Civil Engineering Infrastructures Journal, 51(2): 311 – 337, December 2018
Print ISSN: 2322-2093; Online ISSN: 2423-6691
DOI: 10.7508/ceij.2018.02.005

Application of J-BMS to Performance Evaluation and Remaining Life Prediction of an Existing RC Bridge

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Received: 20 Jul. 2017; Revised: 02 May 2018; Accepted: 21 May 2018

ABSTRACT: This paper describes a method of performance evaluation and remaining life prediction for an aged reinforced concrete (RC) T-girder bridge by J-BMS RC version via close visual inspection data, and also verifies the assessment results obtained as outputs from the Bridge Rating Expert System (RC-BREX) which is a subsystem of the J-BMS, to evaluate the effectiveness of the system. The Bridge Management System (J-BMS) that was previously developed by the authors, and which is capable of forecasting the deterioration process of existing bridge members, was applied to evaluate the safety indices (soundness score) and remaining life of the target bridge based on these test results. Using these methods, the remaining life of an aged RC-T girder bridge (SK-bridge) can be quantitatively estimated by applying the bridge rating expert (BREX) system, which is a subsystem of the J-BMS RC version that incorporates with the field inspection data. In this study, close visual inspection was carried out on the aged bridge by professional visual inspectors, during which all variations of the inspection results were evaluated using a five-step questionnaire. As a result, it was found that the soundness score (safety index) and remaining life predictions were influenced by the learning (supervised) data selection. Additionally, the predicted remaining lives were verified through concrete core tests extracted from main girders and deck slabs.

Keywords: Aged Bridge, Carbonation, Chloride Ion, Close Visual Inspection, Concrete Core, Cross-Section, J-BMS RC Version, Performance Evaluation, RC Bridge, RC-BREX System, Remaining Life.

INTRODUCTION

The authors have been developing a practical bridge management system (J-BMS) to improve efficiency in bridge management (Miyamoto et al. 1998; Miyamoto and Motoshita, 2015; Emoto et al., 2014a). J-BMS is a diagnosis system designed mainly for the evaluation of concrete bridges. J-BMS has two types: J-BMS RC version, which is used to diagnose reinforced concrete (RC) bridges (Emoto et al., 2014b), and J-BMS PC version, which is used to diagnose prestressed concrete (PC) bridges (Miyamoto and Asano, 2017). J-BMS consists of the following subsystems: 1) a bridge maintenance database system (J-BMS DB) for efficiently managing relevant data such as bridge specification data and inspection data, 2) a bridge deterioration diagnosis system (Bridge

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Rating Expert System (RC and PC-BREX) and 3) a maintenance plan optimization system for drawing up an optimum maintenance plan (MPOS). RC-BREX has two types of system: RC-BREX '99 which deals with qualitative input data, and RC-BREX 2000 which deals with quantitative input data. J-BMS has a learning function, then its practical application requires multifaceted verification. Figure 1 shows the whole configuration of the J-BMS.

This paper describes a method of performance evaluation and remaining life prediction of an aged RC-T girder bridge (SK-bridge) by J-BMS RC version based on close visual inspection data, and also verifies the assessment (reasoning) results obtained as outputs from the Bridge Rating Expert System (RC-BREX 2000) which is a subsystem of the J-BMS, to evaluate the effectiveness of the system. In order to enhance the effecitiveness of the J-BMS and put it to practical use as a maintenance support tool, it is necessary to verify the usefulness of the system by using it for the diagnosis of as many bridges as possible.

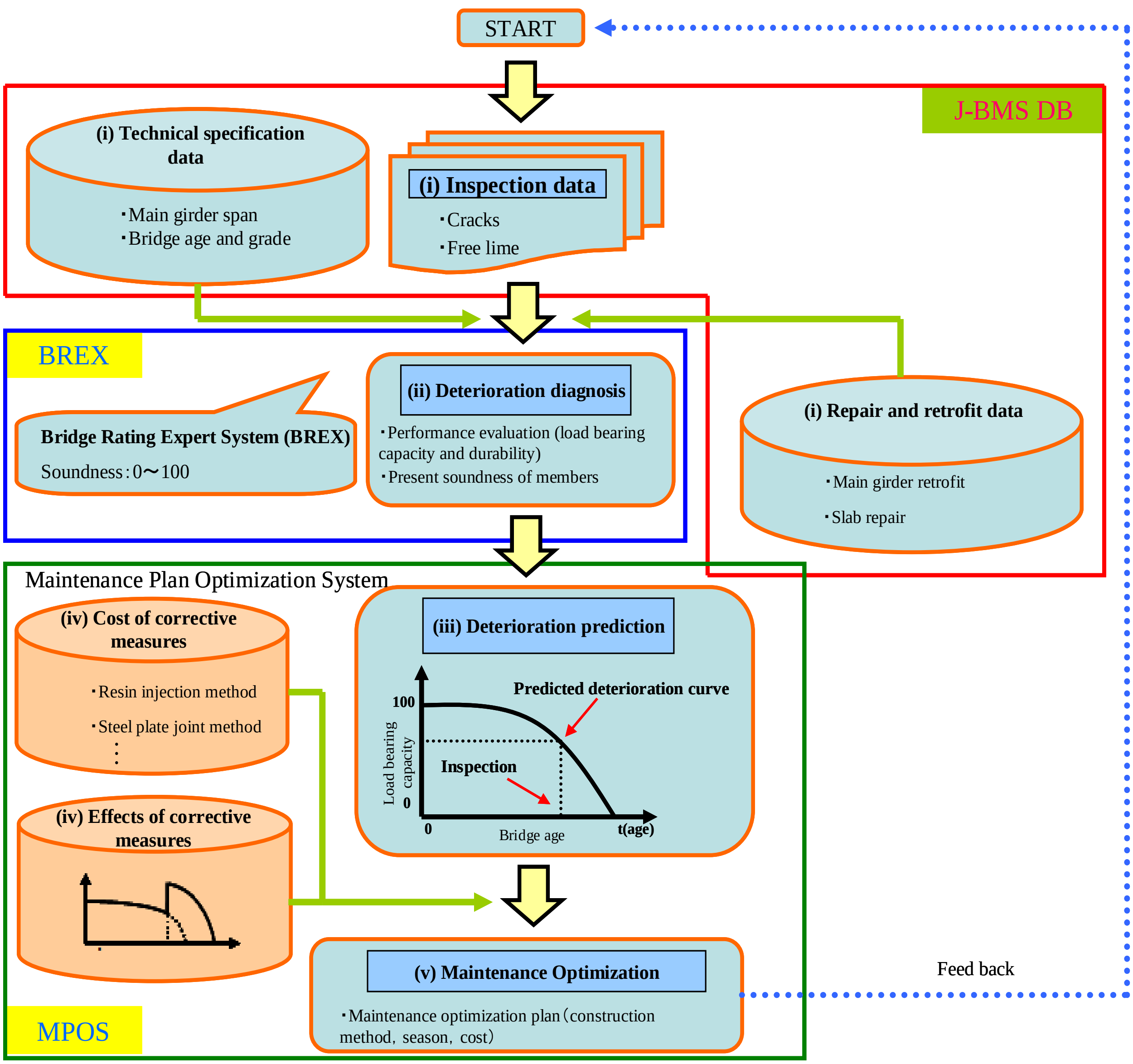


Fig. 1. Whole configuration of J-BMS

In this study, close visual inspection data on an aged bridge to be removed were entered into RC-BREX 2000. Then, diagnosis outputs were taught to the system by using teacher data based on domain expert knowledge and diagnostic results before and after learning was examined in detail. The effecitiveness of the J-BMS was then evaluated by clarifying differences attributable to input methods, inspectors and learning methods and identifying possible improvements. Since the remaining life prediction of the bridge can also be quantitatively estimated by applying the J-BMS with the field inspection data, it needs to be verified through the concrete core specimen tests extracted from some parts on main girders and deck slabs, such as compressive strength, carbonation depth, chloride ion concentration, and so on (Takahashi et al., 2016; Widyawati et al., 2015). In this paper, data obtained from collected concrete core specimens were examined by chloride ion and carbonation tests for make verification of the predicted remaining life of the bridge.

OVERVIEW OF J-BMS RC VERSION AND OPERATION FLOW

As mentioned above, J-BMS RC version was developed to assist in facilitating the maintenance of existing reinforced concrete bridges and consists of three subsystems, namely, J-BMS DB '09, RC-BREX and MPOS. Figure 2 shows the flow of operation of these subsystems.

As shown in Figure 2, J-BMS RC version is used as follows:

1. Extract necessary data from the bridge specification database and the regular inspection database and download those data from J-BMS DB '09 to RC-BREX. Of the data thus downloaded, the inspection record data (xls. file) are used to enter "main girder inspection" and "floor slab inspection" data, and the brx. File is used to enter "bridge specifications" and "investigation / inspection" data.
2. Output RC-BREX diagnosis data calculated from the input data as a CSV. File. The output data includes bridge name and RC-BREX performance evaluation results such as "main girder - load carrying capability" and "floor slab - durability".
3. Upload the CSV. File containing calculation data to J-BMS DB '09.
4. MPOS uses the uploaded data.

J-BMS DB '09

The J-BMS DB '09 is a subsystem capable of efficiently managing various bridge data in the J-BMS. The apostrophe-zero-nine ('09) designation in the system name is an abbreviation for the year 2009 (year of revision).

The J-BMS '09 has a log-in screen for user authentication and a menu screen for accessing various support functions. The system also has bridge specification, regular inspection and repair and strengthening databases, annual reporting support functions, and input, search, correction and output functions associated with those functions. Figure 3 shows the whole configuration of the J-BMS DB '09 and the flow between various functions (Miyamoto et al., 2009).

Bridge Specification Database

Conventional practice has been to store bridge specification data such as bridge length and the year of completion in the form of paper documents or xls. files. Because the amount of data thus stored is huge, it has been difficult to extract necessary data quickly according to the intended use of such data. As a solution to this problem, a bridge specification database has been developed to make integrated data management and utilization possible. The bridge specification database has the following functions:

"specification data search" for searching and viewing specification data, "specification data input" used to enter data on new bridges or on changes in standards, "specification data deletion" for deleting unnecessary data in the event of data error or bridge reconstruction, and "specification data output" for outputting data from the database in the Excel data format.

Regular Inspection Database

Regular inspection involves close visual inspection conducted by using equipment such as bridge inspection vehicles. By checking on a total of 32 inspection items involving the superstructure and the substructure of the bridge of interest, each item is evaluated on a three-point scale of "no or minor damage", "moderate damage" and "severe damage" and each damaged area is photographed. After the damage level is evaluated with respect to each inspection item, each component or member is evaluated on a four-point scale to decide on the category of corrective action to be taken, and comments are entered. Like the bridge specification database, the regular inspection database consisting of such data has regular inspection data search, regular inspection data input and regular inspection data output functions.

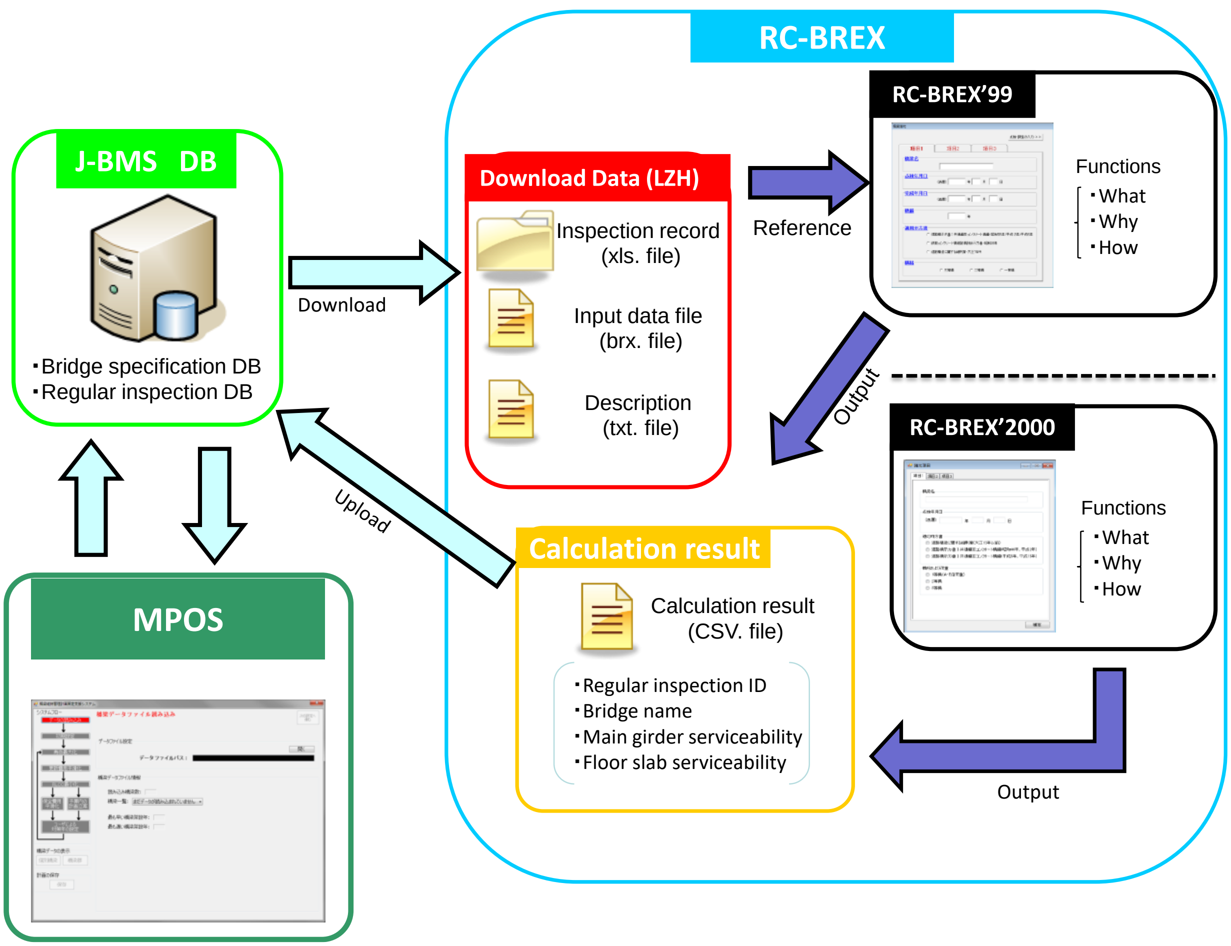


Fig. 2. Operation flow of J-BMS RC version

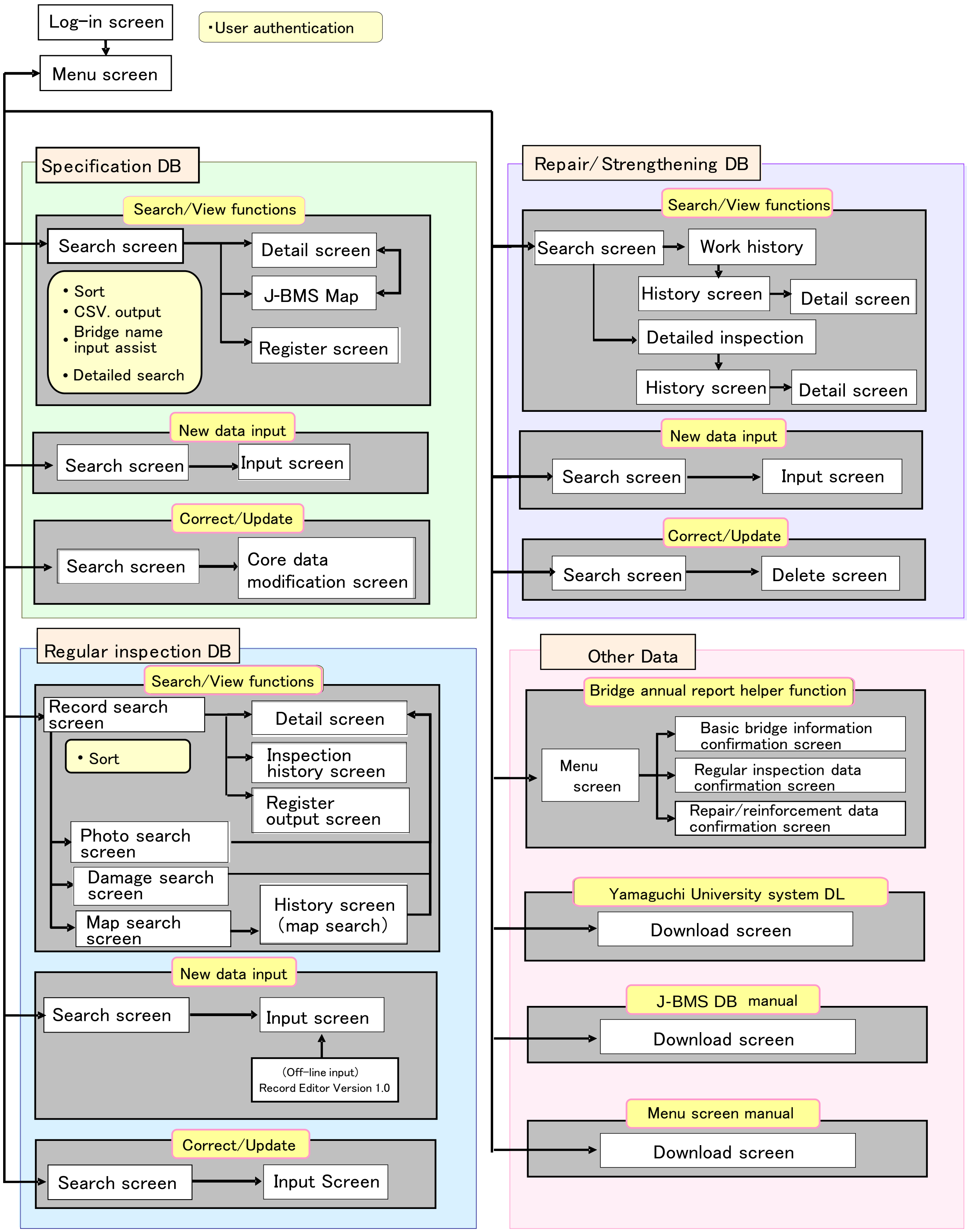


Fig. 3. Whole configuration of J-BMS DB '09

Repair and Reinforcement Database

The repair and strengthening database has been developed for integrated management of various data obtained through the repair and strengthening of existing bridges. This database has the repair / strengthening data search function for searching stored data and the repair / strengthening data input function for entering data to the repair and strengthening database through the Web form. Like the bridge specification database, this database also had problems such as the lack of consideration of input from electronic data and the lack of a function for outputting data in the form of electronic data from the database. This database, therefore, has been upgraded by implementing new functions, namely, the repair / strengthening data upload function for automatic input of electronic data and the repair / strengthening data output function for outputting Excel files containing stored data.

RC-BREX (Miyamoto and Motoshita, 2015; Emoto et al., 2014a)

As shown in Figure 2 mentioned earlier, J-BMS RC version is characterized by the existence of two types of RC-BREX (bridge performance evaluation system), namely, RC-BREX '99 and RC-BREX 2000. As an example, this section explains the flow of performance evaluation associated with flexural cracking made by the two types of RC-BREX. Figure 4 shows an example of hierarchical representation of "load carrying capability" and "durability" evaluation, which is the ultimate goal of the evaluation made in the RC-BREX '99. In this case, a number of characteristic patterns of flexural cracking are listed, and if a flexural crack falling into any of the listed categories is found, checks are made with respect to lower-level check items as shown in Figure 4 such as crack condition or maximum crack width. Inspection itself, therefore, is thought to be relatively simple. For items related to a quantity or degree of cracking, however, such as crack condition, questions may include qualitative and ambiguous descriptors such as "considerably" and "somewhat." Differences in how inspectors feel, therefore, may lead to variability of system evaluation results. Unlike RC-BREX '99, RC-BREX 2000 deals with not only characteristic flexural cracks but also all other damages occurring in main girders and floor slabs. It examines seven items, such as girder number, position in the bridge axis direction, vertical position and direction, quantitatively and outputs the results thus obtained as inspection data to be entered into the performance evaluation system. By so doing, the influence of inspectors' subjective judgments is minimized. Inspection data concerning all anomalies that are taking place can be kept. This is advantageous because such data can be useful during future inspections. Since the two performance evaluation systems have both strengths and weaknesses, the user can select a system better suited to the intended use so as to achieve the maintenance goal efficiently. RC-BREX '99 may be useful for domain experts when conducting simple inspections to prioritize inspection needs. RC-BREX 2000 may be useful for domain experts or local government engineering staff when conducting detailed inspections. The rest of this paper presents the verification results obtained by using RC-BREX 2000, which is a system into which quantitative inspection data are to be entered.

MPOS

The maintenance plan optimization system (MPOS) was developed to enable bridge management organizations to maintain existing bridges efficiently. By using the specification data and regular inspection data in the J-BMS '99 (J-BMS with RC-BREX’99 mentioned earlier), MPOS draws up a maintenance plan and assists in selecting corrective actions.

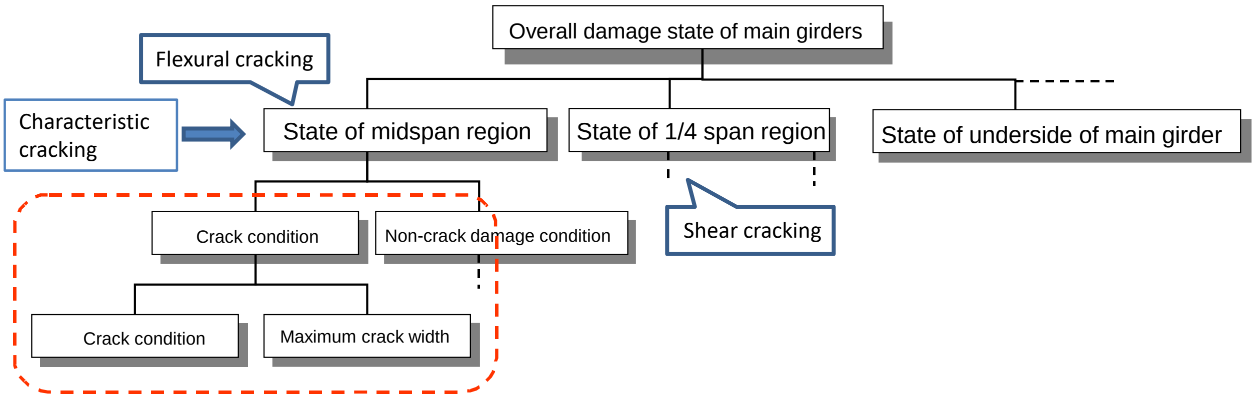


Fig. 4. Example of performance evaluation based on hierarchical criteria in RC-BREX system

Deterioration Prediction

Load carrying capability and durability evaluation results for main girders and floor slabs obtained from RC-BREX 2000 make it possible to evaluate the present soundness of bridge members. They do not make it possible, however, to predict future progress of deterioration. The progress of deterioration of load carrying capability and durability, therefore, was estimated by assuming deterioration prediction curve equations. The deterioration prediction curve equations were derived from data on various girder and floor slab experiments (Miyamoto, 1984) conducted by using bridge beams. For the purpose of formulation, load carrying capability was assumed to be a quartic function of time *t* because the load carrying capability curve was found to be close to a quartic function of time t. Durability was assumed to be the derivative (one degree lower) of load carrying capability because durability is defined as resistance to change due to aging in bridge performance or functionality such as load carrying capability. For the purpose of formulation of a deterioration prediction curve equation, therefore, durability was assumed to be a cubic function of time *t* (Kawamura et al., 2001). Figure 5 shows an example of an initial setting screen for defining a deterioration prediction curve in Japanese system. The screen structure is composed form 3 different forms of purpose like shown below; main window and 2 windows in order to display bridge data:

System flow

The form that allows the user to access optionally into each function, and the process which is executed on the system is clarifies (function display). It is composed from the button of "*Starting of system*", "*Data assign*", "*Service life maximization*", "*Reconstruction cost stabilizing*", "*RLCC minimization*", "(*Prevention*) *Cost stabilizing*", "*Budget constraint*" and "*Specified year by user*". By clicking on flow button, it is able to perform the correspondence step.

Data window display button

The form to call up the screen which displayed bridge data. It is composed from the button of "*Single bridge*" and "*Multi bridges* (*group*)".

Each type specify screen

The different specification screen for each step of flow is displayed, and the input of data and condition is done by the user.

Service Life Maximization Function

On the basis of the initial setting values mentioned earlier and regular inspection data, a combination of maintenance measures that maximizes the useful life of each bridge is identified. At this stage, calculation is performed under the conditions within the specified range, and they do not include budget. It is assumed that if two or more members are damaged, the useful life of the shortest-life member is regarded as the useful life of the bridge as a whole, and all members are replaced in that year. Figure 6 shows an example of a screen showing an output from the life maximization function. In Figure 6, a deterioration prediction curve after life maximization is shown. The deterioration prediction curve shown there is a result obtained after corrective measures are taken three times. The maximum number of corrective measures that can be set is five. In reconstruction cost spreading, only moving up of the reconstruction schedule is considered. Moving down the schedule is ruled out.

Reconstruction Cost Spreading

As mentioned earlier, the process described above does not take funding availability into consideration. Consequently, maintenance workload may be concentrated in a certain period of time so that an unrealistic maintenance plan is suggested. To avoid such problems, this function shaves reconstruction cost peaks to reduce concentration.

OVERVIEW OF BRIDGE REMOVAL AND SITE INVESTIGATION

This chapter describes the diagnosis obtained from RC-BREX 2000 (hereinafter referred simply as "BREX") as a result of a detailed close visual inspection, conducted for the purpose of data collection, of a reinforced concrete (RC) T-girder bridge soon to be removed prior to the construction of a new bridge, and verifies the validity of the system from various viewpoints.

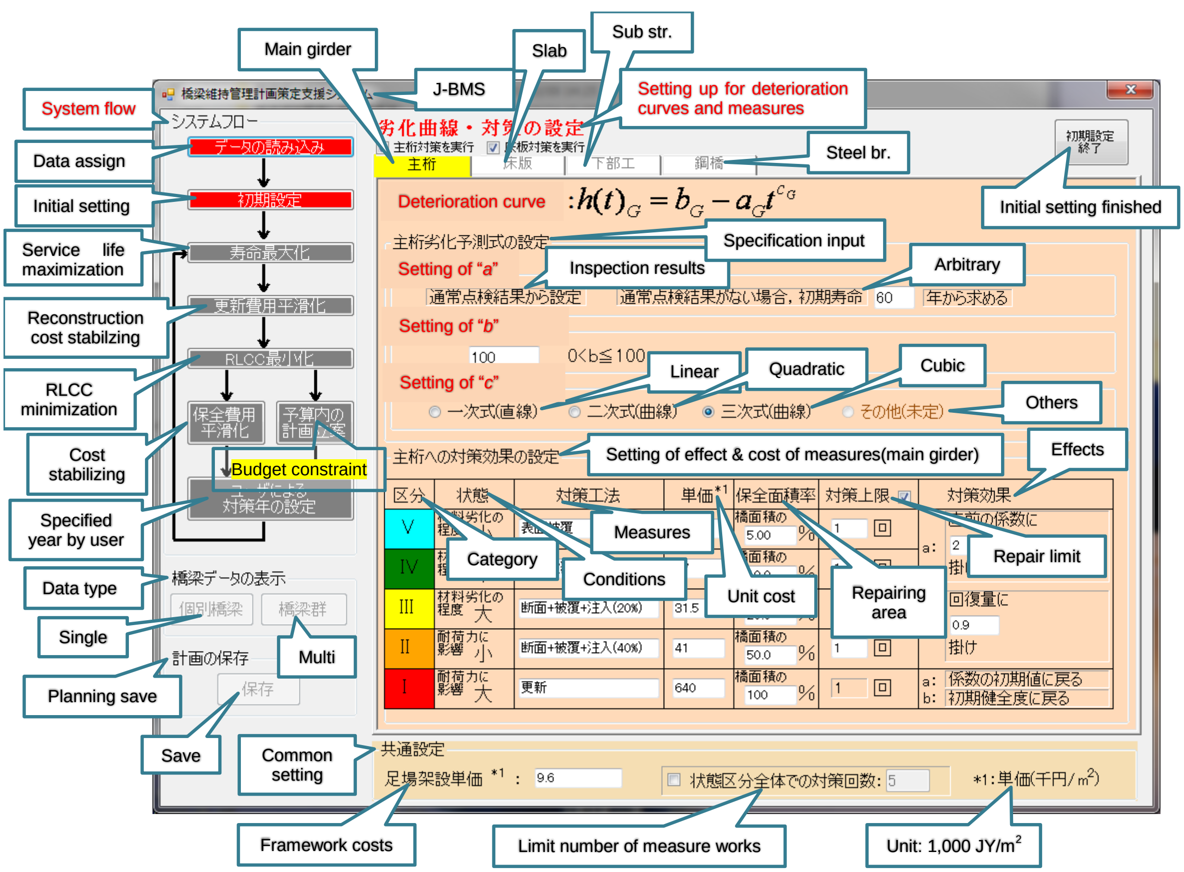


Fig. 5. Example of initial setting screen for deterioration curve predicting parameters (in Japanese system)

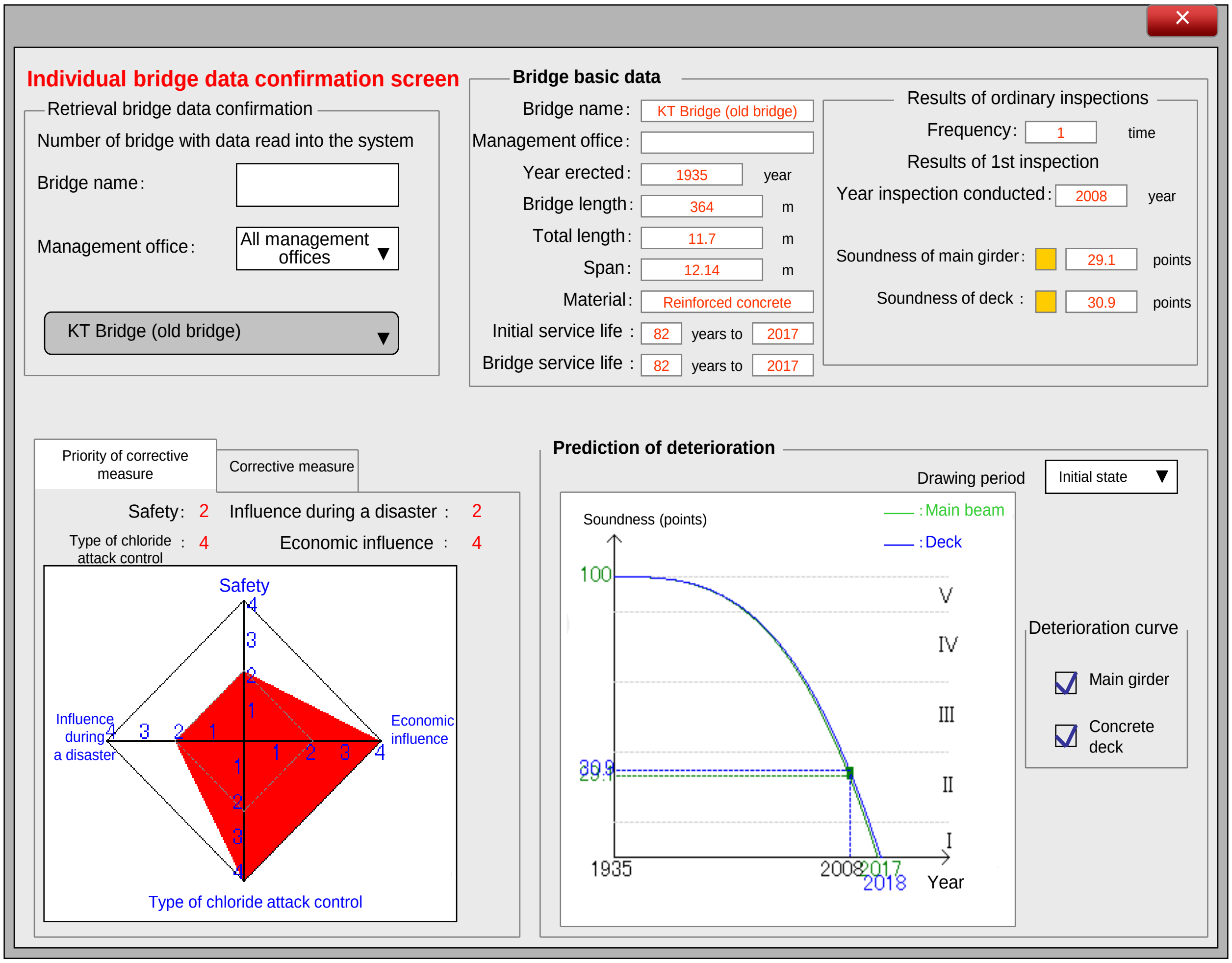


Fig. 6. Example of service life maximization function of MPOS (after reconstruction cost spreading)

Overview of the Aged Bridge to be Removed

The existing bridge investigated for the purpose of this study is an aged bridge to be removed (referred to as "SK-Bridge") located at the border between Yamaguchi and Hiroshima prefectures. A 168.3-meter-long, 11-meter-wide, 5-main girders bridge completed in 1942, the SK-Bridge is a simple eight-span reinforced concrete cantilever T-girder structure. The bridge was removed over a period of two years from 2011. Table 1 shows the specifications of the bridge (SK-Bridge), and Figure 7 shows the configuration and dimensions of the SK-Bridge before removal.

Site Investigation

The on-site investigation of the bridge was conducted by close visual inspection. For the purpose of close visual inspection, the work platform set up under the main girders (superstructure) of the bridge during demolition and removal work was used. As shown in Figure 7, the areas inspected are two spans, namely, Span 1 and Span 3. A total of eight experts who have 10 or more years of experience in bridge designing or inspection as employees of consulting or other construction-related firms participated in the close visual inspection. The close visual inspection was conducted two times on different dates. In the first inspection, after a simple briefing, the participating experts were asked to freely conduct visual inspection and write down noted damages. Before conducting the second inspection, on the basis of the comparison of first inspection results, the experts exchanged opinions (hereinafter referred to as a "hearing session") based on their experiences in the first inspection and reached consensus on what to do in the next visual inspection.

Flow and Content of Close Visual İnspection

Close visual inspection was conducted by eight inspection experts in accordance with "J-BMS Inspection Manual and Its Utilization" (Yamaguchi Prefectural Government and Yamaguchi University, 2003). The inspection consisted of 1) preparing damage drawings, 2) preparing a damage record list and 3) evaluating each damage. The first step involved recording damages on the developed view drawings of the bridge and completing damage drawings. The second step involved preparing an damage record list, after visual inspection, based on the damage drawings prepared in the first step and entering the data thus obtained into the BREX. In the third step, on the basis of the close visual inspection results, the inspectors rated the "load carrying capability and durability of main girder" and the "load carrying capability and durability of floor slab" on a five-point scale in a questionnaire format. Table 2 show the relationship between the evaluation scores and safety (deterioration) levels in the BREX.

Table 1. Specifications of the aged bridge to be removed

Bridge Name	SK-Bridge on the National Highway Route No. 2
Bridge length	L = 168.29 m
Width	W = 11.0 m (2 lanes + sidewalk) W = 2.5 m (sidewalk)
Type of superstructure	Cantilever reinforced concrete (RC) T-girder bridge
Type of substructure	Abutments: 2 Bridge piers: Rigid piers (RC): 7
Foundation	Abutments: Pine piles Piers: Open caissons
Year constructed	1941
Traffic volume (2010)	28,281 vehicles/day
Large vehicle traffic volume (2010)	24.4%

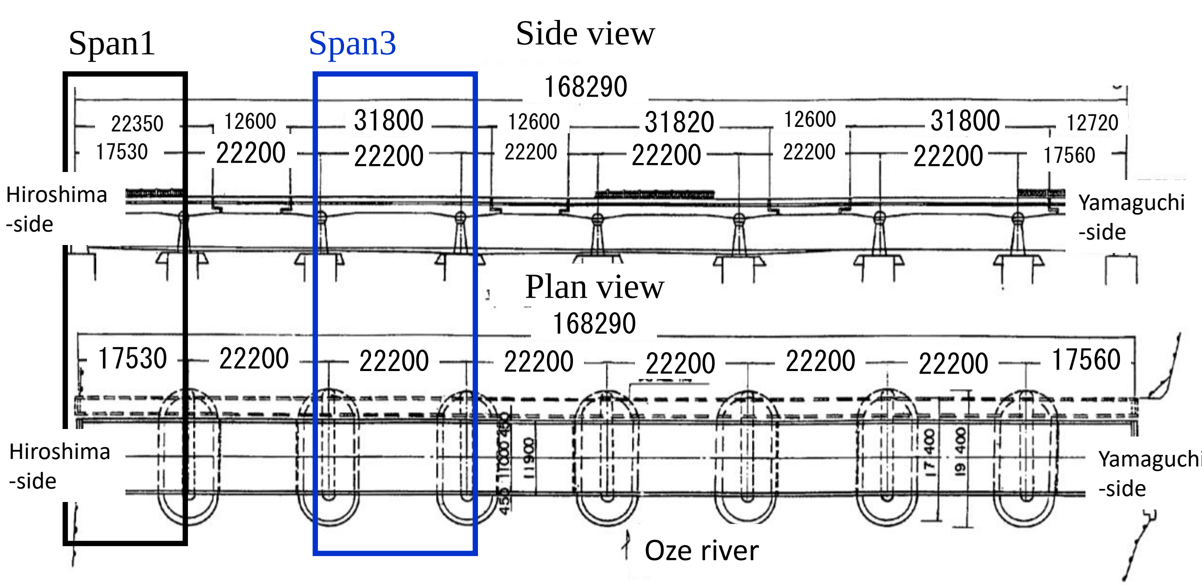


Fig. 7. Side and plan views of SK-Bridge (before removal) and inspection area (span) (unit: mm)

Table 2. Evaluation scores and ranks

Unsafe: 0.0 < 12.5 (points)
There is an urgent need for corrective measures to ensure traffic and general safety. The point 0.0 indicates a non-serviceable condition (maintenance limit).

Severe deterioration: 12.5 ≤ p < 37.5 (points)
In need of repair. Detailed inspection is necessary.

Moderate deterioration: 37.5 ≤ p < 62.5 (points)
Deterioration can be seen, and periodic inspection needs to be conducted earlier than usually scheduled. Follow-up investigation is required.

Mild deterioration: 62.5 ≤ p < 87.5 (points)
Deterioration can be seen and the degree of deterioration needs to be recorded, but there is as yet no need to consider repair.

Safe: 87.5 ≤ p < 100.0 (points)
In a sound condition though slight deterioration can be seen. The point 100.0 indicates a perfectly problem-free condition.

Reducing Variability of İnspection Results through Hearing Session

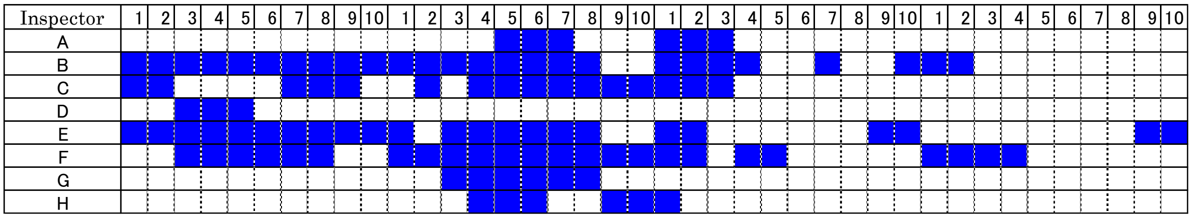
It has been reported (Uchimura et al., 2010) that in a close visual inspection conducted at a bridge site, even inspection results and ratings obtained from inspection experts vary to some extent depending on such factors as differences in the length of experience and individual criteria. The virtual reality (VR)-based visual bridge inspection support system being developed by the authors (Uchimura et al., 2010), therefore, was used as a tool for minimizing the variability of inspection results. In this study, a hearing session utilizing the BREX and the damage drawings prepared by the inspection experts was conducted. The aim was to determine whether or not the variability of visual inspection results obtained from different experts can be reduced by so doing. To evaluate variability, the damages pointed out by the experts (inspectors) in the inspection of Girder 1 in Span 3 (see Figure 13) before and after the hearing session were compared as shown in Figure 8 on the basis of the list of damage drawings obtained through the close visual inspection. From the results thus obtained, the degree of agreement between the inspection results obtained from the different inspectors was calculated by using the formula shown in Figure 8 (Uchimura et al., 2010). Table 3 compares the before- and after-hearing results for different girders. If the value (degree of agreement) obtained from the formula is large, it indicates that the inspection results vary widely. As shown in Table 3, the degree of agreement increased for most of the girders as a result of the hearing session. This indicates that a hearing session is very effective in improving the quality of close visual inspection results.

PERFORMANCE EVALUATION AND REMAINING LIFE PREDICTION BY RC-BREX

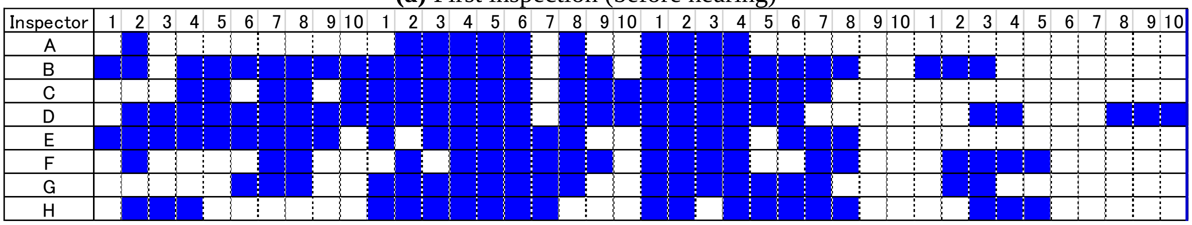
Figure 9 systematically shows the flow of performance evaluation and remaining life prediction of the target bridge to be removed by use of the close visual inspection results mentioned earlier. This chapter describes the diagnostic results according to the diagnosis flow shown in Figure 9.

Table 3. Comparison of calculated degrees of agreement before and after hearing

		Girder 1	Girder 2	Girder 3	Girder 4	Girder 5
Span 1	Before hearing session	53	25	56	31	47
	After hearing session	54	45	60	45	54
Span 3	Before hearing session	48	42	52	53	68
	After hearing session	66	52	66	68	61



(a) First inspection (before hearing)



(b) Second inspection (after hearing)

Formula:

$$Q = \left(\sum (P \times N) / \sum N\right) / P_0.$$

P: number of persons who pointed out the same crack
N: number of cases in which a damage was pointed out by the same numbers of inspectors
P_0: total number of inspectors

Fig. 8. Differences in crack locations pointed out before and after the hearing sessions (first and second inspections)

Performance Evaluation Based on Initial Knowledge

The first output obtained after entering close visual inspection results into the BREX is referred to as performance rating based on initial knowledge. In other words, initial knowledge is the first evaluation result obtained from the BREX on the basis of bridge specifications and other conditions and damage data. At this stage, the BREX is in the default state.

Figure 10 shows the total number of damages identified by each expert in Span 1 and Span 3 of the SK-Bridge and the main girder and floor slab performance (load carrying capability and durability) evaluation results obtained from the BREX. As shown in figure 10, the total number of damages identified in the close visual inspection varies among the experts. A likely reason is that because the close visual inspection was conducted in a limited amount time, damage identification varied between experienced experts and less experienced experts. Another likely reason is that damage identification varies depending on the line of work each expert is in.

Examination of the performance evaluation results obtained from the system shown in Figure 10 reveals that the load carrying capability scores of both main girder and floor slab are as low as about 30. The 72-year-old bridge was designed in accordance with the old design standard and is located on a major arterial road. Consequently, load carrying capability is thought to have decreased because automobile traffic increased and large vehicles increased. The results mentioned above, therefore, are thought to be reasonable. Paying attention to durability, we notice that scores range from 60 to 70 for both main girder and floor slab. Because repairs had been made to some extent, it is thought to be a reason why durability was rated higher than load carrying capability. It can be concluded, therefore, that the performance evaluation results based on initial knowledge obtained from the system are reasonably reliable.

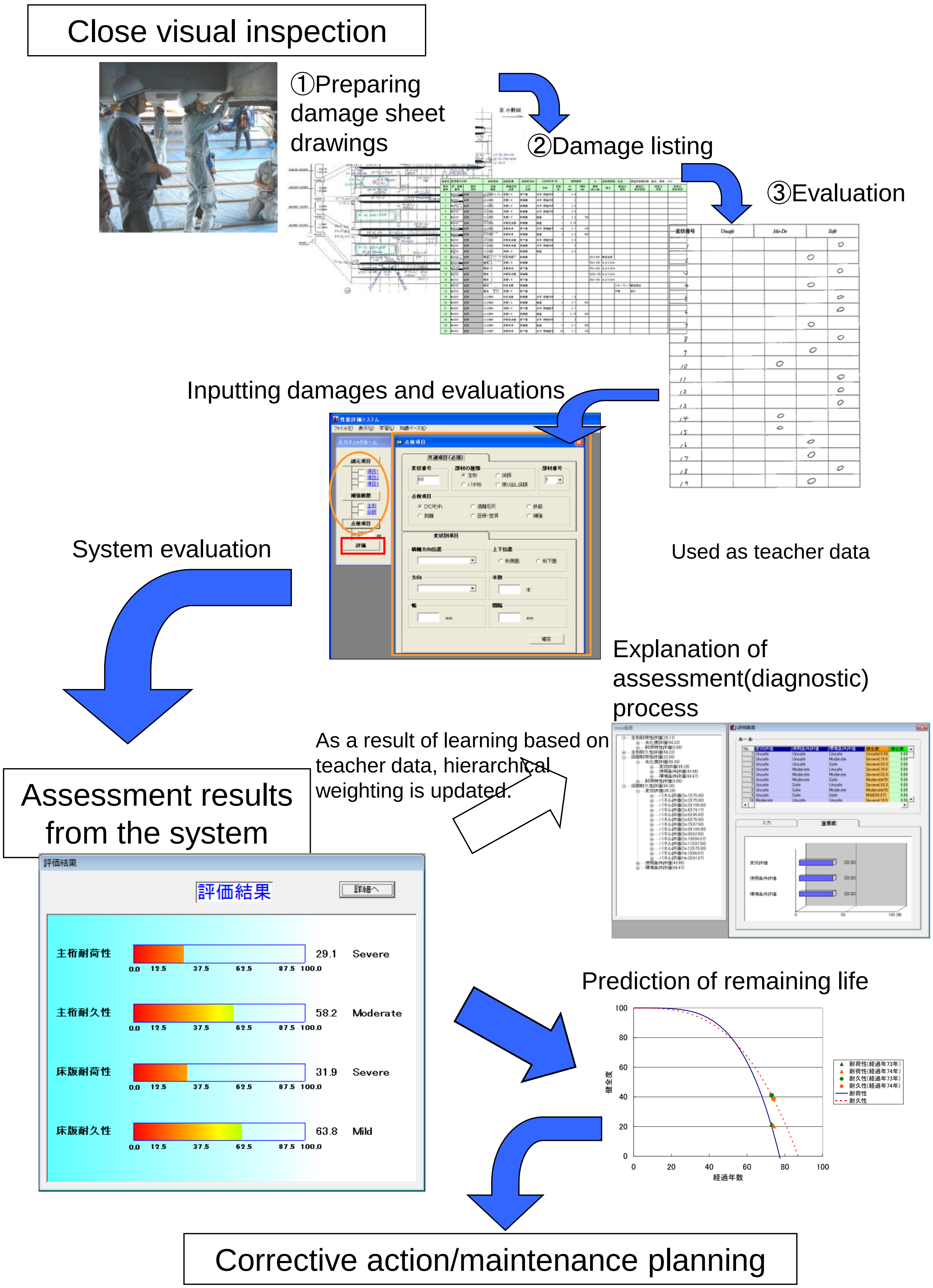
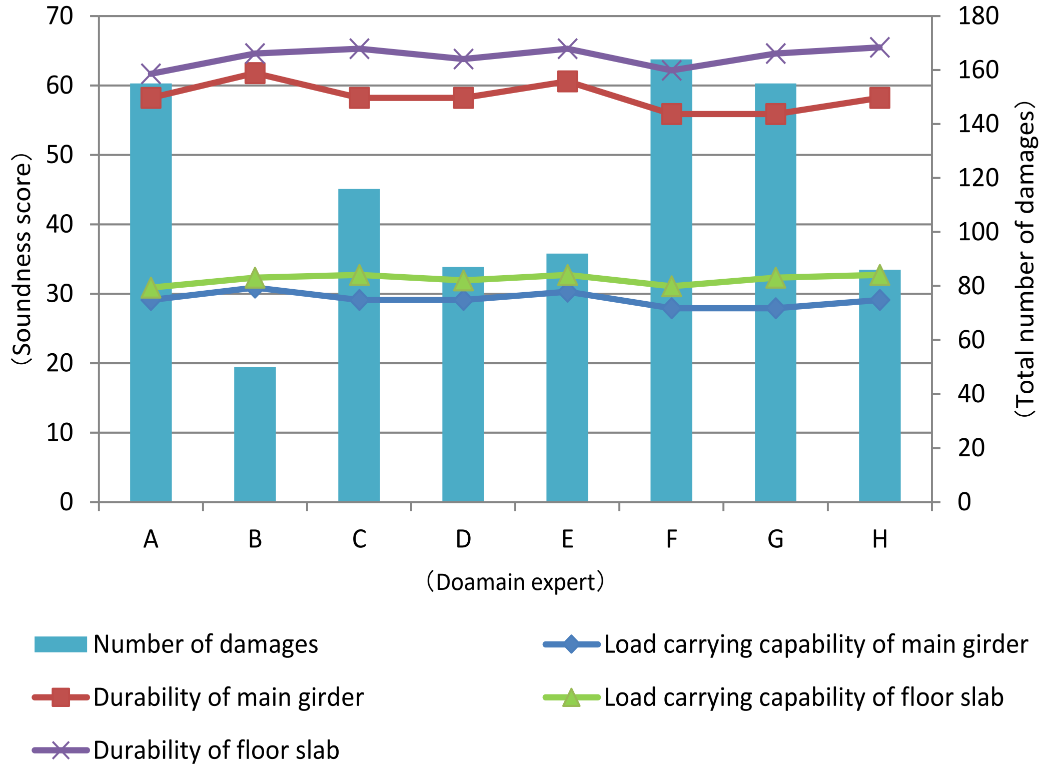
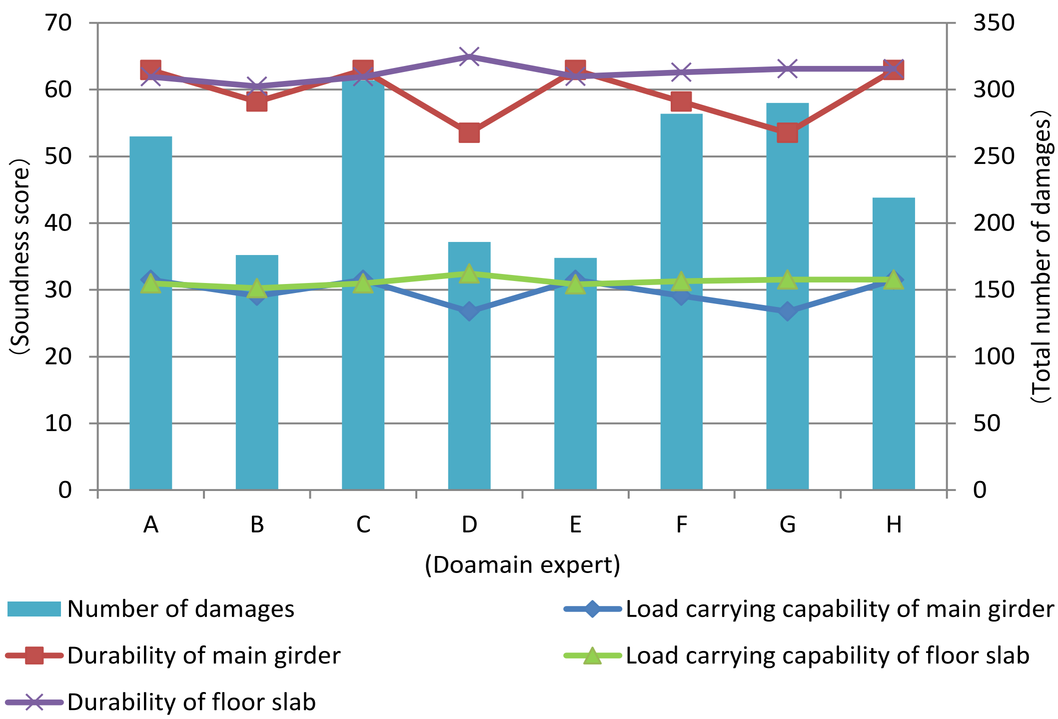


Fig. 9. Flow of bridge diagnosis based on close visual inspection results



(**a**) Span 1



(b) Span 3

Fig. 10. Total number of damages and performance evaluation results for SK-Bridge by domain experts

Examination, however, of the relationship between the total number of damages and performance evaluation results shown in Figure 10 reveals that the number of damages, although varying significantly, has little effect on performance evaluation results. This indicates that the system performs evaluation according to the degree of severity of damages instead of the total number of damages alone. On the other hand, the fact that performance evaluation results do not vary significantly even though the input damage data vary considerably seems contradictory. The knowledge base of the performance evaluation system, therefore, was updated by means of the knowledge update function of the system by using the subjective performance evaluation questionnaire results for learning. Then, the performance evaluation results obtained after learning were compared with the results obtained by use of the initial knowledge.

Comparison of Performance Evaluation: Before vs. After Learning

The results of the questionnaire survey of the experts were used for expert-by-expert learning by the system, and the effect of the learning was evaluated by comparing the performance evaluation results before and after learning. The questionnaire results mentioned above are the results of the questionnaire survey in which experts evaluated damages such as cracks and main girder and floor slab performance on a five-point scale. The questionnaire results thus obtained were used as teacher data for the system, and the evaluation results obtained from the updated system were used as post-learning performance evaluation results.

Table 4 compares the main girder and floor slab (Span 1 and Span 3) performance evaluation results based on the initial knowledge (before learning) and the performance evaluation results obtained after learning by use of the teacher data. As shown in Table 4, main girder and floor slab durability scores given by most of the experts tend to become lower as a result of learning. In view of the fact that the subjective performance evaluation results roughly correspond to the range from "unsafe" to "moderate deterioration" defined in Table 2, the evaluators, although being experts, may have underestimated performance unconsciously because the bridge was supposed to be removed soon. Examination of the floor slab load carrying capability scores reveals that performance scores became higher as a result of learning.

Table 4. Comparison of SK-Bridge performance evaluation results before and after learning

Span1	**Expert**		**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Main girder	Load-carrying capability	Before learning	29.11	30.88	29.11	29.11	30.29	27.93	27.93	29.12
		After learning	40.73	46.69	16.77	21.60	16.12	31.64	27.64	28.41
	Durability	Before learning	58.22	61.77	58.22	58.22	60.58	55.86	55.86	58.23
		After learning	44.65	39.82	55.87	37.04	44.87	43.69	37.49	39.88
Floor slab	Load-carrying capability	Before learning	30.86	32.29	32.65	31.88	32.65	31.10	32.29	32.73
		After learning	40.94	51.79	43.05	27.31	35.62	50.91	37.33	42.44
	Durability	Before learning	61.72	64.58	65.30	63.77	65.30	62.20	64.59	65.46
		After learning	52.79	57.62	50.24	44.04	57.00	59.86	45.91	48.10
Span3	**Expert**		**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Main girder	Load-carrying capability	Before learning	31.47	29.11	31.47	26.75	31.47	29.10	26.75	31.47
		After learning	32.21	23.79	29.83	28.30	25.40	30.64	19.15	20.92
	Durability	Before learning	62.93	58.22	62.93	53.50	62.93	58.22	53.50	62.93
		After learning	49.74	45.32	47.22	38.22	42.51	46.00	41.06	41.06
Floor slab	Load-carrying capability	Before learning	30.96	30.27	30.96	32.46	30.84	31.30	31.55	31.55
		After learning	34.28	39.63	31.32	30.46	44.43	38.96	18.59	20.01
	Durability	Before learning	61.92	60.50	61.92	64.93	61.96	62.61	63.11	63.11
		After learning	49.42	44.59	40.76	41.89	45.84	52.78	34.67	41.42

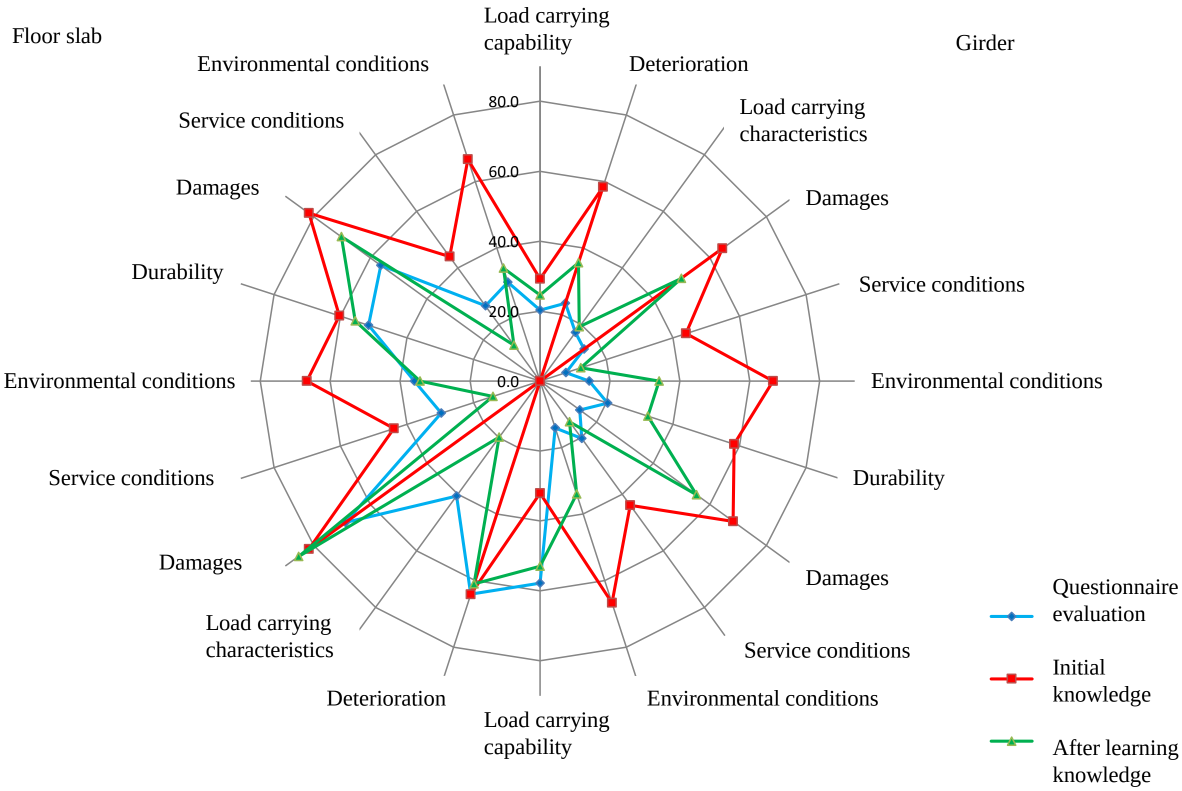


Fig. 11. Visualized comparison of bridge girder and floor slab performance evaluation results (in case of Span 1)

The main girder load carrying capability results include both higher and lower post-learning scores. This means that the performance evaluation based on the initial knowledge (before learning) resulted from incomplete capture of expert knowledge. It can therefore be said that it is not appropriate to evaluate the performance of a bridge based solely on scores obtained from such evaluation. It can be said that post-learning performance evaluation results obtained from the experts provide useful data based on both subjective evaluation by the experts and quantitative evaluation by the performance evaluation system. Post-learning performance evaluation results, however, vary considerably. The next section, therefore, considers a learning method that makes it possible to reduce the variability of subjective evaluation knowledge extracted from different experts.

Performance Evaluation Using Exhaustive Learning Method

Table 5 shows the averages of performance evaluation system outputs based on the results of the close visual inspections conducted by the eight experts. As an example, the table compares the results of three types of performance evaluation, namely, evaluation based on initial knowledge, questionnaire-based evaluation and post-learning evaluation, for Span 1. The learning method used here is the exhaustive learning method, in which all sample data (in this case the data obtained from the eight experts) are used as teacher data. As an example, Figure 11 shows the averages of the main girder and floor slab performance evaluation results for Span 1 of the SK-Bridge. Figure 11 visually compares the results of three types of performance evaluation, namely, evaluation based on initial knowledge, questionnaire-based evaluation and post-learning evaluation.

As shown in Table 5, except for floor slab load carrying capability, the scores in the questionnaire results tend to be lower than the scores obtained in the initial-knowledge-based evaluation. This is because the subjective performance evaluation by the experts gives the lowest score for each deterioration level (rank) so that conservative evaluation results are obtained. The reason why the questionnaire results for floor slab load carrying capability showed high scores is thought to be that initial knowledge scores in the load carrying capability evaluation tended to be low so as to make questionnaire scores high on relative terms. Turning our attention to the performance evaluation after exhaustive learning, we notice that as a result of learning, the scores for almost all evaluation items became closer to the questionnaire scores.

Table 5. Comparison of SK-Bridge performance evaluation results before and after learning (Span 1)

Span 1			Initial Knowledge (Average)	Evaluation	Questionnaire Result (Average)	Evaluation	Exhaustive Learning Method	Evaluation	Learning (Average)	Evaluation
Main girder	Load carrying capability	Load carrying capability evaluation	29.19	S-D	23.44	S-D	24.62	S-D	28.75	S-D
		Evaluation of deterioration	58.37	Mo-D	26.56	S-D	35.06	S-D	47.41	Mo-D
		Evaluation of load carrying characteristics	0.00	U	23.44	S-D	19.15	S-D	10.38	U
	Durability	Durability evaluation	58.37	Mo-D	20.31	S-D	32.12	S-D	43.18	Mo-D
		Evaluation of damages	64.49	Mi-D	20.31	S-D	54.34	Mo-D	59.69	Mo-D
		Evaluation of service conditions	43.95	Mo-D	23.44	S-D	14.36	S-D	37.91	Mo-D
		Evaluation of environmental conditions	66.67	Mi-D	17.19	S-D	33.94	S-D	34.96	S-D
Floor slab	Load carrying capability	Load carrying capability evaluation	32.06	S-D	54.69	Mo-D	52.96	Mo-D	41.14	Mo-D
		Evaluation of deterioration	64.12	Mi-D	60.94	Mo-D	60.98	Mo-D	57.57	Mo-D
		Evaluation of load carrying characteristics	0.00	U	37.50	Mo-D	19.85	S-D	12.81	S-D
	Durability	Durability evaluation	64.12	Mi-D	48.78	Mo-D	55.61	Mo-D	51.40	Mo-D
		Evaluation of damages	81.73	Mi-D	53.13	Mo-D	70.25	Mi-D	74.23	Mi-D
		Evaluation of service conditions	43.95	Mo-D	20.31	S-D	12.69	S-D	34.83	S-D
		Evaluation of environmental conditions	66.67	Mi-D	23.44	S-D	33.93	S-D	35.87	S-D

The reason is that by learning the questionnaire results showing subjective evaluation results, the system extracted expert knowledge so as to improve performance (soundness) evaluation results. Comparison between the results obtained by exhaustive learning and the post-learning expert evaluation results shows that the performance scores obtained by using the exhaustive learning method are close to the questionnaire scores. This, too, indicates that by making the system learn subjective evaluation results repetitively, the system can be made to extract knowledge from experts. It can be said that the performance evaluation system has a knowledge base reflecting expert knowledge.

Remaining Life Prediction and Verification by Concrete Core Tests

Results of Remaining Life Prediction

On the basis of the performance (soundness) evaluation results obtained from RC-BREX, remaining life is estimated by using the deterioration prediction curves (Eqs. (1) and (2)) in the MPOS. As assumed in Section 2.3.1, performance (load carrying capability S_L and durability S_D) deterioration formulas are expressed as functions of bridge age t:

$$S_L(t) = f(t) = b_L - a_L t^4 \tag{1}$$

$$S_D(t) = g(t) = b_D - a_D t^3 \tag{2}$$

where S_L: is the soundness of load carrying capability; S_D: is the soundness of durability; and a_L, b_L, a_D and b_D: are constants. The values of b_L and b_D at the time the bridge went into service are assumed to be 100, and the values of a_L and a_D are calculated by using the soundness of performance (load-carrying capacity and durability) at the time of bridge inspection.

For example, substituting the performance evaluation results obtained by the exhaustive learning method shown in Table 5 in Eq. (1) and Eq. (2) gives the remaining life estimation results shown in Table 6. Figures 12 (a) and (b) show the main girder and floor slab deterioration prediction curves used as the basis for the remaining life estimation.

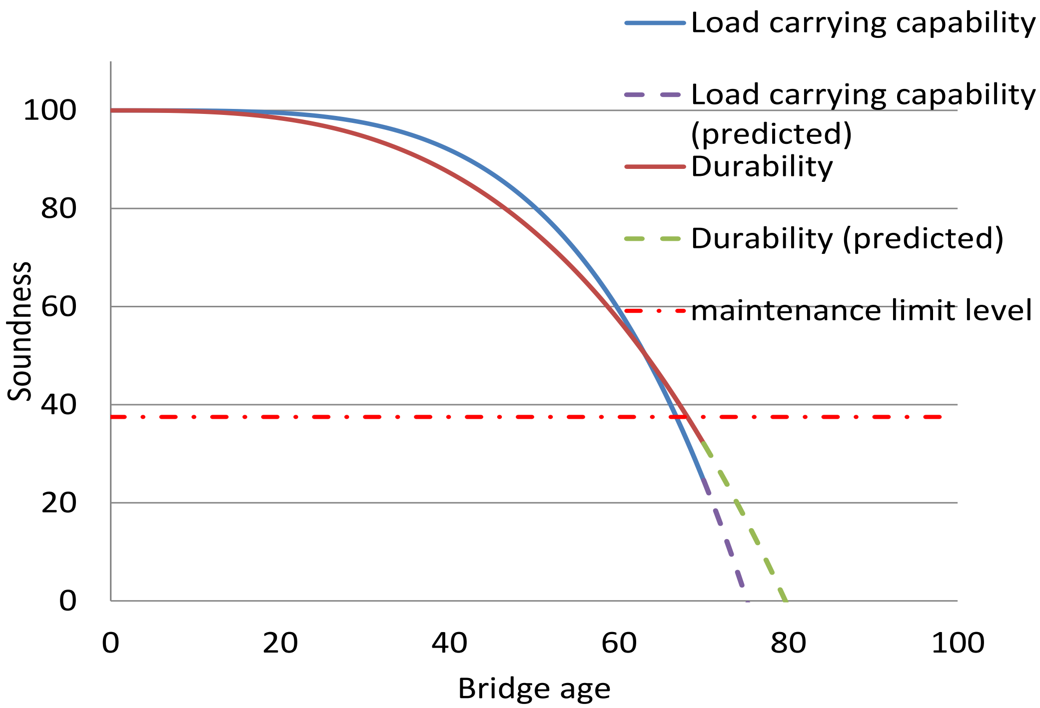
Examination of RC-BREX outputs reveals that for both main girders and floor slabs, the remaining life estimated from durability tends to be longer than the remaining life estimated from load carrying capability. This is thought to be due mainly to the use of a cubic function of bridge age t as an approximation to the durability deterioration curve.

Verification Based on Concrete Core Tests

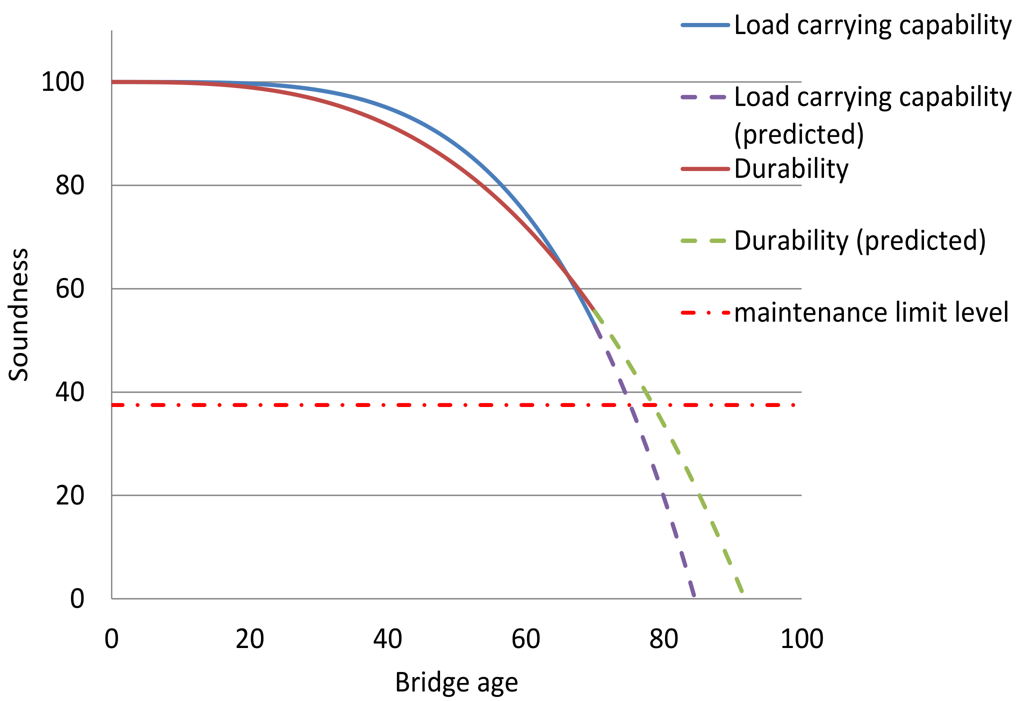
Remaining life prediction from the system needs to be verified through the concrete core specimen tests, which were extracted from some parts of the target bridge (SK-bridge), such as compressive strength, carbonation depth, and chloride ion content. The collected concrete cores were analyzed firstly for the identification of the main deterioration factors, either carbonation or chloride attack. Then, the remaining life can be predicted by a prediction flow related to the main factor of deterioration (Tarighat et al., 2014; Widyawati, 2015).

Table 6. Performance evaluation results and remaining life prediction results (yrs) for SK-Bridge

	Load-carrying Capability		Durability	
	Soundness (points)	**Remaining life(yrs)**	**Soundness (points)**	**Remaining life (yrs)**
Main girder	24.6	5	32.5	10
Floor slab	53.0	15	55.6	22



(a) Deterioration prediction curve for main girder



(b) Deterioration prediction curve for floor slab

Fig. 12. Deterioration prediction curves for different members of SK-Bridge

Extract of concrete cores

In this study, the collected concrete cores were extracted from Girder 1 to Girder 5 of Span 3 (see Figure 7), which is one of the inspected girder spans. The coring locations are shown in Figure 13 with black dots (●) and white dots (○). Concrete cores were extracted from four regions roughly demarcated according to cross beam locations in each span. It was assumed, for purpose of this study, that each core shows the average state of internal deterioration in each coring region (Nakamura et al., 2009).

The concrete cores thus extracted were used for chloride ion content test (C-series: concrete cores identified with ● and "C"; 12 specimens) and carbonation and mechanical properties testing (M-series: concrete cores identified with ○ and "M"; 20 specimens).

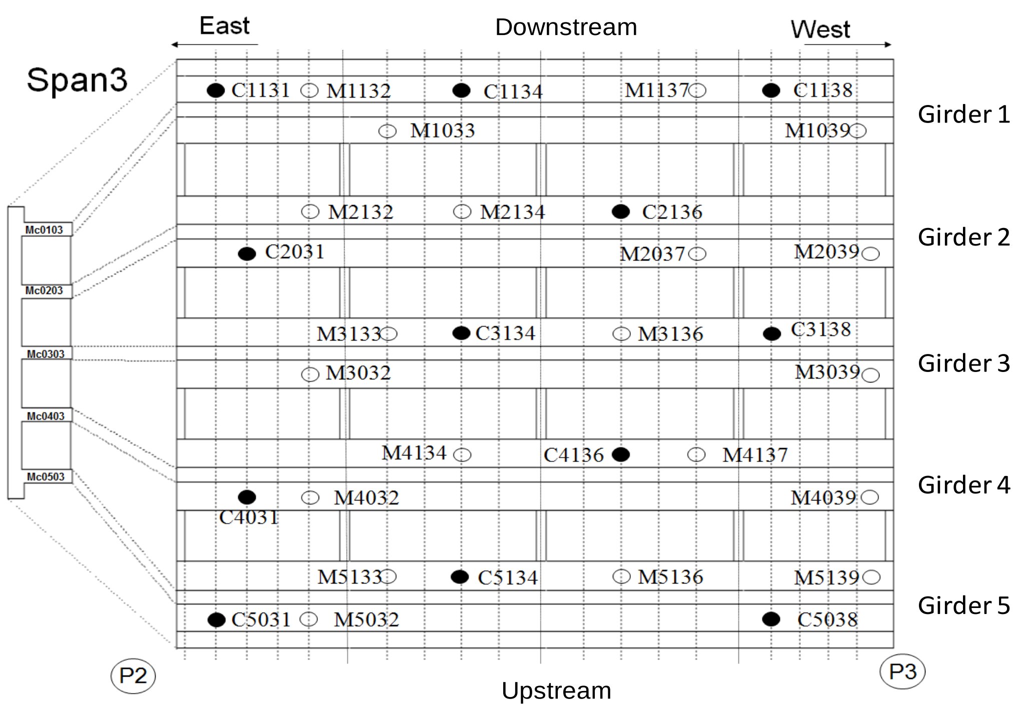
Analysis of chloride ion content

The collected concrete cores of the C-series were analyzed for chloride ion content. The collected concrete cores at depths between 0 and 105 mm in depth direction were divided into seven pieces (at 15 mm intervals) and, thus, prepared for analyzing the chloride ion content. The measurement was conducted in accordance with JIS A 1154: 2003; "Methods of Test for Chloride Ion Content in Hardened Concrete," and the specimens were examined down to the depth at which the initial chloride ion content could be determined. In the test method, the total amount of chloride ions contained in the powder sample is extracted with nitric acid, and its mass rate to the sample was measured. The initial chloride ion and surface chloride ion contents were predicted by fitting curve of data.

On the basis of the analysis results obtained previously, the apparent diffusion coefficient of chloride ion was calculated from the following equation (JSCE, 2007):

$$C(x,t) = C_0 . (1 - erf\left[\frac{x}{2\sqrt{(D_{ap} . t)}}\right]) + C_i(x,0) \quad (3)$$

where $C(x,t)$: is the chloride ion content in depth x at time t, C_0: is the chloride ion content at the concrete surface, D_{ap}: is the apparent diffusion coefficient of the chloride ions, and $C_i(x,0)$: is the initial chloride ion content in concrete.



●: concrete coring location for chloride ion investigation
○: concrete coring location for carbonation depth investigation

Fig. 13. Collected concrete core locations (Span 3)

Carbonation depth measurement

The collected concrete cores of the M-series were analyzed for carbonation depth. The measurement was conducted in accordance with JIS A 1152: 2011; "Method for Measuring Carbonation Depth of Concrete." The carbonation test is most commonly carried out by spraying 1% phenolphthalein solution on freshly exposed surfaces of concrete girders or on concrete cores. The carbonation depth was assessed using 1% phenolphthalein solution, the indicator that appears pink (or purple) in contact with alkaline concrete. Colored area is detected alkaline area, defined as the healthy concrete area (un-carbonated). Colorless area is defined as the carbonation area.

Chloride content analysis results

Table 7 summarizes the results related to the chloride ion content of the collected concrete cores (C-series). The surface chloride ion content C_0, the apparent diffusion coefficient of the chloride ion content D_{ap}, and the initial chloride ion content $C_i(x,0)$ shown in Table 7, which are unknown parameters corresponding to Eq. (3), were determined by using the respective analysis results obtained from the divided concrete core specimens. The thickness concrete cover was approximately 40 mm on average from cross-sectional observation. The analysis results, therefore, obtained from corresponding depth (30-45 mm) in the collected concrete cores were used as chloride ion contents at the reinforcement locations.

The chloride ion content distributions in the collected concrete cores can be classified into three types as shown in Figure 14 (Sakai et al., 2006; Kuroda et al., 2005). Table 7 shows the chloride ion content distribution types of different cores corresponding to Figure 13. Type (a) is affected by small chloride ion content and carbonation, type (b) is affected by large chloride ion content and carbonation, and type (c) is affected by only chloride ion content.

As it can be seen from the chloride ion content, distributions are shown in Figure 14. Eq. (3) is difficult to apply to the type (a) and type (b) distributions are shown in Table 7. Therefore, Table 7 shows the calculated values of C_0, D_{ap} and $C_i(x,0)$ for only type (c) distribution.

Carbonation depth measurement results

Table 8 shows the results of carbonation depth measurement for the collected concrete cores (M-series). The carbonation depth results shown in Table 8 are the averages of the values obtained from 10-point measurements, maximum values, standard deviations, and carbonation rate values corresponding to the averages.

Identification of main deterioration factors

On the basis of the Standard Specification Design of JSCE (JSCE, 2007), the critical chloride ion content for steel corrosion is assigned by 1.2 kg/m^3. As shown in Table 7, the average chloride ion content in the investigated main girders is 0.47 kg/m^3, which is lower than the critical chloride ion content for steel corrosion (1.2 kg/m^3). It can be seen in Table 7 that only 1 of the 12 points on the bridge older than 70 years at which measurements were taken showed a value slightly higher than the critical chloride ion content for steel corrosion.

Table 8 shows the result of carbonation depth measurements. As shown in Table 8, the average value of the carbonation depth in the main girder is 49 mm, which is greater than the thickness of concrete cover. This means that the requirement of the remaining (un-carbonated) concrete cover (10 mm), which is an indicator of the degree of influence of carbonation, was considerably exceeded. In nearly half of the concrete cores investigated, the maximum value of carbonation depth was reaching 60 mm or greater, which is considerably greater than the concrete cover.

To take the concrete coring environment into consideration, the water samples taken near the SK-Bridge (the target bridge) and the estuary were analyzed. This water analysis revealed that the Cl^- and the Na^+ contents of the water near the SK-Bridge were lower than those of the seawater in the estuary, and that they were also lower than half the Cl^- and Na^+ contents of the water near KT-Bridge (Miyamoto et al., 2011), which was deemed to have deteriorated because of chloride attack.

Table 7. Results of chloride ion content analysis

Main girder No.	Core specimen No.	Surface chloride ion content C_0 (kg/m^3)	Apparent diffusion coeficient D_{ap} (×10^{-8} cm^2/s)	Initial chloride ion content $C_i(x,0)$ (kg/m^3)	Chloride content at reinforcement location $C(x,t)$ (kg/m^3)	Types shown in Fig. 14
1	C1131	-	-	-	0.58	(a)
	C1134	1.00	0.08	0.30	0.32	(c)
	C1138	-	-	-	0.53	(a)
2	C2031	-	-	-	0.90	(a)
	C2136	-	-	-	1.36	(b)
3	C3134	1.10	0.45	0.10	0.46	(c)
	C3138	0.85	0.10	0.15	0.21	(c)
4	C4031	0.85	0.50	0.15	0.48	(c)
	C4136	1.32	0.05	0.12	0.14	(c)
5	C5031	1.27	0.04	0.22	0.21	(c)
	C5134	1.32	0.04	0.12	0.16	(c)
	C5038	1.30	0.03	0.30	0.30	(c)

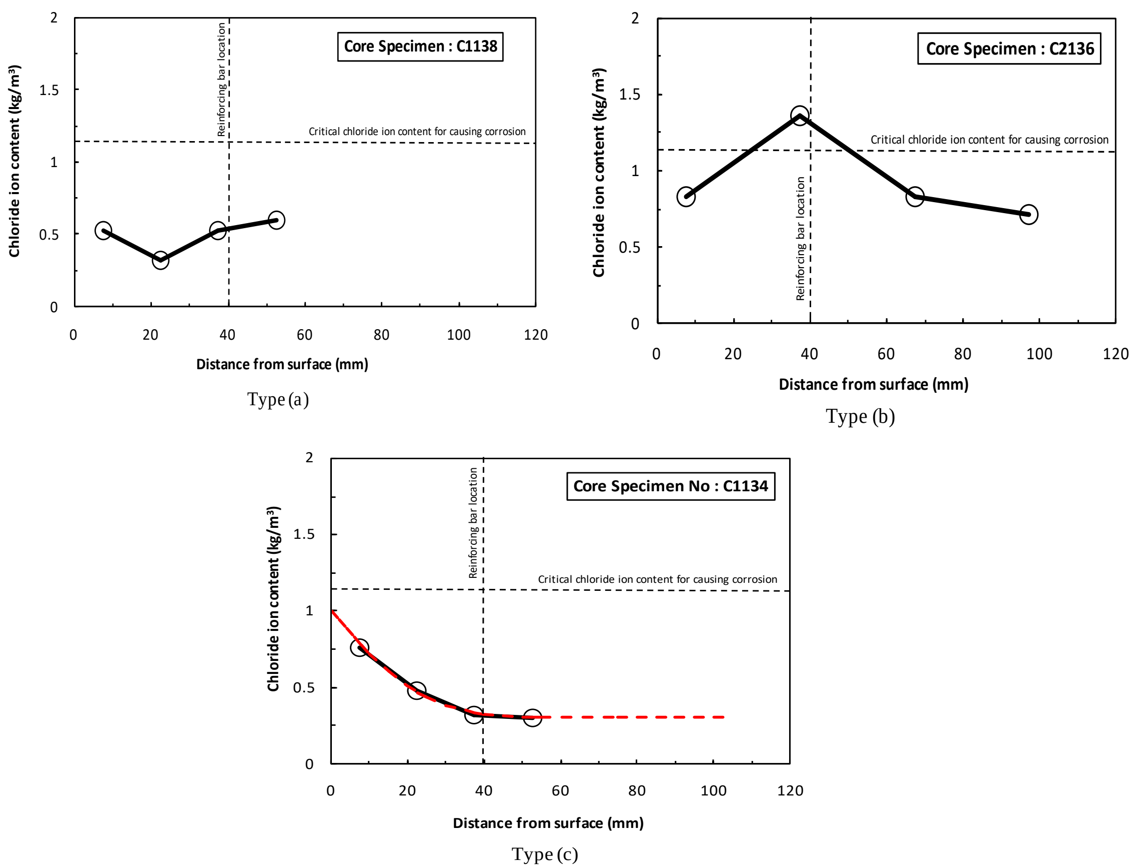


Fig. 14. Types of chloride ion content distribution

Table 8. Results of carbonation depth measurement

Main Girder No.	Core Specimen No.	Carbonation depth, *x* (mm) Average Value	Maximum Value	Standard Deviation	Carbonation Rate *A* (mm/$\sqrt{\text{years}}$)
1	M1132	54.0	60	5.7	6.45
	M1033	52.6	55	2.1	6.29
	M1137	40.2	47	5.9	4.80
	M1039	52.4	56	1.9	6.26
2	M2132	43.6	48	4.3	5.21
	M2134	58.2	56	4.2	6.96
	M2037	53.8	57	3.1	6.43
	M2039	79.8	90	8.5	9.54
3	M3032	11.2	15	4.5	1.34
	M3133	44.6	80	27.0	5.33
	M3136	46.0	55	5.3	5.50
	M3039	40.8	58	14.5	4.88
4	M4032	58.4	77	9.6	6.98
	M4134	51.4	55	2.9	6.14
	M4137	42.2	47	3.7	5.04
	M4039	51.6	70	12.1	6.17
5	M5032	56.8	62	2.8	6.79
	M5133	37.4	48	7.0	4.47
	M5136	60.6	90	19.9	7.24
	M5139	43.8	55	9.5	5.24

From these results, it was concluded that the deterioration of SK-Bridge was caused mainly by carbonation in view of the fact that the chloride ion contents at the reinforcement locations had not reached the critical chloride ion content for steel corrosion and that the carbonation depth was considerably greater than the thickness concrete cover.

Remaining life prediction

The remaining life prediction for a concrete structure in case where section loss due to steel corrosion is expressed as the number of years of life expected if the section loss is left uncorrected (JSCE, 2006). Therefore, the remaining life *R* can be expressed by using the life expectancy *X* (years) and the period of service *N* (years) as Eq. (4).

$$\text{Remaining life } (R) = \text{Life expectancy } (X) - \text{Period of service } (N) \quad (4)$$

The method for predicting the service life is available for calculation based on allowable stress, remaining reinforcing bar cross-sectional percentage, and limited state design method. In this paper, however, the remaining life was assessed in terms of the progress of deterioration over time due to carbonation, which is a deterioration factor identified earlier. It is assumed that the deterioration due to carbonation provides an environment that affects factors contributing to corrosion of the reinforcing bar, such as chloride ions and moisture content. Attention is paid on the cumulative amount of steel corrosion due to the spread of carbonation, and the service life of a bridge is deemed to exceed when the cumulative amount of steel corrosion reaches the critical value. The remaining life then was predicted by using Eq. (4).

Figure 15 shows the flowchart of the remaining life prediction methods in the case where deterioration is caused by chloride attack and the case where it is caused by carbonation (area shown by a dotted line in Figure 14). On the basis of Figure 14, it can be seen that when the remaining carbonation cover is 10 mm or less, it can be recognized that the main deterioration factor is carbonation. In order to predict the life expectancy *X* in year, it is necessary to have three types of information: carbonation depth, cumulative amount of steel corrosion, and steel corrosion limit as the criterion for determining service life.

It has been reported (JSCE, 2007) that the criterion value *Q* of steel corrosion assumed for the purpose of the remaining life prediction ranges widely from 1 to 576 mg/cm^2. In the remaining life prediction by RC-BREX system, deterioration curves are applied to structural soundness scores obtained on the basis of visual inspection results. It has also been reported (Miyamoto et al., 2012; Takahashi et al., 2011) that in the prediction method by the RC-BREX system, the cumulative amount of steel corrosion in the last year of the predicted remaining life was Q = 75 mg/cm^2.

In this paper, therefore, the remaining life prediction was made both in the case where the criterion value Q_{CR} is defined as the cumulative amount of steel corrosion of Q_{CR} = 10 mg/cm^2, which is said to be the critical amount of corrosion for initial cracking due to carbonation (JSCE, 2007), and the case where Q_{CR} is defined as the cumulative amount of steel corrosion of Q_{CR} = 75 mg/cm^2, which is the same as the remaining life indicated by the RC-BREX system in the evaluation of deterioration due to chloride ions shown in Figure 14. This prediction was made for the eight collected concrete cores (C-series) shown in Table 7 for which the apparent diffusion coefficient of chloride ions was determined. For the carbonation rate, the results for M-series concrete cores extracted from the nearest locations were used (Widyawati, 2015).

Table 9 shows the results of the remaining life prediction. As shown in Table 9, the time before reaching the critical amount of corrosion for initial cracking due to carbonation (JSCE, 2007) is 37.5 years on average, and approximately 40 years later, the cumulative amount of steel corrosion specified as the criterion value indicating the end of the remaining life is reached. Furthermore, the average value of the remaining life prediction of the eight collected concrete cores extracted from the target span (Span 3) is 7.8 years on average, and it can be seen that the remaining life prediction varies between 13 years and 40 years, depending on the coring locations.

Table 9. Results of remaining life prediction

Main Girder No.	**Core Specimen No.**	***Q* = 10 mg/cm²** **Cracking Limit (years)**	***Q* = 75 mg/cm²** **Predicted Life, *X* (years)**	**Remaining Life, *R* (years)**
1	C1134	27	62	-8
3	C3134	38	69	-1
	C3138	46	92	22
4	C4031	24	57	-13
	C4136	44	95	25
5	C5031	28	62	-8
	C5134	54	110	40
	C5038	39	76	6
Average (years)		37.5	77.9	7.9

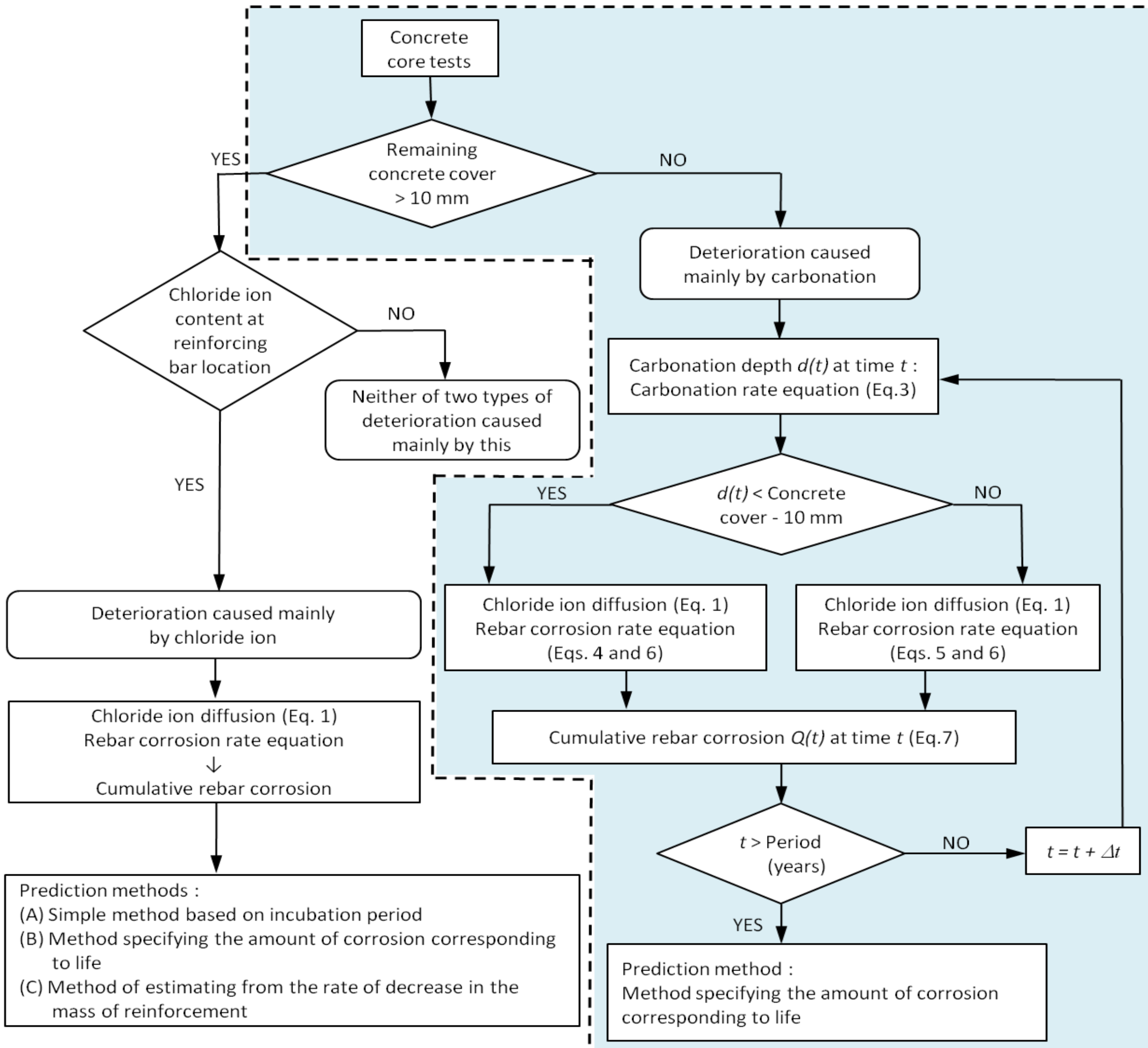


Fig. 15. Flowchart of remaining life prediction

Discussions

The remaining life prediction results listed in Table 9 are based on measured values obtained by using the collected concrete cores. And the remaining life prediction based on the cumulative amount of steel corrosion of Q = 75 mg/cm^2 as an end of life indicator showed that the remaining life of the bridge is predicted approximately seven years. However, because the setting values such as the moisture content, etc. are thought to be important in the remaining life prediction, for example, the degree of influence of assume values of the cumulative amount of steel corrosion on the remaining life prediction results for each core is necessary to consider the value of parameter Q through comparison with the results of the remaining life prediction by the RC-BREX system, taking into consideration the fact that main deterioration factors may be different.

CONCLUSIONS

In this study, with the aim of putting J-BMS RC version to practical use, close visual inspection of an aged (old) bridge (SK-Bridge) to be removed for the construction of a new bridge was conducted to collect inspection data. The collected data were entered into RC-BREX 2000, a quantitative deterioration diagnosis system, and the usefulness of the RC-BREX 2000 was verified on the basis of the diagnostic results. The main conclusions of this study are as follows:

1) Close visual inspection data on the SK-Bridge were entered into RC-BREX 2000, one of the deterioration diagnosis subsystems of the J-BMS RC version, and diagnostic results were examined from various viewpoints. As a result, it can be said that RC-BREX 2000 is a practical system capable of reflecting expert knowledge in performance evaluation by use of the system's learning function.

2) Variability of damages pointed out by inspection experts in the close visual inspection conducted at a bridge site was evaluated. As a result, it was found that a pre-inspection hearing session (exchange of information on damage identification) involving experts is effective in reducing the variability of inspection results.

3) It was found that performance evaluation based solely on the system's initial knowledge is not enough to achieve high accuracy in evaluating bridge performance. The application of the exhaustive learning method improved system performance, and the post-learning performance evaluation results output from the system became closer to the results of a questionnaire survey of experts. This indicates that the system is capable of performing performance evaluation that reflects the knowledge of experts.

4) The remaining life, from the viewpoints of load carrying capability and durability, of the (aged) bridge estimated by RC-BREX was 5 and 10 years, respectively. This shows that remaining life estimation by the system is reliable to a certain degree.

5) The remaining life prediction obtained based on concrete cores is affected by the cumulative amount of steel corrosion (Q), which is used as an end of life indicator. The remaining life prediction made by a cumulative amount of steel corrosion of Q = 75 mg/cm^2 as an end of life indicator showed that the remaining life of the bridge is predicted approximately 7 years. The remaining life prediction result obtained by RC-BREX system designed for evaluating the present performance of the target bridge is almost similar to these obtained based on concrete core tests, which represent the local properties of the bridge.

ACKNOWLEDGMENTS

The authors would like to express their heartfelt thanks to the staff of the Chugoku Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism, for giving the authors the invaluable opportunity for the on-site inspection of the aged bridge in connection with this study.

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