Civil Engineering Infrastructures Journal, 48(1): 189-216, June 2015
ISSN: 2322-2093

Development and Practical Application of a Bridge Management System (J-BMS) in Japan

Miyamoto, A.[1]* and Motoshita, M.[2]

[1] Professor, Yamaguchi University, Ube, Japan
[2] B.Sc., Kyowa Sekkei CO., LTD., Kobe, Japan

Received: 29 May 2014 Revised: 23 Dec. 2014 Accepted: 12 Jan. 2015

Abstract: This paper presents a new bridge management system (J-BMS). It is integrated with a concrete bridge rating expert system that can be used to evaluate the serviceability of existing concrete bridges. The proposed J-BMS not only evaluates the performance of bridges, but also offers a rehabilitation strategy based on a combination of maintenance cost minimization and quality maximization. In this system, the genetic algorithm (GA) technique was used to search for an approximation of the optimal maintenance plan. This was constructed using *Visual Basic* and the *C language*. Furthermore, this paper examines the results of applying this system to some in-service bridges and the results of questionnaire surveys of experts. A comparison of these results shows that this system can accurately predict optimal maintenance planning, as well as bridge rating.

Keywords: Bridge Management System (J-BMS), Concrete Bridge Rating Expert System (BREX), Information Technology, Integrated Lifetime Management, RC Bridge

INTRODUCTION

In Japan, many highway bridges were constructed under the national highway network project, launched in 1955. However, due to factors such as the increase in traffic volume and weight of vehicles, many bridges have seriously deteriorated over the years. Such bridges must be repaired or strengthened, depending on the severity of their deterioration. Nevertheless, due to the limited budget, funds must be split equally between maintaining the deteriorated bridges and constructing new ones.

Despite this, since around 1990, bridge maintenance costs in many developed countries have become higher than the cost of constructing new ones. Thus, the increasing maintenance costs must be reduced by changing bridge maintenance methods. These were once limited to emergency measures against unpredicted events. The new concept of designing and constructing more durable bridges and consequently, reducing maintenance costs, has become common in many countries (Thompson et al. 1998; Yanev, 2007). Japan’s highway networks are comparatively newer than those in other advanced nations. Thus, the financial situation regarding maintenance costs has not yet faced serious problems. However, one report estimates that by around 2010, the ratio of bridges of 50 years of age will be approximately 35%. For this reason, comprehensive bridge management systems are essential. The systems should not only evaluate the serviceability of bridges, but also make an optimum maintenance plan considering the limited funds available.

The authors of this paper have been developing a Bridge Management System

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*Corresponding author E-mail: miya818@yamaguchi-u.ac.jp

(J-BMS), integrated with the Concrete Bridge Rating Expert System (Miyamoto et al., 1995; Kawamura et al., 2003; Kawamura et al., 2003) that can be used to evaluate the serviceability of existing concrete bridges. The J-BMS will predict the deterioration process of existing bridge members and construct a maintenance plan for repair and/or strengthening based on minimizing maintenance costs and maximizing quality. Additionally, it will be able to estimate the maintenance costs (Miyamoto et al., 1997; Miyamoto et al., 1998). In this system, the Genetic Algorithm (GA) technique was used to search for an approximation of the optimal maintenance plan (Konno et al., 2003; Goldberg, 1989; Gen et al., 1997; Gen et al., 1996; Michalewicz, 1995; Orvosh et al., 1994).

This study aims to develop a practical bridge management system for deteriorated concrete bridges, integrated with the Concrete Bridge Rating Expert System (BREX) (Miyamoto et al., 1995; Emoto et al., 2014). This can be used to evaluate the serviceability of existing concrete bridges. The proposed system uses multi-layered neural networks to predict deterioration processes in existing bridges, construct an optimal maintenance plan for repair and/or strengthening measures based on minimizing life cycle cost and also, estimates the maintenance cost. In this system, the Genetic Algorithm (GA) technique was used to search for an approximation of the optimal maintenance plan. A comparison of the results of applying this system to some actual in-service bridges with the results of questionnaire surveys of experts, shows that this system can accurately predict optimal maintenance planning, as well as bridge rating.

DEVELOPMENT OF J-BMS

Figure 1 shows the flowchart of the proposed J-BMS. The J-BMS is mainly applied to the existing reinforced concrete bridges. At the present stage, the target members are main girders and slabs. The proposed J-BMS was constructed on a personal computer using the *Visual Basic* and *C language*.

For existing concrete bridges, the first step in the proposed J-BMS involves a wide range visual inspection data relating to the target bridge (①). Next, the performance of the bridge members is evaluated using the obtained inspection data and the technical specifications of the target bridge (②). This evaluation is performed using a program referred to as the Concrete Bridge Rating Expert System (BREX). This is currently under development by the present authors. The outputs of this evaluation include the mean soundness scores for load-carrying capability, durability, etc., which are given on a scale of 0-100 (Miyamoto et al., 1999; Emoto et al., 2014). Then, based on the results of the expert system, present deterioration can be characterized and the remaining life of the bridge can be estimated using the predicted function of deterioration (③). As a preliminary step, the effect of repairs and strengthening were estimated. Furthermore, the cost of each maintenance measure was determined, thereby enabling the estimation of maintenance costs and the prediction of remaining life after maintenance (④). Finally, if the present remaining life calculated by J-BMS does not exceed the expected service life, the rehabilitation strategy is obtained from the prediction curve according to the cost and effect of repairs and strengthening. This strategy includes various maintenance plans provided by the cost minimization or quality maximization (⑤).

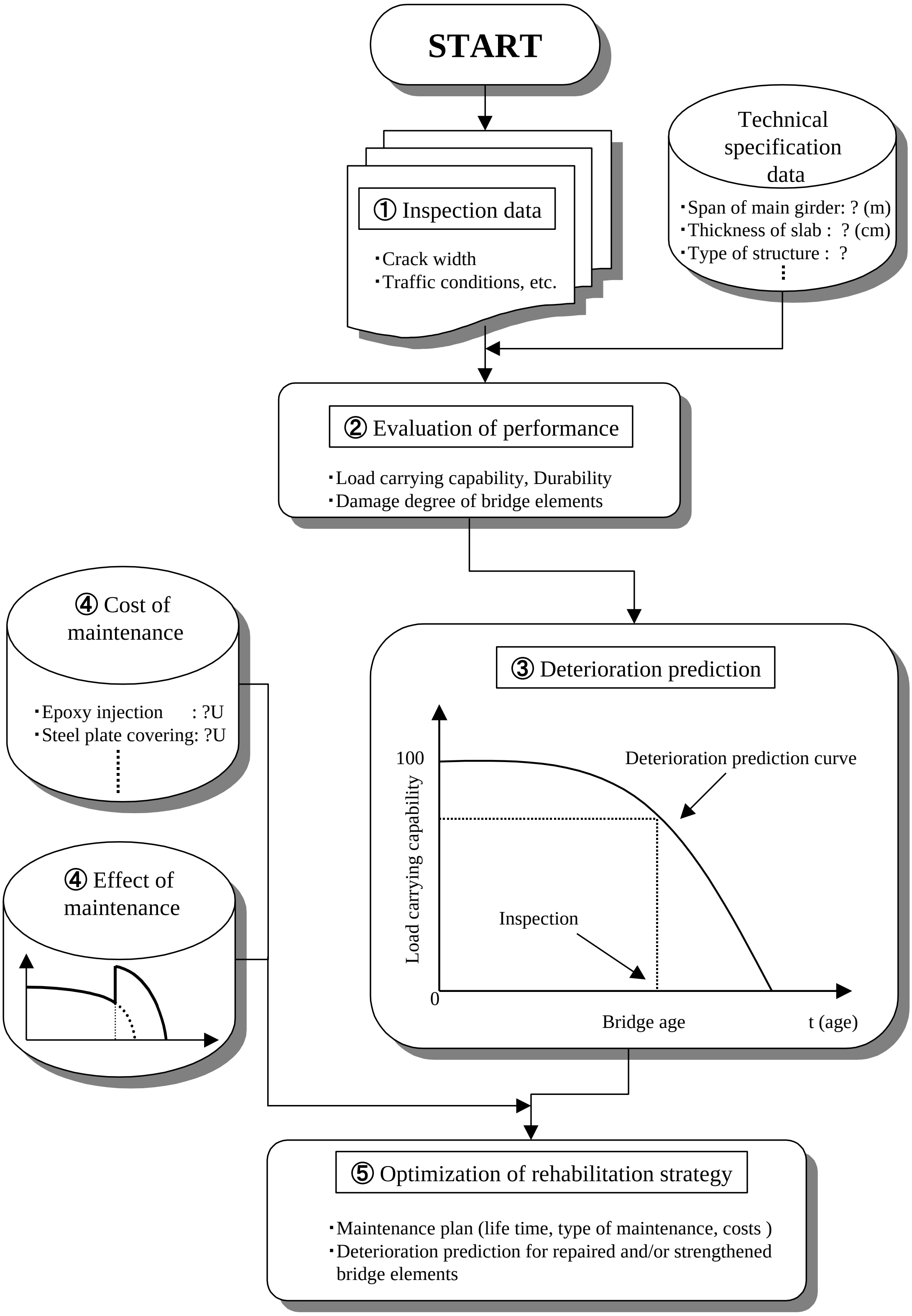


Fig. 1. Flow of J-BMS.

Bridge Rating

For some time, the authors of this study have been working on the development of an expert system. This system can be used to evaluate the performance of existing concrete bridges, based on knowledge and experience acquired from domain experts (Uchimura et al., 2010; Miyamoto et al., 2013). The proposed expert system evaLuates aspects of a bridge's present performance such as serviceability, load-carrying capability and durability. It is primarily based on information obtained from a simple visual inspection such as traffic conditions or crack width. However, various performances, such as serviceability, aesthetic, environmental, functionality, etc., are mentioned as other indexes for evaluation of existing bridges. In the present study, serviceability is defined by the estimated load-carrying capability and durability. Additionally, load-carrying capability is defined as the bridge performance based on the load-carrying capacity of the bridge members. Furthermore, durability is defined as the ability of the bridge members to resist deterioration based on the deterioration speed of the members. Thus, these two performances are used as indexes to consider the necessity of maintenance for deteriorated bridges. In fact, load-carrying capability, which is defined as the bridge performance based on the load-carrying capacity of the bridge members, is applied as an index to estimate the necessity of strengthening. Durability, which is defined as the resistance against the bridge member deterioration based on the deterioration speed of the bridge members, is applied as an index to estimate the necessity of repair in the proposed J-BMS.

In this expert system, diagnosis is performed according to a diagnostic process. This process is modelled on the inference mechanism of the domain expert for bridge rating (Kawamura et al., 2003; Kawamura et al., 2003). This process has a hierarchy structure in which the ultimate goal is "serviceability". As an example, the diagnostic process for a main girder is shown in Figure 2. In this process, the lowest judgment factors, such as flexural cracking, shear cracking, corrosion cracking, bond failure cracking and material deterioration, are first evaluated using the visual inspection data and/or technical specifications. Continuing with this example, the degree of flexural cracking is determined using the inspection data such as spall of cover concrete, free lime, crack pattern, crack width in terms of [degree of cracking] and [degree of free lime deposition]. Next, the higher judgment factors, such as total damage, execution of work and service condition, are determined using the results of the lowest judgment factors, the inspection data and the technical specifications. The final judgment factor of this system is the serviceability, which is evaluated according to the load-carrying capability and durability. These judgment factors are assigned a mean soundness score as an output of the expert system. The score obtained is categorized into five groups: 0-19, 20-39, 40-59, 60-79 and 80- 100. These groups are classified as "dangerous", "slightly dangerous", "moderate", "fairly safe" and "safe", respectively. In the present study, "safe" indicates that the bridge has no problem. "Fairly safe" indicates that there are no serious damages. "Moderate" indicates that there are some damages which need continuous inspection. "Slightly dangerous" indicates that the bridge should be repaired and/or strengthened. "Dangerous" indicates that the bridge should be removed from service and requires rebuilding.

Finally, the construction of the proposed expert system is described in the following. The proposed expert system uses neural networks to provide a machine learning method and fuzzy inference method. This diagnostic process is drawn using if-then rules, which include fuzzy sets, in order to perform the machine learning and fuzzy inference. The if-then rules are divided into three parts: if-then relationships, antecedents and consequents. In constructing the inference mechanism, the antecedents and consequents are represented as neural networks with three layers and can be used to identify nonlinear functions. The if-then relationships are interconnected by bidirectional associative memories. The detailed description of developing this expert system is written in reference (Miyamoto et al., 1997).

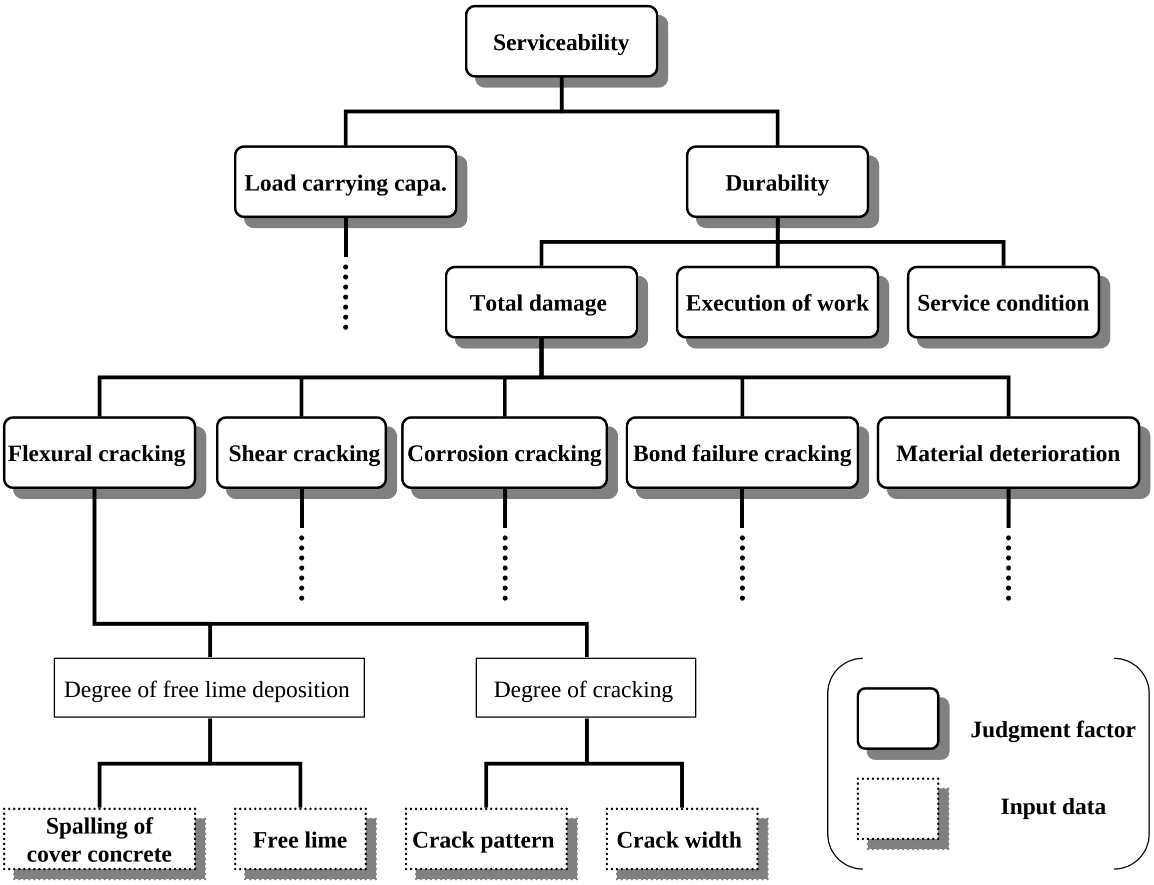


Fig. 2. Diagnostic process in BREX.

Deterioration Prediction

The present performance of existing bridge members can be evaluated using the proposed expert system. However, this system cannot be used to estimate future deterioration of bridge members. Thus, prediction curves for the load-carrying capability and durability, respectively, are used to perform deterioration estimation. Despite this, various deterioration prediction methods, such as transition probability matrix, have been proposed in several other papers (Hawk et al., 1998; Soderqvist et al., 1998; Thompson et al., 1998). In the present study, the following assumptions were made in constructing the deterioration prediction curves.

① The deterioration curves for the bridge members are drawn as an integrated convex graph, in which the vertical axes represent the mean soundness scores of load-carrying capability and durability. The horizontal axes represent bridge age, due to the fact that deterioration progresses rapidly with bridge age. The mean soundness scores of load-carrying capability and durability, which were obtained from the expert system, are described below as $S_L(t)$ and $S_D(t)$, respectively.

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

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

where a_L, b_L, a_D, b_D: are constants and t: is bridge age (years).

In the present study, $f_{(0)}(t)$ and $g_{(0)}(t)$: are the deterioration functions that represent the deterioration for the period from the beginning of bridge service, namely, bridge age = 0 until first inspection, using the proposed expert system. In addition, $f_{(i)}(t)$ and $g_{(i)}(t)$ express the deterioration functions after the i^{th} maintenance. In this paper, the repair and strengthening measures are collectively referred to as maintenance.

Since, at present, no data exists for the deterioration curve of load-carrying capability, the curve is defined as a biquadratic function. This is based on experimental data collected from previous experiments by the present authors (Morikawa et al., 1996; Nishimura et al., 1983). In addition, the deterioration curve for durability is defined as a cubic function because the durability is one order of magnitude smaller than the load-carrying capability. This difference occurs because durability reduces faster than load-carrying capability. However, these deterioration functions should be modified according to the data acquired from experiments and monitoring (continuous inspections). This is because the transition of the deterioration state is impacted by factors, such as bridge location and other deterioration factors.

② The mean soundness scores of load-carrying capability and durability are ranked on a scale of 0-100. Here, a score of 100 represents a newly built bridge. As the bridge deteriorates, the score decreases and finally reaches 0, indicating that the bridge can no longer remain in service and requires rebuilding.

③ Up to the first inspection, the deterioration curves, that is, $f_{(0)}(t)$ and $g_{(0)}(t)$ are given by two elements. These are the score when the newly built bridge enters service (100) and the mean soundness score at first inspection, which is obtained using the expert system.

④Repairs and strengthening influence the load-carrying capability and the durability of the bridge members. After maintenance, the deterioration curve differs according to the type of maintenance performed. In the next section, the effect of repairs and/or strengthening is described in detail.

An example is given to show the determination of $f_{(0)}(t)$ and $g_{(0)}(t)$ and calculation of the target bridge's remaining life.

Example 1. Consider a problem with the following sources. The age of the target bridge is 60 years. The mean soundness scores of load-carrying capability and durability are both 50, which are obtained using the expert system.

- $f_{(0)}(t)$ and remaining life with respect to load-carrying capability

(t, S_L)=(0, 100), (60, 50) are assigned to Eq. (1). As a result, $a_{L(0)}=50/60^4$, $b_{L(0)}=100$ are obtained. Therefore,

$$f_{(0)}(t) = 100 - \left(50/60^4\right)t^4$$

In order to calculate the remaining life, $f_{(0)}(t)=0$ is considered. Therefore,

$$t = \sqrt[4]{b_{L(0)}/a_{L(0)}} - 60 ≒ 11.3 \qquad (years)$$

- $g_{(0)}(t)$ and remaining life with respect to durability

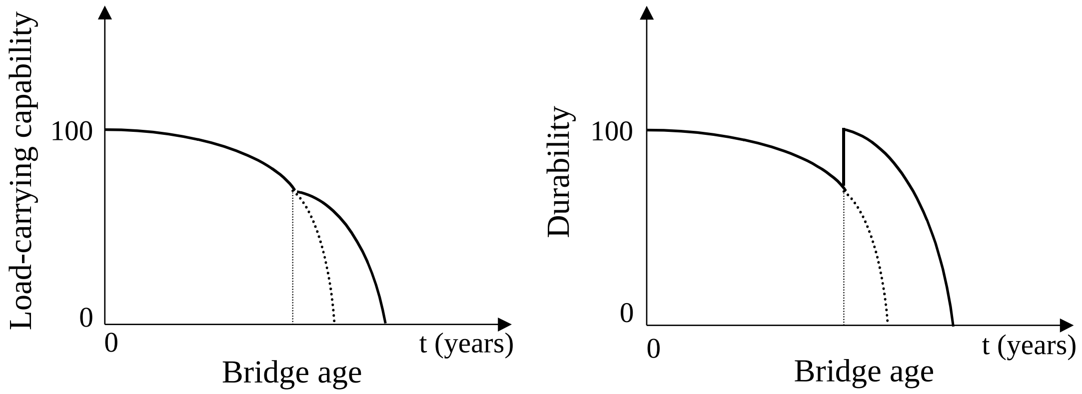
These are obtained by the same procedure as the case of load-carrying capability. The results are as follows.

$$g_{(0)}(t) = 100 - \left(50/60^3\right)t^3$$

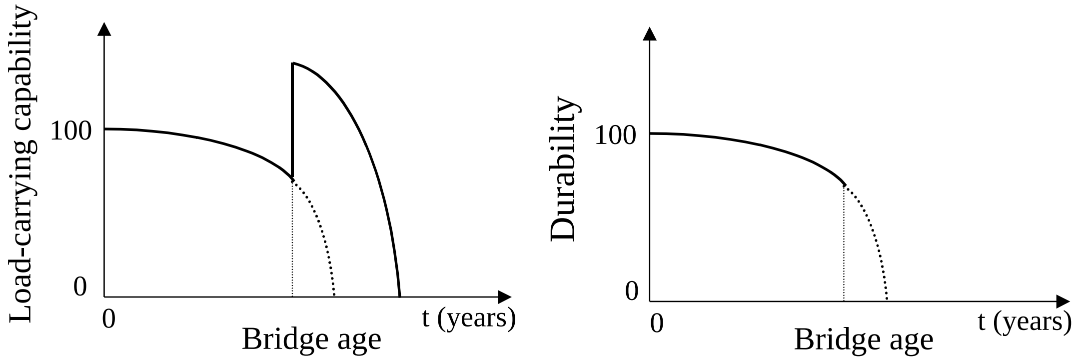
$$t = \sqrt[3]{b_{D(0)}/a_{D(0)}} - 60 ≒ 15.6 \qquad (years)$$

Effect of Maintenance

A new method which clarifies the effect of repairs and/or strengthening on the deterioration prediction curves of the load-carrying capability and the durability has been presented. However, this method cannot be applied to conventional evaluation systems. In the present study, a repair is assumed to affect the deterioration curve of durability, whereas strengthening is assumed to affect the deterioration curve of load-carrying capability. As a result, the basic concept of the strengthening effect is to show that the mean soundness score of the load-carrying capability would grade up if the bridge is strengthened. On the other hand, the basic concept of the repair effect is to show that the mean soundness score of the durability would grade up and the velocity of the prediction curve for the load-carrying capability would also slow down (the deterioration speed of the load-carrying capability would slow down), if the bridge is repaired. The basic concept of this effect is depicted in Figure 3. Furthermore, the degrees of recovery of performance (load-carrying capability and durability) associated with repairs and/or strengthening, as judged by an expert and comparing the present standard of design with the previous one, were obtained. These are listed in Table 1 and Table 2 (Miyamoto et al., 1997). In future studies, these tables should be modified using experimentally acquired data, since the values presented here are strictly hypothetical.



(a) Effect of repair



(b) Effect of strengthening

Fig. 3. Basic concept of maintenance effect.

Table 1. Effect and cost of repair and strengthening measures for main girder.

Maintenance Measure	**Type of Maintenance**	**Load Carrying Capability**	**Durability**	**Cost (1U≒\1,000/m^2)**
Epoxy injection	R	※1	100	23.8U
Recovery of cross section	R	※1	100	14.0U
Glass cloth	R	No effect	※1	25.2U
Mortar spraying	R	No effect	※2	14.0U
Steel plate covering	S	See Table 2	70	112.5U
FRP covering	S	See Table 2	70	2 layers:112.5U 4 layers: 78.0U
External cables	S	See Table 2	No effect	150.0U

Note: R = Repair, S = Strengthening

*1. The deterioration rate is reduced by half. *2. The deterioration rate is reduced by three-fifths.

Table 2. Degree of recovery of load-carrying capability for strengthening measures.

Year Designed	Steel Plate Covering (FRP: 4 layers)	FRP Covering (2 layers)	External Cables
~1939	130	120	150
~1956	120	110	140
1956~	100	100	100

As an example, the influences of maintenance measures for the main girder are explained. In order to determine the recovery degree of performance, the following assumptions were made, according to the above basic concept for the effect of maintenance. In the present J-BMS, epoxy injection, recovery of cross section, glass cloth and mortar spraying are classified as repair measures. Steel plate covering, FRP and external cables are considered as strengthening measures.

[Effect of Repair Measures]

① If epoxy injection or recovery of cross section is performed, the mean soundness score of durability would grade up to 100. This is because the purpose of repair is to recover durability reaching the newly built condition.

② It is assumed that the repair effects the recovery of durability, as well as the deterioration speed of load-carrying capability. Thus, if epoxy injection or recovery of cross section is performed, the velocity of the prediction curve for load-carrying capability would slow down. As a result, the deterioration rate of load-carrying capability is reduced by half.

③ Although the surface coating measure is classified as a repair method, this effect differs from the basic concept of effect on repair. If the surface coating measures are used, there is a decrease in the velocity of the prediction curve for durability. It is assumed that the surface coating measure enables the speed of deterioration of durability to be restrained, though the durability cannot be recovered, that is, grading up by these measures. In the present study, glass cloth and mortar spraying are considered as surface coating methods for the main girder.

As the initial value, it is assumed that glass cloth enables the deterioration speed of durability to be reduced by half. Furthermore, the effect of mortar spraying was set to three-fifths, which is 80% of the effect of grass cloth.

[Effect of Strengthening Measures]

① If steel plate covering, FRP or external cables is performed, the mean soundness score of load-carrying capability would grade up to 100 or more. The design basis has undergone many changes according to the increase in traffic volume, increase in the weights, etc. Thus, in the case of strengthening, Retrofit has to be considered. The load-carrying capability of bridges designed by the old basis would recover at least to 100 or more, if the bridge is strengthened by the present design basis. In the present study, it is assumed that steel plate covering and FRP (four layers) have similar effects. The effect of the steel plate covering is shown in Table 2. This was calculated according to the transition of design load for uniform load. In addition, the following assumptions were made. The effect of FRP (two layers) is smaller than that of steel plate covering and FRP (four layers). The effect of external cables is more effective than that of steel plate covering.

Although the basic concept of strengthening is only ①, in the present paper, the two following assumptions were suggested.

② If steel plate covering, FRP or external cables is performed, the deterioration speed of load-carrying capability is reduced by two-thirds. This is because it is assumed that the strengthening creates the redundancy of load-carrying capacity and the redundancy impacts the deterioration speed of load-carrying capability.

③ Additionally, the deterioration speed of load-carrying capability is reduced by (R_{old}/R_{new}), where, R_{new}: the recovery degree of target bridge strengthened by a strengthening measure and R_{old}: the recovery degree, before being strengthened by one strengthening measure. This is due to the assumption that the effect of retrofit is not only the recovery of load-carrying capability, but also the reduction of deterioration speed. For example, consider a problem with the following sources. The target bridge was designed using the design basis applied from 1940 to 1956. In 1994, the target bridge was strengthened by steel plate covering. Then, in 1996, it was strengthened by external cables. When this bridge was strengthened by steel plate covering in 1994, the values of R_{new}=120 and R_{old}=100 because the recover score was 100 when the target bridge entered service. Then, when the external cables was performed, the values of R_{new}=140 and R_{old}=120 because the recovery degree is 120 before being strengthened by external cables.

Finally, in the following example, calculation of the deterioration curve after maintenance is shown.

Example 2. Consider a bridge applied epoxy injection as maintenance.

- How to make $f_{(i)}(t)$, namely, the deterioration curve of load-carrying capability after i^{th} maintenance

The deterioration curve of load-carrying capability before i^{th} maintenance is expressed as follows.

$$f_{(i-1)}(t) = b_{L(i-1)} - a_{L(i-1)}t^4 \tag{3}$$

Since epoxy injection enables the deterioration speed of load-carrying capability to be reduced by half, this curve before i^{th} maintenance is written as follows.

$$f_{(i)}(t) = b_{L(i)} - a_{L(i)}t^4 = b_{L(i)} - (1/2)a_{L(i-1)}t^4 \tag{4}$$

Then, assuming that the bridge age is *t”* years when this maintenance is performed, the following relation is satisfied.

$$f_{(i)}(t'') = f_{(i-1)}(t'') \tag{5}$$

Therefore,

$$b_{L(i)} = b_{L(i-1)} - (1/2)a_{L(i-1)}(t'')^4 \tag{6}$$

Lastly, this curve of load-carrying capability after epoxy injection performed is presented as follows.

$$\begin{aligned} f_{(i)}(t) &= b_{L(i)} - a_{L(i)}t^4 \\ &= \left\{b_{L(i-1)} - (1/2)a_{L(i-1)}(t'')^4\right\} - (1/2)a_{L(i-1)}t^4 \end{aligned} \tag{7}$$

- How to make $g_{(i)}(t)$, namely, the deterioration curve of durability after i^{th} maintenance

The deterioration curve of durability before i^{th} maintenance is expressed as follows.

$$g_{(i-1)}(t) = b_{D(i-1)} - a_{D(i-1)}t^3 \tag{8}$$

In addition, the deterioration curve of durability after i^{th} maintenance is expressed as follows.

$$g_{(i)}(t) = b_{D(i)} - a_{D(i)}t^3 \tag{9}$$

Epoxy injection enables the mean soundness score of durability to be graded up to 100. Therefore, assuming that the bridge age is *t”* years when this maintenance is performed, the mean soundness score of durability grades up to

100 in *t"* years. The following equation is given.

$$b_{D(i)} = 100 + a_{D(i)}(t'')^3 \quad (10)$$

Since epoxy injection cannot reduce the deterioration speed of durability, the following relation is satisfied.

$$a_{D(i)} = a_{D(i-1)} \quad (11)$$

Lastly, this curve of durability after epoxy injection performed is presented as follows.

$$\begin{aligned} g_{(i)}(t) &= b_{D(i)} - a_{D(i)}t^3 \\ &= \left\{100 + a_{D(i-1)}(t'')^3\right\} - a_{D(i-1)}t^3 \end{aligned} \quad (12)$$

OPTIMIZATION OF REHABILITATION STRATEGY

(1) Modelling of Maintenance Planning

(Chikata et al., 1995; Komai et al., 1991; Liu et al., 1997; Miyamoto et al., 2008; Miyamoto et al., 2006)

The proposed J-BMS estimates the remaining life of a target bridge, in terms of durability and load-carrying capability, after diagnosis of the present performance using the proposed expert system. Additionally, if the present remaining life calculated using the deterioration curve is found to be shorter than that predicted by the expected service life (denoted by *T*), some maintenance plans are presented as the rehabilitation strategy based on life cycle costs, the prediction curve and the effects of repairs and/or strengthening measures.

In the present study, maintenance planning is modelled as a combinatorial optimization problem. This is because the maintenance plan comprises various maintenance measures, as illustrated in Figure 4. The analysis period begins from the present age of the bridge (denoted by *t'*) and runs until the expected service life (*T*). It is important to note that, even though T is the end of the analysis period, this point does not represent the end of the target bridge's life. In the present analysis, one maintenance measure is chosen every year in order to construct a maintenance plan. Thus, maintenance may include no maintenance (no repair or strengthening), as well as combinations of repairs and/or strengthening measures.

Many aspects influence the choice of rehabilitation strategy. Thus, the rehabilitation strategy should be optimized for budgets, damage, safety, policy, environment, road users, etc. As a preliminary step, the present study only examines the direct-cost minimization of maintenance measures (Eq. (13)) and the maximization of bridge quality (Eq. (14)) as the optimization method. From a practical point of view, the quality of a bridge is defined as the total sum of the mean soundness scores of durability and load-carrying capability during the analysis period. As a result, the present optimization problem of rehabilitation strategy is described by the following multi-objective combinatorial optimization:

Objective:

$$F_1 = \sum_{t=t'}^{T-1} C_{tj} \quad \rightarrow \quad \min \quad (13)$$

$$F_2 = \sum_{t=t'}^{T} \left\{S_L(t) + S_D(t)\right\} \quad \rightarrow \quad \max \quad (14)$$

Subject to:

$$S_L(t) > 0, \quad \mathrm{S_D}(t) > 0, \quad 0 \le t \le T \quad (15)$$

where, *t*: is bridge age (years), *j*: is type of maintenance measure chosen for the year *t*, *t'*: present age of bridge (initial time, corresponding to the first year of the analysis period), *T*: expected service life (final time, corresponding to the last year of the analysis period), $S_L(t)$: is mean soundness score of load-carrying capability in the year *t*, $S_D(t)$: is mean soundness score of durability in the year t, C_{tj}: is cost of maintenance measure j carried out in the year t, F_1: is total cost of maintenance measures, F_2: is total sum of mean soundness scores of load-carrying capability and durability during the analysis period, corresponding to bridge quality.

Since this is a multi-objective combinatorial optimization problem, GAs are adopted for the combinatorial problem due to the large number of combinations. GAs are used to search for an optimal maintenance plan. In addition, the Σ-constraint method was applied to the multi-objective problem. In order to suggest various maintenance plans according to cost constraints that are established by the J-BMS user, the Σ-constraint method is applied to the following algorithm for suggesting the rehabilitation strategy of target member. In this case, F_1 is assumed to be prior to F_2, that is, cost minimization is more important than quality maximization (Eqs. (13,14)). The procedure works with the following three main steps:

Step 1. The maintenance plan based on cost minimization is searched using GAs. Cost 1 and Quality 1 are obtained from this calculation, where Cost 1 = minimum cost, corresponding to the cost of the obtained maintenance plan and Quality 1 = quality of the maintenance plan obtained in this calculation.

Step 2. GAs are applied to the following problem and search for the optimal maintenance plan based on quality maximization. The additional budget α is established by the BMS user.

Objective: $$F_2 \rightarrow \max \tag{16}$$

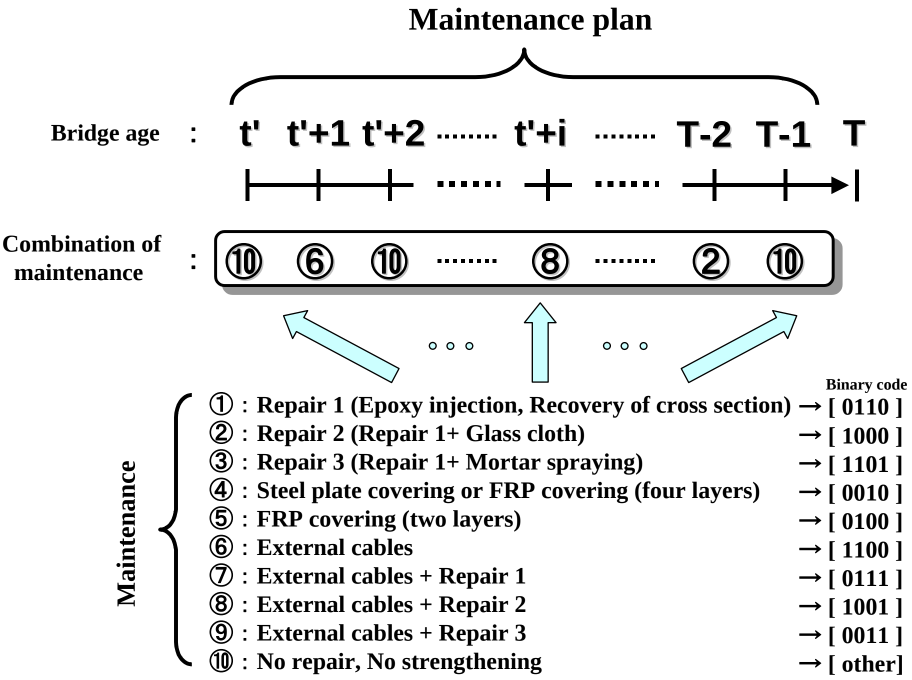
Subject to: $$F_1 \leq \varepsilon = Cost1 + \alpha \tag{17}$$

where α: is additional budget.

Step 3. Return to Step 2 after altering α. This repetition enables various maintenance plans to be suggested.

(2) Application of GAs to a Combinatorial Optimization Problem

Genetic algorithms are stochastic search techniques based on the mechanism of natural selection and natural genetics (Golberg, 1989; Orvosh et al., 1994). Genetic algorithms start with an initial set of random solutions, referred to as the population. This differs from conventional search techniques which generally search from a single solution. The population contains individuals and each individual contains several genes. The number of individuals in each generation is known as the population size. Each individual represents a candidate solution to a given problem. Each individual is represented by a string of symbols, usually a binary bit string. These individuals evolve through generations, namely, generation alternation. During each generation, the fitness of each individual is evaluated using a fitness function. Offspring or new individuals are formed by merging two individuals from a current generation using a crossover operator and/or altering some of the genes of the offspring using a mutation operator. This creates the next generation. A new generation is formed by selecting some of the parents and offspring according to their fitness. Their fitness values are determined by the fitness function. Others are then rejected in order to maintain a constant population size. In this selection process, fitter individuals have a higher probability of being selected as part of the new generation. After several generations, the algorithms converge to the fittest individual, which represents the optimum or suboptimal solution to a given problem. This following illustrates how genetic algorithms are applied to the combinatorial optimization problems in the present J-BMS.



① : Repair 1 (Epoxy injection, Recovery of cross section) → [0110]
② : Repair 2 (Repair 1+ Glass cloth) → [1000]
③ : Repair 3 (Repair 1+ Mortar spraying) → [1101]
④ : Steel plate covering or FRP covering (four layers) → [0010]
⑤ : FRP covering (two layers) → [0100]
⑥ : External cables → [1100]
⑦ : External cables + Repair 1 → [0111]
⑧ : External cables + Repair 2 → [1001]
⑨ : External cables + Repair 3 → [0011]
⑩ : No repair, No strengthening → [other]

Fig. 4. Maintenance planning.

(a) Representation and Evaluation of a Candidate Solution

Generally, the genetic operators are performed on symbolic strings. Consequently, the method of encoding a candidate solution into an individual for a given problem is of primary importance for genetic algorithms. Since binary encoding allows fast computation and an easy manipulation of genes, this method of encoding is used in the present study, as shown in Figure 5. Each individual expresses a candidate solution, that is, a possible maintenance plan. Each set of genes (4-bit code) in the individual expresses an individual maintenance. Thus, the candidate solution can be expressed as a $(T-t')$ 4 matrix, in which T is the expected service life and t' is the present age of bridge. As an example, the binary representation of maintenance measures for a main girder is as follows. Since there are 10 possible maintenance measures for a main girder, as shown in Figure 4, the maintenance measures for a main girder are represented by a 4-bit binary code. However, since a 4-bit binary code is capable of expressing 16 different values (and hence 16 different types of maintenance measure), one-to-one correspondence between maintenance and binary code would yield a number of illegal offspring with lethal genes due to simple crossover or mutation operations. The presence of lethal genes decreases the efficiency of calculation. Therefore, with the exception of “⑩: No repair, No strengthening” all maintenance measures were assigned one binary code. “⑩: No repair, No strengthening” was assigned the extra codes. This is because this maintenance measure was expected to be chosen more frequently than any other measure in this optimum calculation.

The fitness of each individual is important for selection. During each generation, individuals are evaluated using the fitness function. In the present study, fitness is evaluated as follows. A fitter individual has a higher fitness value of fitness function G. For cost minimization, the fitness value is given by the inverse of total cost, as given in Eq. (18). For quality maximization, the fitness value is given by Eq. (19).

$$G_1 = \frac{1}{F_1} = \frac{1}{\sum_{t=t}^{T-1} C_{ij}} \qquad (18)$$

$$G_2 = F_2 = \sum_{t=t}^{T} \left\{ S_L\left(t\right) + S_D\left(t\right) \right\} \qquad (19)$$

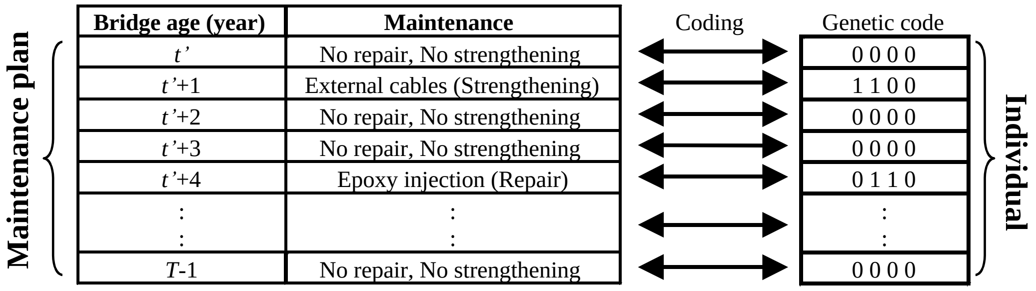
where G_1 and G_2: are the fitness function, F_1 and F_2: are the objective function corresponding to Eqs. (13) and (14).

Since the maintenance planning is a constrained optimization problem, the penalty method is adopted for constraints. If an individual can not satisfy the constraints for the condition, such that the mean soundness score of load-carrying capability and durability is higher than 0 (Eq. (15)), then 5000U is added to the total cost. Additionally, for quality maximization, if the cost of the individual exceeds the cost constraint, the fitness value of the individual is set to 0. As a result, the individual given these penalties has a low probability of being chosen as a parent in the next generation.

(b) Genetic Operators

GAs have genetic operators such as selection, crossover and mutation. Selection refers to the choosing of parents for recombination. The next generation is formed by replacing parents with their offspring. In this study, a combination of tournament selection and elitist selection was adopted as the selection technique. Tournament selection randomly chooses a set of individuals. The best one is selected from the set as a parent of the next generation. The number of individuals in this set is referred to as the tournament size. The tournament size of this study was set to two, which is a common size. Here, the individual with high fitness has a high probability of becoming a parent in the next generation. Elitist selection is often embedded within other selection methods in order to enforce the preservation of the best individual of the current generation in the next generation. Thus, this type of selection can overcome stochastic sampling errors through generation alternation. Experimental experience revealed that the embedded elitist method yields a better solution than the tournament selection. As a result, both tournament selection and elitist selection were adopted.

Crossover is the main genetic operator in GAs. Crossover operates on two individuals (parents) and generates two offsprings (children) by combining the features of these two individuals. These parents are chosen according to a selection procedure. The crossover method used in the present study is the one-cut-point method. With this, a randomly selected cut-point is used to divide the parents into upper and lower segments (Figure 5). The upper segments of the parents are then exchanged to generate the two offsprings. In the present study, the parents are chosen by tournament selection. The cutting direction is horizontal. Each child is generated by combining the upper segment of one parent with the lower segment of the other parent.



Bridge age (year)	Maintenance	Genetic code
t'	No repair, No strengthening	0 0 0 0
t'+1	External cables (Strengthening)	1 1 0 0
t'+2	No repair, No strengthening	0 0 0 0
t'+3	No repair, No strengthening	0 0 0 0
t'+4	Epoxy injection (Repair)	0 1 1 0
: :	: :	: :
T-1	No repair, No strengthening	0 0 0 0

t' : Present age T : Expected service life

Fig. 5. Binary representation of maintenance plan.

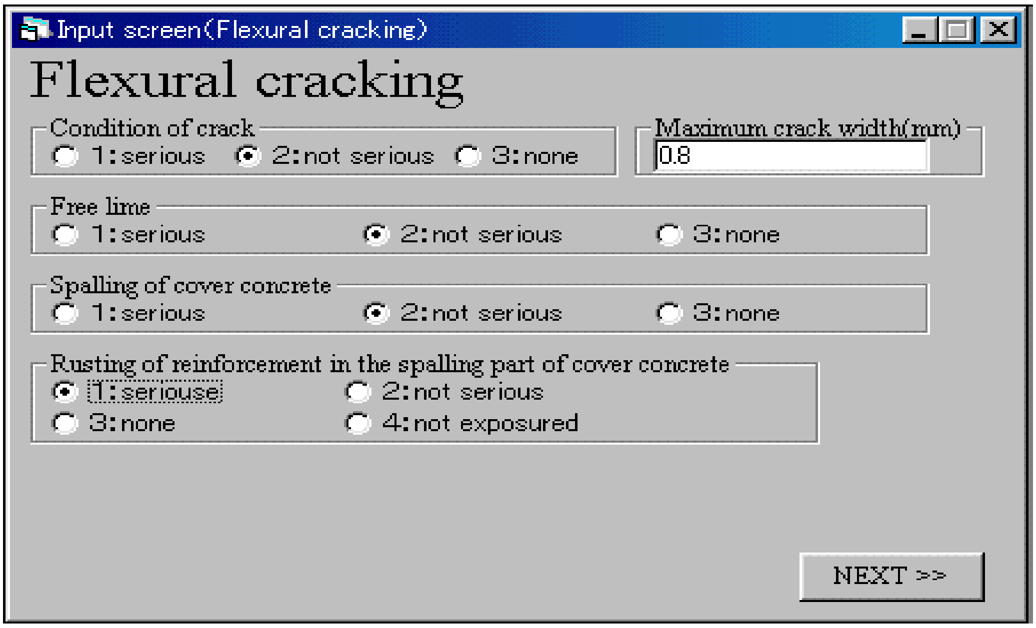
Although crossover operations are used to improve the fitness of individuals, GAs occasionally give a local solution as the optimal solution. As a result, GAs include a mechanism called mutation, which randomly changes one or more genes in an individual in order to avoid a local solution. The mutation used in the present application is described as follows. When mutation is performed for an individual, one maintenance measure (represented by a row of genes) is chosen from among (T-t') maintenance measures in the individual. Next, one bit (one gene) is chosen from among these four bits (four genes) and the value of the chosen bit is flipped. For example, a gene having a value of one is changed to zero. This mutation method transfers the maintenance measure to four other measures of which the Hamming distance is one. The correspondence between the maintenance measure and the binary code should be considered with respect to the Hamming distance. Thus, each maintenance measure is represented by a binary code, as shown in Figure 4.

When the GAs are applied to the optimization problem, various parameters of genetic operators must be set. Table 3 shows the parameters used in the present application. The parameters are adjusted by trial and error.

APPLICATION OF J-BMS to EXISTING BRIDGES

In order to test its validity, the J-BMS is applied to seven existing bridges (nine spans) which are all RC T- girder type bridges. In this example, the expected service life (T) of the target bridges was set to 90 years. The parameters used in the present application of GAs are shown in Table 3.

In the proposed J-BMS, the target bridge data are first entered into the computer, as shown in Figure 6, which is an input screen of inspection data. As an example, Figures 7 and 8 give a partial listing of the technical specifications and inspection data related to the Hataka-Bridge (H-bridge) main girder (span 1) for the BREX system. Using this data, the J-BMS evaluates the present performance of the bridge. Figure 9 shows the performance evaluation of H-bridge main girder obtained using the BREX system.



Input screen(Flexural cracking)

Flexural cracking

Condition of crack
○ 1:serious ● 2:not serious ○ 3:none

Maximum crack width(mm)
0.8

Free lime
○ 1:serious ● 2:not serious ○ 3:none

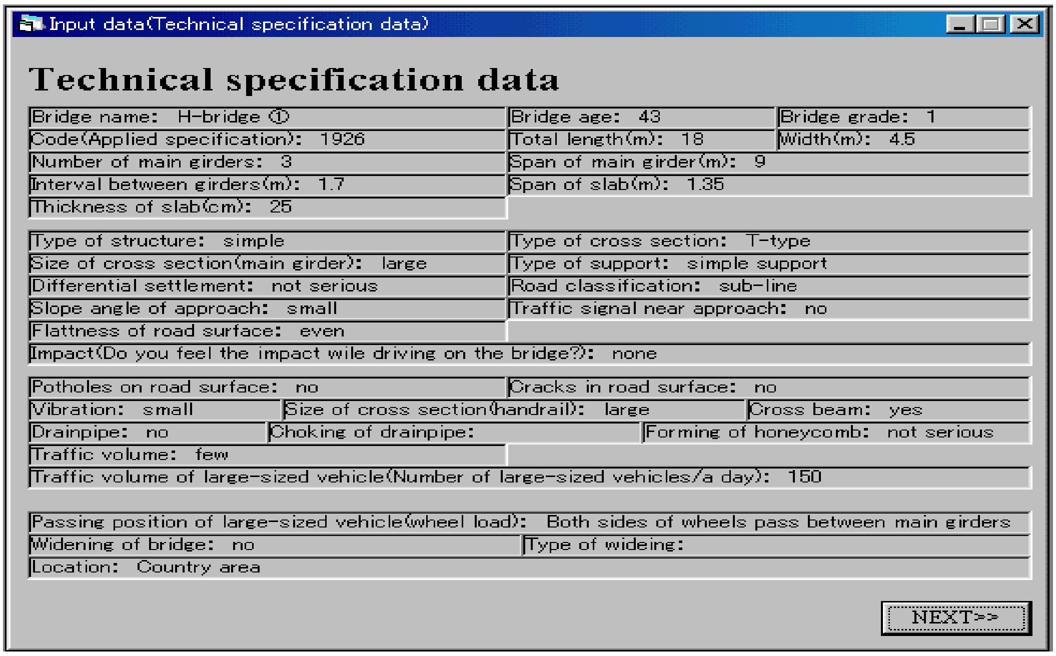
Spalling of cover concrete
○ 1:serious ● 2:not serious ○ 3:none

Rusting of reinforcement in the spalling part of cover concrete
● 1:seriouse ○ 2:not serious
○ 3:none ○ 4:not exposured

Fig. 6. Input screen.

Table 3. Parameters of the genetic operator used in this study.

Item	Parameter Value or Method
Population size	30 individuals
Max generation	300 generations
Selection method	Tournament selection and Elitist selection
Crossover method	one–cut-point crossover
Crossover rate	100%
Mutation rate	10%



Technical specification data

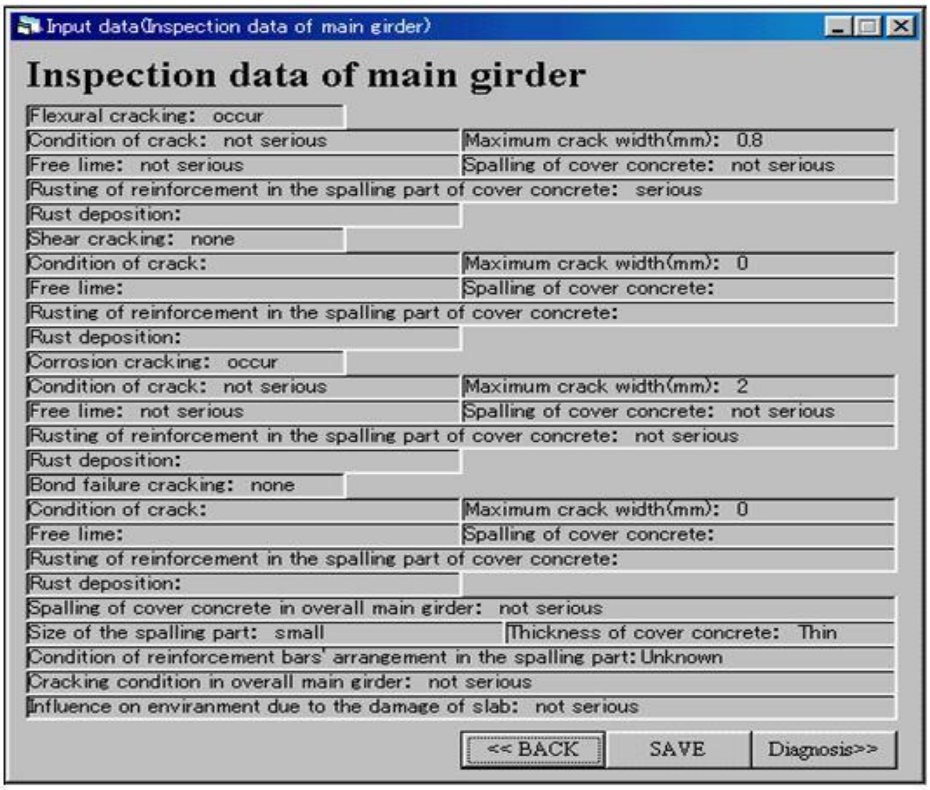
Bridge name: H-bridge ①
Bridge age: 43
Bridge grade: 1
Code(Applied specification): 1926
Total length(m): 18
Width(m): 4.5
Number of main girders: 3
Span of main girder(m): 9
Interval between girders(m): 1.7
Span of slab(m): 1.35
Thickness of slab(cm): 25

Type of structure: simple
Type of cross section: T-type
Size of cross section(main girder): large
Type of support: simple support
Differential settlement: not serious
Road classification: sub-line
Slope angle of approach: small
Traffic signal near approach: no
Flattness of road surface: even
Impact(Do you feel the impact wile driving on the bridge?): none

Potholes on road surface: no
Cracks in road surface: no
Vibration: small
Size of cross section(handrail): large
Cross beam: yes
Drainpipe: no
Choking of drainpipe:
Forming of honeycomb: not serious
Traffic volume: few
Traffic volume of large-sized vehicle(Number of large-sized vehicles/a day): 150

Passing position of large-sized vehicle(wheel load): Both sides of wheels pass between main girders
Widening of bridge: no
Type of wideing:
Location: Country area

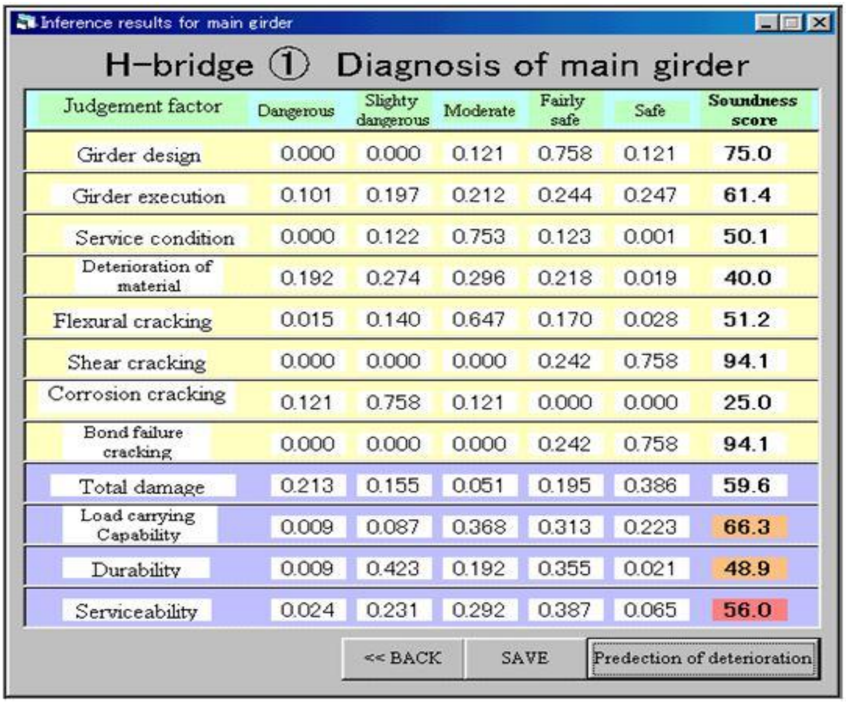
Fig. 7. List of technical specification data.



Inspection data of main girder

Flexural cracking: occur
Condition of crack: not serious
Maximum crack width(mm): 0.8
Free lime: not serious
Spalling of cover concrete: not serious
Rusting of reinforcement in the spalling part of cover concrete: serious
Rust deposition:
Shear cracking: none
Condition of crack:
Maximum crack width(mm): 0
Free lime:
Spalling of cover concrete:
Rusting of reinforcement in the spalling part of cover concrete:
Rust deposition:
Corrosion cracking: occur
Condition of crack: not serious
Maximum crack width(mm): 2
Free lime: not serious
Spalling of cover concrete: not serious
Rusting of reinforcement in the spalling part of cover concrete: not serious
Rust deposition:
Bond failure cracking: none
Condition of crack:
Maximum crack width(mm): 0
Free lime:
Spalling of cover concrete:
Rusting of reinforcement in the spalling part of cover concrete:
Rust deposition:
Spalling of cover concrete in overall main girder: not serious
Size of the spalling part: small
Thickness of cover concrete: Thin
Condition of reinforcement bars' arrangement in the spalling part: Unknown
Cracking condition in overall main girder: not serious
Influence on environment due to the damage of slab: not serious

Fig. 8. List of inspection data for main girder.



H-bridge ① Diagnosis of main girder

Judgement factor	Dangerous	Slighty dangerous	Moderate	Fairly safe	Safe	Soundness score
Girder design	0.000	0.000	0.121	0.758	0.121	75.0
Girder execution	0.101	0.197	0.212	0.244	0.247	61.4
Service condition	0.000	0.122	0.753	0.123	0.001	50.1
Deterioration of material	0.192	0.274	0.296	0.218	0.019	40.0
Flexural cracking	0.015	0.140	0.647	0.170	0.028	51.2
Shear cracking	0.000	0.000	0.000	0.242	0.758	94.1
Corrosion cracking	0.121	0.758	0.121	0.000	0.000	25.0
Bond failure cracking	0.000	0.000	0.000	0.242	0.758	94.1
Total damage	0.213	0.155	0.051	0.195	0.386	59.6
Load carrying Capability	0.009	0.087	0.368	0.313	0.223	66.3
Durability	0.009	0.423	0.192	0.355	0.021	48.9
Serviceability	0.024	0.231	0.292	0.387	0.065	56.0

Fig. 9. Evaluation of performance.

(1) Questionnaire Survey of Domain Experts and Visual Inspection of Bridges.

- ***Purpose of Questionnaire Survey and Visual Inspection***

The purpose of the questionnaire survey is firstly, to collect data that can be used to verify the practical applicability of the functions of the bridge management system (J-BMS). Secondly, it is used to acquire teacher data necessary for learning associated with the deterioration estimation function of the system. Moreover, the purpose of the visual inspection of bridges is to collect inspection data to be entered into the system for verification of J-BMS. The inspection results are also used by domain experts to fill out the questionnaire.

- ***Survey Method***

The visual inspection of bridges and the questionnaire survey were conducted over two days. Seven domain experts (six on the second day) from four construction consulting companies in and around Yamaguchi Prefecture participated in the survey. The timetable is described below. On the morning of the first day, the survey procedure was explained to the respondents. In the afternoon, two spans of two bridges under the jurisdiction of Hofu Office of Civil and Building Engineering Division (Yamaguchi Prefecture Government) were visually inspected. On the morning of the second day, three spans of two bridges under the jurisdiction of Mine Office of Civil and Building Engineering Division were visually inspected. In the afternoon, visual inspection of four spans of three bridges under the jurisdiction of Toyoda Office of Civil and Building Engineering Division was carried out. Thus, the survey covered a total of nine spans of seven bridges.

One set of questionnaire forms (prepared for each span) used in the survey consisted of: 1. inspection record sheets (eight pages), to be used to record visual inspection results; 2. a model drawing of each bridge on which to write down whatever comes to mind during inspection and 3. a set of questionnaire sheets (10 pages), to obtain teacher data needed for the deterioration estimation function and verification data necessary for the deterioration prediction function and the repair/strengthening selection function.

The inspection record sheets were formatted so that the respondents could choose a score from an 11-point rating scale (between 0 and 1 in increments of 0.1), answer multiple-choice questions and enter numbers. Answers to questions that can be answered even by non-experts, e.g, whether there is a traffic signal or transverse beams, were entered on behalf of the respondents in advance. For questions designed to obtain teacher data necessary for the deterioration estimation function, the questionnaire sheets were formatted so that the respondents could answer in the form of a score on a 0-to-100 scale in increments of 5 points. For questions aimed at obtaining data needed to verify the deterioration prediction function, the respondents were to choose from a number of indicated ranges of periods, e.g, 10 years or less, 11 to 20 years and so on. Questions concerning repair/strengthening methods were of the open-ended format.

(2) Practical Application and Verification of the Bridge Management System (J-BMS)

In this section, outputs of the bridge management system (J-BMS) based on mainly the visual inspection data are compared with the questionnaire results to verify the practical applicability of the system.

- ***Deterioration Estimation Function***

The results of the deterioration estimation by domain experts of the bridges mentioned earlier are summarized in Tables 4 and 5. The numerals in parentheses are the averages of scores assigned by the domain experts as a result of their evaluation of the RC slabs and main girders. The alphabet characters (*S*, *f*-*s*, *M*, *s*-d, *D*) represent "safe," "fairly safe," "moderate," "slightly dangerous," and "dangerous." These labels classify the average values in the parentheses into five categories. The criteria used by the respondents for this categorization are the following: "dangerous" ($0.0 \leq G < 12.5$), "slightly dangerous" ($12.5 \leq G < 37.5$), "moderate" ($37.5 \leq G \leq 62.5$), "fairly safe" ($62.5 < G \leq 87.5$) and "safe" ($87.5 < G \leq 100.0$).

The number following each bridge name indicates a span number. Tables 6 and 7 show the results of the deterioration estimation of the RC slabs and main girders obtained in the form of outputs from the bridge management system (J-BMS). These results are system outputs reflecting learned weights obtained by using data for a number of bridges, other than those covered in the deterioration estimation as training data for learning (leave-one-out method (Orvosh et al., 1994). In the leave-one-out method of learning used in this study, to estimate the deterioration of "Hataka-Bridge ① (Span 1)," for example, data on the eight spans (other than the "Hataka-Bridge ①”) are used for the training of the inference engine. Estimating the degree of deterioration of the only span whose data were not used for learning by the above method is equivalent to estimating the deterioration of a newly encountered span, after completing learning sessions for a number of spans. The data entered into the system were the averages of the results of on-site visual inspection made by the cooperating domain experts. The data used as the teacher data for learning were the averages of the results of deterioration estimation made by the cooperating domain experts. The shaded areas in the tables indicate the following:

▨ indicates a system output value that is one order deviant from the teacher value (Tables 4 and 5). ■ indicates an output value that is two or more orders deviant from the teacher value. The total error at the bottom of the table is a span-by-span sum total of errors for each evaluation item.

Table 4. Results of RC slab deterioration estimation by domain experts (training data).

Age of Bridge (years)	**43**	**58**	**41**	**31**		**32**	**42**		**29**
Bridge name Judgment Item	Hataka①	Niji⑥	Nobutaka①	Mine①	Mine③	Getusyou③	Tobimatu①	Tobimatu②	Ougame②
Slab design	M(57.1)	M(52.8)	M(48.3)	M(60.0)	M(59.2)	M(62.5)	f-s(80.0)	f-s(75.8)	f-s(76.7)
Slab execution	f-s(73.6))	M(52.1)	M(44.2)	M(45.0)	M(48.3)	M(56.5)	f-s(79.2)	f-s(76.7)	f-s(77.5)
Road surface condition	f-s(75.0)	M(55.0)	M(45.0)	f-s(65.8)	f-s(70.8)	s-d(30.8)	f-s(81.7)	f-s(76.7)	f-s(73.3)
Service condition	f-s(80.7)	M(55.0)	M(50.0)	f-s(65.8)	f-s(68.3)	M(37.5)	f-s(83.3)	f-s(79.2)	f-s(73.3)
Deterioration of material	f-s(77.1)	M(40.7)	f-s(63.3)	M(51.7)	M(53.3)	f-s(74.2)	f-s(80.8)	f-s(80.8)	f-s(81.7)
Cracking in haunch	f-s(85.7)	s-d(31.4)	f-s(83.3)	M(42.5)	M(37.5)	f-s(72.5)	f-s(85.0)	f-s(85.8)	S(89.2)
Cracking in support zone	S(87.9)	f-s(65.0)	f-s(85.0)	M(60.0)	f-s(66.7)	f-s(73.3)	S(90.8)	S(90.8)	S(89.2)
Midspan cracking	f-s(87.1)	s-d(36.4)	f-s(78.3)	f-s(68.3)	f-s(68.3)	f-s(69.2)	f-s(85.0)	f-s(85.0)	f-s(76.7)
Overall damage	f-s(80.0)	M(40.7)	f-s(65.0)	M(49.2)	M(45.0)	f-s(67.5)	f-s(85.8)	f-s(85.8)	f-s(82.5)
Load-carrying capability	f-s(75.0)	M(45.0)	M(44.2)	M(51.7)	M(54.2)	f-s(64.2)	f-s(81.7)	f-s(81.7)	f-s(80.0)
Durability	f-s(80.0)	M(45.0)	M(50.0)	M(46.7)	M(50.0)	M(58.3)	f-s(84.2)	f-s(82.5)	f-s(82.5)
Serviceability	f-s(72.9)	M(42.9)	M(45.8)	M(47.5)	M(52.5)	M(61.7)	f-s(82.5)	f-s(83.3)	f-s(80.8)

Note: S: safe, f-s: fairly safe, M: moderate, s-d: slightly dangerous, D: dangerous

Table 5. Results of main girder deterioration estimation by domain experts (training data).

Bridge Name Judgment Item	**Hataka①**	**Niji⑥**	**Nobutaka ①**	**Mine①**	**Mine③**	**Getusyou ③**	**Tobimatu ①**	**Tobimatu ②**	**Ougame②**
Girder design	M(59.3)	M(47.9)	M(58.3)	f-s(75.8)	f-s(75.0)	f-s(77.5)	f-s(70.8)	M(60.8)	f-s(78.3)
Girder execution	M(55.0)	s-d(31.4)	M(62.5)	f-s(75.0)	f-s(73.3)	f-s(72.5)	f-s(71.7)	M(53.3)	f-s(74.2)
Service condition	f-s(72.1)	M(47.1)	M(59.2)	f-s(82.5)	f-s(85.0)	f-s(85.0)	f-s(75.8)	f-s(73.3)	f-s(76.7)
Deterioration of material	M(48.6)	M(47.9)	f-s(75.0)	f-s(72.5)	f-s(74.2)	f-s(87.5)	f-s(77.5)	M(62.5)	f-s(85.0)
Flexural cracking	f-s(75.0)	s-d(37.1)	f-s(73.3)	f-s(80.0)	f-s(75.8)	f-s(87.5)	f-s(81.7)	f-s(72.5)	f-s(75.0)
Shear cracking	S(92.9)	f-s(67.9)	f-s(87.5)	S(95.8)	S(95.8)	S(98.3)	S(92.5)	S(97.5)	S(98.3)
Corrosion cracking	M(40.7)	M(45.7)	f-s(86.7)	f-s(87.5)	f-s(75.0)	S(92.5)	f-s(73.3)	M(53.3)	f-s(75.8)
Bond cracking	S(90.0)	f-s(80.7)	S(95.0)	S(91.7)	S(90.0)	S(94.2)	S(93.3)	S(93.3)	S(93.3)
Overall damage	M(55.7)	s-d(37.1)	f-s(77.5)	f-s(76.5)	f-s(74.2)	f-s(87.5)	f-s(75.0)	f-s(64.2)	f-s(80.0)
Load-carrying capability	f-s(67.1)	s-d(35.7)	f-s(70.0)	f-s(76.7)	f-s(76.7)	f-s(81.7)	f-s(70.0)	f-s(63.3)	f-s(81.7)
Durability	M(55.0)	s-d(35.0)	f-s(69.2)	f-s(78.3)	f-s(75.8)	f-s(85.8)	f-s(71.7)	M(56.7)	f-s(81.7)
Serviceability	f-s(62.9)	s-d(33.6)	f-s(66.7)	f-s(75.0)	f-s(70.8)	f-s(85.0)	f-s(71.7)	M(60.8)	f-s(81.7)

Comparison of these outputs with the questionnaire survey results reveals that, of the 108 evaluation items (9 spans · 12 evaluation items), for the RC slabs and the main girders, 72 RC-slab-related items and 79 main-girder-related items were in agreement with the questionnaire results. Furthermore, 36 RC-slab-related items and 27 main-girder-related items show a value one order deviant from the teacher value and two main-girder-related items show a value two orders deviant from the teacher value. Thus, the overall agreement ratio for the RC slabs and the main girders is 66.7% and 73.1%, respectively. The overall error for the Niji-Bridge's main girder is greater than that of any other bridge inspected in this study. Table 5 shows that teacher values for the evaluation items for Niji-Bridge are smaller than those for the other bridges. Table 5 shows that, of the bridges inspected in this study, the surveyed domain experts believe Niji-Bridge is in the most severely damaged condition. The other bridges show values indicating that they are in a relatively sound condition. A likely explanation for why the system outputs differ considerably from the domain experts' judgments is that, in the case where the bridge management system evaluates bridge damage after completing training sessions carried out by the leave-one-out (or jack-knife) method, the system must evaluate the degree of damage of the type that the system has never been trained to evaluate. In other words, the differences between the system outputs and the domain experts' judgments are likely to have occurred because the data used for neural network learning were obtained from bridges that were in a relatively sound condition. On the other hand, it can also be seen that small overall error values for some bridges, such as the RC slab, the main girder of Mine-Bridge and the main girder of Tobimatu-Bridge ① (Span 1), indicate that learning for the deterioration estimation function based on data on other bridges was adequately completed. These results indicate that, although the reliability of the deterioration estimation function depends on information regarding the distribution of bridge damage used for neural network learning, the problem can be solved by increasing the number of sample bridge data sets.

• *Deterioration Prediction Function*

Tables 8 to 11 show the remaining useful life of the bridges predicted by the domain experts. These are from the viewpoints of the durability and load carrying capability of RC slabs and main girders. As shown, the questionnaire survey focused on which 10 year periods the predicted service lives fall into. The numerals in parentheses, shown under the bridge names, are load carrying capability or durability values predicted by domain experts (see Tables 4 and 5). In the tables, characters A through G represent the domain experts who participated in the questionnaire survey. Table 12 summarizes the position in which each domain expert is in when working in connection with bridges, the types of bridges that each expert deals with and each expert's experience - measured in years. The bottom lines of Tables 8 to 11 show the predicted remaining service lives in the form of outputs from the deterioration prediction function, based on the load-carrying capability and durability estimations (Tables 4 and 5) made by the domain experts. The shaded areas in the tables indicate the remaining service life categories to which the remaining service life predictions outputted by the deterioration prediction function belong.

Table 6. Estimation results obtained by using the deterioration estimation function (RC slabs).

Bridge Name **Judgment Item**	**Hataka①**	**Niji⑥**	**Nobutaka ①**	**Mine①**	**Mine③**	**Getusyou ③**	**Tobimatu ①**	**Tobimatu ②**	**Ougame ②**
Slab design	f-s(79.7)	M(39.6)	M(38.3)	M(60.2)	M(61.3)	M(59.7)	f-s(77.4)	M(46.2)	M(38.0)
Slab execution	M(51.6)	f-s(63.5)	f-s(70.0)	M(60.0)	M(54.3)	M(51.1)	M(61.1)	M(61.7)	f-s(70.2)
Road surface condition	f-s(70.8)	f-s(72.2)	M(60.9)	M(48.3)	f-s(67.3)	s-d(33.5)	f-s(76.7)	f-s(76.5)	M(58.4)
Service condition	M(62.4)	f-s(67.6)	f-s(63.4)	M(61.9)	f-s(65.2)	M(60.5)	f-s(71.2)	f-s(71.8)	M(54.0)
Deterioration of material	f-s(75.3)	M(56.0)	f-s(79.6)	M(55.7)	M(57.4)	f-s(75.3)	f-s(75.6)	f-s(76.5)	f-s(68.8)
Cracking in haunch	f-s(83.3)	s-d(32.4)	f-s(83.8)	s-d(33.0)	M(51.6)	f-s(85.9)	f-s(83.4)	f-s(83.2)	f-s(82.5)
Cracking in support zone	f-s(85.9)	f-s(62.7)	f-s(86.5)	M(56.7)	S(88.8)	S(88.8)	f-s(85.3)	f-s(85.3)	f-s(85.6)
Midspan cracking	f-s(82.8)	M(51.8)	f-s(70.6)	M(44.8)	f-s(66.6)	M(61.9)	f-s(83.4)	f-s(83.4)	S(90.1)
Overall damage	f-s(76.4)	M(51.0)	f-s(73.5)	M(50.8)	f-s(68.1)	f-s(81.2)	f-s(75.3)	f-s(75.4)	f-s(74.6)
Load-carrying capability	f-s(86.8)	M(54.1)	f-s(65.3)	M(53.5)	M(57.3)	f-s(72.1)	f-s(77.6)	M(58.1)	M(61.8)
Durability	f-s(66.9)	M(47.7)	f-s(66.9)	M(46.1)	M(56.1)	f-s(73.8)	f-s(71.0)	f-s(71.7)	f-s(66.3)
Serviceability	f-s(81.4)	M(50.8)	M(60.3)	M(48.4)	M(50.9)	f-s(71.7)	f-s(77.6)	f-s(62.8)	M(61.6)
Overall error	114.6	118.4	152.1	81.8	90.6	118.3	84.4	131.5	178.3

Table 7. Estimation results obtained by using the deterioration estimation function (The main girders).

Bridge Name **Judgment Item**	**Hataka①**	**Niji⑥**	**Nobutaka ①**	**Mine①**	**Mine③**	**Getusyou ③**	**Tobimatu ①**	**Tobimatu ②**	**Ougame ②**
Girder design	f-s(69.1)	M(60.8)	M(60.5)	f-s(68.4)	f-s(69.8)	f-s(71.4)	f-s(67.4)	f-s(64.2)	M(56.7)
Girder execution	f-s(65.2)	M(43.4)	f-s(75.9)	f-s(68.5)	f-s(68.7)	M(61.9)	M(62.0)	f-s(71.5)	f-s(68.5)
Service condition	f-s(70.1)	f-s(74.2)	f-s(73.2)	f-s(83.3)	f-s(82.0)	f-s(67.9)	f-s(69.6)	f-s(70.1)	f-s(69.5)
Deterioration of material	M(50.1)	M(39.1)	f-s(78.3)	f-s(64.6)	f-s(68.3)	f-s(71.2)	f-s(76.7)	M(38.4)	f-s(72.9)
Flexural cracking	M(58.9)	s-d(32.7)	M(58.2)	f-s(79.6)	f-s(81.4)	f-s(78.9)	f-s(79.1)	f-s(84.4)	f-s(82.3)
Shear cracking	S(92.2)	S(95.0)	S(92.7)	S(91.7)	S(91.7)	S(91.4)	S(92.1)	S(91.5)	S(91.4)
Corrosion cracking	M(49.5)	M(46.8)	f-s(84.3)	f-s(84.1)	f-s(65.2)	f-s(82.4)	S(89.0)	M(40.1)	f-s(73.9)
Bond cracking	S(91.6)	S(92.6)	S(91.0)	S(91.4)	S(91.6)	S(91.0)	S(91.2)	S(91.2)	S(91.2)
Overall damage	M(53.4)	M(49.9)	f-s(84.7)	f-s(75.6)	f-s(73.5)	f-s(80.4)	f-s(84.3)	M(37.6)	f-s(81.8)
Load-carrying capability	M(52.8)	f-s(64.3)	f-s(73.5)	S(91.4)	S(91.6)	f-s(65.0)	f-s(64.3)	M(51.7)	M(55.3)
Durability	M(49.9)	M(57.6)	f-s(84.2)	f-s(71.7)	f-s(68.5)	f-s(74.8)	f-s(79.9)	M(44.0)	f-s(78.1)
Serviceability	M(50.9)	f-s(64.8)	f-s(78.7)	f-s(73.8)	f-s(76.5)	f-s(69.3)	f-s(75.4)	M(49.9)	f-s(68.3)
Overall error	84.4	200.5	97.3	54.2	68.4	129.4	67.8	143.9	110.0

Table 8. Remaining service lives of RC slabs from the viewpoint of durability.

Age of Bridge (years)	**43**	**58**	**41**	**31**		**32**	**42**		**29**
Bridge Name **Remaining Service Life**	**Hataka①** **(80.0)**	**Niji⑥** **(45.0)**	**Nobutaka ①** **(50.0)**	**Mine①** **(46.7)**	**Mine③** **(50.0)**	**Getusyou ③** **(58.3)**	**Tobimatu ①** **(84.2)**	**Tobimatu ②** **(82.5)**	**Ougame②** **(82.5)**
10 years or less		FG	C	CF	F				
11 to 20 years	FG	ABDE	ABDF	ABD	ABCDE	ABDF	BF	BDF	DF
21 to 30 years	AC	C	E	E		C	ACD	AC	AB
31 to 40 years	BE					E	E	E	C
40 years or more	D								E
Output	17	9	6	6	6	9	22	22	14

Table 9. Remaining service lives of RC slabs from the viewpoint of load-carrying capability.

Bridge Name **Remaining Service Life**	**Hataka①** **(75.0)**	**Niji⑥** **(45.0)**	**Nobutaka ①** **(44.2)**	**Mine①** **(51.7)**	**Mine③** **(54.2)**	**Getusyou ③** **(64.2)**	**Tobimatu ①** **(81.7)**	**Tobimatu ②** **(81.7)**	**Ougame②** **(80.0)**
10 years or less	D	DFG	CD		F	D			
11 to 20 years	FG	ABE	ABF	BD	ABDE	ABF	BDF	BDF	DF
21 to 30 years	AC	C	E	ACF	C	C	AC	AC	AB
31 to 40 years	BE			E		E	E	E	C
40 years or more									E
Output	30	12	10	7	8	10	35	33	22

Table 10. Remaining service lives of main girders from the viewpoint of durability.

Bridge Name **Remaining Service Life**	**Hataka①** **(55.0)**	**Niji⑥** **(35.0)**	**Nobutaka ①** **(69.2)**	**Mine①** **(78.3)**	**Mine③** **(75.8)**	**Getusyou ③** **(85.8)**	**Tobimatu ①** **(71.7)**	**Tobimatu ②** **(56.7)**	**Ougame②** **(81.7)**
10 years or less	CD	ACDFG	D		D	D		D	
11 to 20 years	AG	BE	ABC	BD	B	B	ABD	AB	
21 to 30 years	F		F	ACF	ACEF	AF	F	CF	ABDF
31 to 40 years	BE		E	E		CE	CE	E	C
40 years or more									E
Output	13	6	14	13	13	16	14	11	15

Table 11. Remaining service lives of main girders from the viewpoint of load-carrying capability.

Bridge Name **Remaining Service Life**	**Hataka①** **(67.1)**	**Niji⑥** **(35.7)**	**Nobutaka①** **(70.0)**	**Mine①** **(76.7)**	**Mine③** **(76.7)**	**Getusyou③** **(81.7)**	**Tobimatu①** **(70.0)**	**Tobimatu②** **(63.3)**	**Ougame②** **(81.7)**
10 years or less	D	ADFG			D	D			
11 to 20 years	AG	BE	ABCD	BD	B	B	ABD	ABD	D
21 to 30 years	CF	C	F	ACF	ACEF	AF	F	CF	ABF
31 to 40 years	BE		E	E		CE	CE	E	C
40 years or more									E
Output	13	8	19	20	18	29	21	13	22

Table 12. Domain expert data.

	Position	**Type of Bridge Involved**	**Experience (years)**
A	Designer	Steel bridges	21～30
B	Designer	(Unknown)	5～10
C	Designer	Concrete bridges, steel bridges	21～30
D	Designer	Concrete bridges, steel bridges	～3
E	Designer	Concrete bridges, steel bridges	11～20
F	Manager	Concrete bridges, steel bridges	21～30
G	Designer	Concrete bridges, steel bridges	5～10

Table 13. Repair/strengthening methods selected for RC slabs by domain experts.

	Necessity of Repair/Strengthening	**Maintenance Measure (Repair/Strengthening Method)**
Hataka①	Not necessary	
Niji⑥	Necessary	Resin grouting, FRP covering, steel plate covering
Nobutaka①	Necessary	Putty method, rustproofing of reinforcements
Mine①	Necessary	Putty, prepacked concrete
Mine③	Necessary	Putty, prepacked concrete
Getusyou③	Not necessary	
Tobimatu①	Not necessary	
Tobimatu②	Not necessary	
Ougame②	Not necessary	

Table 14. Repair/strengthening methods selected for main girders by domain experts.

Bridge Name	**Necessity of Repair/Strengthening**	**Maintenance Measure (Repair/Strengthening Method)**
Hataka①	Necessary	Putty, prepacked concrete, surface protection
Niji⑥	Necessary	Putty, FRP covering, steel plate covering
Nobutaka①	Not necessary	
Mine①	Not necessary	
Mine③	Not necessary	
Getusyou③	Not necessary	
Tobimatu①	Not necessary	
Tobimatu②	Necessary	Putty, prepacked concrete, rustproofing of reinforcements
Ougame②	Not necessary	

The domain experts were asked to specify bridge ages at which they feel a concrete bridge is safe. Although their replies vary somewhat from person to person, the maximum age at which they consider a bridge is safe is about 50 years. Furthermore, they believe a bridge of around 70 years is dangerous. The remaining service life survey of the bridges inspected sums up the present ages of the inspected bridges and the remaining service lives predicted by the domain experts. They gave a rough range from 50 to 70 years of age. The relationship between the load-carrying capability and durability scores assigned by the experts and the predicted remaining service lives do not show any distinctive tendency. These results indicate that domain experts predict the remaining service life of a concrete bridge on the basis of a service life of 50 to 70 years.

Compared with the domain experts, examination of the remaining service life predictions, from the viewpoints of durability and load-carrying capability outputted by the deterioration prediction function, reveals that the bridge management system tends to be slightly more conservative. It can be said, however, that the system outputs are in fairly good agreement with the expert judgments regarding remaining service life. It can be concluded, therefore, that the deterioration prediction method adopted for the deterioration prediction function closely simulates expert judgments regarding the remaining service life of a bridge, based on deterioration estimation.

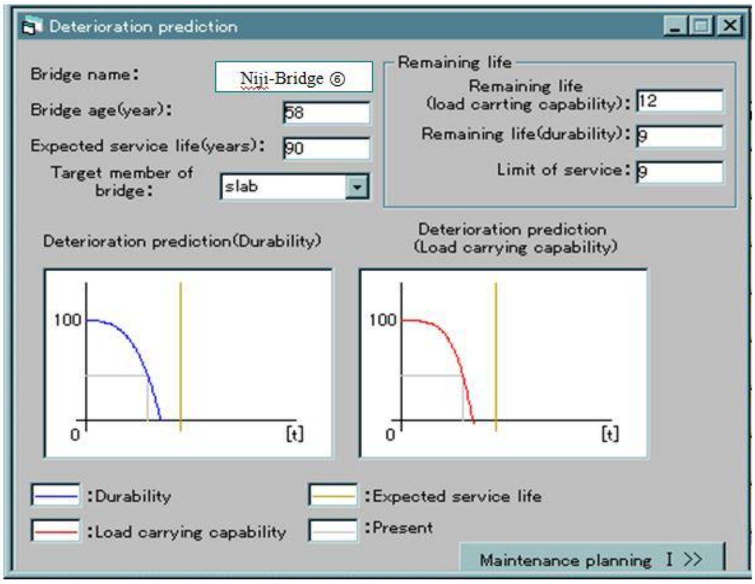
• *Optimal Maintenance Planning Function*

Tables 13 and 14 show the questionnaire survey results concerning the necessity of repair/strengthening, along with the repair/strengthening methods for the bridges that the domain experts believe require maintenance action. From the tables, the following can be found;

1. For Hataka-Bridge, the putty method and the pre-packed concrete method were selected because the main girder has exposed and corroding reinforcing bars.
2. For the RC slab of Niji-Bridge, the resin grouting method and the steel plate or FRP sheet covering method were selected because of cracking and inadequate strength. For the main girder, the putty method was chosen for the exposed reinforcement areas and the steel plate or FRP sheet covering method was selected because of many flexural cracks.
3. For the RC slab of Nobutaka-Bridge, the putty method was selected. It was judged that the main girder requires neither repair nor strengthening.
4. For Mine-Bridge, the putty method and the pre-packed concrete method were selected because of cracking and reinforcement exposure. This is due to inadequate concrete cover.
5. For Getusyou-Bridge, pavement rehabilitation was selected because of the roughness of the pavement surface. This bridge was widened after construction. Since leakage of water and presence of free lime were observed at the joints between new and old concrete, the grouting method was also selected. The RC slab and the main girder were judged not to require repair or strengthening.
6. For Tobimatu-Bridge, the putty method and the pre-packed concrete method were selected because reinforcements in the main girder are exposed at places. This bridge was widened after construction. Since leakage of water and presence of free lime were observed at the joints between new and old concrete, the grouting method was also selected.
7. Ougame-Bridge was judged not to require repair or strengthening.

Next, in order to verify the validity of a plan output by the optimal maintenance planning function, a maintenance plan was optimized using prediction outputs from the deterioration prediction function. For the purpose of this optimal planning validation, the RC slab and the main girder of Niji-Bridge ⑥ (Span 6), which, in the questionnaire survey of the domain experts, was judged to require some kind of maintenance action, were considered. The expected service life was 90 years.

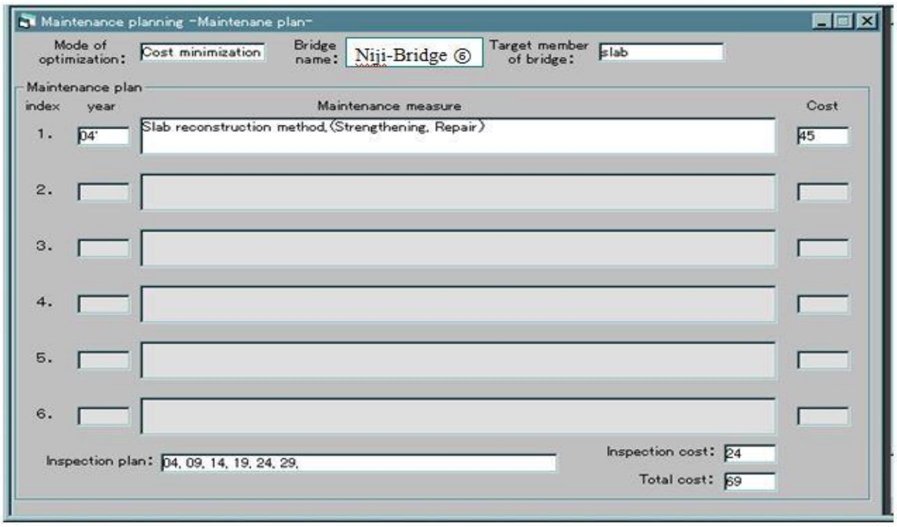
Figures 10 to 12 show the results of optimal maintenance planning for the RC slab. The results for the main girder are shown in Figures 13 to 17. Here, for the main girder, it also shows the results of quality maximization, as well as cost minimization.



Bridge name: Niji-Bridge ⑥
Bridge age(year): 58
Expected service life(years): 90
Target member of bridge: slab

Remaining life
Remaining life (load carrting capability): 12
Remaining life(durability): 9
Limit of service: 9

Fig. 10. Output screen of deterioration prediction for RC slab of Niji-Bridge.



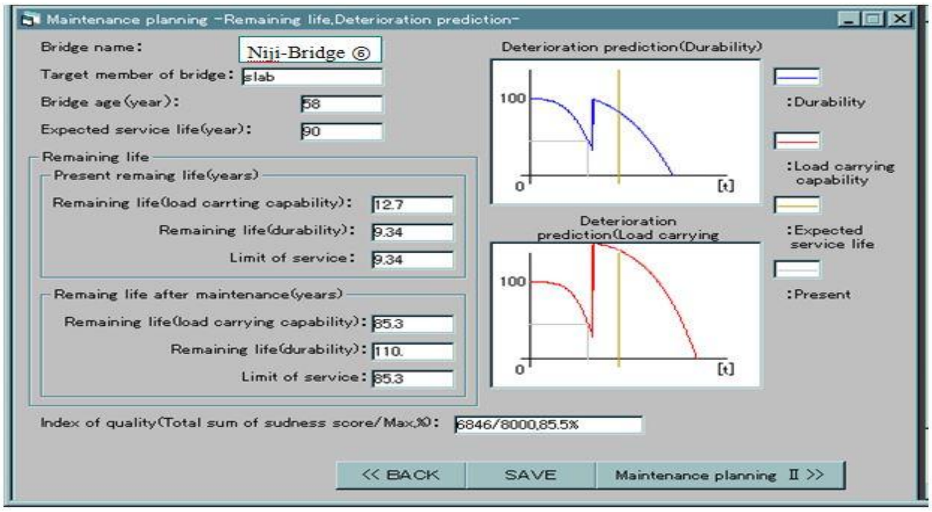
Mode of optimization: Cost minimization
Bridge name: Niji-Bridge ⑥
Target member of bridge: slab

Maintenance plan

index	year	Maintenance measure	Cost
1.	04'	Slab reconstruction method,(Strengthening, Repair)	45
2.			
3.			
4.			
5.			
6.			

Inspection plan: 04, 09, 14, 19, 24, 29,
Inspection cost: 24
Total cost: 69

Fig. 11. Output screen of maintenance plan for RC slab of Niji-Bridge (Cost minimization).



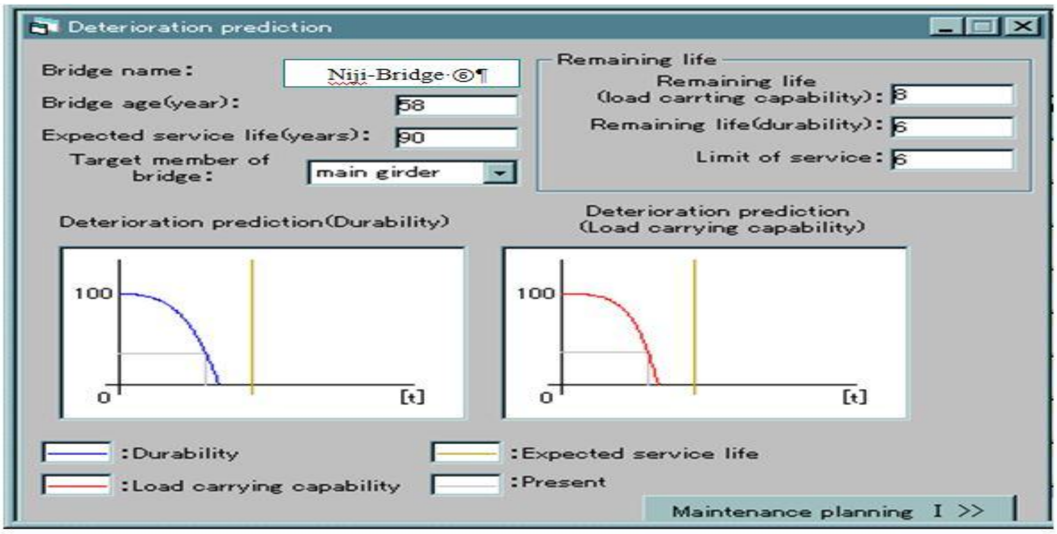
Bridge name: Niji-Bridge ⑥
Target member of bridge: slab
Bridge age (year): 58
Expected service life(year): 90

Remaining life
Present remaing life(years)
Remaining life(load carrting capability): 12.7
Remaining life(durability): 9.34
Limit of service: 9.34

Remaing life after maintenance(years)
Remaining life(load carrying capability): 85.3
Remaining life(durability): 110.
Limit of service: 85.3

Index of quality(Total sum of sudness score/Max,%): 6846/8000,85.5%

Fig. 12. Output screen of prediction of deterioration after maintenance measure implementation (RC slab).



Bridge name: Niji-Bridge ⑥¶

Bridge age(year): 58

Expected service life(years): 90

Target member of bridge: main girder

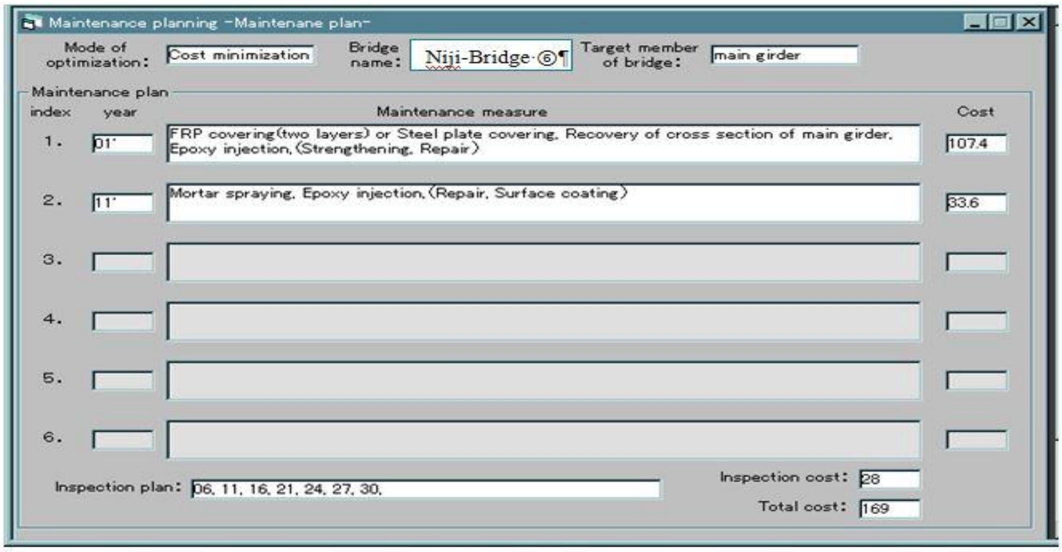
Remaining life

Remaining life (load carrting capability): 8

Remaining life(durability): 6

Limit of service: 6

Fig. 13. Output screen of deterioration prediction for main girder of Niji-Bridge (Span 6).



Mode of optimization: Cost minimization

Bridge name: Niji-Bridge ⑥¶

Target member of bridge: main girder

Maintenance plan

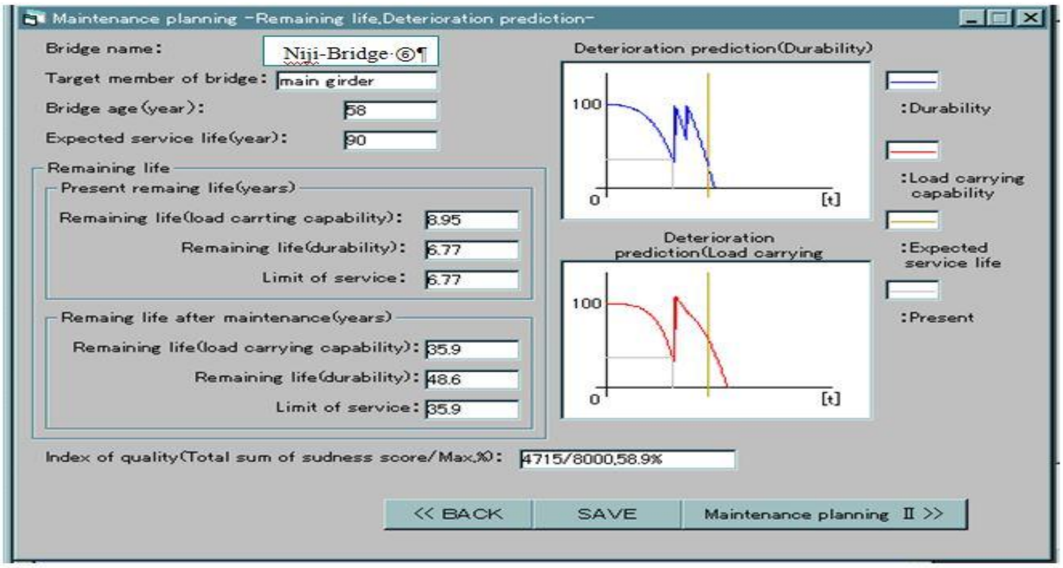
index	year	Maintenance measure	Cost
1.	01'	FRP covering(two layers) or Steel plate covering, Recovery of cross section of main girder, Epoxy injection,(Strengthening, Repair)	107.4
2.	11'	Mortar spraying, Epoxy injection,(Repair, Surface coating)	33.6
3.			
4.			
5.			
6.			

Inspection plan: 06, 11, 16, 21, 24, 27, 30,

Inspection cost: 28

Total cost: 169

Fig. 14. Output screen of maintenance plan for main girder of Niji-Bridge (Cost minimization).



Bridge name: Niji-Bridge ⑥¶

Target member of bridge: main girder

Bridge age (year): 58

Expected service life(year): 90

Remaining life

Present remaing life(years)

Remaining life(load carrting capability): 8.95

Remaining life(durability): 6.77

Limit of service: 6.77

Remaing life after maintenance(years)

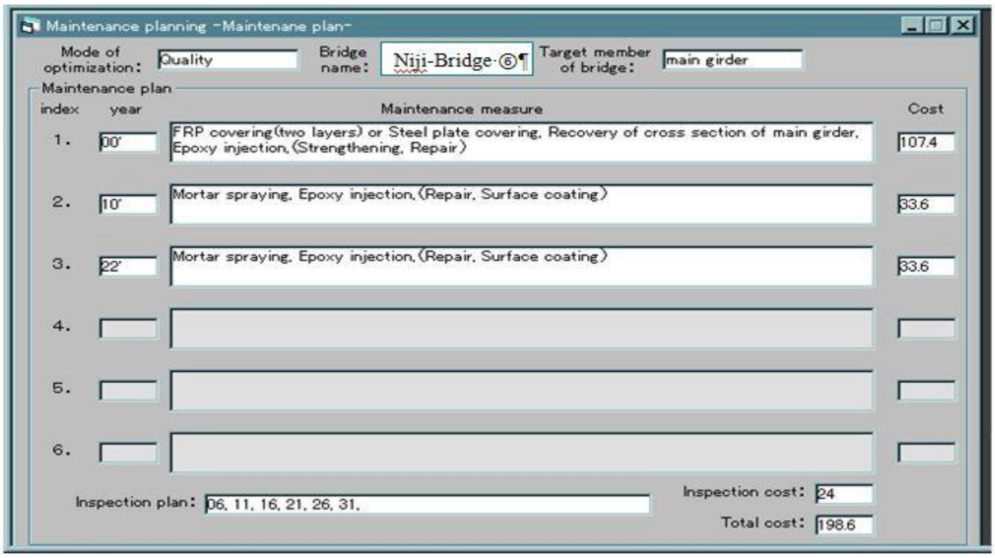
Remaining life(load carrying capability): 35.9

Remaining life(durability): 48.6

Limit of service: 35.9

Index of quality(Total sum of sudness score/Max,%): 4715/8000,58.9%

Fig. 15. Output screen of prediction of deterioration after maintenance measure implementation (Main girder).

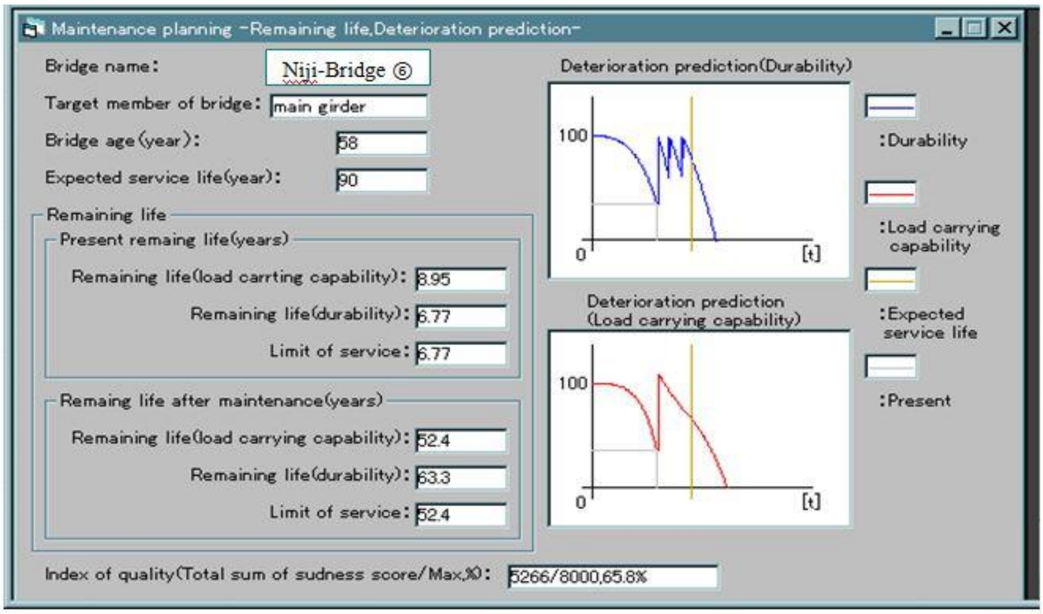


Mode of optimization: Quality
Bridge name: Niji-Bridge ⑥¶
Target member of bridge: main girder

index	year	Maintenance measure	Cost
1.	00'	FRP covering(two layers) or Steel plate covering, Recovery of cross section of main girder, Epoxy injection,(Strengthening, Repair)	107.4
2.	10'	Mortar spraying, Epoxy injection,(Repair, Surface coating)	33.6
3.	22'	Mortar spraying, Epoxy injection,(Repair, Surface coating)	33.6
4.			
5.			
6.			

Inspection plan: 06, 11, 16, 21, 26, 31,
Inspection cost: 24
Total cost: 198.6

Fig. 16. Output screen of maintenance plan for main girder of Niji-Bridge (Quality maximization).



Bridge name: Niji-Bridge ⑥
Target member of bridge: main girder
Bridge age(year): 58
Expected service life(year): 90

Remaining life

Present remaing life(years)
Remaining life(load carrting capability): 8.95
Remaining life(durability): 6.77
Limit of service: 6.77

Remaing life after maintenance(years)
Remaining life(load carrying capability): 52.4
Remaining life(durability): 63.3
Limit of service: 52.4

Index of quality(Total sum of sudness score/Max,%): 5266/8000,65.8%

Fig. 17. Output screen of prediction of deterioration after maintenance measure implementation (Main girder).

The maintenance plan for the RC slab is considered first. Figure 10 shows the deterioration prediction screen. As the graphs indicate, the expected service life cannot be fulfilled unless some kind of maintenance action is taken. Here, the optimal maintenance planning function can be used to optimize a maintenance plan so that the cost is minimized. Figure 11 shows an optimal maintenance plan for Niji-Bridge ⑥ for an expected service life of 90 years. The "year" field shows the year in which a maintenance measure needs to be implemented. The "maintenance measure" field indicates the repair/strengthening method to be used. The cost of the indicated maintenance measure is also shown. The unit of cost, U (unit), is calculated using the conversion rate of 1 U=JY1,000/m^2. Figure 12 shows load-carrying capability and durability deterioration predictions, in the case where the suggested maintenance measure is taken. According to the questionnaire survey results, the domain experts selected the resin grouting method, the steel plate bonding method and the FRP sheet covering method. Domain experts do not usually select the option of RC slab replacement unless traffic can be regulated easily and replacement is thought to be the only means of RC slab restoration. However, the optimal maintenance planning function does not consider traffic regulation and other conditions that need to be taken into account. Furthermore, the "RC slab replacement" option is likely to be selected because the effectiveness of RC slab replacement is rated relatively high. Furthermore, RC slab replacement costs are rated relatively low compared with the other options. The "RC slab replacement" option needs to be made less selectable in the genetic algorithm process by, for example, adding the cost for traffic regulation or requiring inputs as to the feasibility of traffic regulation. Without such improvements, maintenance plan outputs may become unrealistic.

Next, maintenance planning for the main girder is considered. Figure 9 shows a deterioration prediction screen output for the main girder of Niji-Bridge ⑥. The expected service life is set at 90 years and the screen indicates that service life, both in terms of load-carrying capability and durability, cannot be fulfilled unless a maintenance measure of one kind or another is taken. Figure 14 shows a maintenance plan needed to make the expected service life of 90 years possible, whilst meeting the cost minimization requirement. This plan involves the attachment of two layers of FRP sheet covering or steel plating. This is a remedy to be implemented early in the service life. This shows agreement with the remedies recommended by the domain experts (Table 14). Figure 15 shows a screen that indicates load-bearing-capacity- and durability-based deterioration predictions and the remaining service lives in the case that the suggested maintenance measure shown in Figure 14 has been taken. The table indicates that the suggested maintenance measure will enable the bridge to fulfill the expected service life. Figure 16 shows a maintenance plan drawn up so that the requirement of quality maximization is satisfied by increasing the cost under the plan of Figure 14. The modified plan is based on the upper limit of cost of 200U (U is calculated using the conversion rate of 1U=JY1,000/m^2) and includes repair. This was not included in the plan of Figure 14. Thus, as a comparison between Figures 15 and 17 reveals, the quality index has increased from 4715 (58.9%) to 5266 (65.8%). This indicates that the bridge can be maintained with a higher margin of safety.

CONCLUSIONS

This study attempted to develop a decision support system for rehabilitation strategies of existing concrete bridges, based on life cycle analysis. Not only does this proposed system evaluate the serviceability of existing bridge members, but also offers some strategies based on a combination of the maintenance cost minimization and quality maximization approach. Additionally, to demonstrate the suitability of the proposed bridge management system (J-BMS), applications to some existing concrete bridges were presented. The conclusions of this study can be summarized as follows:

1. In order to clarify the difference between repairs and strengthening measures, it was decided to apply load-carrying capability and durability as the respective main indexes of performance for bridge members.
2. The deterioration curve was used to estimate the progressive deterioration of performance of existing bridge members. By assuming functional deterioration, the proposed BMS (J- BMS) is able to estimate the deterioration of the repaired and/or strengthened bridge members. Furthermore, it can display the deterioration on a screen.
3. The proposed J-BMS was applied to an existing bridge. The authors verified that

this BMS is able to estimate the deterioration of bridge members and present various maintenance plans based on cost minimization and quality maximization, using GAs. Thus, GAs are a powerful tool for obtaining an optimal maintenance plan.

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