Development of a Bridge Management System for Existing Bridges

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Abstract

Recently, the rehabilitation of bridges has become a major social concern because the number of damaged bridges has increased in Japan. Thus the necessity of developing a practical bridge management system points out. The present study is an attempt to develop a new bridge management system (J-BMS) for damaged concrete bridges. The 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. Furthermore, application to existing concrete bridges is presented so as to demonstrate the validity of the system.

Key words : Bridge Management System (BMS), repair, strengthening, durability, load-carrying capability, maintenance plan, combinatorial optimization, Genetic algorithms(GAs)

1 Introduction

Unfortunately, since 1990, bridge maintenance costs have increased in several developed countries, to the point where it is now more expensive to maintain damaged bridges than to build new ones. Several bridges have deteriorated considerably in recent years due to factors such as the increase in traffic volume, the increase in the weights of vehicles and the structural aging. However, due to budget limitations, funds for such rehabilitation must be drawn from sources that were originally procured for the construction of new bridges.

Therefore, the reduction of maintenance costs is a challenge that must be met in future bridge maintenance planning, which was previously limited to contingency planning in the event of an emergency. Depending on the severity of deterioration and availability of limited funds, repair or strengthening of these bridges is essential. Fortunately Japan's highway network is comparatively newer than those of other developed countries, because several thousands of highway bridges have been constructed through the National Highway Network project, which was initiated in 1955. Therefore maintenance costs have not yet become a serious problem in Japan. However, a report has indicated that by approximately 2010, the percentage of bridges that are 50 years of age or older will be approximately 35%. Therefore, the development of a comprehensive bridge management system (BMS) for existing bridges is essential. Such a system should enable not only the evaluation of bridge performance, but also the suggestion of rehabilitation strategy which takes into account the limited funds that are available for bridge construction/maintenance. On the other hand, in the case of newly-established bridges, the concept of designing and constructing bridges that have greater durability, thereby reducing maintenance costs during in-service, has attracted several countries.

Although the ultimate goal of the present study is to develop an integrated bridge management system that can be applied to all bridges in a highway network, the present paper suggests a concept to develop a BMS for damaged concrete bridges. In this study, the BMS is referred to as J-BMS which means Japanese Bridge Management System. It is a decision support system. The J-BMS evaluates the performance of concrete bridges based on visual inspection, predicts the deterioration processes for existing bridge members and allows some maintenance plans for repairs and/or strengthening to be created based on maintenance cost minimization and quality maximization as a rehabilitation strategy on a concrete bridge. Furthermore, the system is constructed using Visual Basic and C language so as to demonstrate how J-BMS works concretely.

2 Outline Description of J-BMS

The J-BMS is applied to existing reinforced concrete bridges. Also, target members are main girder and slab at present. **Figure 1** shows the flow of J-BMS.

For existing concrete bridges, the first step in the J-BMS involves a simple visual inspection of the target bridge (see ① in **Figure**

1). Next, the performance of the bridge members is evaluated using the obtained inspection data and the technical specifications of the bridge (see ②). This evaluation is performed using a program referred to as the Concrete Bridge Rating Expert System which is currently under development by the present authors [1, 2, 3, 4]. The system is called BREX, which is the abbreviation of concrete Bridge Rating EXpert system. It is integrated into J-BMS. The outputs of this evaluation include the soundness scores for load-carrying capability, durability, etc., which are given on a scale of 0-100. 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 (see ③). As a preliminary step, the effect of repairs and strengthening are estimated, and the cost of each maintenance measure is determined, thereby enabling the estimation of maintenance costs and the prediction of remaining life after maintenance (see 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. The strategy includes various maintenance plans provided by the cost minimization or quality maximization (see ⑤). Genetic Algorithms (GAs) are adopted to search for an optimal maintenance plan bases on the cost minimization or quality maximization. These algorithms, which are based on the theory of evolution, create a suitable individual (optimal solution) through the repetition of three operators: selection, crossover and mutation. As a result, the application of GAs to the optimization problem enables an approximate optimal solution to be quickly determined.

3 Development of J-BMS

3.1 Performance evaluation of existing damaged bridges

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 [1, 2, 3, 4]. The expert system integrated into J-BMS, namely, BREX evaluates aspects of a bridge's present performance, such as serviceability, load-carrying capability, and durability, though various performances such as aesthetic, environmental and functionality are able to be mentioned as other indexes for evaluation of existing bridges. In the present study, it is also defined that the 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 a bridge member, and durability is defined as the ability of a bridge member to resist material deterioration. Therefore, these two performances are applied as index to consider the necessity of maintenance for damaged 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 J-BMS.

In the expert system, diagnosis is performed according to a process that is modeled on the inference mechanism of the domain expert for bridge rating [1, 3]. This process has a hierarchical structure in which the ultimate goal is “serviceability”. As an example, the diagnostic process for a main girder is shown in **Figure 2**. In the 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 and 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 the system is the serviceability, which is evaluated according to the load-carrying capability and durability. These judgment factors are assigned a 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 is no problem. "fairly safe" indicates that there are not serious damage. "moderate" indicates that there are some damage 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 BREX is described in the following. The system uses neural networks to provide a machine learning method and fuzzy inference method. Although the 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 the expert system is written in reference [1, 4].

3.2 Deterioration prediction

The present performance of existing bridge members can be evaluated using BREX. However, the 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 [5, 6, 7]. The following assumptions were made in constructing the deterioration prediction curves of the present study.

①The deterioration curves for bridge members are drawn as an integrated convex graph in which the vertical axes represent the 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 soundness scores of load-carrying capability and durability obtained from BREX are described below as $S_L(t)$ and $S_D(t)$, respectively.

$$S_L(t) = f(t) = b_L - a_L t^4 \qquad (1)$$

$$S_D(t) = g(t) = b_D - a_D t^3 \qquad (2)$$

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 BREX. In addition, $f_{(i)}(t)$ and $g_{(i)}(t)$ express the deterioration functions after the ith 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 [8, 9].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.

②The 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: one is the score when the newly built bridge enters service, namely, $(t, S_L(t))=(0, 100)$, $(t, S_D(t))=(0, 100)$, and the other is the soundness score at first inspection, which is obtained using BREX.

④Repairs and strengthening influence the load-carrying capability and the durability of 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 a bridge.

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

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

$(t, S_L(t))=(0, 100)$, $(60, 50)$ are assigned to **Equation (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,

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

・ $g_{(0)}(t)$ 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.

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

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

3.3 Effect of maintenance

The following present an idea related to the effect of repairs and/or strengthening on the deterioration prediction curves of the load-carrying capability and the durability. 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 such that if the bridge is strengthened, the load-carrying capability soundness score improves. Then, the basic concept of the repair effect is such that if the bridge is repaired, the durability soundness score improves and the velocity rate of change of the load-carrying capability prediction curve slows down, that is to say, the speed of deterioration in terms of the load-carrying capability slows down. The basic concept of this effect is depicted in **Figure 3**. Furthermore, the recovery degrees of performance (load-carrying capability and durability) associated with repairs and/or strengthening are listed in **Table 1** and **Table 2** [10]. These values were judged by an expert and comparing the present standard of design and the previous one. The recovery degrees of load-carrying capability depend on the year designed, namely, the transition of design load. 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 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]

①If Epoxy injection or Recovery of cross section is performed, the soundness score of durability would grade up to 100, because the purpose of repair is to recover durability reaching the newly built condition. (see **Figure 3** and **Table 1**)

②Since 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. (see **Figure 3** and **Table 1**)

③Although 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 down the velocity of the prediction curve for durability. Therefore, 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. 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. (see **Table 1**)

[Effect of strengthening measures]

①If Steel plate covering, FRP or External cables is performed, the soundness score of load-carrying capability would grade up to 100 or more (see **Figure 3** and **Table 2**). 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 2005, the bridge is strengthened by Steel plate covering. Therefore, the effect of strengthening measures has to take into account the transition of design load (see **Table 2**), because the bridge was designed by old basis. When the bridge is strengthened by Steel plate covering in 2005, the values of R_{new}=120 and R_{old}=100, because the present design basis improves the recover degree from 100 to 120 though the recover score was 100 when target bridge entered service (see **Table 2**).

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 ith maintenance

The deterioration curve of load-carrying capability before ith maintenance is expressed as follows.

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

Since Epoxy injection enables the deterioration speed of load-carrying capability to be reduced by half (see **Table 1**), this curve before i^th maintenance can be written as follows.

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

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

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

Therefore,

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

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

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

・ 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.

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

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

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

Epoxy injection enables the soundness score of durability to be graded up to 100 (see **Table 1**). Therefore, assuming that the bridge age is *t*" years when this maintenance is performed, the soundness score of durability grades up to 100 in *t*" years. The following equation is given as follows.

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

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

$$a_{D(i)} = a_{D(i-1)}$$

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

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

3.4 Optimization of rehabilitation strategy

3.4.1 Modeling of maintenance planning [11, 12, 13, 14, 15, 16]

The 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 BREX. 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 a rehabilitation strategy based on life cycle costs, the prediction curve and the effects of repairs and/or strengthening measures (see **Figure 1**).

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 **Figure 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.

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 **Equation (3)**) and the maximization of bridge quality (see **Equation (4)**) as the optimization method. From a practical point of view, the quality of a bridge is defined as the total sum of the 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: $$F_1 = \sum_{t=t'}^{T-1} C_{tj} \quad \rightarrow \quad \min \qquad (3)$$

$$F_2 = \sum_{t=t'}^{T} \{S_L(t) + S_D(t)\} \quad \rightarrow \quad \max \qquad (4)$$

Subject to: $$S_L(t) > 0, \quad S_D(t) > 0, \quad 0 \le t \le T \qquad (5)$$

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)

$S_L(t)$: Soundness score of load-carrying capability in the year *t*

$S_D(t)$: 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 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 a rehabilitation strategy on a 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 **Equation (3)** and **Equation (4)**). 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 J-BMS user.

Objective: $F_2 \rightarrow \max$ (6)

Subject to: $F_1 \leq \varepsilon$

$= Cost1 + \alpha$ (7)

where α = additional budget

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

3.4.2 Application of Genetic algorithms (GAs) to a combinatorial optimization problem

Genetic algorithms are stochastic search techniques based on the mechanism of natural selection and natural genetics [17, 18]. The following illustrates how genetic algorithms are applied to the combinatorial optimization problems in the J-BMS.

(1) 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 **Figure 5**. Each individual expresses a candidate solution, that is, a possible maintenance plan. In **Figure 5**, the left-hand section is a maintenance plan and the right-hand section is the genetic code that expresses the maintenance plan. Each set of genes (4-bit code) in the individual expresses an maintenance such as Repair 1, External cables and FRP covering (see **Figure 4**). 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 **Figure 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 from 0000 to 1111, 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 (see **Figure 4**).

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 **Equation (8)**. For quality maximization, the fitness value is given by **Equation (9)**. Where $G_1$and G_2 are the fitness function, $F_1$and F_2 are the objective function corresponding to **Equation (3)** and **Equation (4)**.

$$G_1 = \frac{1}{F_1} = \frac{1}{\sum_{t=t'}^{T-1} C_{tj}} \qquad (8)$$

$$G_2 = F_2 = \sum_{t=t'}^{T} \{S_L(t) + S_D(t)\} \qquad (9)$$

Since 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 soundness score of load-carrying capability and durability is higher than 0 (see **Equation (5)**), then 5000U is added to the total cost. In addition, for quality maximization, if the cost of the individual exceeds the cost constraint (see **Equation (7)**), 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.

(2) 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 tournament selection embedded elitist method yields a better solution than the normal 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 **Figure 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 **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.

5 Application of J-BMS to Existing Bridges

The J-BMS is constructed on a personal computer using the Visual Basic and C languages in accordance with the ideas mentioned above. In the present study, the J-BMS is applied to an existing bridge, the H-bridge as an example, in order to demonstrate the validity of J-BMS. The H-bridge is a Reinforced Concrete T-Girder-type bridge.

In the J-BMS, the bridge data is first entered into the computer. **Figure 6** shows the input screen of inspection data. **Figures 7** and **8** gives a partial listing of the technical specifications and inspection data for the H-bridge main girder. Using this data, the J-BMS evaluates the present performance of the bridge. **Figure 9** shows the evaluation of H-bridge main girder obtained using BREX. The expected service life, as established by the BMS user, is then input into the system. In this example, the expected service life (T) of target bridge was set to 70 years. After that, the J-BMS estimates the present deterioration and remaining life of target bridge with respect to load-carrying capability and durability. **Figure 10** shows the screen of deterioration prediction. The upper right section indicates the present remaining life with respect to load-carrying capability and durability. The lower section illustrates the graphs of the deterioration prediction curves for load-carrying capability and durability. These outputs show that the present remaining life does not exceed the expected service life, namely, 70 years. If the present remaining life calculated using the J-BMS does not exceed the expected service life, the maintenance plan is generated based on the direct-cost minimization approach. Then the J-BMS user can establish the required additional budget based on the results provided by the direct-cost minimization. Then, by inputting various additional budgets, the system shows a variety of maintenance plans based on bridge quality maximization and taking into account the cost constraints, i.e., the sum of the minimum costs and the additional budget. **Figures 11** to**14** are the results provided by the direct-cost minimization or quality maximization. **Figures 11** and **13** show the detail information such as the optimal maintenance plan and the required costs. **Figures 12** and **14** indicate the graphs of the deterioration prediction curves for load-carrying capability and durability after maintenance, present remaining life, remaining life after maintenance, etc.

Figure 11 shows the maintenance plan based on cost minimization. The maintenance plan costs 109U. The output shows that in order to satisfy the expected service life (T=70), this system requires two different maintenance actions on the bridge in the years 2002 and 2010 as an optimal maintenance plan. **Figure 12** shows the deterioration prediction curves after maintenance. This maintenance will extend the remaining life of the bridge for an additional 16.6 (27.3-10.7=16.6) years. Thus, the expected service life will be satisfied even though the present remaining life with respect to durability and load-carrying capability are 10.7 years and 13.4 years respectively. Also, from the deterioration graphs shown in the right section, the remaining life after maintenance is revealed to exceed the expected service life.

As an example of quality optimization, the maintenance plan suggested an additional budget of 66U, that is, the cost constraint is 175U (109+66=175). **Figure 13** shows the maintenance plan based on quality maximization. The system suggested that FRP covering (two layers) is added to the maintenance plan as a strengthening measure and requires two different maintenance actions in the years 2000 and 2010. The maintenance plan costs 165U, which satisfies the cost constraint of 175U. **Figure 14** shows the deterioration prediction after maintenance. The effect of the maintenance plan is that the quality index of the bridge is improved from 45.7% to 64.5%, as shown in the bottom of **Figure 12** and **14**. The remaining life is extended an additional 20.4 (31.1-10.7=20.4) years. In order to demonstrate the validity of GAs, the results of GAs were compared with the results of branch-and-bound optimization method. It was found that the maintenance plan proposed by GAs corresponded closely to those for the method. In addition, the calculation speed using GAs was much faster than that for the method. These results show that GAs are a powerful tool for solving the combinatorial optimization problem.

6 Conclusions

In this study, the basic concept of the J-BMS was suggested and developed. The results of the present study are summarized as follows.

①In 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.

②The deterioration curve was presented as a method of estimating the progressive deterioration of performance on existing bridge members. By assuming the functional deterioration, the J- BMS is able to estimate the deterioration of the repaired and/or strengthened bridge members.

③The prototype BMS was constructed using the Visual Basic and C languages. The J-BMS was applied to an existing bridge in order to demonstrate how J-BMS works concretely.

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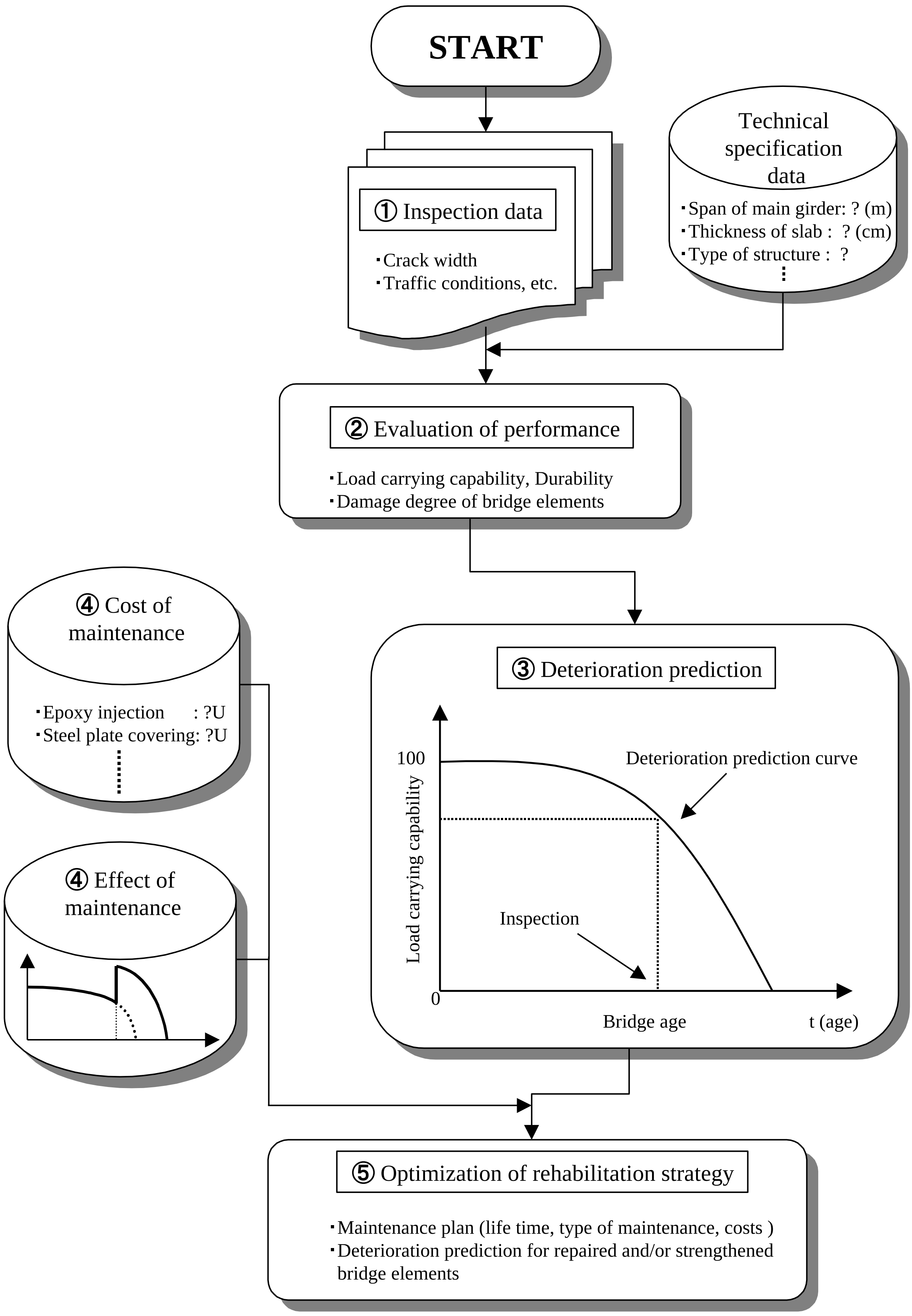
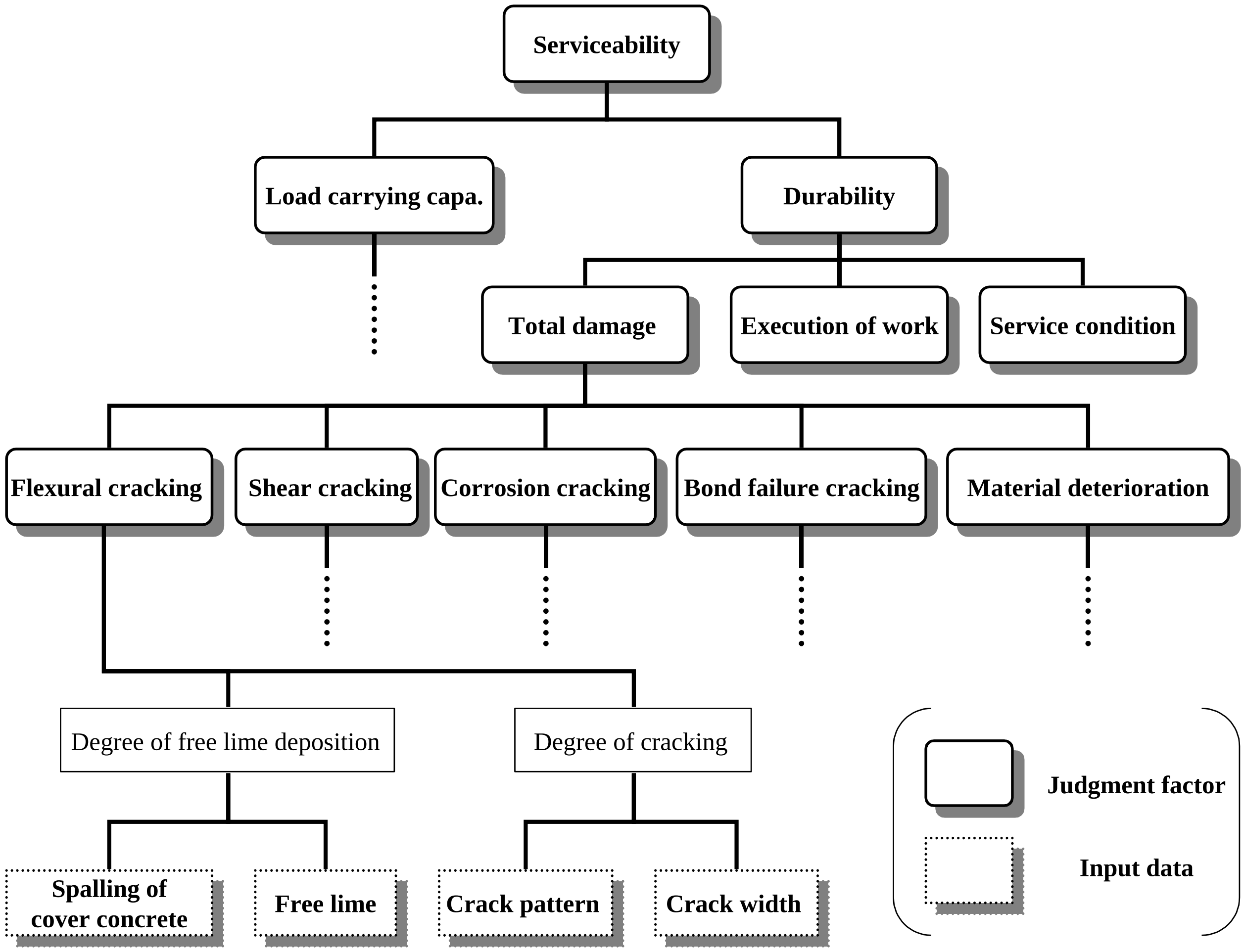
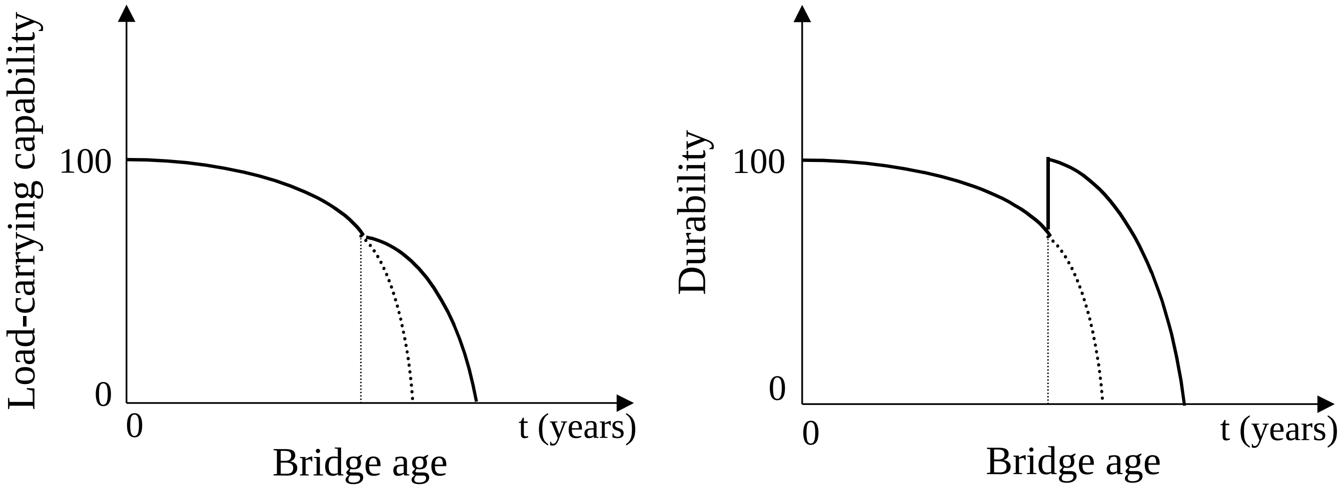

START
① Inspection data
・Crack width
・Traffic conditions, etc.
Technical specification data
・Span of main girder: ? (m)
・Thickness of slab : ? (cm)
・Type of structure : ?
② Evaluation of performance
・Load carrying capability, Durability
・Damage degree of bridge elements
④ Cost of maintenance
・Epoxy injection : ?U
・Steel plate covering: ?U
④ Effect of maintenance
③ Deterioration prediction
100
Load carrying capability
Deterioration prediction curve
Inspection
0
Bridge age
t (age)
⑤ Optimization of rehabilitation strategy
・Maintenance plan (life time, type of maintenance, costs)
・Deterioration prediction for repaired and/or strengthened bridge elements
Fig.1

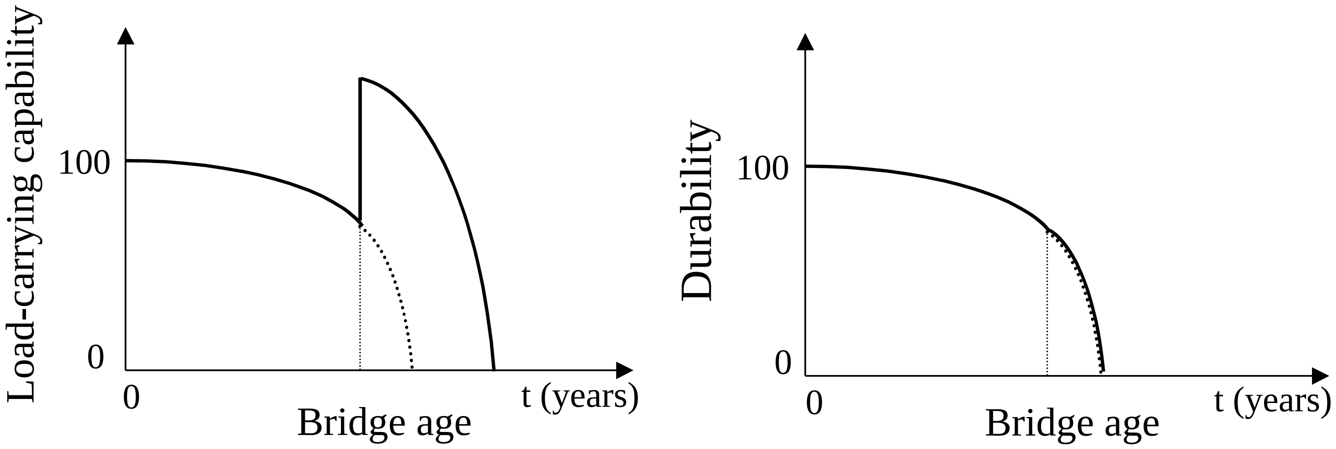


Serviceability
Load carrying capa.
Durability
Total damage
Execution of work
Service condition
Flexural cracking
Shear cracking
Corrosion cracking
Bond failure cracking
Material deterioration
Degree of free lime deposition
Degree of cracking
Spalling of cover concrete
Free lime
Crack pattern
Crack width
Judgment factor
Input data

Fig.2

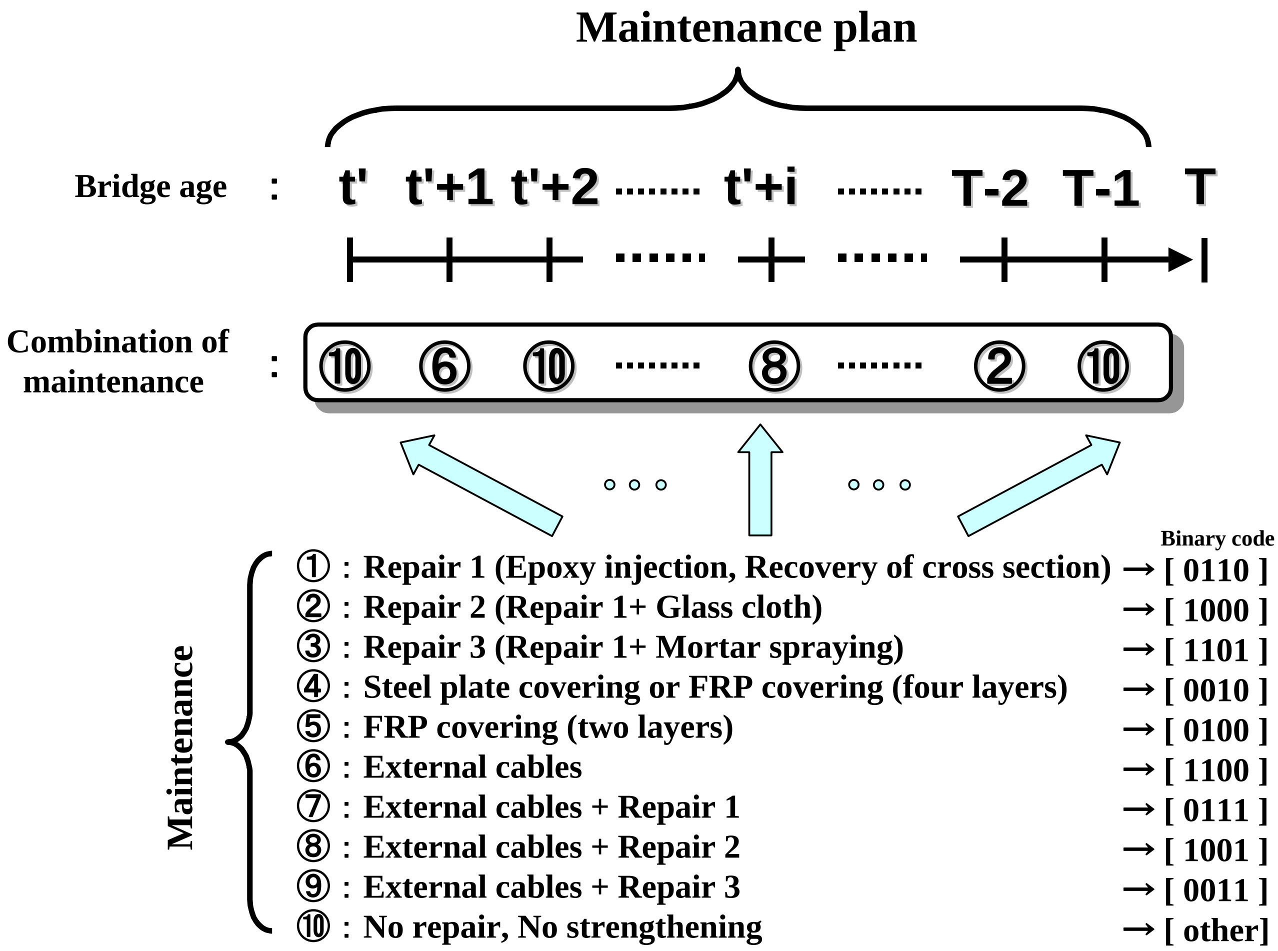


(a) Effect of repair



(b) Effect of strengthening

Fig.3



Maintenance plan
Bridge age :
t' t'+1 t'+2 .... t'+i .... T-2 T-1 T
Combination of maintenance :
⑩ ⑥ ⑩ .... ⑧ .... ② ⑩
Maintenance
Binary code
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 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

Fig.5

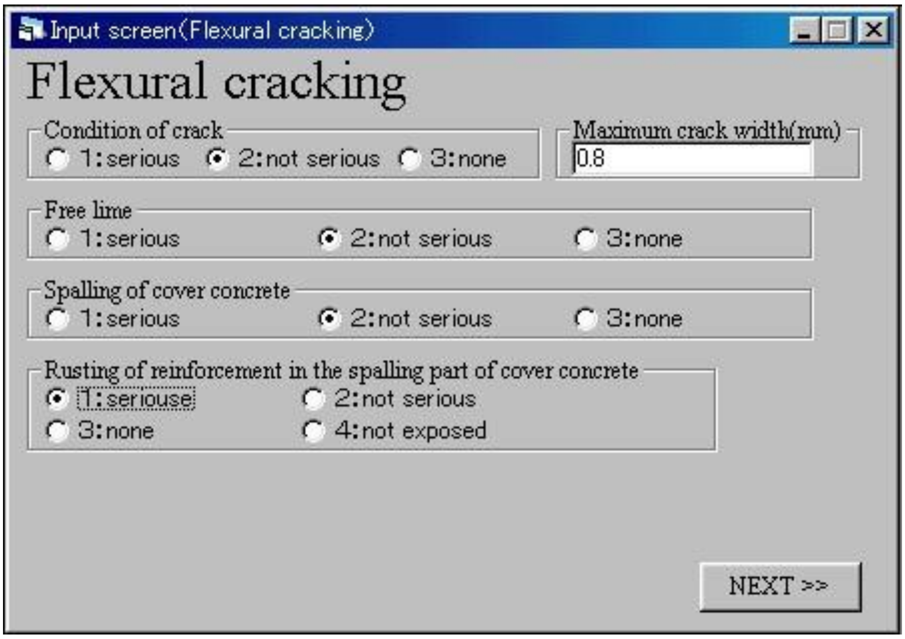
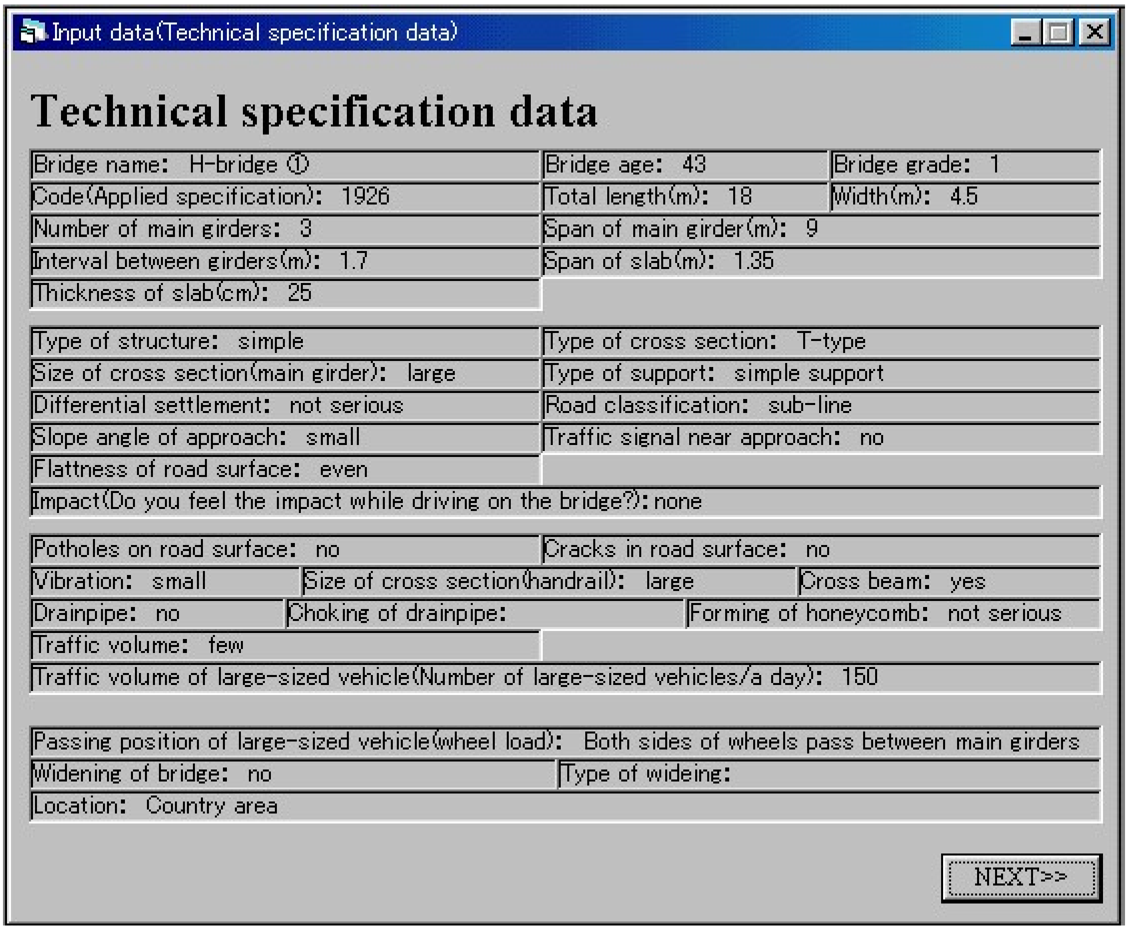

Input screen(Flexural cracking)
Flexural cracking
Condition of crack
1:serious
2:not serious
3:none
Maximum crack width(mm)
0.8
Free lime
1:serious
2:not serious
3:none
Spalling of cover concrete
1:serious
2:not serious
3:none
Rusting of reinforcement in the spalling part of cover concrete
1:seriouse
2:not serious
3:none
4:not exposed
NEXT >>

Fig.6



Input data(Technical specification data)

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 while 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

NEXT>>

Fig.7

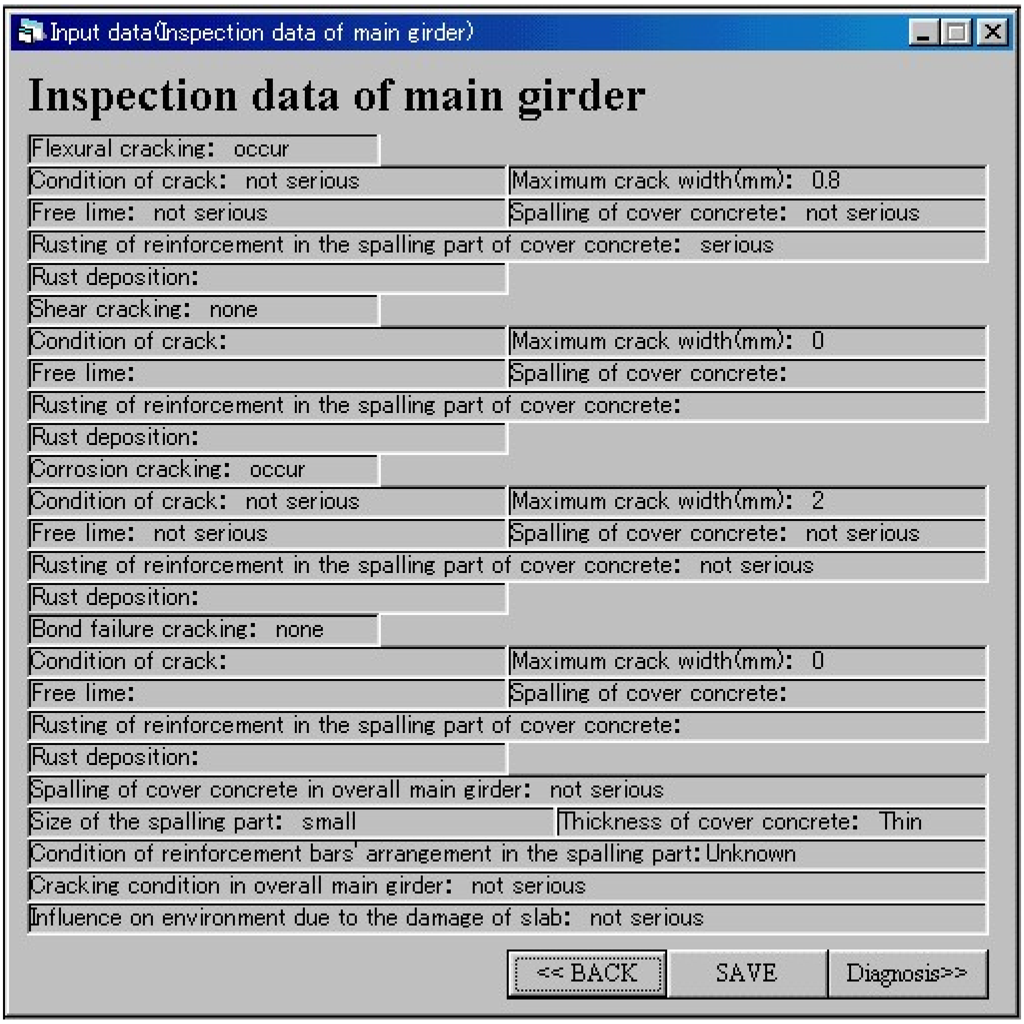

Input data(Inspection data of main girder)
Inspection data of main girder
Flexural cracking: occur
Condition of crack: not serious
Maximum crack width(mm): 0.8
Free lime: not serious
Spalling of cover concrete: not serious
Rusting of reinforcement in the spalling part of cover concrete: serious
Rust 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
<< BACK
SAVE
Diagnosis>>

Fig.8

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

Fig.9

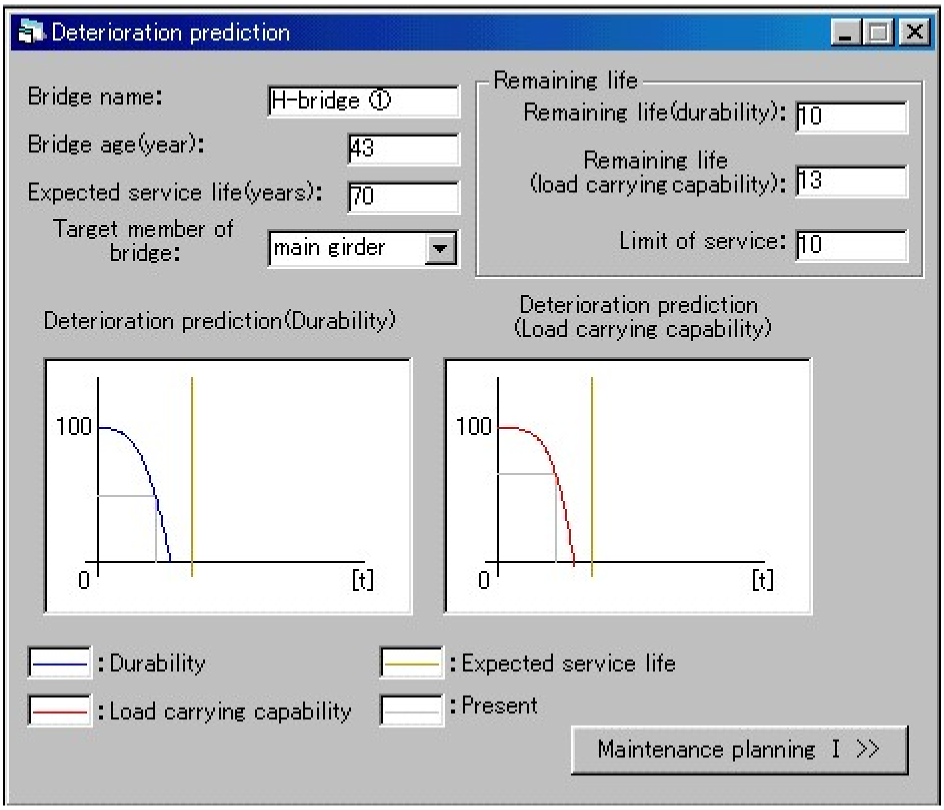

Deterioration prediction
Bridge name:
H-bridge ①
Bridge age(year):
43
Expected service life(years):
70
Target member of bridge:
main girder
Remaining life
Remaining life(durability):
10
Remaining life (load carrying capability):
13
Limit of service:
10
Deterioration prediction(Durability)
Deterioration prediction (Load carrying capability)
100
0
[t]
100
0
[t]
: Durability
: Load carrying capability
: Expected service life
: Present
Maintenance planning I >>

Fig.10

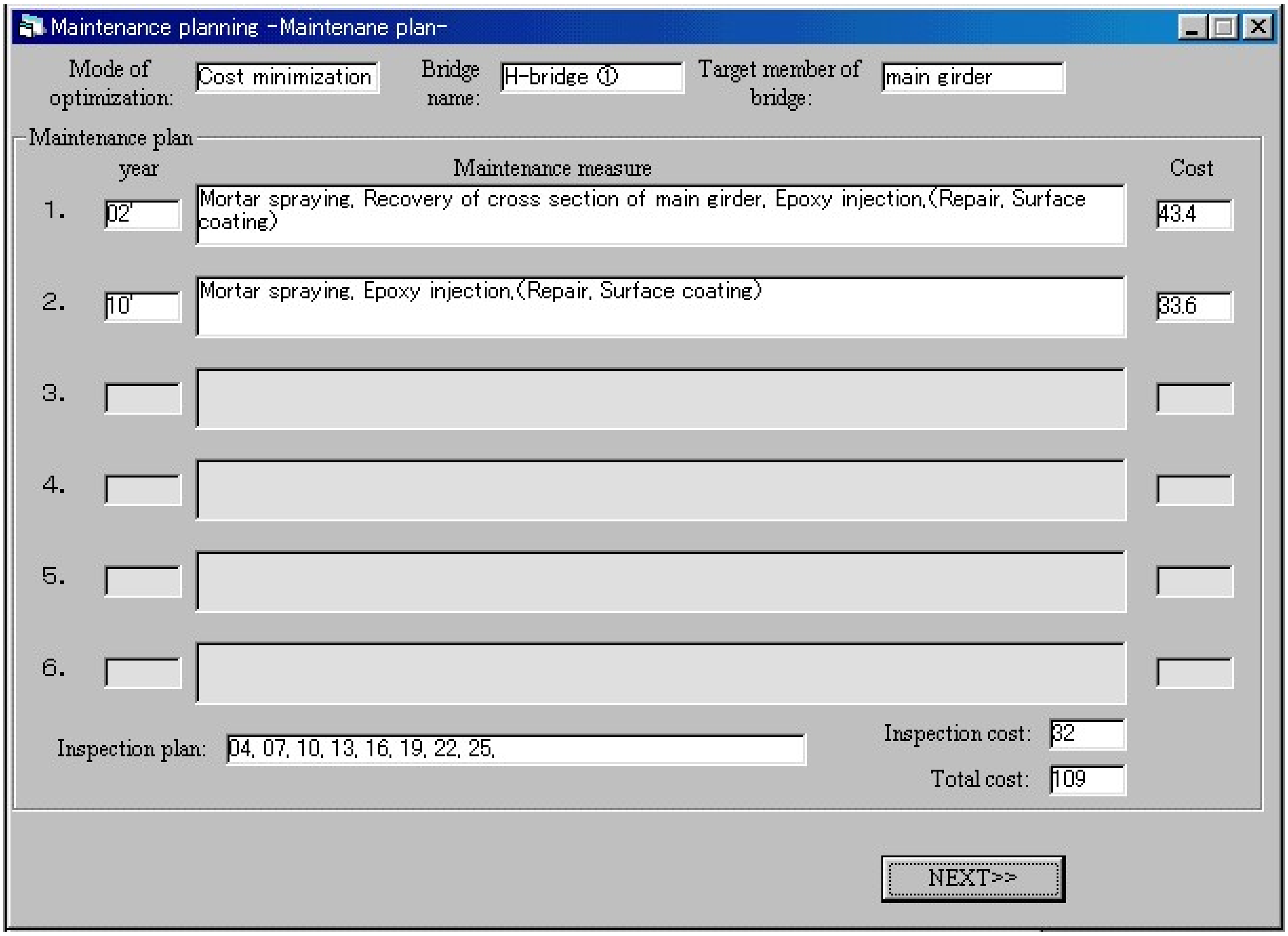

Maintenance planning -Maintenane plan-
Mode of optimization:
Cost minimization
Bridge name:
H-bridge ①
Target member of bridge:
main girder
Maintenance plan
year
Maintenance measure
Cost
1.
02'
Mortar spraying, Recovery of cross section of main girder, Epoxy injection,(Repair, Surface coating)
43.4
2.
10'
Mortar spraying, Epoxy injection,(Repair, Surface coating)
33.6
3.
4.
5.
6.
Inspection plan:
04, 07, 10, 13, 16, 19, 22, 25,
Inspection cost:
32
Total cost:
109
NEXT>>

Fig.11

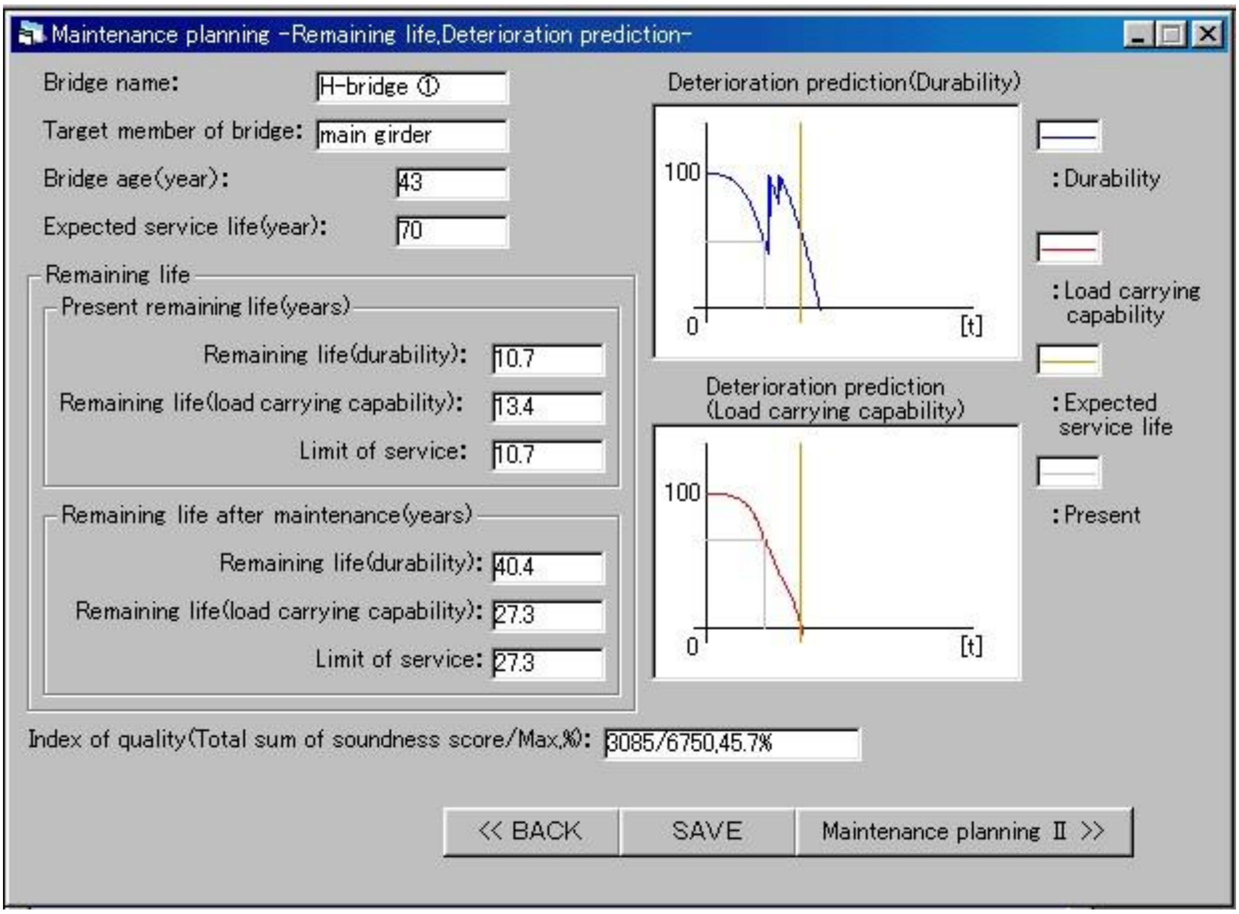

Maintenance planning -Remaining life,Deterioration prediction-
Bridge name:
H-bridge ①
Target member of bridge:
main girder
Bridge age(year):
43
Expected service life(year):
70
Remaining life
Present remaining life(years)
Remaining life(durability):
10.7
Remaining life(load carrying capability):
13.4
Limit of service:
10.7
Remaining life after maintenance(years)
Remaining life(durability):
40.4
Remaining life(load carrying capability):
27.3
Limit of service:
27.3
Deterioration prediction(Durability)
100
0
[t]
Deterioration prediction
(Load carrying capability)
100
0
[t]
:Durability
:Load carrying capability
:Expected service life
:Present
Index of quality(Total sum of soundness score/Max,%):
3085/6750,45.7%
<< BACK
SAVE
Maintenance planning II >>

Fig.12

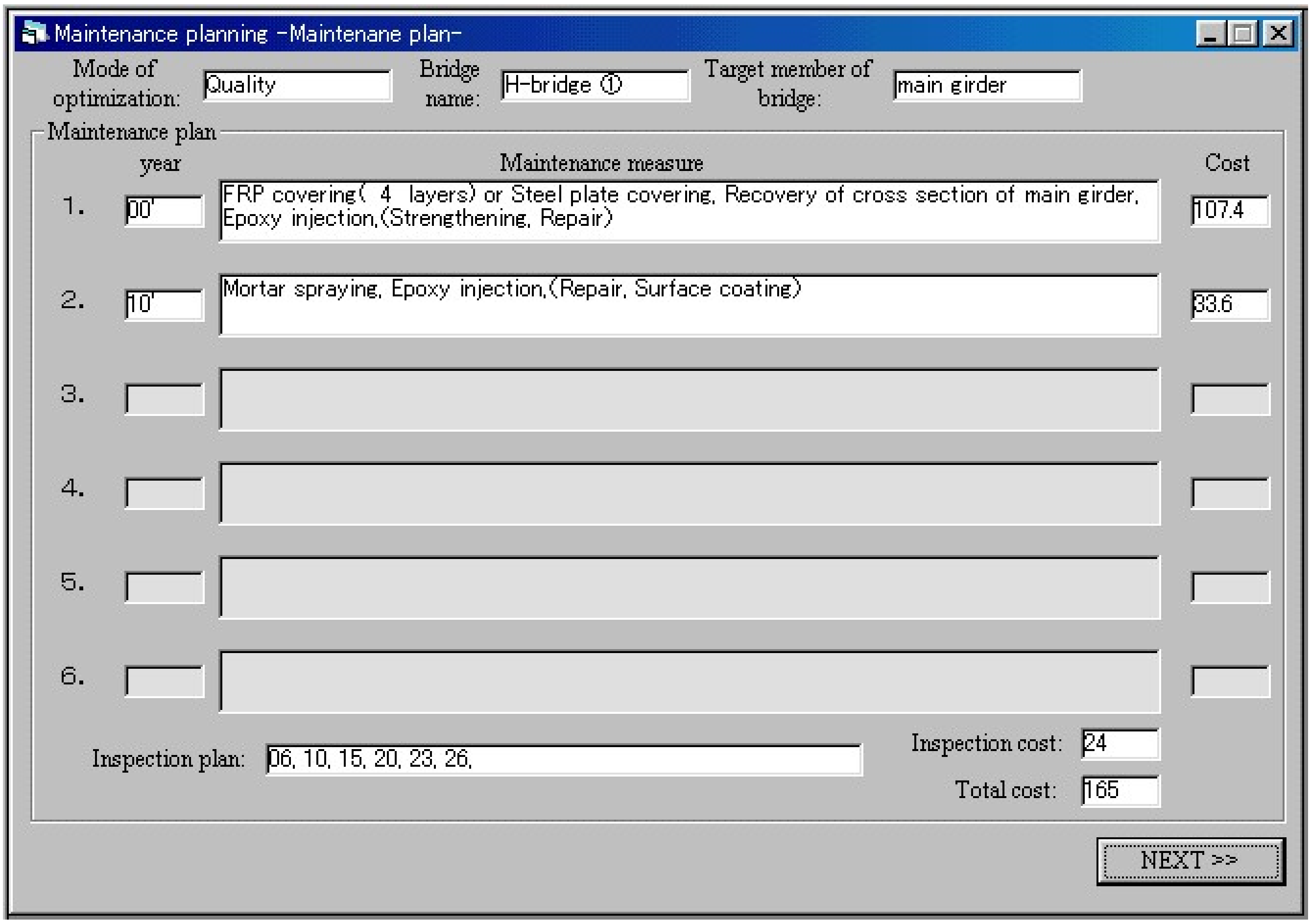

Maintenance planning -Maintenane plan-
Mode of optimization:
Quality
Bridge name:
H-bridge ①
Target member of bridge:
main girder
Maintenance plan
year
Maintenance measure
Cost
1.
00'
FRP covering(4 layers) or Steel plate covering, Recovery of cross section of main girder, Epoxy injection,(Strengthening, Repair)
107.4
2.
10'
Mortar spraying, Epoxy injection,(Repair, Surface coating)
33.6
3.
4.
5.
6.
Inspection plan:
06, 10, 15, 20, 23, 26,
Inspection cost:
24
Total cost:
165
NEXT >>

Fig.13

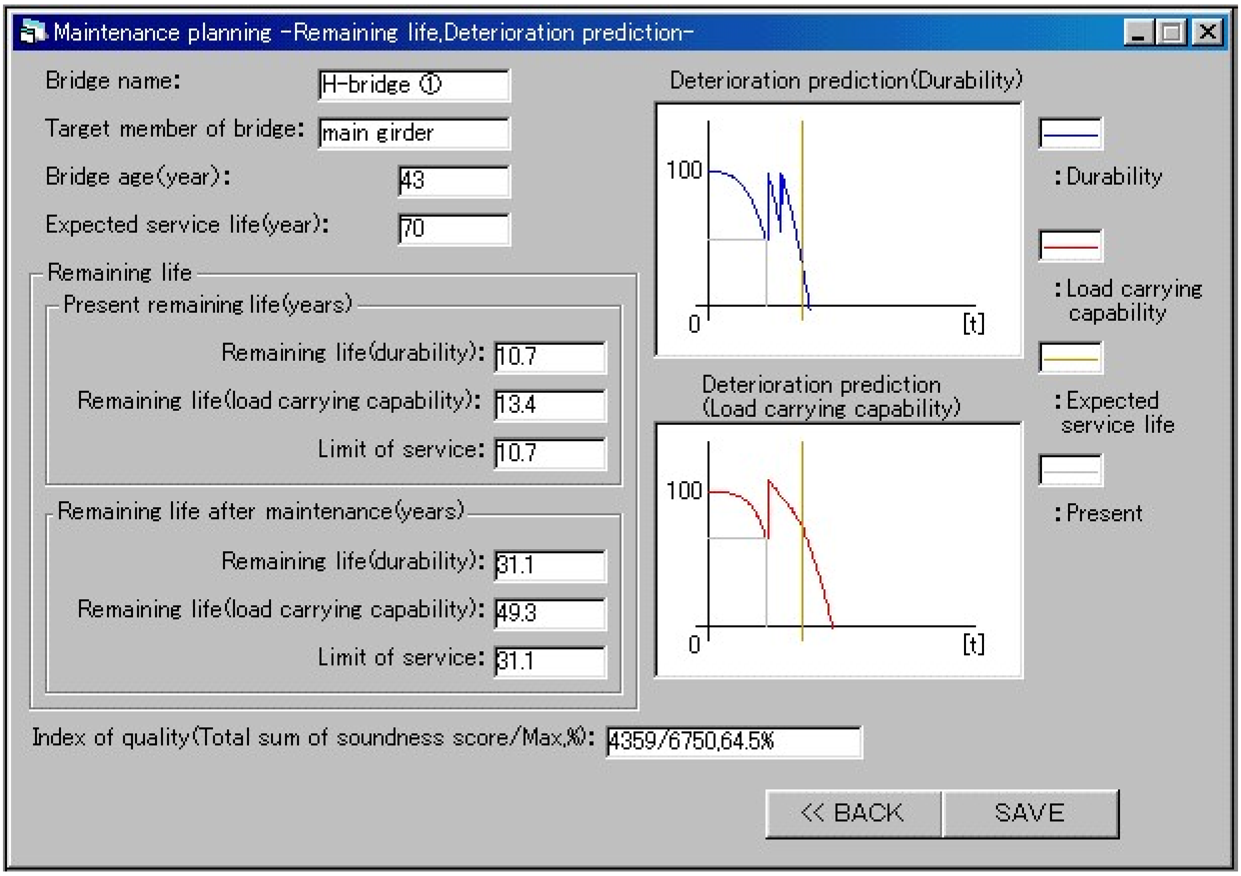

Maintenance planning -Remaining life,Deterioration prediction-
Bridge name:
H-bridge ①
Target member of bridge:
main girder
Bridge age(year):
43
Expected service life(year):
70
Remaining life
Present remaining life(years)
Remaining life(durability):
10.7
Remaining life(load carrying capability):
13.4
Limit of service:
10.7
Remaining life after maintenance(years)
Remaining life(durability):
31.1
Remaining life(load carrying capability):
49.3
Limit of service:
31.1
Index of quality(Total sum of soundness score/Max,%):
4359/6750,64.5%
Deterioration prediction(Durability)
100
0
[t]
Deterioration prediction
(Load carrying capability)
100
0
[t]
:Durability
:Load carrying capability
:Expected service life
:Present
<< BACK
SAVE

Fig.14

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.U

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
1940 ～ 1956	120	110	140
1957～	100	100	100

Note:　Year designed corresponds to the transition of design basis in Japan.

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%