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Development and Practical Application of a Lifetime Management System for Prestressed Concrete Bridges

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ABSTRACT: A practical Bridge Management System has been developed by the author, which is referred to as the Japanese Bridge Management System (J-BMS) for existing concrete bridges. This paper introduces a newly developed bridge management system for the prestressed concrete (PC) bridges (J-BMS PC version) which is integrated with the PC bridge rating expert system (PC-BREX). The proposed system is able to predict the deterioration process of the existing PC bridge superstructure components as well as assess a broad array of optional corrective strategies. The system also has the capability to search and retrieve from a J-BMS database system (J-BMS DB), the necessary information, carry out suitable analyses to arrive at some recommendations that would help users to optimize their decisions based on engineering aspects, cost and economic issues and bridge management policies. A comparison of the results of applying the system to some actual in-service PC bridges with a special designed survey form to experts shows that optimal maintenance planning as well as bridge rating can be predicted accurately by using the system.

Keywords: Bridge Rating Expert System (BREX), J-BMS DB, Lifetime Management System, Practical Application, Prestressed Concrete Bridge.

INTRODUCTION

A practical Bridge Management System has been developed by the author, which is referred to as the Japanese Bridge Management System (J-BMS) integrated with the Concrete Bridge Rating Expert System (BREX) that can be used to evaluate the serviceability of existing concrete bridges. J-BMS is composed of three subsystems, namely, J-BMS Data Base System (J-BMS DB), Bridge Rating Expert System (BREX) and Maintenance Plan Optimization System (MPOS) (Asano 2015; Kawamura and Miyamoto, 2003; Kawamura et al., 2003; Miyamoto and Motoshita, 2015). The J-BMS uses multi-layered neural networks to predict deterioration processes in existing concrete bridges, construct an optimal maintenance plan for repair and/or strengthening measures based on minimizing life-cycle cost and maximizing quality (Brühwiler and Denarié, 2013; Nader and Frangopol, 2012), and also estimate the maintenance cost. In this system, the Genetic Algorithm (GA) technique (Abbasnia et al., 2014) was used to search for an approximation of the optimal maintenance

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plan (Miyamoto and Motoshita, 2015; Miwa 2001). The J-BMS subsystems were developed at different points in time and no compatibility had been established. In order to solve the problem, the J-BMS subsystems were integrated and a version of J-BMS for prestressed concrete bridges (J-BMS PC version) was developed in this study. The practical application of the system requires further multifaceted verification (National Institute for Land and Infrastructure Management, 2010). Verifications from diverse viewpoints are, however, required before practical system implementation. The authors have been applied and made comparison of the results of applying the system to some actual in-service PC bridges (Asano, 2015) until now. In this paper, as a specific example, the proposed system was applied for an actual PC bridge (called MH bridge) with simply supported T-girder in Yamaguchi Prefecture. Numerous data obtained in the inspections of an actual bridge were input to PC-BREX and the diagnostic results were closely verified, as a specific example. For consideration, variances were identified according to the structural type, input method and inspector, and points to be improved and problems were organized.

CONFIGURATION OF J-BMS

The configuration of J-BMS is shown in Figure 1. The figure shows J-BMS functions corresponding to the steps of the bridge management flow for developing an optimum maintenance plan taking life-cycle cost into consideration. As the steps of the flow, i) bridge specification data such as the age and grade of the bridge and inspection data on cracks and other parameters are extracted (J-BMS DB), ii) performance and soundness of the bridge are assessed based on the extracted data (BREX), iii) deterioration of the bridge is predicted using deterioration curves based on the diagnostic results (MPOS), iv) cost and effect of corrective measures are verified based on the results of deterioration prediction (MPOS), and v) optimum timing and cost of corrective measures are proposed based on the verification results and an optimum management plan is developed (MPOS). The J-BMS functions (subsystems) are described in detail and their characteristics and problems are organized below:

(1) J-BMS Data Base System (J-BMS DB) ((i) in Figure 1): J-BMS DB is composed of the "bridge specification DB", "ordinary inspection DB" and "repair and retrofit DB" (Konno 2003). The subsystem was developed to efficiently accumulate all types of data on bridges such as bridge specification data, inspection data that is collected in ordinary and detailed inspections and data on the history of repair and retrofit.

(2) Bridge Rating Expert System (BREX) ((ii) in Figure 1): BREX assesses the present bridge performance (e.g. load bearing capacity and durability of main girders and slabs) based on the bridge specification data and various inspection data provided by J-BMS DB, using neural networks and fuzzy theory (Konno et al., 2003; Miyamoto, 2000). BREX is composed of RC-BREX for reinforced concrete bridges and PC-BREX for prestressed concrete bridges.

(3) Maintenance Plan Optimization System (MPOS) ((iii)-(v) in Figure 1): MPOS helps develop optimum maintenance plans for efficiently managing bridges by inputting the bridge specification data and ordinary inspection data (soundness determined by BREX) output by J-BMS DB and having users set "deterioration prediction equations", "cost of maintenance and renovation", "period of applying corrective measures" and "renovation budget" (Miyamoto, 2000).

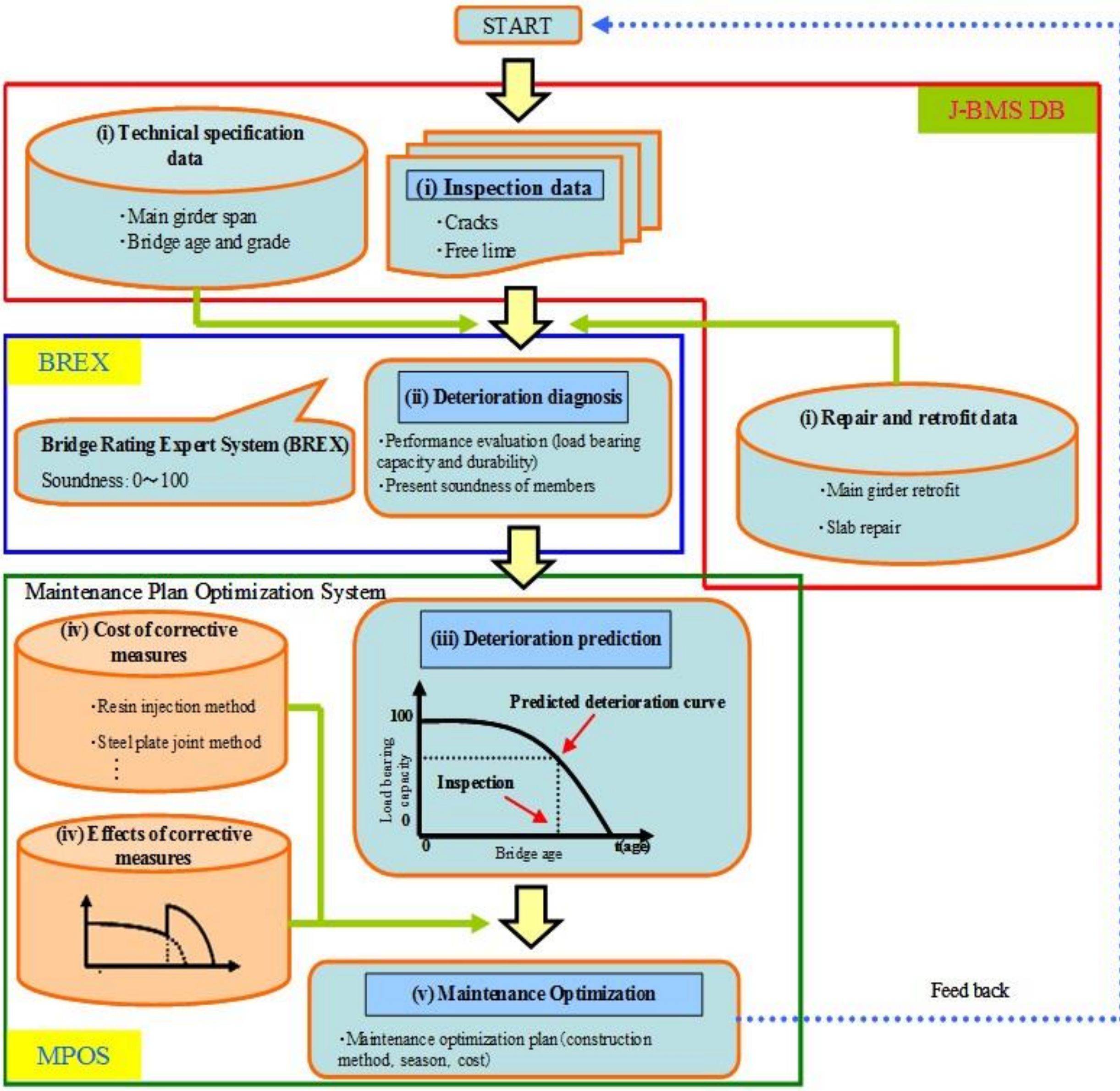

Fig. 1. Configuration of J-BMS

DEVELOPMENT OF J-BMS PC VERSION

Re-Building of PC-BREX

PC bridges are more effective than Reinforced Concrete (RC) bridges because prestressing the cross section of a member eliminates an unfavourable stress condition that is created by external forces and thus enable an effective use of the total cross section. If the tensile stress in any given cross section of a concrete member is controlled so as not to cause surface cracking under any combination of predictable external forces, it is possible to construct a structure that requires minimum maintenance in the future. Then, it is generally say that cracking or other types of damage to concrete surface of a PC structure designed based on the above assumption therefore implies that the durability of member has already been lost. To introduce of prestressing in all parts of a PC bridge is, however actually impossible. Especially, prestressing is often difficult at joints in cast-in-place backfill, in the longitudinal direction of a bridge slab, or at the anchorage of prestressing steel, then, reinforced concrete(RC) is used in some parts (Miwa, 2001; Tarighat and Jalalifar, 2014). Then, for the diagnosis of a PC bridge, re-building of a deterioration diagnosis (evaluation) process in the BREX for PC bridges (PC-BREX), etc. are also required for total maintenance of the PC bridges.

PC-BREX was re-built because i) no compatibility was provided with Microsoft Windows Vista or later versions of OS, ii) no explanation functions were available and iii) bugs occurred in the case where a specified folder contained no data. PC-BREX evaluates the overall durability of main members (main girders and slabs). Overall durability means comprehensive performance of members identified through composite evaluation of load bearing capacity and durability.

This chapter describes the evaluation process and evaluation function of newly developed PC-BREX.

Evaluation Process

The evaluation process is the key component of PC-BREX. The hierarchical process shows the steps of evaluation leading to the evaluation of overall durability of main girders and slabs conducted by domain experts (bridge administrators with expertise and the people with adequate basic knowledge and experience concerning bridges in Yamaguchi Prefecture) (Kawamura and Miyamoto, 2003; Kawamura et al., 2003). The evaluation process enables the evaluation of overall durability at the highest level by transferring evaluation results from lower to higher levels (Morcous et al., 2010; Yang et al., 2011). Figure 2 shows part of a process of evaluating the overall durability of main girders. In this process, the lowest judgement items, such as "Condition of cracking", "Development of free lime" and "Occurrence of rust fluid" are first evaluated using the visual inspection data and/or technical specifications. Continuing with this example, the degree of "Damage at mid span" is determined by using the inspection data such as "Crack width", "Number of cracked location", "Free lime" and "Concrete spalling" in terms of "Condition of cracking", "Development of free lime" and "Occurrence of rust fluid". As an example, the results were obtained by inputting inspection data. Especially, for PC bridges, results of inspection for deformation at the anchorage of longitudinal prestressing tendons, near the tendon sheath and at the anchorage of transverse prestressing tendons are also input to represent impacts on prestressing tendons. For example, the lowest judgement items (2nd layer) in Figure 2, such as "Condition of cracking" is evaluated from inspection data such as "Crack width" and "Number of cracked locations". Next, the higher judgement items (3rd layer or more) are diagnosed from the results of lower judgement items and/or input data (inspection data and technical specifications), and so on. The final judgement items in Figure 2 is "Overall durability of main girder" which is diagnosed according to "Load bearing capacity of main girder" and "Durability of main girder". These judgement items are assigned a mean soundness score as an output of the system. The score obtained is categorized into five groups: 0-12.5, 12.5-37.5, 37.5-62.5, 62.5-87.5 and 87.5-100. These group are classified as "Unsafe", "Severe", "Moderate", "Mild" and "Safe", respectively. Table 1 show the relationship between the evaluation scores and safety (deterioration) levels in the PC-BREX.

In this paper, "Safe" indicates that the bridge has no problem, "Mild" indicates that there are no serious damages, "Moderate" indicates that there are some damages which need continuous inspection, "Severe" indicates that the bridge should be repaired and/or strengthened and "Unsafe" indicates that the bridge should be removed from service and requires rebuilding.

Evaluation Function

Evaluation function such as durability, load carrying capability aims at evaluating various types of performance of main members (main girders and slabs) (Wang et al., 2011). PC-BREX users can obtain the results of performance evaluation by inputting required data on the specific bridge. PC-BREX outputs evaluation results based on the conditions of cracking and free lime in various positions, which are typical of prestressed concrete bridges. Figure 3 shows a sample screen presenting the results of evaluation of main girders produced by PC-BREX. Users can visually confirm on the evaluation result screen the ratings on the overall durability of main members with respect to the load bearing capacity and durability, and design, general damage, construction and damage at specific positions.

Table 1. 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.

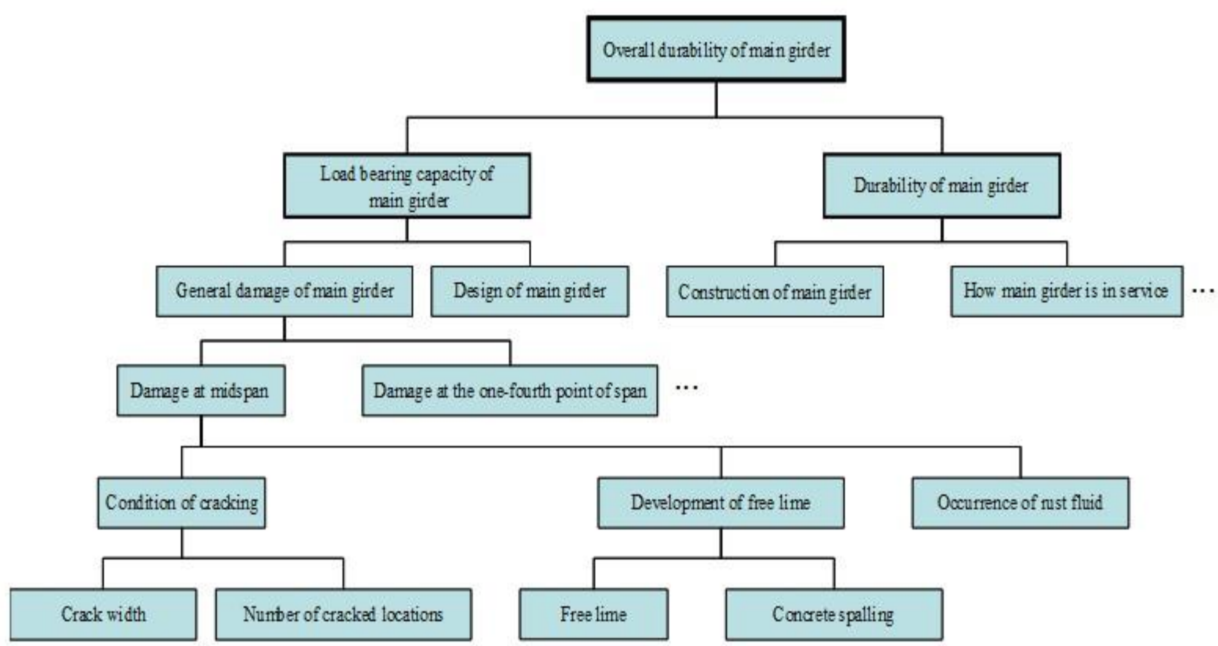

Fig. 2. Part of the process of evaluating overall durability of main girder

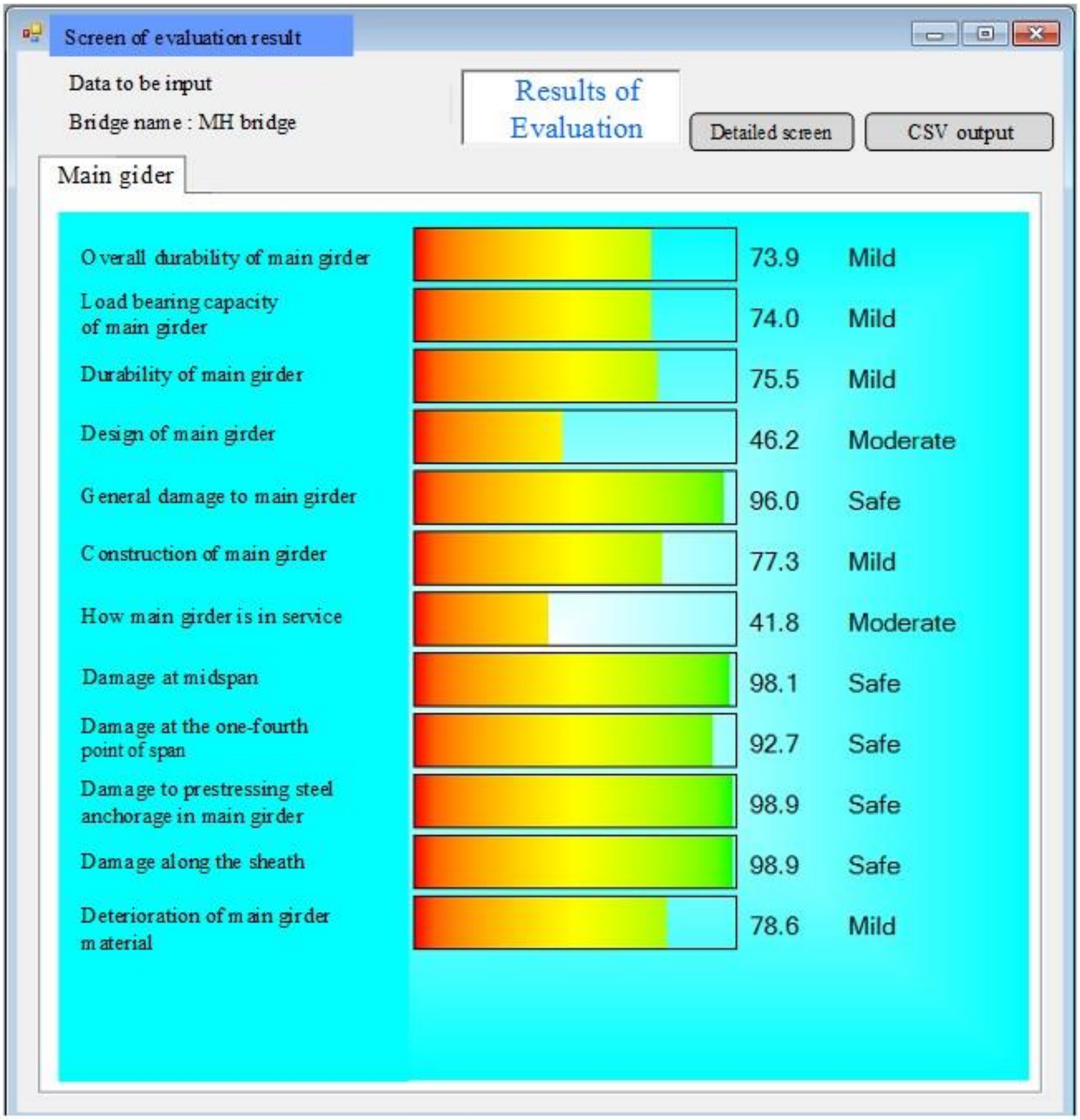

Fig. 3. Sample screen showing evaluation results for parameters of main girder

The sensitivities of the lowest judgement items such as tendon's corrosion for prestressed concrete bridges on evaluation process for main girders and slabs are evaluated by using the exhaustive learning method which is used as teacher data from domain experts (Miwa, 2001).

Development of J-BMS PC Version

The subsystems of J-BMS were developed at different points in time. Development environments and programming technology therefore varied and no adequate compatibility was established among the subsystems. This section discusses the development of J-BMS PC version for the purpose of integrating J-BMS subsystems and effectively managing prestressed concrete bridges. A general view of data flow to deprive an optimum maintenance plan that specifies the selected method, timing of maintenance and life-cycle cost of J-BMS PC version is given in Figure 4.

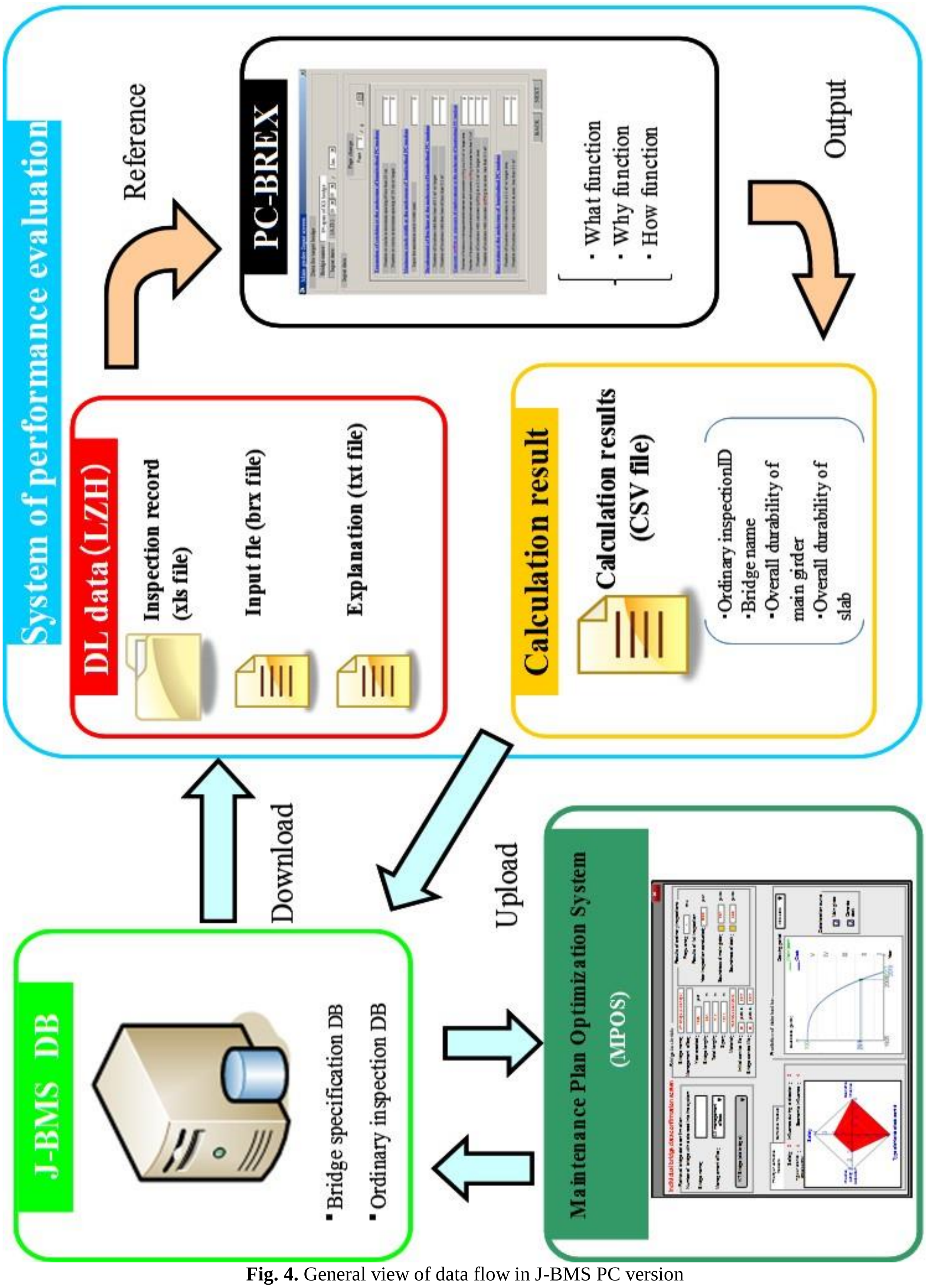

Fig. 4. General view of data flow in J-BMS PC version

The processes of system integration conducted in this study are described below:

i) J-BMS DB was integrated with PC-BREX by downloading BREX data from J-BMS DB, outputting the results of evaluation by PC-BREX as CSV files and uploading the CSV files to J-BMS DB. BREX data includes an inspection report, input file (brx. file) and explanation file containing compressed data, which can separately be downloaded.

ii) J-BMS DB was integrated with MPOS by using bridge specification and inspection data stored in J-BMS DB. Corrective measures are stored in J-BMS DB in three or five levels (Safe, Mild, Moderate, Severe and Unsafe) (Emoto et al., 2014). Soundness is evaluated on a scale from 0 to 100 by diagnosis using PC-BREX and is input to MPOS as shown in Figures 1 and 3.

SYSTEM VERIFICATION

This chapter presents the results of application of re-built PC-BREX to an actual prestressed concrete bridge in Yamaguchi Prefecture and an optimum maintenance plan that was developed using developed J-BMS PC version, and verifies the systems. The target bridge, called MH Bridge for which tests were performed is shown in Figure 5 with its specification data. The bridge consists of four PC-T simply supported girder bridge and is located in rural area, Japan.

Results of Application of PC-BREX to an Actual Bridge

The MH Bridge (Mine City in Yamaguchi Pref.) was inspected on-site through the cooperation of four experts who work in consulting firms and have adequate knowledge about bridges. Figure 6 shows some damage situations of the target bridge by photos and the damages identified by an inspector (domain expert). Figure 7 shows part of the input screen of inspection data for main girders. Dozens of parameters (data) are input such as technical specifications for the bridge, various investigation and inspection results, and cracking conditions in slabs and main girders. Especially for PC bridges, results of inspection for deformations at the anchorage of longitudinal prestressing tendons, near the tendon sheath and at the anchorage of transverse prestressing tendons are also input to represent impacts on prestressing tendons (see Figure 6). Some parameters require multiple choice answers based on subjective judgements. Choices can be made at the click of a mouse.

Table 2 lists the results of evaluation of specific parameters obtained by inputting the inspection data collected by domain experts (Inspectors assumed to be full independence to PC-BREX and standard deviations (Experts A-D did not communicate with each other during the inspection in situ). The table indicates that ratings are low for “design” and “serviceability” either for main girders or for slabs. This may be because the MH Bridge has been in service for 42 years and because out-of-date specifications were applied at the time of design and the bridge was designed under smaller design loads than at present. General evaluation results show that the rating of overall durability by BREX is approximately 70 on a 100-point scale. It is therefore evident that the MH Bridge needs no urgent repair, because 62.5-87.5 points of evaluation result is in a rank of “Mild (deterioration)” (Emoto et al., 2014).

A comparison of results of evaluation by four inspectors shows great variations in “construction” either for main girders or slabs. Figure 8 shows a hierarchical structure of “main girder construction” as an example. “Slab construction” is of a similar structure. As is obvious from Figure 8, construction is evaluated in terms of two parameters, “discoloring and deterioration” and “occurrence of honeycombing”. The ratings in these terms seem to greatly govern the final scores. The options concerning the "discoloring and deterioration" and "occurrence of honeycombing" are shown in Figures 9 and 10, respectively. The options are similar for slabs. Specific figures are input concerning the "occurrence of honeycombing" (Figure 10). Slight difference in number of locations of occurrence therefore has no impact on evaluation results. Figure 9 shows that a checkbox on the display is used for inputting subjective decisions by domain expert. Small difference in the determination of damage by inspectors greatly affects evaluation results.

Figure 11 shows almost all the diagnostic process developed for PC bridges on the left. It also presents in the upper right details about the diagnostic processes for the item (damage to the anchorage of prestressing tendons on the girder in this example) for which the diagnostic results need to be verified (inspection items) and the relevant sets of production riles (if-then rules) ((i) damage to and rust stains on the anchorage of longitudinal prestressing tendons, (ii) appearance of free lime at the anchorage of prestressing tendons on the main girder and (iii) cracking in pattern (7)). Thus, it is easy verified how the rules are applied to deduce the final diagnostic results. Present shapes of membership functions are also provided in the lower right for the sets of production rules (i) through (iii).

Table 2. Results of evaluation of the MH Bridge

	Inspector **Rating Parameter**	**Expert A**	**Expert B**	**Expert C**	**Expert D**	**Standard Deviation**
Main girder	**Overall durability of main girder**	63.6	63.8	79.7	70.8	6.58
	Load bearing capability of main girder	73.2	73.4	73.6	73.9	0.26
	Durability of main girder	65.2	65.3	81.6	72.8	6.78
	Design of main girder	46.2	46.2	46.2	46.2	0.00
	General damage to main girder	91.0	91.7	93.0	95.3	1.64
	Construction of main girder	52.8	52.8	98.3	73.8	18.70
	How main girder is in service	41.8	41.8	41.8	41.8	0.00
	Damage at midspan	93.2	80.4	82.7	92.6	5.74
	Damage at the one-fourth point of span	81.9	98.9	98.9	93.3	6.94
	Damage to prestressing steel anchorage in main girder	98.9	98.9	98.9	98.9	0.00
	Damage along the sheath	98.9	82.0	82.6	98.9	8.30
	Deterioration of main girder material	69.4	76.8	78.4	77.3	3.55
Slab	**Overall durability of slab**	64.1	71.1	57.3	79.1	8.10
	Load bearing capability of slab	66.6	70.7	58.0	68.4	4.80
	Durability of slab	73.0	76.2	69.5	91.5	8.40
	Design of slab	48.6	52.2	26.7	53.4	10.80
	General damage to slab	79.0	83.7	80.7	80.6	1.70
	Construction of slab	73.8	74.5	28.3	99.0	25.50
	How slab is in service	70.1	70.2	82.5	82.5	6.18
	Damage at the center	72.3	93.2	75.5	74.3	8.38
	Damage at the point of filling	37.2	81.2	60.9	48.0	16.40
	Damage in other areas than at the point of filling	98.9	98.9	94.2	98.9	2.04
	Damage to slab overhangs	98.9	79.7	95.6	98.9	7.95
	Damage to the anchorage of perpendicular prestressing steel	98.6	99.0	99.0	99.0	0.17
	Deterioration of slab material	48.8	61.3	49.7	58.1	5.36
	Surface condition	78.1	78.4	78.4	78.3	0.12

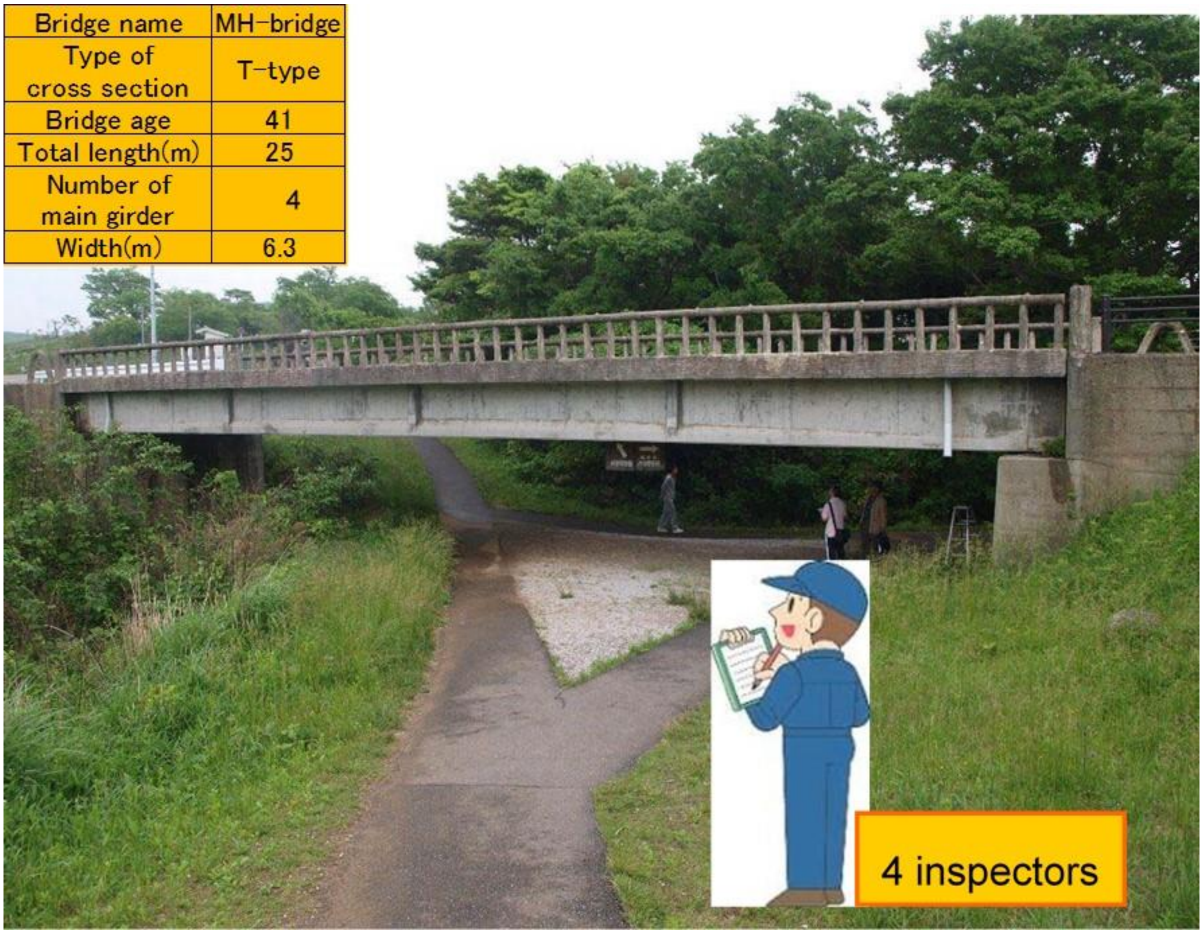

Fig. 5. Outline of MH Bridge (a target bridge)

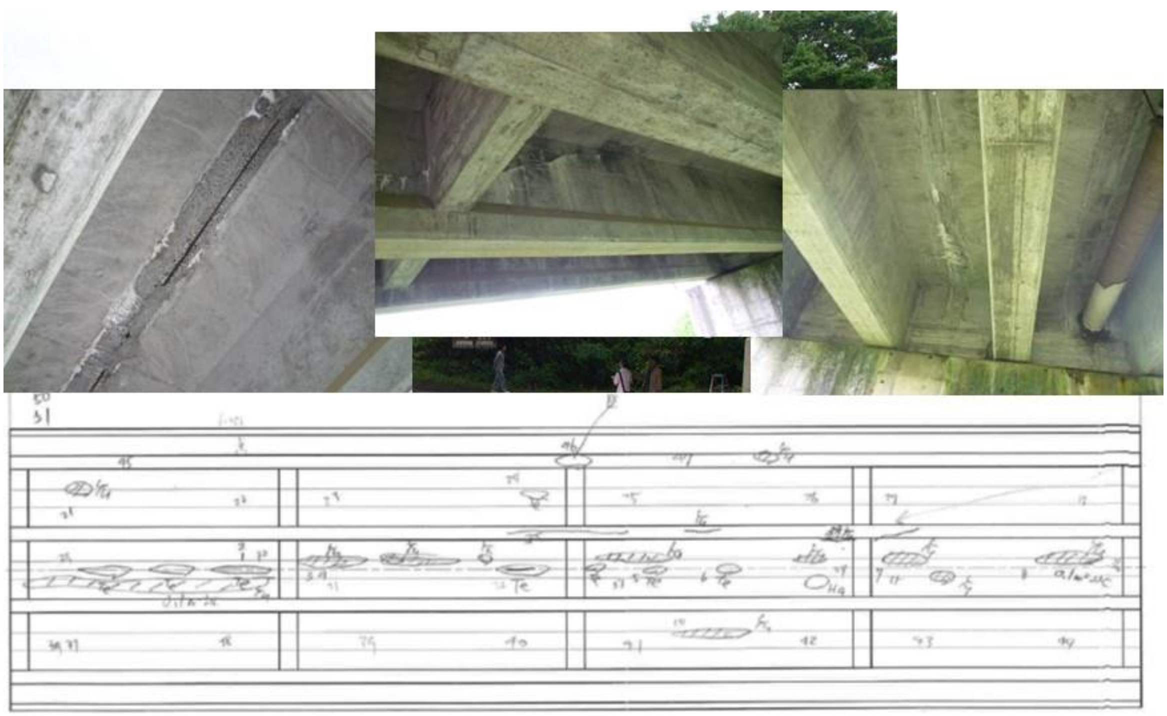

Fig. 6. Damage situation of the target bridge and the damages identified by an inspector

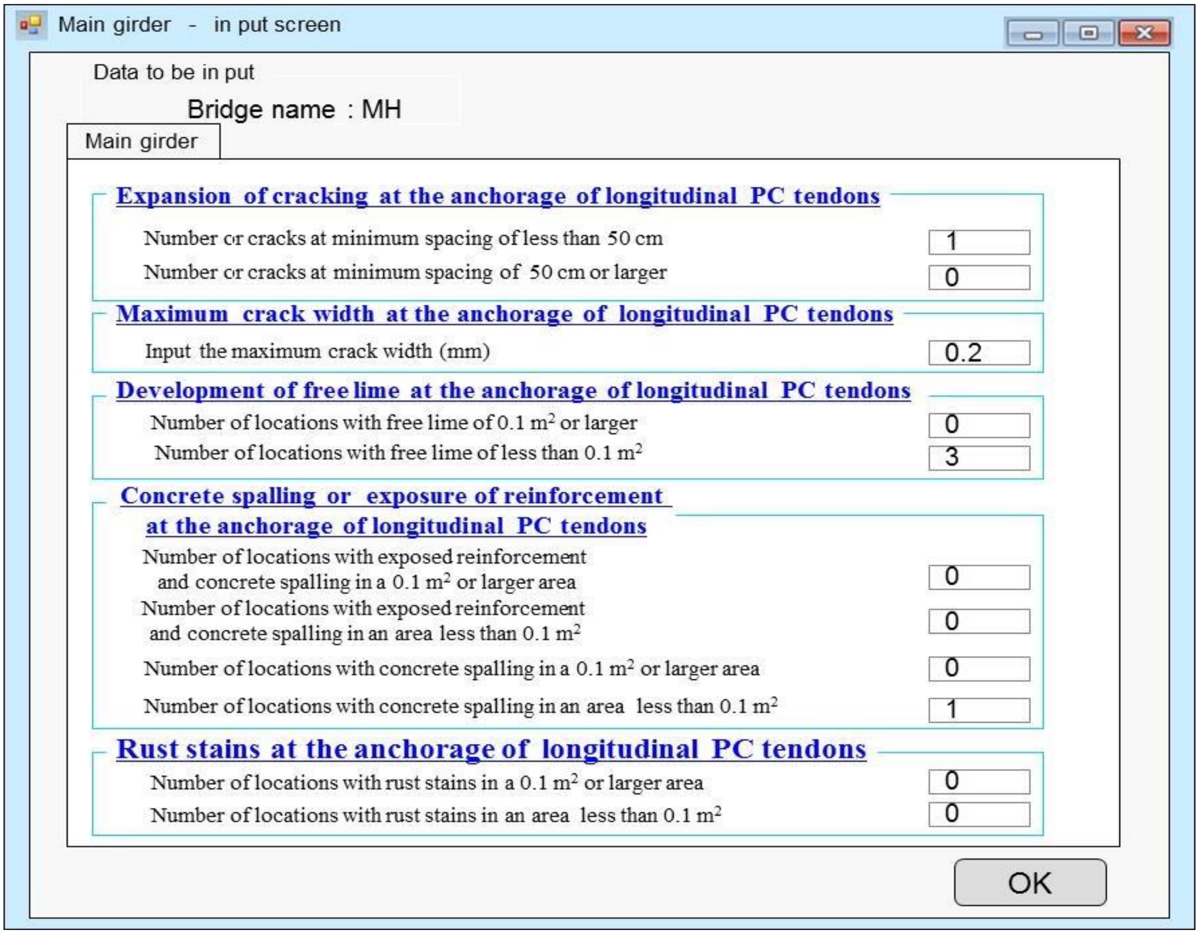

Fig. 7. Input screen of inspection data on the target bridge

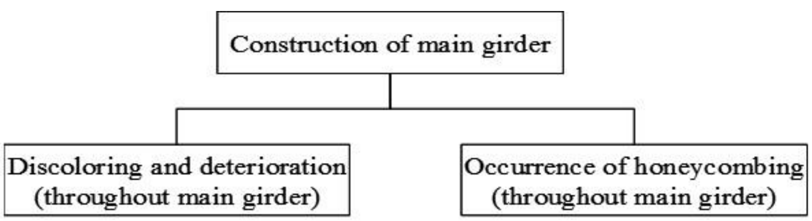

Fig. 8. Hierarchical structure for evaluating main girder construction

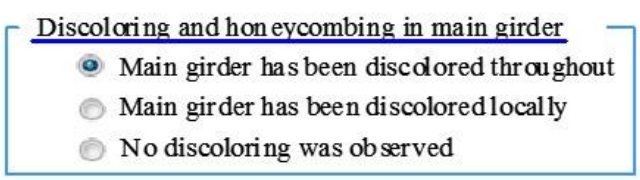

Fig. 9. Options for determining the discoloring and honeycombing of main girder

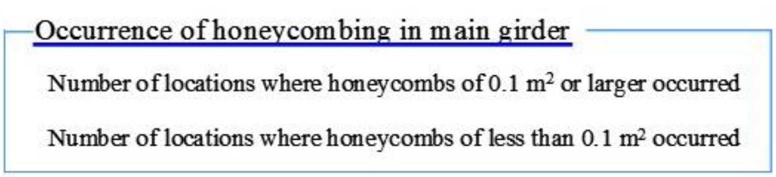

Fig. 10. Options concerning the occurrence of honeycombing

The objective is to enable the verification of knowledge base update (effects of learning) in the case of variance of the diagnostic result from "right answers" such as opinions of domain experts and experimental results. Thus, effective support is provided in communication between engineers and systems developers. The system enables not only the soundness diagnosis by 0 to 100 of existing PC bridges and the selection of repair and strengthening methods according to the diagnosis but also effective and efficient development of an optimum maintenance plan that produces the maximum effect within limited budgets. Then, the system was constructed by applying the latest information processing technologies such as neuro-fuzzy expert system and genetic algorithm (GA).

The evaluation results obtained through comprehensive review may be used effectively if the difference in inspection is adjusted in prior interviews.

Development of an Optimum Maintenance Plan

The maintenance plan optimization system (MPOS) (Miyamoto and Motoshita, 2015) was developed to enable bridge management organizations to maintain existing PC bridges efficiently. By using the specification data and regular inspection data stored in J-BMS DB, mentioned earlier, MPOS draws up a maintenance plan and assists in selecting corrective actions on the computer screen. An optimum maintenance plan was developed using J-BMS PC version based on the inspection data on the MH Bridge in Mine City (Yamaguchi Pref.) as a specific example. For understanding of the outline of this function, a sample screen is shown in Figure 12 of the optimum maintenance plan output by MPOS after the input of conditions for developing the optimum maintenance plan. Not only deterioration curves before and after repair or retrofit and predicted remaining service life but also optimum timing of repair or retrofit may be output for the bridge under study.

Deterioration Prediction

Load carrying capability and durability evaluation results for main girders and floor slabs obtained from PC-BREX make it possible to evaluate the present soundness (0-100) 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* (Miyamoto, 2000).

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.

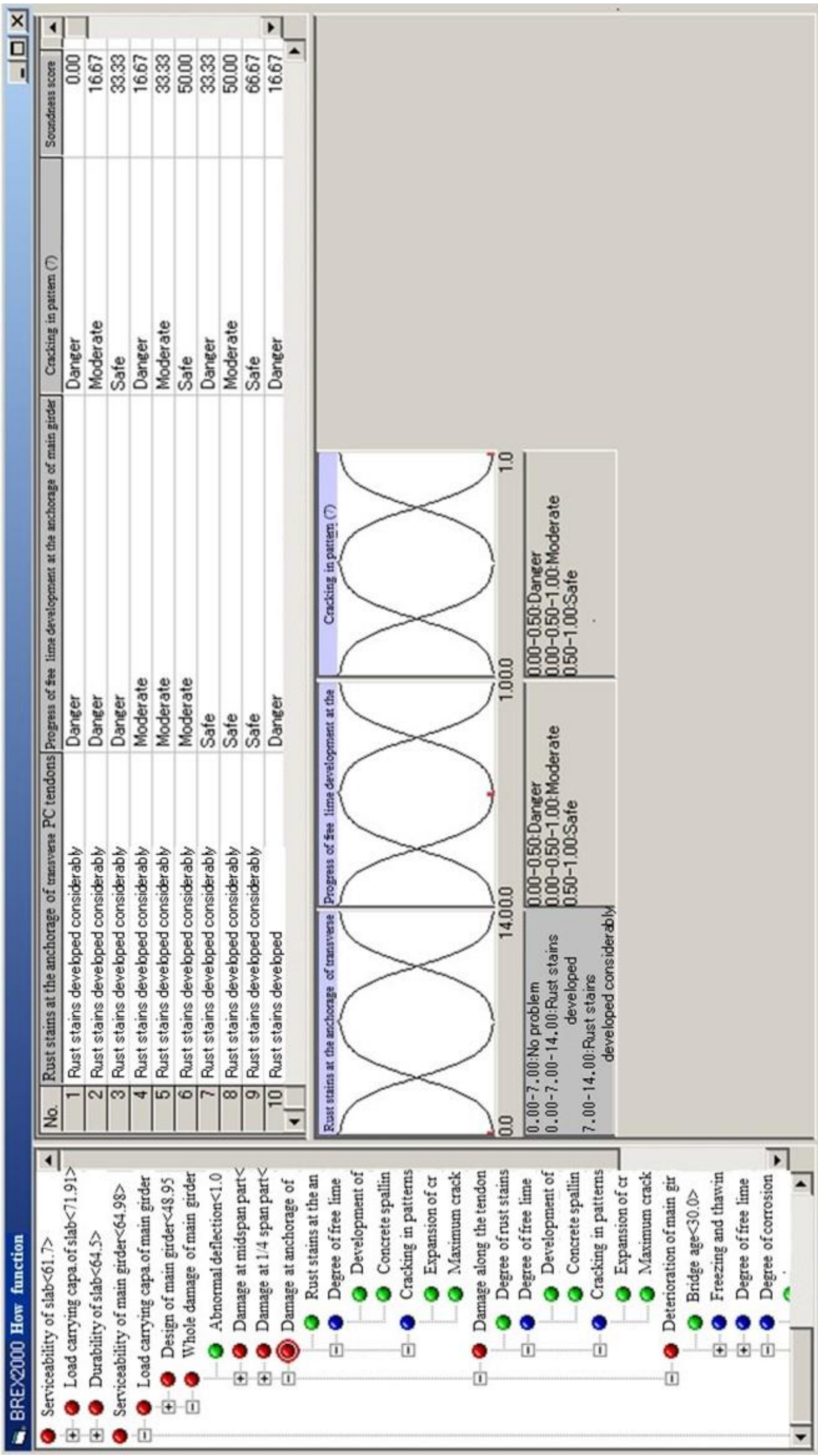

Fig. 11. Screen display for supporting final result verification and knowledge update

Figure 12 shows an example of a screen showing an output from the life maximization function. In in Figure 12, 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.

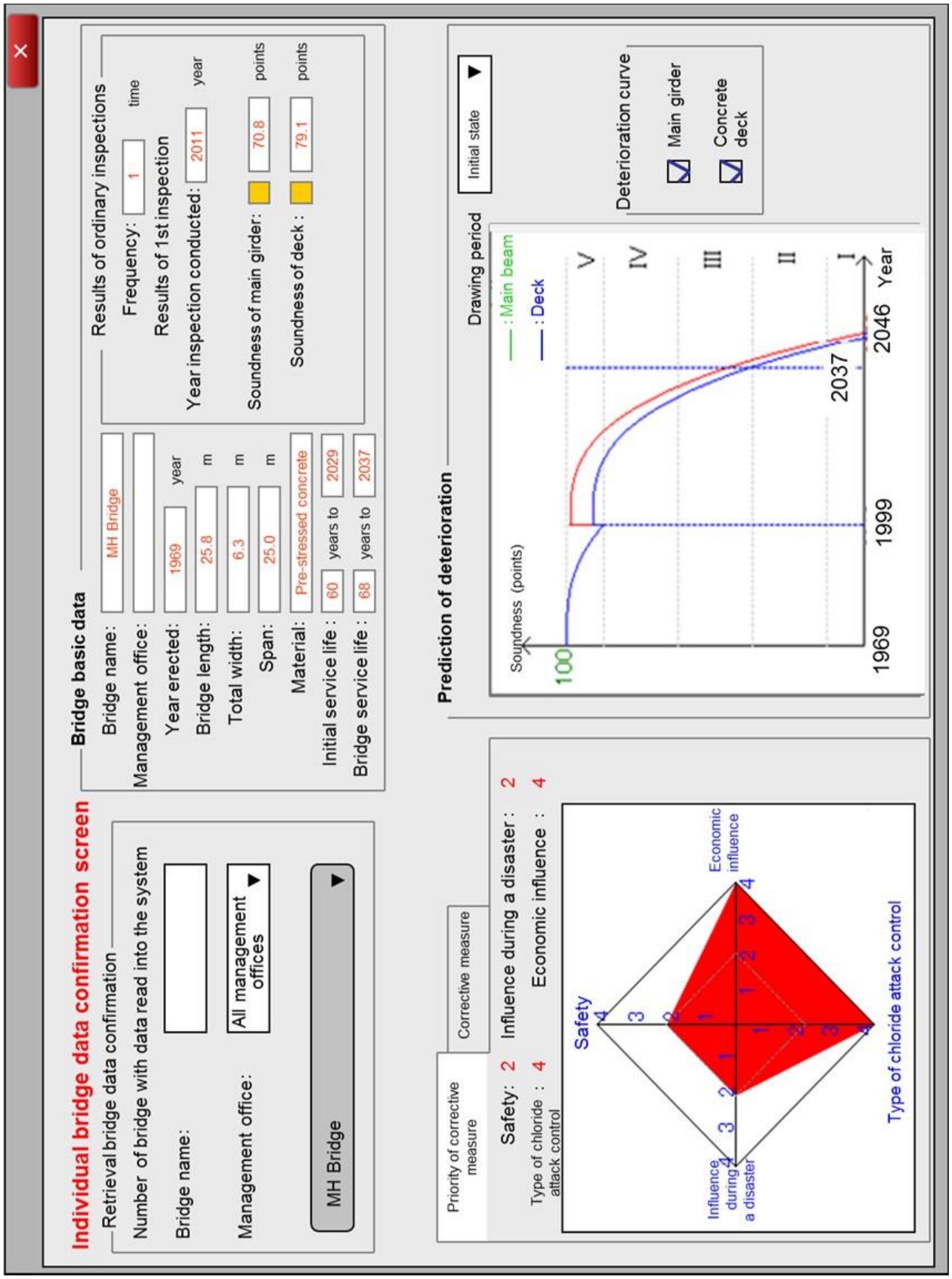

Fig. 12. Sample screen of an optimum maintenance plan for MH bridge

Reconstruction Cost Spreading

As mentioned in above, 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.

In the future, it is necessary to review the integration of subsystems for reinforcing final evaluation results.

CONCLUSIONS

The authors have been developing PC-BREX as a bridge rating expert system for prestressed concrete bridges. J-BMS DB and MPOS, subsystems of J-BMS that is capable of effectively maintaining prestressed concrete bridges, were developed and implemented separately and coordination between the subsystems required various improvements. In order to meet the requirement, PC-BREX was re-built and J-BMS subsystems that had been developed separately were integrated. For putting J-BMS into practical use, data obtained in inspections of an actual bridge was input to PC-BREX and the results of diagnosis were verified. As a result, J-BMS PC version was completed that enables comprehensive bridge management by J-BMS.

The results of this study are described below:

1- Combining J-BMS DB and PC-BREX enabled direct downloading of compressed BREX data (brx. file) and ensured the flow from the reading of inspection data into PC-BREX to performance evaluation.
2- It was made possible to output deterioration curves and develop an optimum maintenance plan by MPOS based on the bridge specification data and inspection data stored in J-BMS DB; and on the overall durability of main girders and slabs obtained by PC-BREX.
3- Subsystems of J-BMS were integrated based on the results in (i) and (ii). Then, it became possible to develop J-BMS PC version, a variation of J-BMS for prestressed concrete bridges and to increase the efficiency of maintenance work for prestressed concrete bridges.
4- It was revealed that the results of evaluation varied with respect to some parameters even among domain experts. For most of the parameters for which variations occurred, lower level evaluation depended on a checkbox. For solving the problem, using a virtual-reality-based three-dimensional bridge (3D-CG) models, using a diagram showing damaged positions for on-site inspections and other means are considered to enable the sharing of recognition of damage. Reinforcing the explanation function built in the system for supporting users to add detailed explanations about the damage is expected to reduce the variations of inspection results from inspector to inspector.

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