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Ayaho Miyamoto
Yamaguchi University

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A Bridge Management System (J-BMS) in Japan

A. Miyamoto
Graduate School of Science & Engineering
Yamaguchi University, Ube, Japan

Abstract

This paper presents a new bridge management system (J-BMS) 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 the 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, and was constructed by using Visual Basic and the C language. Furthermore, a comparison of the results of applying this system to some in-service bridges with the results of questionnaire surveys to experts shows that optimal maintenance planning as well as bridge rating can be predicted accurately using this system.

Keywords: integrated lifetime management, information technology, RC bridge, bridge management system (J-BMS), concrete bridge rating expert system (BREX)

1 Introduction

In Japan, many highway bridges were constructed under the national highway network project launched in 1955. However, due to such factors 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. However, due to the limited budget, funds must be split equally between maintaining the deteriorated bridges and constructing new ones.

In practice, however, since around 1990 bridge maintenance costs have increased more than the cost of constructing new ones in many developed countries. Thus, the increasing maintenance costs must be reduced by changing bridge maintenance methods, which once were limited to emergency measures against unpredicted events. The new concept of designing and constructing more durable bridges and thus reducing maintenance costs is becoming common in many countries[1,2]. The highway networks in Japan are comparatively newer than those in other advanced nations. Thus, the financial situation regarding maintenance costs has not faced serious problems yet. However, one report estimates that by around 2010, the ratio of bridges of 50 years of age will be about 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 have been developing a Bridge Management System (J-BMS) integrated with the Concrete Bridge Rating Expert System[3,4,5] that can be used to evaluate the serviceability of existing concrete bridges. The J-BMS will be able to predict the deterioration process of existing bridge members, construct a maintenance plan for repair and/or strengthening based on minimizing maintenance costs and maximizing quality, and estimate the maintenance costs [6,7]. In this system, the Genetic Algorithm (GA) technique was used to search for an approximation of the optimal maintenance plan [8,9,10,11,12,13].

The aim of this study is to develop a practical bridge management system for deteriorated concrete bridges, integrated with the Concrete Bridge Rating Expert System (BREX) [3,4,5] that 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 estimate 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 to experts shows that optimal maintenance planning as well as bridge rating can be predicted accurately using this system.

2 Development of J-BMS

Fig. 1 shows the flowchart of the proposed J-BMS. The J-BMS is applied mainly to the existing reinforced concrete bridges, and target members are main girders and slabs at present stage. The proposed J-BMS is 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 related 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) which 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 [15]. 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, and the

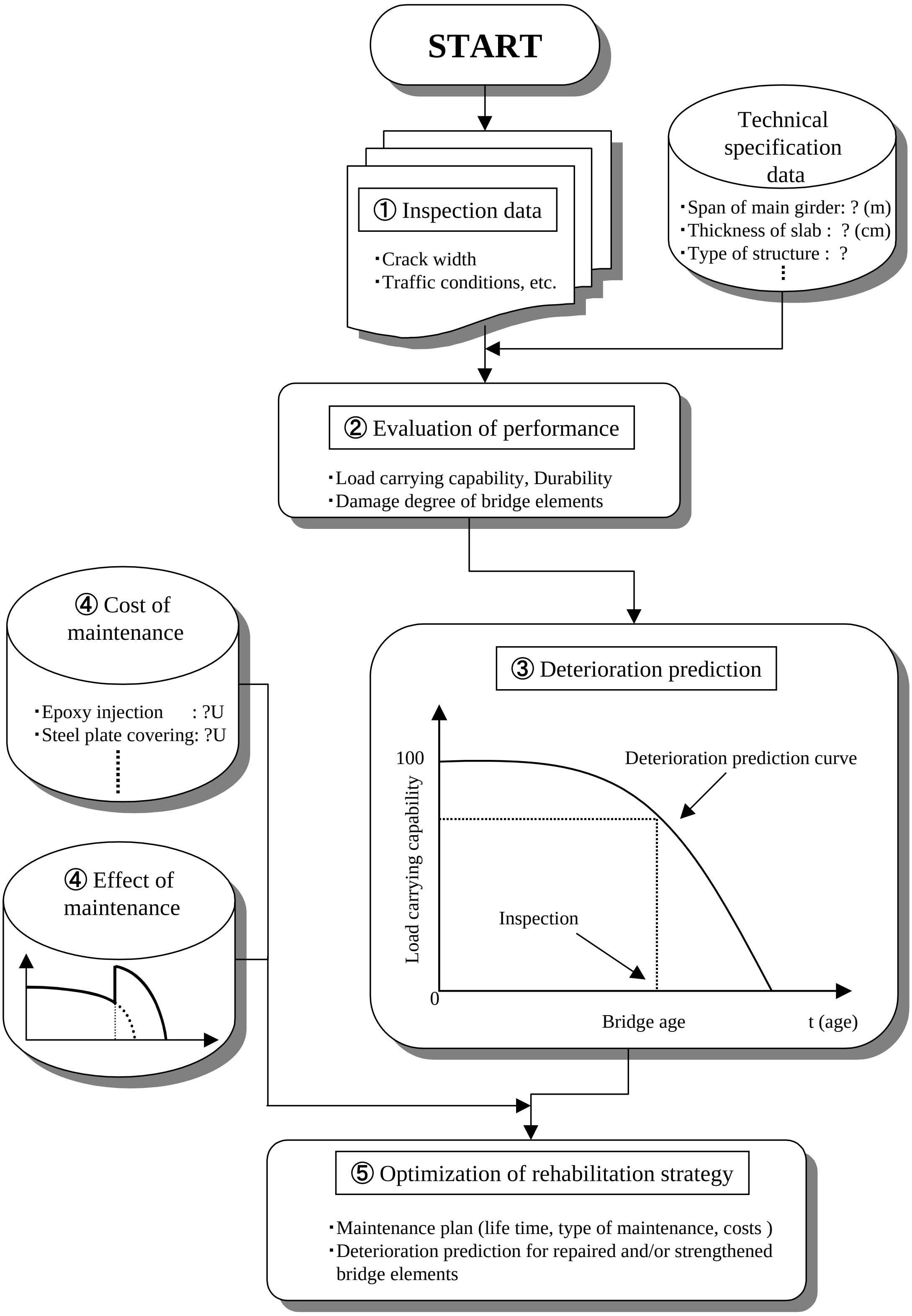


Figure 1: Flow of J-BMS

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).

2.1 Bridge Rating

The authors have been working for some time on the development of an expert system that can be used to evaluate the performance of existing concrete bridges based on knowledge and experience acquired from domain experts [3,4,5]. The proposed expert system evaluates aspects of a bridge's present performance, such as serviceability, load-carrying capability, and durability. It is based primarily on information obtained from simple visual inspection, such as traffic conditions, crack width, etc. though various performances such as serviceability, aesthetic, environmental, functionality, etc. are able to be mentioned as other indexes for evaluation of existing bridges. In the present study, it is also defined that this serviceability is estimated by load-carrying capability and durability. In addition, load-carrying capability is defined as the bridge performance based on the load-carrying capacity of the bridge member, and durability is defined as the ability of the bridge member to resist deterioration based on the deterioration speed of the member. Therefore, these two performances are applied as index to consider the necessity of maintenance for deteriorated bridges. In fact, load-carrying capability is applied as an index to estimate the necessity of strengthening, and then durability 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 which is modeled on the inference mechanism of the domain expert for bridge rating [4,5]. 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 Fig. 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 the present example, the degree of flexural cracking is determined using the inspection data such as spalling 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 in 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 not 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. Although 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 having three layers and can be used to identify nonlinear functions. The if-then relationships are interconnected by bidirectional associative memories. The detail description of developing this expert system is written in reference [6].

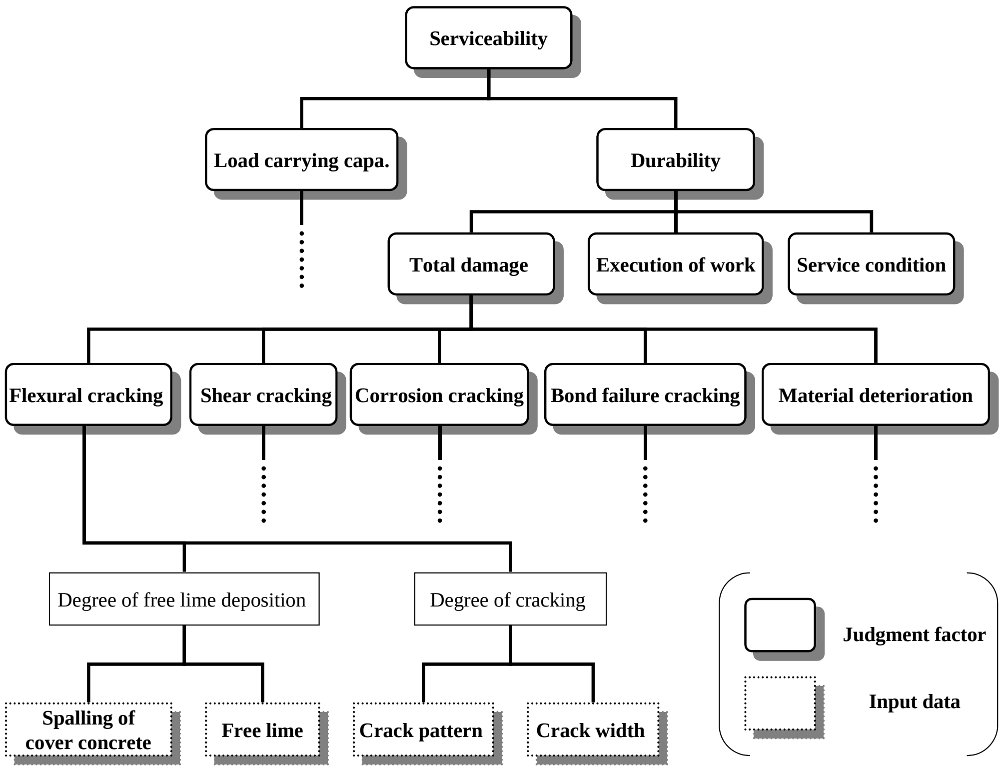


Figure 2: Diagnostic process in BREX

2.2 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. Therefore, prediction curves for the load-carrying capability and durability, respectively, are used to perform deterioration estimation though various deterioration prediction methods such as transition probability matrix have been proposed in several other papers [14,16,17]. The following assumptions were made in constructing the deterioration prediction curves of the present study.

①The 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 and 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 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 : constants, t : 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 referred to collectively as maintenance.

Since at present no data exists for the deterioration curve of load-carrying capability, the curve is defined as a biquadratic function based on experimental data collected in previous experiments by the present authors [18,19]. 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) because the transition of the deterioration state is affected 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, on which 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.

③The deterioration curves up to the first inspection ,that is, $f_{(0)}(t)$ and $g_{(0)}(t)$ are given by two elements: 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.

④ Repairs and strengthening influence the load-carrying capability and the durability of the bridge members. The deterioration curve after maintenance 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 the remaining life of the target bridge.

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,

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

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

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

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

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

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

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

2.3 Effect of maintenance

Although a new method has been presented which clarifies the effect of repairs and/or strengthening on the deterioration prediction curves of the load-carrying capability and the durability, this method can not 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. Therefore, 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, while 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 Fig. 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 and the previous one were obtained and are listed in Table 1 and Table 2 [6]. In future studies, these tables should be modified using experimentally acquired data since the values presented here are strictly hypothetical.

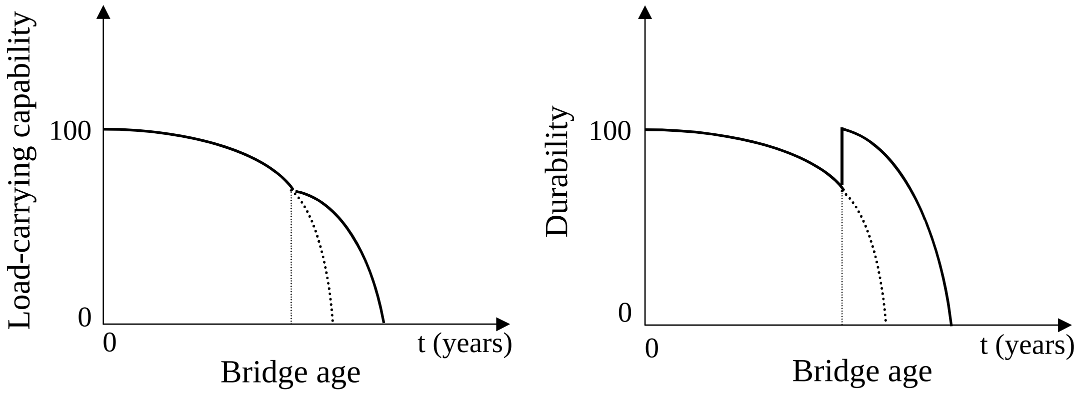
As an example, the influences of maintenance measures for the main girder are explained. In order to determine the recovery degree of performance, the following assumptions were made according to the above basic concept for the effect of maintenance. In the present J-BMS, epoxy injection, recovery of 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*]

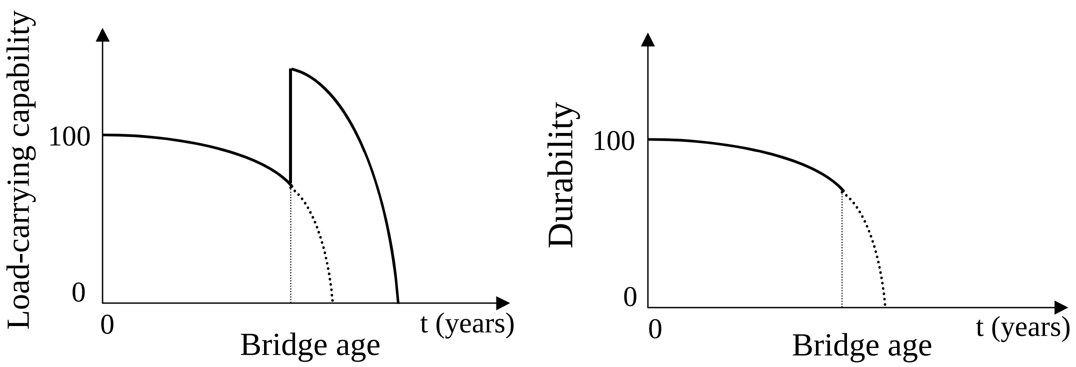
① If epoxy injection or recovery of cross section is performed, the mean soundness score of durability would grade up to 100, because the purpose of repair is to recover durability reaching the newly built condition.

② Since it is assumed that the repair affects not only the recovery of durability but also the deterioration speed of load-carrying capability, if epoxy injection or recovery of cross section is performed, the velocity of the prediction curve for load-carrying capability would slow down. 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 is different from the basic concept of effect on repair. If the surface coating measures are used, the effect of that is to slow gown the velocity of the prediction curve for durability. As it is assumed that the surface coating measure enables the speed of deterioration of durability to be restrained, though the durability can not be recovered, that is, grading up by these measures. In the present study, glass cloth and mortar spraying are considered as surface coating method for the main girder.



(a) Effect of repair



(b) Effect of strengthening

Figure 3: Basic concept of maintenance effect

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

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.U

Note: R = Repair, S = Strengthening

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

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

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

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

[*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. Therefore, Retrofit has to be considered in the case of strengthening. The load-carrying capability of bridges designed by 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 (4 layers) have similar effect. The effect of steel plate covering is shown in Table 2, which is calculated according to the transition of design load for uniform load. In addition, the following assumptions were made. The effect of FRP (2 layers) is smaller than that of steel plate covering and FRP (4 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.

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

③In addition, 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. 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, this bridge 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 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 can be 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.

$$f_{(i)}(t) = b_{L(i)} - a_{L(i)}t^4 = \{b_{L(i-1)} - (1/2)a_{L(i-1)}(t'')^4\} - (1/2)a_{L(i-1)}t^4 \tag{7}$$

- 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 as follows.

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

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

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

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

$$g_{(i)}(t) = b_{D(i)} - a_{D(i)}t^3 = \left\{100 + a_{D(i-1)}(t'')^3\right\} - a_{D(i-1)}t^3 \tag{12}$$

2.4 Optimization of rehabilitation strategy

(1) Modeling of maintenance planning [18,20,21,22]

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. In addition, 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 modeled as a combinatorial optimization problem, because the maintenance plan is comprised of various maintenance measures as illustrated in Fig. 4. The analysis period begins from the present age of bridge (denoted by *t'*) and runs until the expected service life (*T*). 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, No strengthening) as well as combinations of repairs and/or strengthening measures.

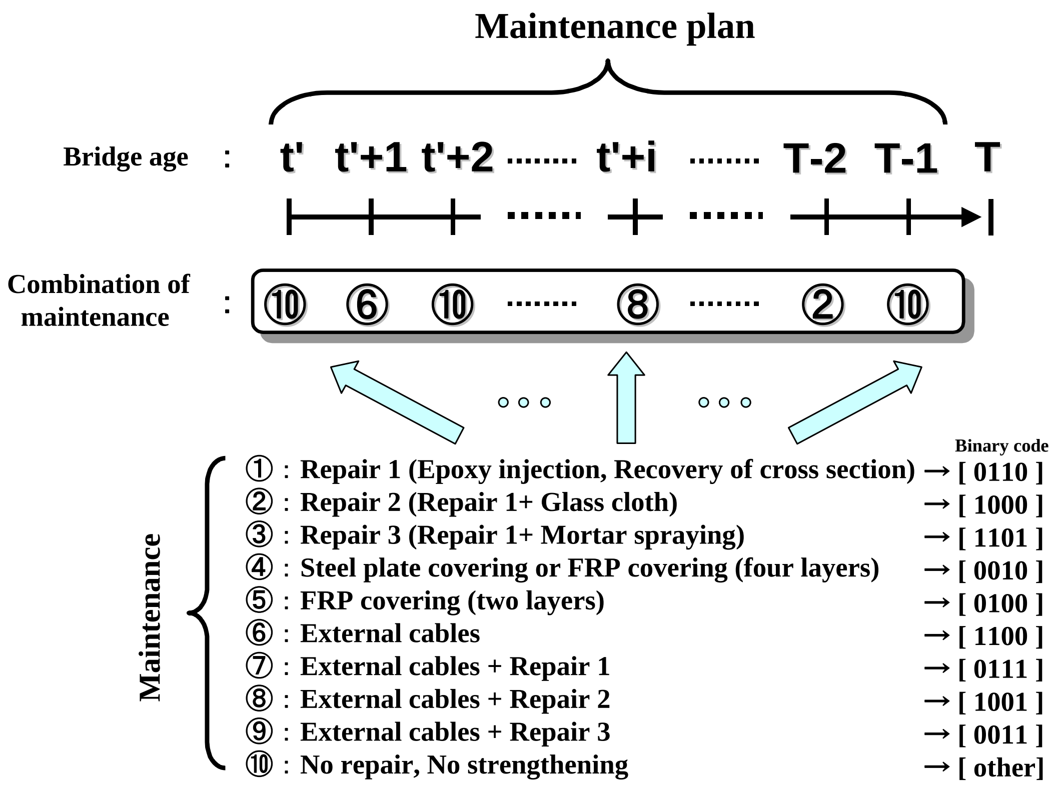


Figure 4: Maintenance planning

Many aspects influence the choice of rehabilitation strategy. Therefore, 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 (see Eq. (13)) and the maximization of bridge quality (see 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. Therefore, the present optimization problem of rehabilitation strategy is described by the following multi-objective combinatorial optimization:

Objective: $$F_1 = \sum_{t=t'}^{T-1} C_{tj} \quad \rightarrow \quad \min \tag{13}$$

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

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

where

t : Bridge age (years),

j : 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),
$S_L(t)$: Mean soundness score of load-carrying capability in the year t,
$S_D(t)$: Mean soundness score of durability in the year t,
C_{tj} : Cost of maintenance measure j carried out in the year t,
F_1 : Total cost of maintenance measures,
F_2 : 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 ε-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 ε-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 (see Eq. (13) and Eq. (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: $F_2 \rightarrow \max$ (16)

Subject to:
$$F_1 \leq \varepsilon = Cost1 + \alpha \quad (17)$$

where α= 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 [9,24]. 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, each of which contain 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, so as to create the next generation. A new generation is formed by selecting some of the parents and offspring according to their fitness, the fitness values determined by the fitness function, and rejecting others 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.

(a) Representation and Evaluation of a candidate solution

Generally, the genetic operators are performed on symbolic strings. Therefore, 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 easy manipulation of genes, this method of encoding is used in the present study, as shown in Fig. 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 ten possible maintenance measures for a main girder, as shown in Fig. 4, the maintenance measures for a main girder are represented by a 4-bit binary code. However, since 4-bit binary code is capable of expressing sixteen different values, and hence sixteen different types of maintenance measure, one-to-one correspondence between maintenance and binary code would yield a number of illegal offspring having 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 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. The 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). Where G_1 and G_2 are the fitness function, F_1 and F_2 are the objective function corresponding to Eq. (13) and Eq. (14).

$$G_1 = \frac{1}{F_1} = \frac{1}{\sum_{t=t'}^{T-1} C_{tj}} \tag{18}$$

$$G_2 = F_2 = \sum_{t=t'}^{T} \{S_L(t) + S_D(t)\} \tag{19}$$

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 (see Eq. (15)), then 5000U is added to the total cost. In addition, 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.

Maintenance plan

Bridge age (year)	Maintenance	Coding	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

Individual

t' : Present age *T* : Expected service life

Figure 5: Binary representation of maintenance plan

(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 is 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 2, which is a common size. Here, the individual having higher 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. Therefore, 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. Therefore, 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, in which a randomly selected cut-point is used to divide the parents into upper and lower segments (see Fig. 5). The upper segments of the parents are then exchanged to generate the two offsprings. The parents are chosen by tournament selection in the present study. 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.

Although crossover operations are used to improve the fitness of individuals, GAs occasionally give a local solution as the optimal solution. Therefore, 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 4 bits (4 genes), and the value of the chosen bit is flipped. For example, a gene having a value of 1 is changed to 0. This mutation method transfers the maintenance measure to four other measures of which the Hamming distance is 1. The correspondence between the maintenance measure and the binary code should be considered with respect to the Hamming distance. Therefore, each maintenance measure is represented by a binary code as shown in Fig. 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.

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%

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

3 Application of J-BMS to Existing Bridges

In here, the J-BMS is applied to seven existing bridges (nine spans) which are all RC T- girder type bridges, in order to test its validity. 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 also shown in Table 3.

In the proposed J-BMS, the target bridge data are first entered into the computer as shown in Fig. 6 which is an input screen of inspection data. As an example, Figs. 7 and 8 gives 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 those data, the J-BMS evaluates the present performance of the bridge. Fig. 9 shows the performance evaluation of H-bridge main girder obtained using the BREX system.

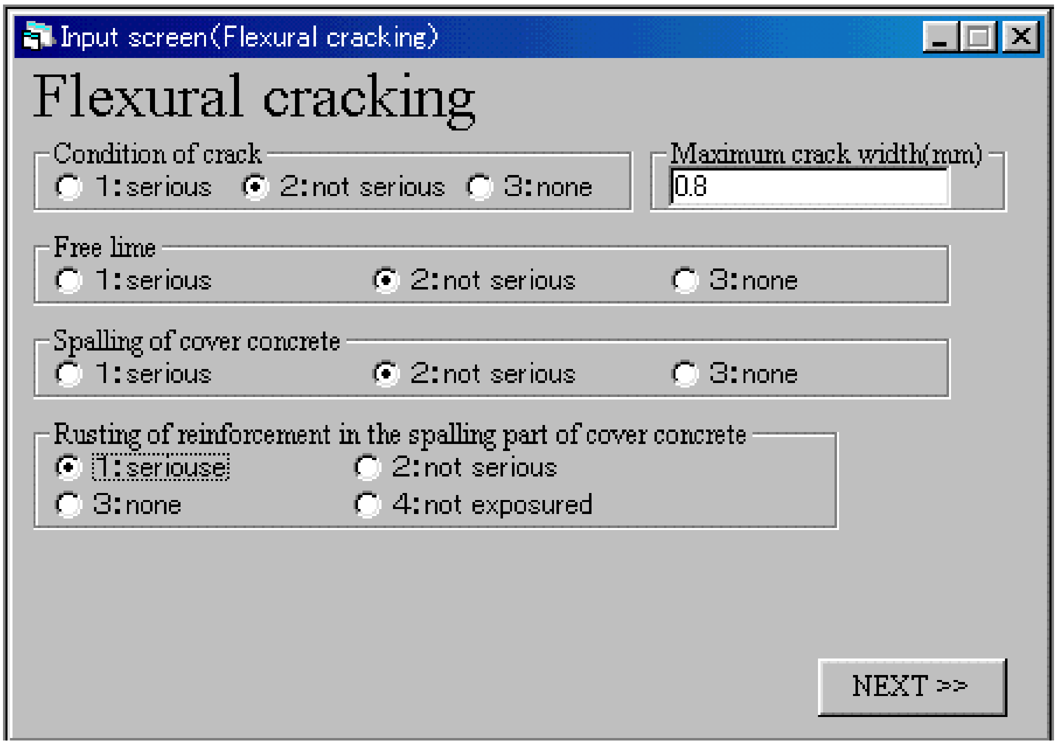


Figure 6: Input screen

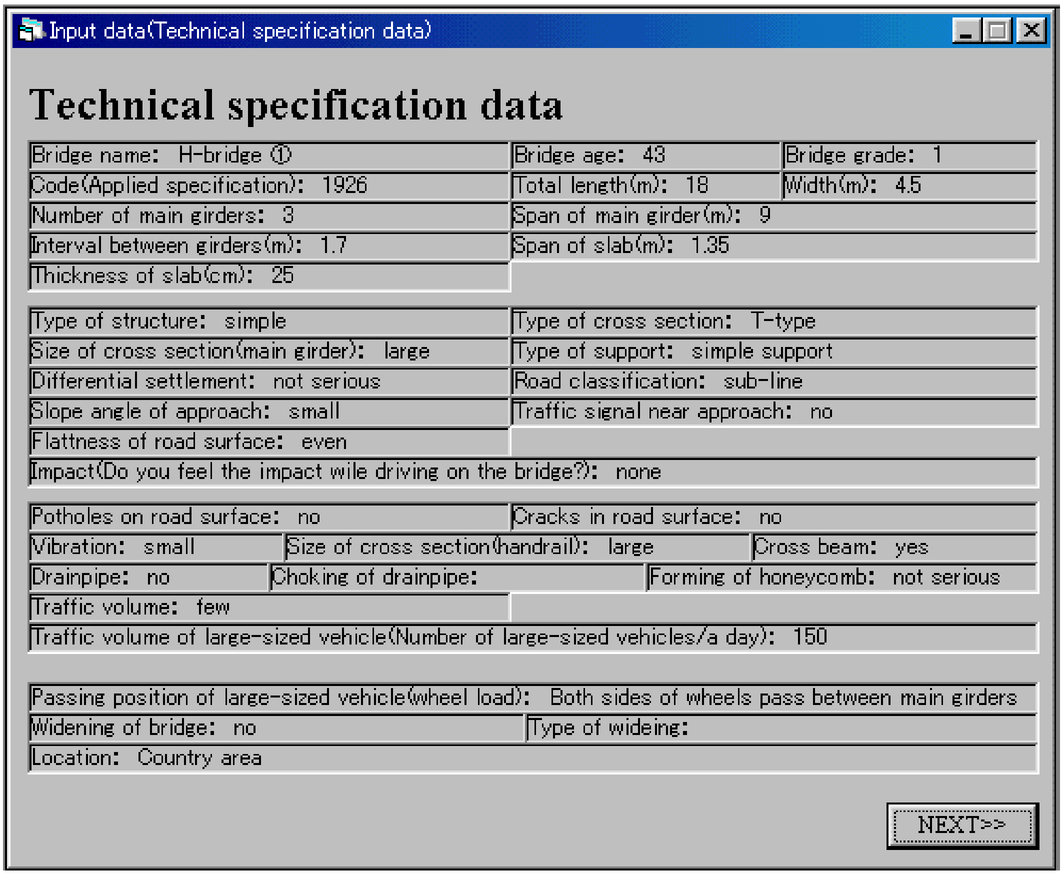


Figure 7: List of technical specification data

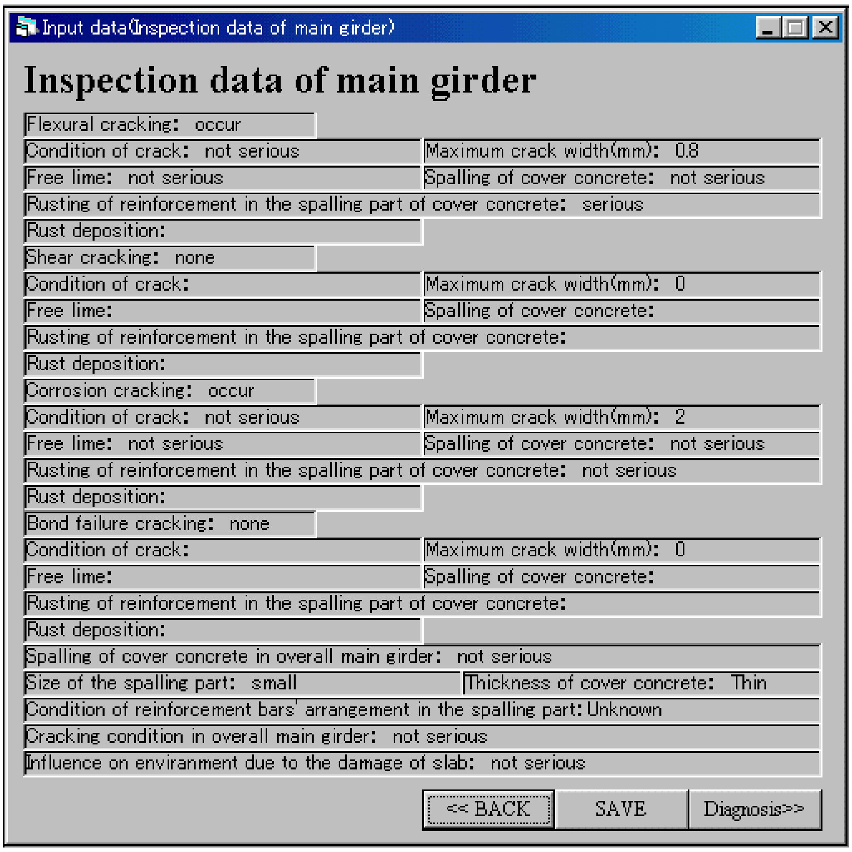
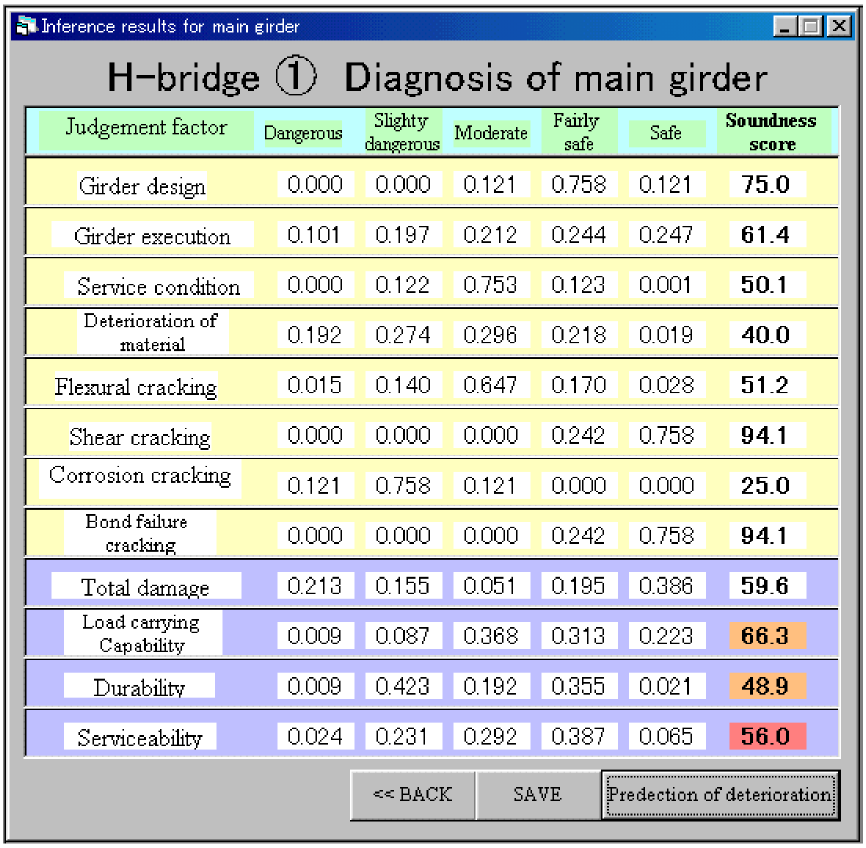


Figure 8: List of inspection data for main girder



Inference results 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

<< BACK SAVE Predection of deterioration

Figure 9: Evaluation of performance

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

Purposes of Questionnaire Survey and Visual Inspection

The purpose of the questionnaire survey is, 1) to collect data that can be used to verify the practical applicability of the functions of the bridge management system (J-BMS) and, 2) to acquire teacher data necessary for learning associated with the deterioration estimation function of the system. On the other hand, 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. In 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 inspected visually. In the morning of the second day, three spans of two bridges under the jurisdiction of Mine office of civil and building engineering division were inspected visually, and then, 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 consists of 1) inspection record sheets (8 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 are formatted so that the respondents can 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, for example, whether there is a traffic signal and whether there are transverse beams, were entered in advance on behalf of the respondents. The questionnaire sheets are formatted so that for questions designed to obtain teacher data necessary for the deterioration estimation function, the respondents can 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 are to choose from a number of indicated ranges of periods, for example, 10 years or less, 11 to 20 years, and so on. Questions concerning repair/strengthening methods are 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.

<u>*Deterioration Estimation Function*</u>

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≤G<12.5), "slightly dangerous" (12.5≤G<37.5), "moderate" (37.5≤G≤62.5), "fairly safe" (62.5<G≤87.5), and "safe" (87.5<G≤100.0).

Age of bridge (years)	43	58	41	31		32	42		29
Bridge name / Judgment item	Hataka①	Niji⑥	Nobutaka ①	Mine①	Mine③	Getusyou ③	Tobimatu ①	Tobimatu ②	Ougame ②
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 4: Results of RC slab deterioration estimation by domain experts (training data)

Bridge name / Judgment item	Hataka①	Niji⑥	Nobutaka ①	Mine①	Mine③	Getusyou ③	Tobimatu ①	Tobimatu ②	Ougame ②
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)

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

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[24]). 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 was not used for the 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 are 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 are 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), and 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.

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 show agreement with the questionnaire results, 36 RC-slab-related items and 27 main-girder-related items show a value one order deviant from the teacher value, and 2 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. Overall error for the Niji-Bridge's main girder was greater than that for any other bridge inspected in this study. As can be seen from Table 5, which shows that teacher values for the evaluation items for Niji-Bridge are smaller than those for the other bridges, the domain experts surveyed think that of the bridges inspected in this study, 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 reason why the system outputs differed considerably from the domain experts' judgments is this: 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 and 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 done adequately. These results indicate that although the reliability of the

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 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
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 7: Estimation results obtained by using the deterioration estimation function (main girders)

deterioration estimation function is depend on information on the distribution of bridge damage used for neural network learning, that 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 from the viewpoints of the durability and load carrying capability of RC slabs and main girders. As shown, the questionnaire survey focused on which ten-year periods the predicted service lives fall into. The numerals in parentheses shown under bridge names are load carrying capability or durability values predicted by domain experts (see Tables 4 and 5). The characters A through G shown in the tables represent the domain experts who participated in the questionnaire survey.

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 are summarized in Table 12. 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 are shown at the bottom lines of Tables 8 to 11. The shaded areas in the tables indicate the following: indicates the remaining service life categories to which the remaining service life predictions outputted by the deterioration prediction function belong.

The domain experts were asked to specify bridge ages at which they feel a concrete bridge is safe. Although their replies varied somewhat from person to person, the maximum age at which they feel a bridge is safe is about 50 years, and a bridge age at which they begin to feel that the bridge is dangerous is around 70 years. The results of the remaining service life survey of the bridges inspected are such that the sums of the present ages of the inspected bridges and the remaining service lives predicted by the domain experts roughly range from 50 to 70 years. The relationship between the load-carrying capability and durability scores assigned by the experts and the predicted remaining service lives does 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.

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 than the domain experts. It can be said, however, that the system outputs show fairly good agreement with expert judgments about remaining service

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)	Ougame ② (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 8: Remaining service lives of RC slabs from the viewpoint of durability

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)	Ougame ② (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 9: Remaining service lives of RC slabs from the viewpoint of load-carrying capability

life. It can be concluded, therefore, that the deterioration prediction method adopted for the deterioration prediction function closely simulates expert judgments about 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 thought require a maintenance action. From the tables, it can be cleared as followings;

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, while it was

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 10: Remaining service lives of main girders from the viewpoint of durability

Bridge name / Remaining Service life	Hataka① (67.1)	Niji⑥ (35.7)	Nobutaka ① (70.0)	Mine① (76.7)	Mine③ (76.7)	Getusyou ③ (81.7)	Tobimatu ① (70.0)	Tobimatu ② (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 11: Remaining service lives of main girders from the viewpoint of load-carrying capability

	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 12: Domain expert data

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 of reinforcement exposure 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, and 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, and 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 by 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 assumed to be 90 years.

Bridge Name	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 13: Repair/strengthening methods selected for RC slabs 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	

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

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

The maintenance plan for the RC slab is considered first. Fig. 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. The optimal maintenance planning function can be used here to optimize a maintenance plan so that cost is minimized. Fig. 11 shows an optimal maintenance plan for Niji-Bridge ⑥ for an expected service life of 90 years. The "year" field shows a year in which to implement a maintenance measure, and 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. Fig. 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 usually do not 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. The optimal maintenance planning function, however, does not take into consideration traffic regulation and other conditions that need to be taken into account. Furthermore, the "RC slab replacement" option is likely to be selected easily because the effectiveness of RC slab replacement is rated relatively high and its cost rated relatively low compared with those of 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. Fig. 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. Fig. 14 shows a maintenance plan needed to make the expected service life of 90 years possible while meeting the requirement of cost minimization. This plan involves the attachment of two layers of FRP sheet covering or of steel plating as a remedy to be implemented early in the service life, showing agreement with the remedies recommended by the domain experts (see Table 14). Fig. 15 shows a screen that shows load-bearing-capacity- and durability-based deterioration predictions and the remaining service lives in the case the suggested maintenance measure shown in Fig. 14 has been taken. The table indicates that the suggested maintenance measure will enable the bridge to fulfill the expected service life. Fig. 16 shows a maintenance plan drawn up so that the requirement of quality maximization is satisfied by increasing the cost under the plan of Fig. 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, which was not included in the plan of Fig. 14. Thus, as comparison between Figs. 15 and 17 reveals, the quality index has increased from 4715(58.9%) to

5266(65.8%), indicating that the bridge can be maintained with a higher margin of safety.

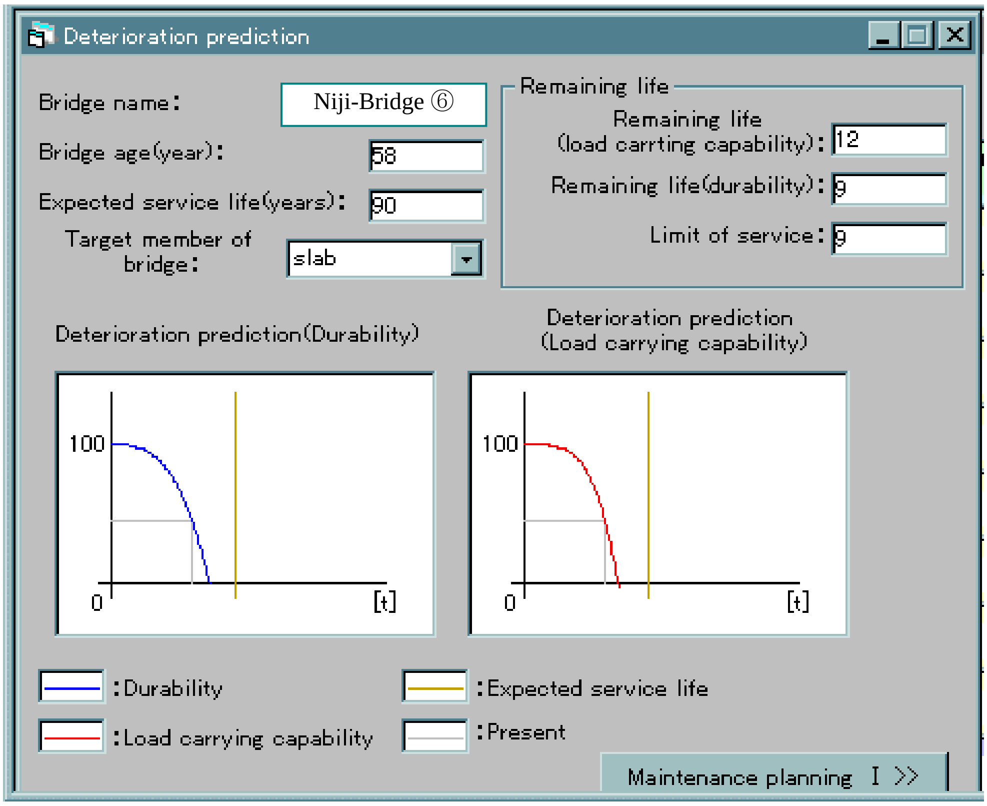


Figure 10: Output screen of deterioration prediction for RC slab of Niji-Bridge

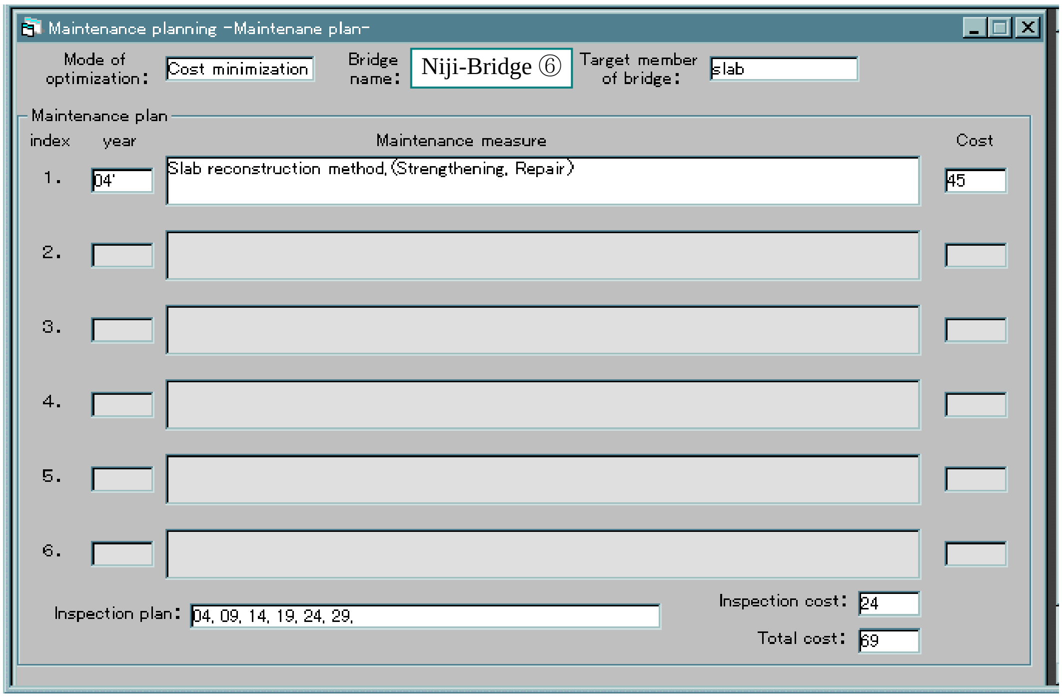


Figure 11: Output screen of maintenance plan for RC slab of Niji-Bridge (Cost minimization)

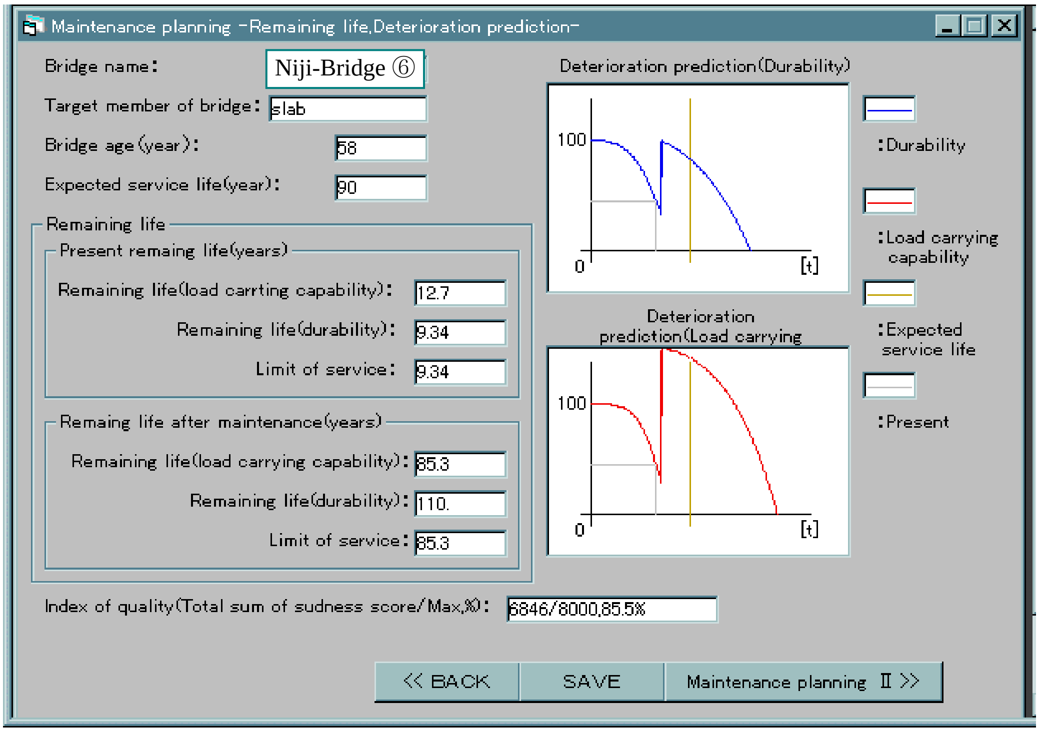


Figure 12: Output screen of prediction of deterioration after maintenance measure implementation (RC slab)

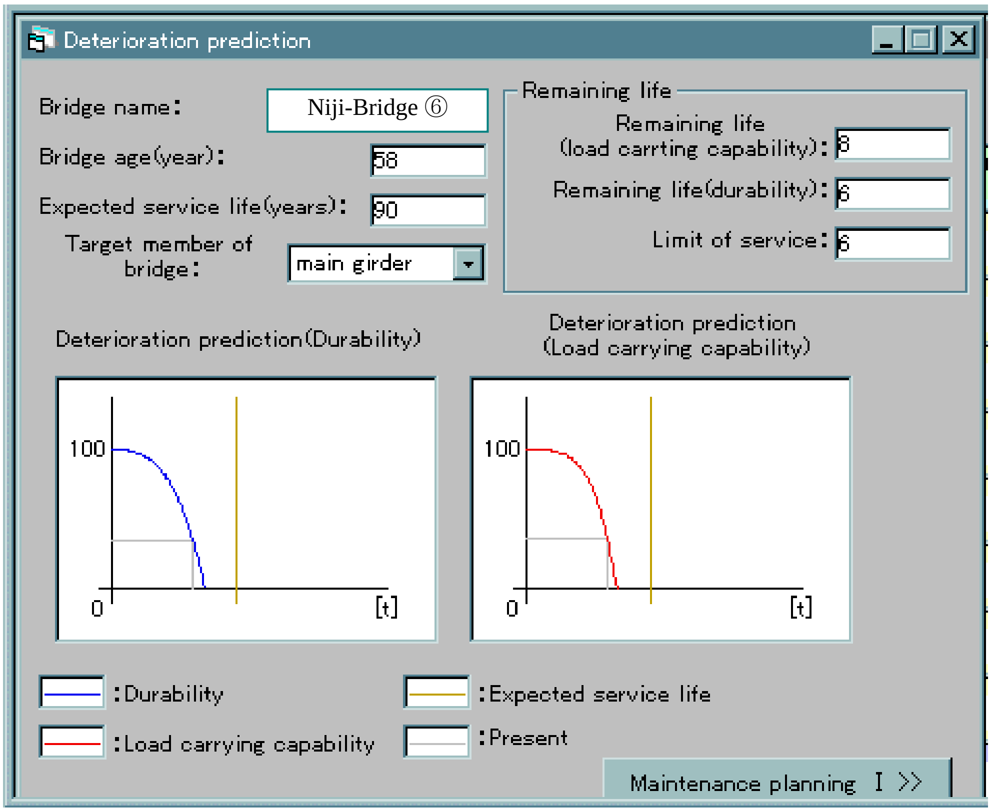


Figure 13: Output screen of deterioration prediction for main girder of Niji-Bridge (span 6)

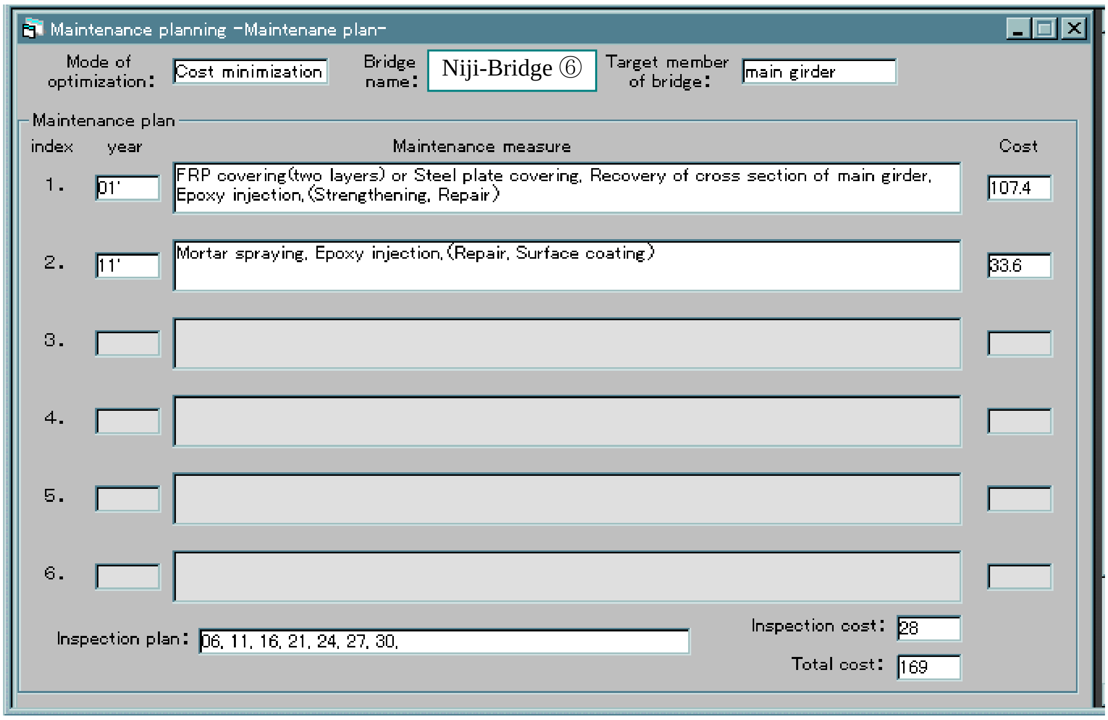


Figure 14: Output screen of maintenance plan for main girder of Niji-Bridge (Cost minimization)

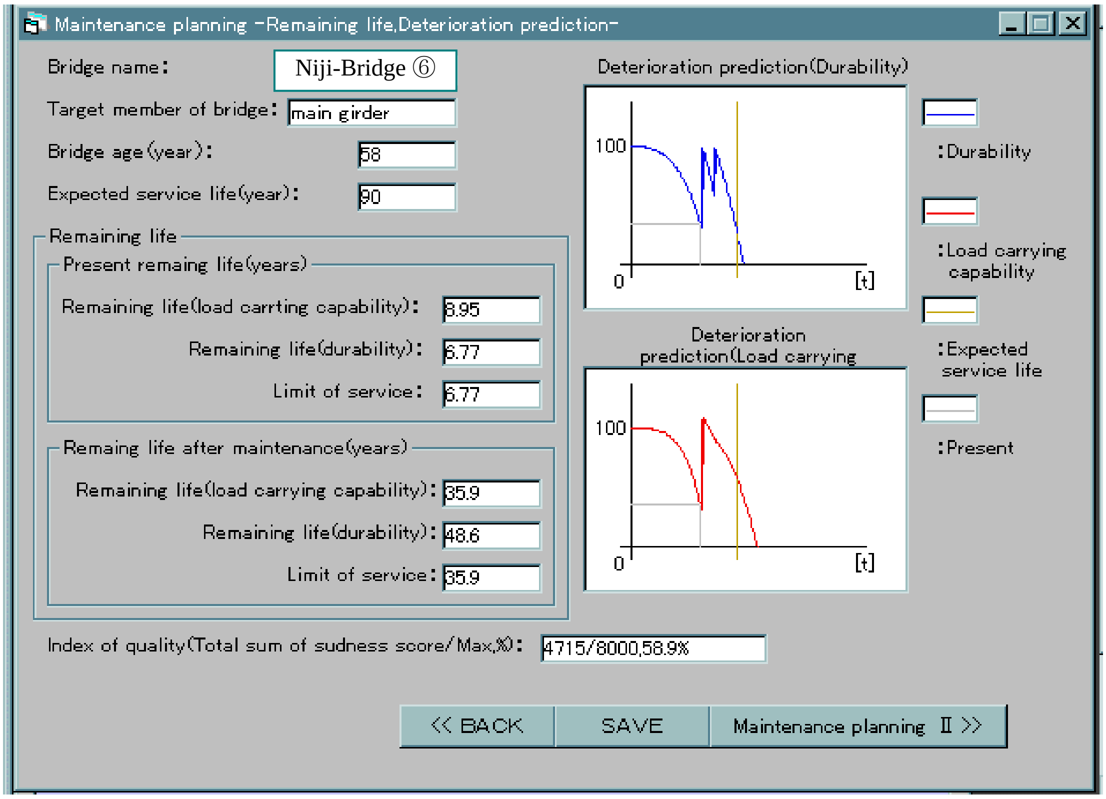


Figure 15: Output screen of prediction of deterioration after maintenance measure implementation (Main girder)

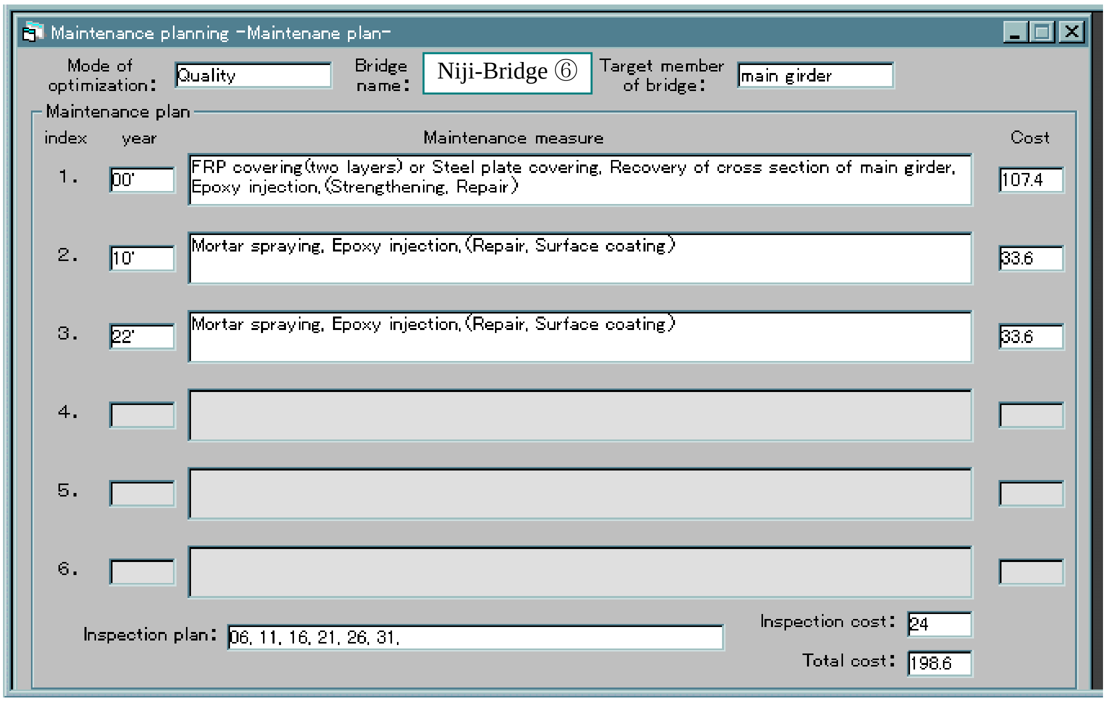


Figure 16: Output screen of maintenance plan for main girder of Niji-Bridge (Quality maximization)

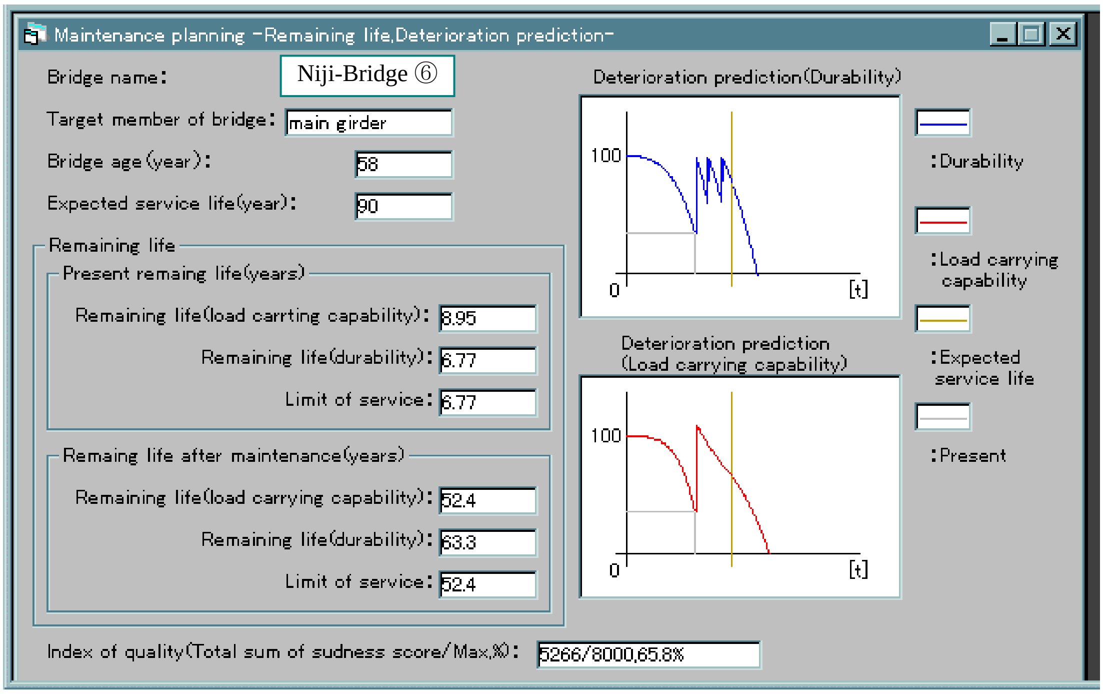


Figure 17: Output screen of prediction of deterioration after maintenance measure implementation (Main girder)

4 Conclusions

This study attempted to develop a decision support system for rehabilitation strategies of existing concrete bridges based on life cycle analysis. This proposed system is able to not only evaluate the serviceability of existing bridge members, but also offer some strategies based on a combination of maintenance cost minimization and quality maximization approach. And also, applications to some existing concrete bridges were presented so as to demonstrate the suitability of proposed bridge management system(J-BMS). 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, and also to 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 also quality maximization using GAs. GAs are thus a powerful tool for obtaining an optimal maintenance plan.

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