 15, 18, and 22) where the calculated durability score was too low to effectively use the Proposed Recommendation for relevant evaluation of design/construction work, and one (No. 19) where the soundness score dropped despite sufficient durability score, totaling seven bridges.

Table 3 and Fig. 3 indicate that, in general, the Proposed Recommendation can be effectively used for the evaluation of the durability of PC railway bridges. Still, in order to satisfactorily apply the Proposed Recommendation to the design of actual structures, we are faced with the challenge of further verification in certain areas. These include such points as differences in structural systems, the effect of personnel-related factors (competence, qualifications, and experience of those in charge), the appropriateness of adding 30 points to the durability score for cases where the width of flexural cracking due to the permanent load is zero, the relevance of a constant term of 30 points for calculating the durability index, the identification of the grounds for calculation of the environmental index, etc. Still, the above discussion leads to the conclusions given in the following section.

In order to introduce durability validation based on the Proposed Recommendation into design practice, we need to accumulate further data on actual bridges, and thereby refine this approach to achieve greater accuracy.

4. CONCLUSIONS

Twenty-eight PC railway bridges with representative technical characteristics that had been in service for at least twenty years were selected for a visual evaluation of durability. The results of this evaluation were compared with the Proposed Recommendation on the Durability Design of Concrete Structures by the Japan Society of Civil Engineers. The bridges surveyed include six T-girder bridges, thirteen box-girder bridges, three through-girder bridges, four truss bridges, one rigid frame bridge, and one cable-stayed bridge. Classified by environmental conditions, there were 16 bridges sited on temperate lowland plains, one near the coast in a temperate climate, 10 in cold or mountainous areas, and one near the coast in a cold climate. That is to say, the survey involved a variety of bridge types and environmental conditions.

The following understandings were obtained through the survey.

1) Visual inspections showed that the type and degree of deterioration differed in all bridges surveyed. The most frequent type of deterioration was discoloration/precipitated free lime, followed by cracking and exposure of steel reinforcement. These three types of deterioration were found in more than a half of the surveyed bridges. The number of separate points of deterioration per bridge was 3.5 on average, regardless of structure type.

2) Among the bridges studied, 17 had already been repaired. No distinct relationship was found between the implementation of repairs and the number of years since construction. That is to say, deterioration had occurred in some PC railway bridges regardless of age, and repairs were sometimes implemented early in their life according to the type and degree of deterioration.

3) On the basis of the inspection results, the durability of the bridges was evaluated. As an index for assessing soundness, a soundness scoring system was proposed. Using this system, the bridges were classified into three groups: Group A with excellent soundness not requiring maintenance for the time being, Group B for which ordinary inspections are sufficient, and Group C requiring continuous monitoring and repair in some cases. Though no noticeable difference by structure type is discerned among these groups, the following tendency was noted: Group A includes many truss bridges, Group C includes through-girder bridges, and T-girders and box-girders are distributed among all three groups.

4) There was no clear relationship between soundness score and age of the bridge. In the case of PC railway bridges ranging in age from about 20 to 40 years, soundness is affected more by poor construction practices, defective concrete materials, or malfunction of bearings than by the number of years elapsed since construction. With some bridges in severe environmental conditions, a tendency was seen for certain types of deterioration to have occurred, such as cracks induced by defects in initial design and construction.

5) The durability score for each bridge was calculated according to the Proposed Recommendation. Among the items determining the durability score of the bridges, three items were found to vary significantly: design work/geometry of members/types of reinforcing members/detail of reinforcing members /detail of design drawing; concrete specifications and quality; and concrete work performance. For twenty-one bridges of the twenty-eight, the durability score according to the Proposed Recommendation properly evaluates the actual state of deterioration.

6) Using the durability indexes obtained from the durability scores according to the Proposed Recommendation, the ratio (durability index)/(environmental index) (Tp/Sp) was obtained and its relationship to the soundness score was studied. The soundness score generally correlates with the Tp/Sp, revealing that evaluation by the Proposed Recommendation in general reflects the actual durability of PC railway bridges.

7) The durability of PC railway bridges can be summarized as follows. For the bridges surveyed, no problems were found in terms of load-carrying capacity, though some deterioration was found in all bridges. The soundness of each bridge was determined with reference to the category and degree of deterioration, its progressive nature, and whether or not repairs had yet been implemented. The bridges can be classified into three groups according to their level of soundness: a group not needing maintenance, a group for which usual observations is sufficient, and a group needing regular inspections and attention.

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