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Performance evaluation and remaining life prediction of an aged bridge by J-BMS

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Abstract

This paper describes health examination and remaining service life prediction procedures for an aged reinforced concrete (RC) T-girder bridge via visual inspection data. 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 (health score) and remaining service life of the subject bridge based on these test results. Using these procedures, the remaining service life of an aged RC-T girder bridge can quantitatively be estimated by applying the bridge rating expert (BREX) system, which is a subsystem of the J-BMS that incorporates field inspection data. In this study, visual inspection was carried out on an aged bridge by professional visual inspectors, during which all variations of the inspection results were evaluated using a five-step questionnaire. Additionally, it was found that health score (safety indices) and remaining service life predictions were influenced by the learning (supervised) data selection.

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Keywords: Aged bridge; Visual inspection; J-BMS; BREX system; Remaining service life

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1. Introduction and research significance

During Japan's postwar period of strong economic growth, it was urgently necessary to build large-span bridges capable of transporting the vast amounts of people and products the burgeoning economy required. Simultaneously, the civil engineers of the era faced a similar important need for numerous small- and medium-span bridges. In our current era, which is marked by an aging population, lower birthrates, and a decreased population base, it is now vitally important to maintain these bridges efficiently, and extend their service lives to the greatest extent possible.

The bridge evaluation and remaining service life prediction process (health check), which is conducted in order to efficiently maintain existing bridges, is based on the results of periodical visual inspections. Following the inspection process, design plans for repairing and reinforcing the bridge under evaluation are formulated. However, it has been found that the results of the visual inspection (as input data) process can result in a variety of evaluated values and conflicting data because it relies on the knowledge and experience of individual professional visual inspectors.

Therefore, the authors have developed a Bridge Management System (J-BMS) [1-3], which is capable of predicting the deterioration process for existing bridge members. Using this process, the remaining service life of an aged reinforced concrete (RC) T-girder bridge can be estimated quantitatively by applying the bridge rating expert (BREX) system [4], which is a subsystem of the J-BMS that incorporates field inspection data. In this study, visual inspections were carried out by a number of professional inspectors on an aged bridge, after which the inspection inconsistencies were evaluated using a five-step questionnaire. Additionally, the selection of learning (supervised) data was found to influence the health score (safety indices) and remaining service life prediction for the bridge.

2. Target bridge and visual inspection for J-BMS

A large aged bridge known as the "SK Bridge", which was constructed to allow Japan's National Highway Route No. 2 to cross the Oze River between Hiroshima and Yamaguchi Prefectures, was selected for use in our evaluation. This RC-T Gerber type girder bridge, which was constructed in 1941, is now under the jurisdiction of the Ministry of Land, Infrastructure and Transport and Tourism (MLIT). The bridge is 168 m in length, 11 m wide, and is supported by eight spans set 22 m apart, as shown in Fig.1. The inspected spans (Spans 1 and 3), are highlighted in the figure. Over the years following its construction, several significant repairs were performed on this bridge, and in 2009, it was finally removed from service due to deteriorating conditions and was scheduled for dismantling.

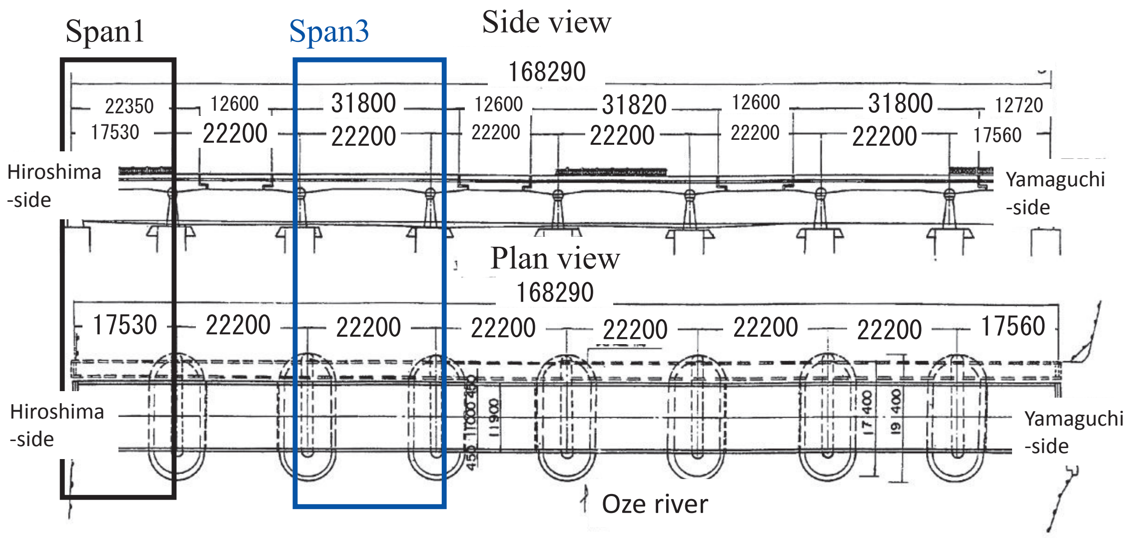


Fig. 1. Dimension of SK-Bridge and inspection span.

Table 1. Visual inspection items and defined evaluation

Conditions	Inspection items	Define of Evaluation	
		Load-carrying capability	Durability
Crack	a bridge axis direction position Width (Maximum value) and number of crack	The bridge performance based on the load-carrying capacity of a bridge member	The ability of a bridge member to resist material deterioration
Spalling	a bridge axis direction position Area and depth		
Corrosion of steel	Type of steel rust fluid, the exposed reinforcing bars		

Table 2. List of carriers for visual inspection engineering

Inspector	Years of experience	Type of company	Target material	Occupation
A	23	Constructor	Steel/Concrete Structure	Maintenance Repair/strength
B	18	Consultation	Concrete Structure	Design of repair Maintenance, Structural analysis
C	10	Constructor	Concrete Structure	Repair/strength
D	10	Constructor	Concrete Structure	Repair/strength
E	5	Constructor	Concrete Structure	Repair/strength
F	32	Consultation	Steel/Concrete Structure	Design of repair
G	5	Consultation	Steel/Concrete Structure	Structural analysis
H	35	Consultation	Steel/Concrete Structure	Maintenance, Structural analysis

Professional inspectors performed visual examinations of the bridge twice in 2012. This visual inspection data is proving useful in the development of a framework that can be used to manage the reliability of existing bridges, establishing appropriate inspection methods, developing repair and/or reinforcement methods, and in the construction of a management database system for MLIT or local government usage.

In addition, the use of visual inspection data has attracted significant attention particularly in Europe and the US, where the maintenance of civil infrastructures, as well as the development of practical systems that can support maintenance duties are considered priorities. It is expected that such matters will be topics of significant concern in the near future.

This study presents the results of the checks performed during the bridge dismantling and removal process using J-BMS. The J-BMS was used to predict the remaining service life of a bridge using visual inspection data provided by eight specialists on two spans of the bridge, in accordance with the inspection manual. This manual describes inspection items and definitions for evaluation, as shown in Table 1. The qualifications of the specialists, all of which are professional visual inspectors, are summarized in Table 2.

3. Performance evaluation and remaining service life prediction

3.1. Outline of J-BMS RC-Version

The J-BMS physical check framework consists of an "evaluated health score (BREX System)" and "remaining service life prediction". The data evaluation flow of the visual inspection as input data (shown in Fig. 2) is used to

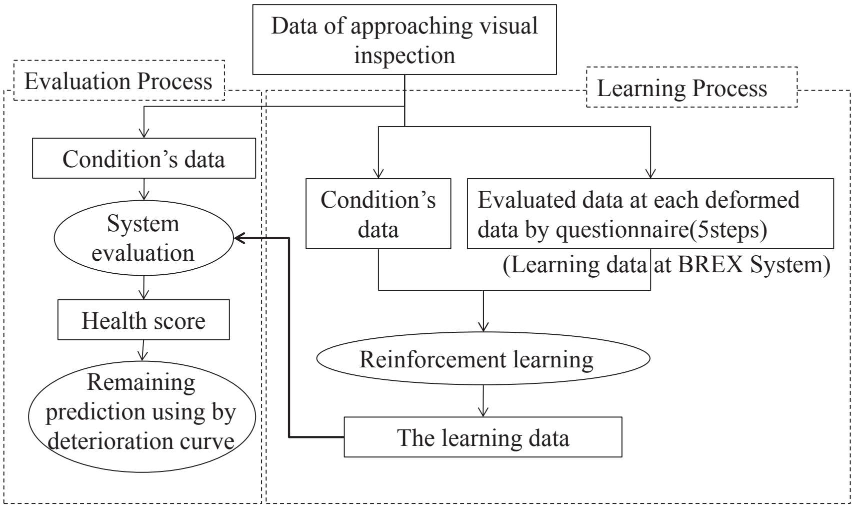


Fig. 2. Evaluation Flow of J-BMS RC-Version process.

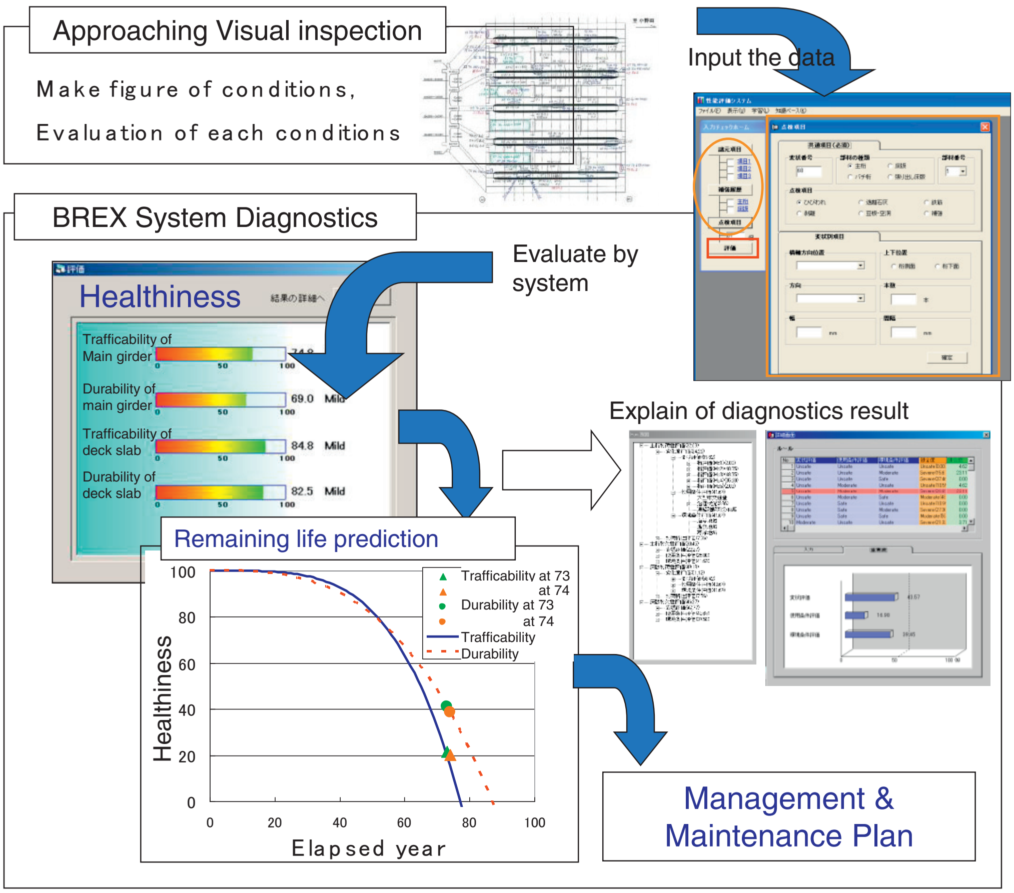


Fig. 3. Outline of the remaining service life prediction process using by BREX.

evaluate the bridge health score. This health score value is then used to predict the remaining service life of the bridge and as background information for repair, reinforcement, and future maintenance plans. The evaluated health score (BREX System) focuses on the load-carrying capability and durability using the conditions shown in Table 1. Here, the important point to note is that the BREX system uses the entire bridge (unit of span) as the target of evaluation.

As for the learning process, the learning data produced by the BREX system as reinforcement for the learning process can be seen in the right broken-line box of Fig. 2. In this process, the input data are the conditions and each point of inconsistency in the evaluated data is identified from the questionnaire responses. Ultimately, the BREX system evaluates learning data such as the connection weight value and condition's data value. Thus, when inputting the inspection data into BREX, an objective physical check result score of 100 points indicates perfect bridge conditions.

Fig. 3 shows the flow of management and maintenance planning, including the remaining service life prediction process, resulting from the visual inspections. As can be seen in the figure, the visual inspection data is input into the bridge BREX system. Then, the BREX system outputs point values (health value) representing the durability and load-carrying capability of the structure. The BREX system also evaluates the remaining service life of the bridge based on the expected deterioration curve.

3.2. Data acquisition

The targeted conditions in this system are "cracks", "free lime", "cavities" and "spalling". The targeted parts are the "main girder" and "slab deck". In the main girder, specific input data focuses on bridge axial direction and the sides and/or bottom. For "crack" conditions, the direction (vertical, diagonal, etc.), patterns (tortoise-shell, etc.) numbers, maximum width, and minimum spacing are all particularly important input data. As for "spalling" input data, important conditions are area and depth which is located only at the covered concrete or location of steel. Input data for the slab deck is similar to data used for the "main girder", except for the bridge axial direction and side or bottom of main girder. Once collected, all relevant data are inputted via the BREX system.

3.3. Numerical conversion by fuzzy set theory

In order to evaluate the input conditions, BREX is converted to numeric values using fuzzy theory. Here, taking cracks as an example, the input data contents are "the numbers" (width (mm) and space (mm)) of the cracks. In Example 1, "the number" for 1, "crack width", is 0.2 mm, while in Example 2, "the number" for 1, "crack width" is 0.3 mm. Note that the "space of cracks" is not taken into consideration because "the numbers" are 1 in both cases.

In the following step, crack width is converted from a continuous to a discrete value by the membership function, as shown in Fig. 4. When the "crack width" is 0.2 mm (Example 1), the "small" category is 50%, the "large" is 50%, and the "huge" is 0%. Next, membership value of the crack rule is calculated. Table 3 shows the picking up crack rules, which are rules of crack patterns. The membership value of the antecedent part is calculated as Example 1 and the weight of the consequents ($w_i \times \mu_i$) is calculated by multiplication.

Finally, the health score value is calculated. In the case of Example 1, (50 + 50 + 41.65 + 41.65 + 0 + 0) / 2 = 91.65 points; while in the case of Example 2, (0 + 0 + 41.65 + 41.62 + 33.35 +33.35) / 2 = 75 points. In addition, the health score value is influenced by changing the weight of the consequents (w_i), as shown in Table 3[A1].

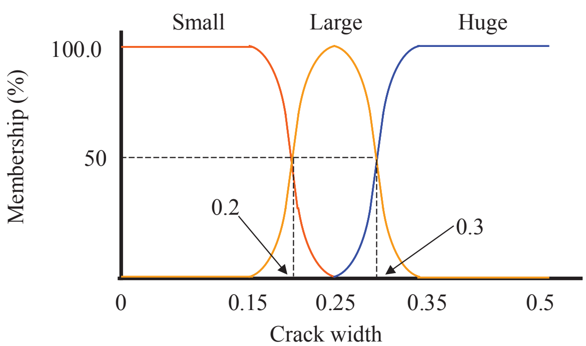


Fig. 4. Membership function of crack width.

3.4. Application of artificial neural network (ANN)

Each main girder (main girder n) is evaluated via generalizations for six conditions. Using a crack condition as an example, the evaluation formula used is Eq. (1).

$$y_c = 100 - N_{Unsafe} \times w_{Unsafe} - N_{Severe} \times w_{Severe} - N_{Moderate} \times w_{Moderate} - N_{Mild} \times w_{Mild} - N_{Safe} \times w_{Safe} \quad (1)$$

where, y_c: crack (generalization), N_{rank}: number of each conditions, w_{rank}: weight of each conditions. The health value corresponds with the rank (Category).

Table 3. Picking up crack rule and calculated example

NO	Antecedent part			Consequents part	Example 1		Example 2	
	Number of crack	***Crack width***	***Crack spacing***	***weight(w_i)***	***Membership (μ_i)***	$w_i \times \mu_i$	***Membership(μ_i)***	$w_i \times \mu_i$
1	1	Small	—	1	50 (=1×50)	50	0 (= 1×0)	0
2	1	Small	—	1	50 (=1×50)	50	0 (= 1×0)	0
3	1	Large	—	0.833	50 (=1×50)	41.65	50 (=1×50)	41.65
4	1	Large	—	0.833	50 (=1×50)	41.65	50 (=1×50)	41.65
5	1	Huge	—	0.667	0 (= 1×0)	0	50 (=1×50)	33.35
6	1	Huge	—	0.667	0 (= 1×0)	0	50 (=1×50)	33.35

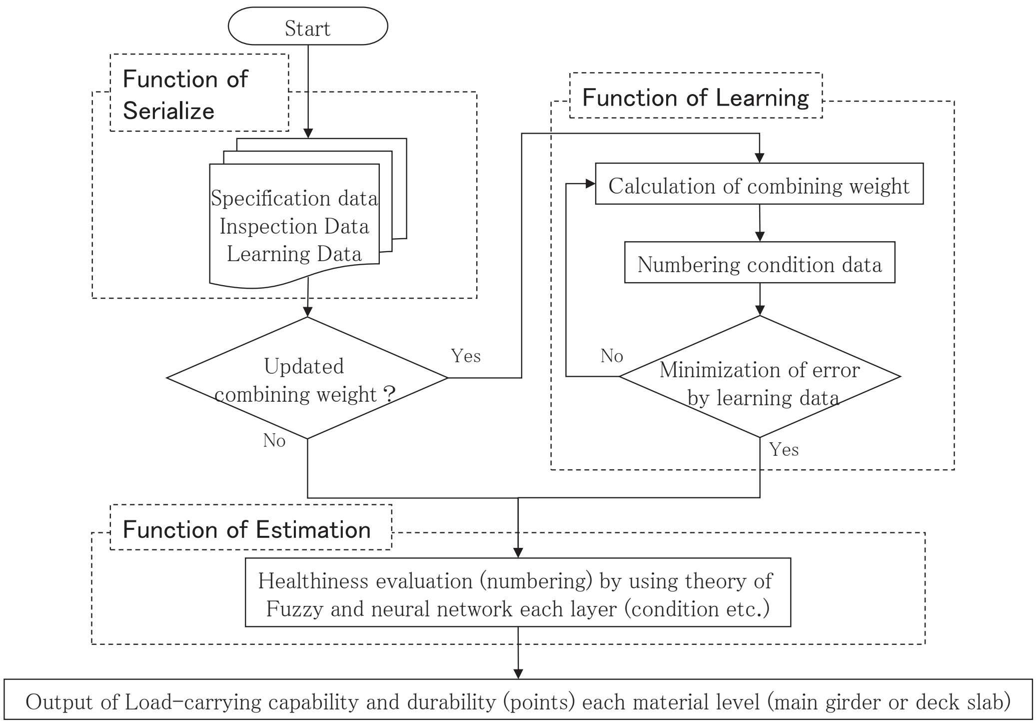
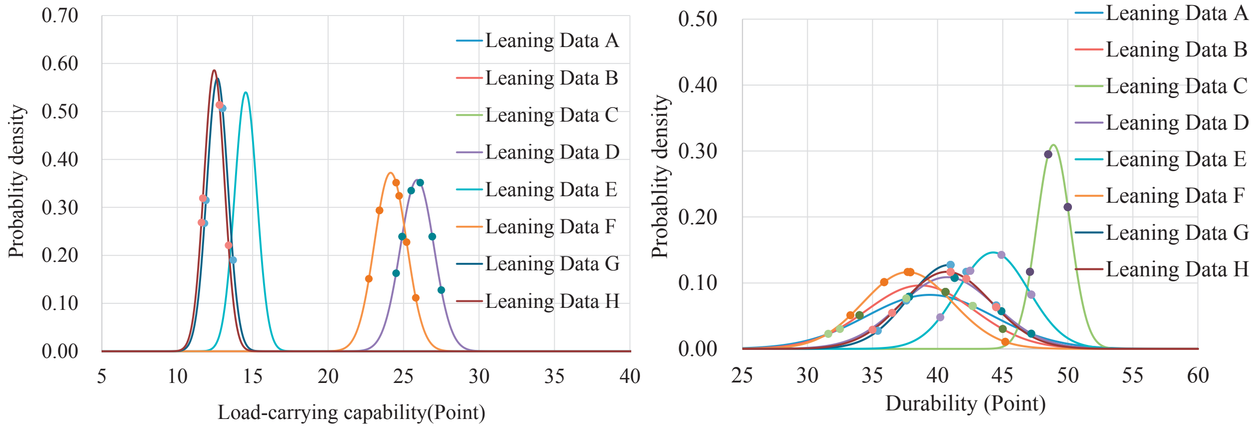
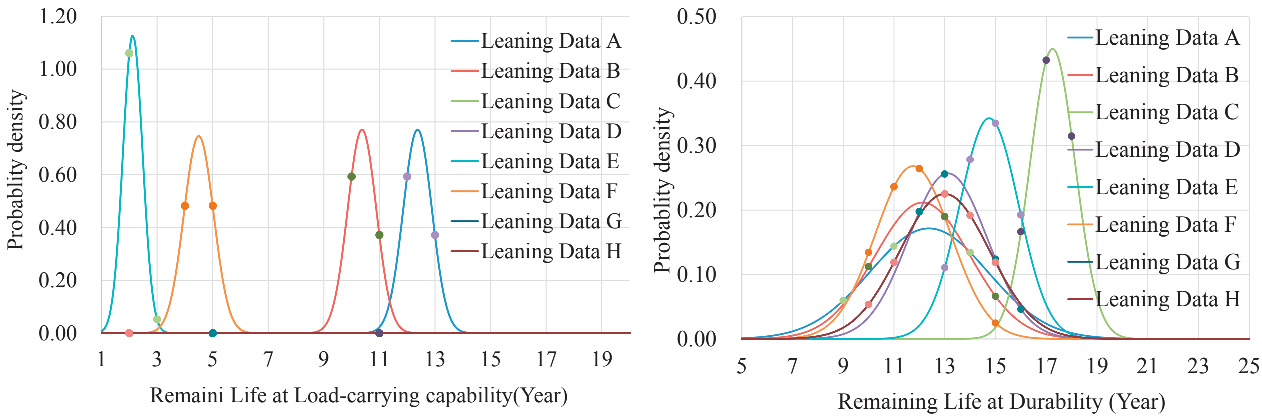


Fig. 5. BREX system procedure.



(a) Load-carrying capability (b)Durability

Fig. 6. Results of health score learning data at SK-Bridge Span 1 (2nd Time).



(a) Load-carrying capability (b)Durability

Fig. 7. Results for remaining service life for learning data at SK-Bridge Span 1 (2nd Time).

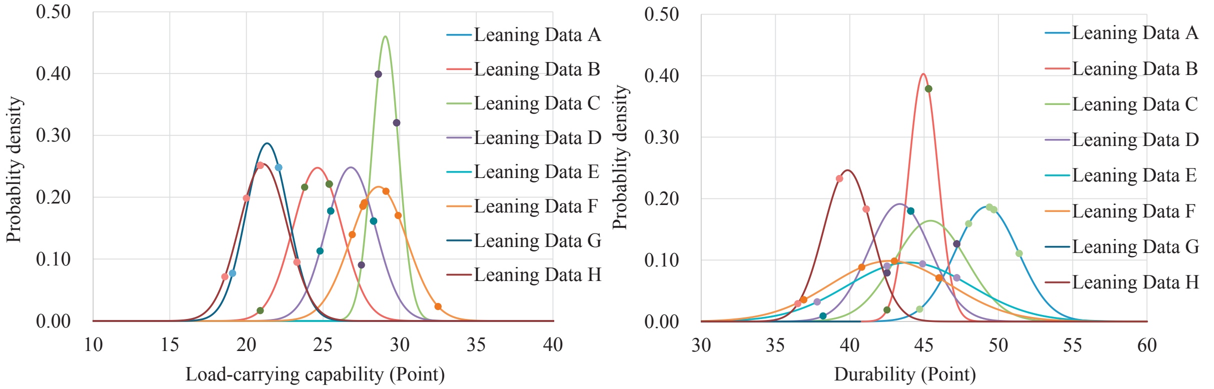
In the next step, "conditions" without crack, "girders", and "durability" are evaluated in order to calculate the healthiness value. The healthiness value is calculated by the sum of the fitness value products of each layer on the hierarchic structure multiplied by weight, as shown in Eq. (2).

$$y = \sum_{i=1}^{n} \mu_i \cdot w_i \tag{2}$$

where, y: healthiness value, μ_i: fitness value, w_i: connection weight.

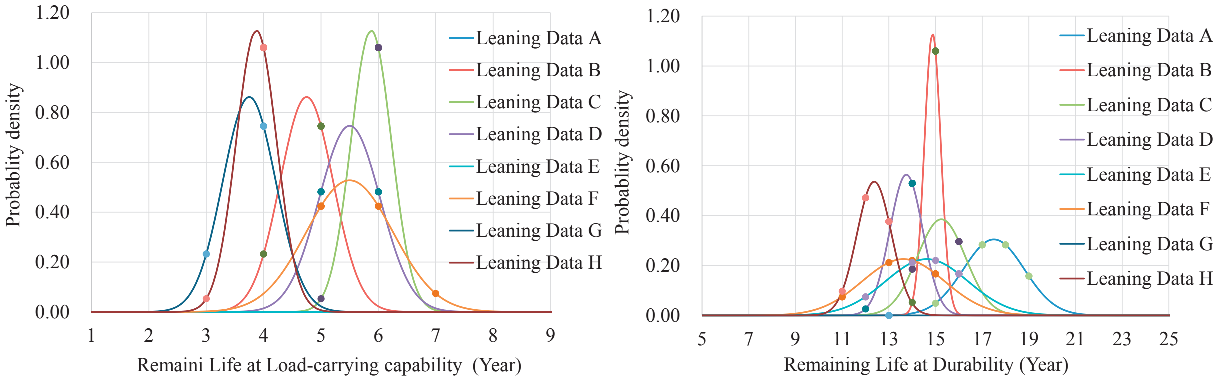
3.5. Performance evaluation

The BREX system supports the bridge deterioration analysis by managing the bridge diagnosis produced by the specialists. Fig. 5 show the BREX input procedures for the base specifications (service conditions, environmental conditions, etc.) and the visual inspection data. The objects of evaluation are one span, the main beam, and the slab deck. The results obtained using this system are used to evaluate the "load-carrying capability" and "durability" of each of the parts based on the bridge inspectors' assessments.



(a) Load-carrying capability (b) Durability

Fig. 8. Results for health score for learning data at SK-Bridge Span 3 (2nd Time).



(a) Load-carrying capability (b)Durability

Fig. 9. Results for remaining service life for learning data at SK-Bridge Span 3 (2nd Time).

In this paper, “load-carrying capability” means the deterioration of a structure with respect to the designed load capability, while “durability” means the deterioration of the material immediately after construction. Part of the BREX evaluation and learning function (as shown in Fig. 5) is a combination of a “neural network” and “fuzzy inference” based on extracting the knowledge of the experts (visual inspection specialists) using a questionnaire. Specifically, this system calculates the weight of the hierarchical structure from the inspection data and learning data, which is then used by the specialist to evaluate the deterioration conditions. This evaluation process then presents a health score, which has a maximum value of 100.

3.6. Remaining service life prediction

The procedure for predicting the remaining service life of the bridge is shown below. First, damage conditions must be assessed via visual inspection. Next, the bridge health must be evaluated at the time of the investigation. Finally, the remaining service life is predicted. In order to predict the remaining service life of the bridge, it is necessary to use an estimation formula (deterioration curve) that can predict the bridge health from the time of the investigation into the future. Here, Eqs. (3) and (4) are adopted for the deterioration curve [5,6]. The term “S_L” in Eq. (3) represents the “load-carrying capability” and “S_D” in Eq. (4) represents the “durability”.

$$S_L = b_L - a_L t^4 \tag{3}$$

$$S_D = b_D - a_D t^3 \tag{4}$$

Here, “b_L” and “b_D” represent the start time of the services, and are set to 100. The health value becomes “0” when the maximum limit of the bridge management system is reached.

4. Evaluation results and discussion

Figs. 6 and 7 show the health score and remaining predicted service life compared to the leaning data with respect to the “load-carrying capability” and “durability” at Span 1, while Figs. 8 and 9 show the health score and predicted remaining service life compared to the leaning data with respect to the “load-carrying capability” and “durability” at Span 3.

Initially, the health score from the differential learning data is considered. The load-carrying capability shown in Figs. 6-8(a) indicates that, using this 100 total point based method, it is possible to change the health ranking based on this value. On the other hand, the “durability” values shown in Figs. 6-8(b) indicate that, while the difference in learning data influences the unevenness of the evaluation to some extent, evaluation score differences were smaller than that for the “load-carrying capability” evaluation. Therefore, in order to improve the reliability of the “durability” evaluation, it is necessary to reduce inspection data variations while simultaneously complementing the investigation data. For example, it is thought that, when collecting core piece information, more effective utilization of actual survey investigations would contribute to reliability improvements of the “durability” evaluation. Furthermore, it has been shown that the selection of learning data is an important part of health evaluation reliability since differences in learning data influence the health evaluation itself.

Next, in Figs. 6-7(a), two patterns resembling mountain peaks can be seen in Span 1, and it should be noted that the health score and remaining service life values are smaller than the Span 3 values. Since the location under evaluation is the edge of the bridge where its structural members are subject to severe conditions involving load carrying capacity, and since professional visual inspectors make judgments based on knowledge and experience, some professional visual inspectors gave lower health score evaluations than others.

Next, probability densities of the health score are evaluated in relation to the remaining service life density, as shown in Eqs. (3) and (4). If the health score value is small, the remaining service life is not influenced; otherwise, the remaining service life is changed.

Finally, the average remaining service life of Span 1 was evaluated at two years (health score: 12.5) in terms of the load-carrying capability and 13 years (health score: 40.7) in terms of the durability. On the other hand, the average of remaining life of Span 3 was evaluated at four years (health score: 21.1) based on the load-carrying capability, and 12 years (health score: 39.9) based on the durability.

5. Conclusion

In this study, we report on an attempt to diagnose bridge conditions (physical check) and predict remaining service life using two visual inspections of the aged “SK Bridge” (which had been withdrawn from service after 60 years of continuous usage) performed by professional visual inspectors. The main conclusions of this paper can be summarized as follows:

1) This paper discussed bridge evaluation conditions using the Bridge Rating Expert System (BREX), which is a subsystem of the bridge management system (J-BMS). From the results, it was determined that selection of the training data was an important component of the BREX system evaluation. In addition, a method for evaluating the bridge conditions and estimating the remaining service life using the BREX system was presented, and an example showing the method used to diagnose the bridge conditions (physical check) at the time of decommissioning was

given. The results showed that the remaining service life was less than 10 years for both main beams of the SK Bridge.

2) The remaining service life of Span 1 was found to be smaller than that of Span 3. This result is logical because Span 1 is located at the edge of the bridge, which is generally more affected by heavy loading.

3) This BREX system accounted for a reduction in the variation to the visual inspection data, bridge condition diagnosis, and the remaining service life prediction. In the future, physical infrastructure checks will be important in the selection of bridge maintenance strategies (i.e., rebuilding and removal).

4) It is important to select appropriate “learning data” in order to efficiently evaluate bridge conditions. However, since this method does not establish a selection method, further studies will be necessary to determine methods for selecting such data.

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References

[1] A. Miyamoto, H. Nakamura, K. Yamaoka, K. Kawamura, Practical application of bridge management system (BMS), Memoirs of the Faculty of Eng., Yamaguchi University.Vol.49, No.2.,1999.
[2] A. Miyamoto, K. Kawamura, H. Nakamura, Multiobjective optimization of maintenance planning for existing bridges by using bridge management system, Proc. of JSCE 588 (1998) 191-208.
[3] A. Miyamoto, M. Kushida, Y. Adachi, M. Matsumoto, Development of bridge management system (BMS), Proc. of JSCE 560 (1997) 91-106.
[4] H. Emoto, J. Takahashi, A. Miyamoto, Visual inspection of aged bridge and reliability of evaluation, Proc. of Society of the Mat. Sci., 2010.
[5] A. Miyamoto, Mechanical characteristic of RC slab deck on road and basic study on this evaluation for durability, Kyoto Univ., 1984.
[6] J. Takahashi, H. Emoto, A. Miyamoto, Proposed of verification of bridge evaluation system based on concrete core examination, Proc. of the JCI 34(2) (2012).