Computers and Concrete, *Vol. 14, No. 6 (2014) 727-743*
DOI: http://dx.doi.org/10.12989/cac.2014.14.6.727

Advanced performance evaluation system for existing concrete bridges

Ayaho Miyamoto[1a], Hisao Emoto[*1] and Hiroyoshi Asano[2b]

[1]*Graduate School of Science & Engineering, Yamaguchi University, Tokiwadai,Ube, 755-8611, Japan*
[2]*Ube Industries Consultant Co., Ltd., Ube, 759-0206, Japan*

(*Received February 24, 2013, Revised July 28, 2014, Accepted August 20, 2014*)

Abstract. The management of existing concrete bridges has become a major social concern in many developed countries due to the large number of bridges exhibiting signs of significant deterioration. This problem has increased the demand for effective maintenance and renewal planning. In order to implement an appropriate management procedure for a structure, a wide array of corrective strategies must be evaluated with respect to not only the condition state of each defect but also safety, economy and sustainability. This paper describes a new performance evaluation system for existing concrete bridges. The system evaluates performance based on load carrying capability and durability from the results of a visual inspection and specification data, and describes the necessity of maintenance. It categorizes all girders and slabs as either unsafe, severe deterioration, moderate deterioration, mild deterioration, or safe. The technique employs an expert system with an appropriate knowledge base in the evaluation. A characteristic feature of the system is the use of neural networks to evaluate the performance and facilitate refinement of the knowledge base. The neural network proposed in the present study has the capability to prevent an inference process and knowledge base from becoming a black box. It is very important that the system is capable of detailing how the performance is calculated since the road network represents a huge investment. The effectiveness of the neural network and machine learning method is verified by comparing diagnostic results by bridge experts.

Keywords: performance evaluation; concrete bridge; load-carrying capability; durability; expert system; fuzzy set theory; machine learning; neural network

1. Introduction

Information technologies such as cellular phones, car navigation systems, etc. have been advancing more rapidly than concrete technologies, and have been applied globally. There has been growing interest in the maintenance of civil infrastructure systems not only in Japan (Furuta 2010) but worldwide (Yanev 2007, Elbehairy 2009, Fan 2010). Therefore, rational and economical diagnostic and remedial measures (G.Morcous 2010, Furuta 2007, Nakatsu 2011, Kyung-hoon 2012, Liu 2012, Nader 2012, Safi 2012, Wang 2011, Yang 2011) through the sharing of maintenance experience in Japan and other countries are required. One of the means of meeting

∗Corresponding author, Assistant Professor, E-mail: emoto@yamaguchi-u.ac.jp
[a]Professor, E-mail: miya818@yamaguchi-u.ac.jp
[b]Ph.D., E-mail: asano@ube-ic.co.jp

http://www.techno-press.org/?journal=cac&subpage=8 ISSN: 1598-8198 (Print), 1598-818X (Online)

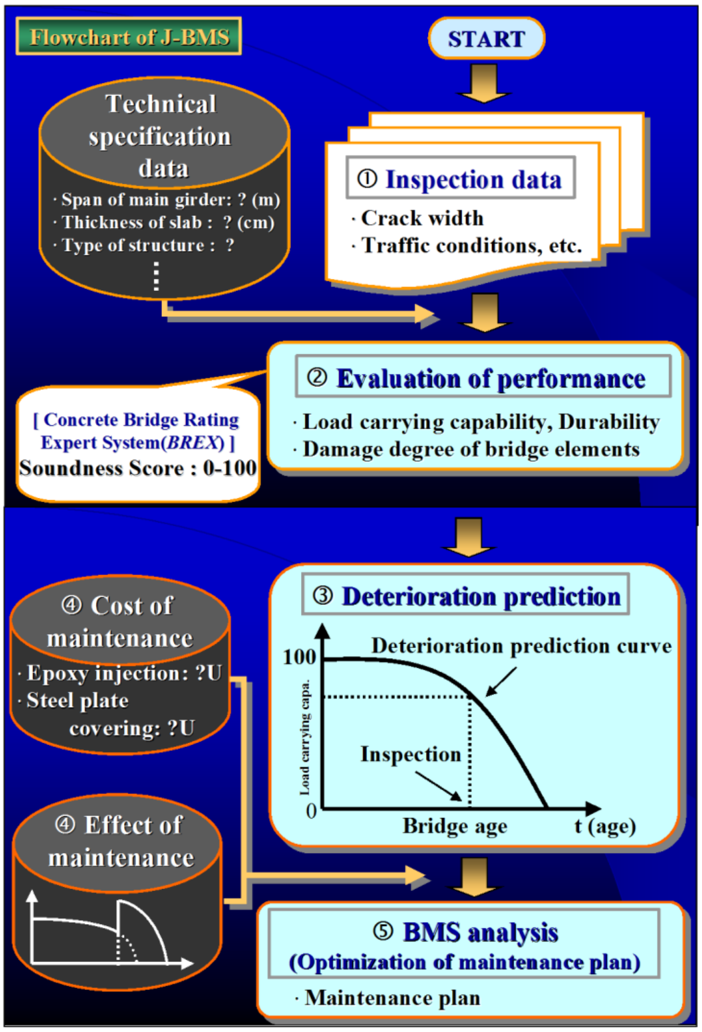

Fig. 1 System configuration of J-BMS

this demand is rapidly advancing computer and information and communication technologies.

The authors have been developing a Bridge Management System (J-BMS)(see Fig. 1) (Miyamoto 2000) aimed mainly at increasing maintenance efficiency and assisting bridge administrators' decision making for concrete bridges. J-BMS is an integrated system composed of the "BMS database", "Concrete Bridge Rating Expert System (BREX)", (Kawamura 2003, Tarighat 2009) "maintenance planning optimization system" and "maintenance measure selection system". J-BMS was built using the latest information and communication technologies including database systems based on information networks, and neural networks (Kawamura *et all*. 2003) .

This paper describes the application of the concrete bridge rating expert system (BREX) to existing bridges. It specifically presents a method for efficiently building a Web-based database using the Internet, application of the durability diagnostic system to existing concrete bridges, and the effect of knowledge update (learning) in the system.

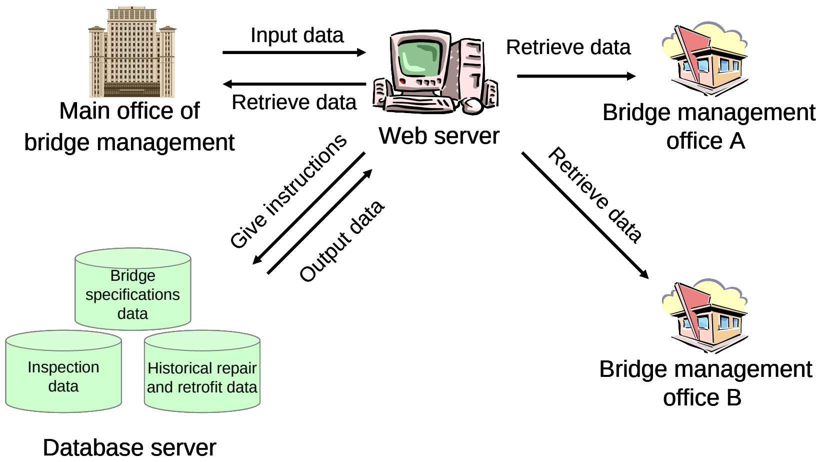

Fig. 2 How the bridge maintenance database system works

2. Bridge maintenance database system using the web

This section first describes the composition of a Web-based bridge maintenance database system and outlines the system. Then, specific methods for using the database system are discussed (Miyamoto 2010).

2.1 Composition and outline of web-based database system

The database system stores the "bridge specifications data", basic data on bridges, "historical inspection data", the results of investigations and inspections conducted for bridge diagnosis, and "historical repair and retrofit data", the history of repair and retrofit work performed for damaged or deteriorated bridges. The system is operated to centrally control these data as shown in Fig. 2. The database system is made accessible via an intranet to prevent a loss of maintenance data and enables the main and branch offices for bridge management to share bridge data.

For smooth bridge maintenance, not only inputting and retrieving data in the database s ystem but also sharing the bridge data stored in the database with other systems are neces sary. It has thus been made possible to output bridge data in the XML (eXtensible Marku p Language) format which is widely used in the field of information processing. To store data smoothly, an inspection report preparation support system was developed as a subsyst em of the database system to improve inspection procedures. To increase the efficiency of bridge maintenance, the database system has been equipped with bridge data output and i nspection report preparation support features in addition to ordinary retrieval, input and up date features.

2.2 Use of the database system

2.2.1 Improvement of inspection procedure

At present, no bridge administrators inspect bridges or take remedial measures by thems elves but administrators generally contract bridge inspection to private contractors, which h

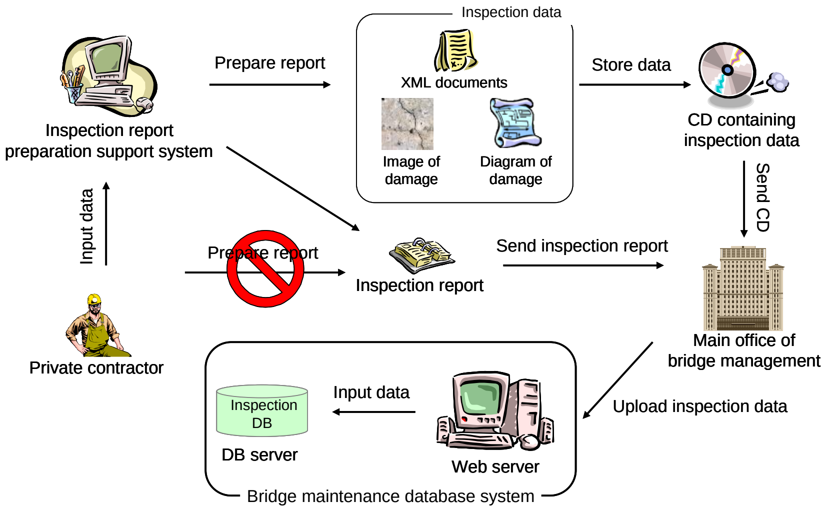

Fig. 3 Improved procedure for inspection data input

ave authorized inspection engineers to inspect bridges. The private contractor submits an inspection report to the bridge administrator. No standard formats are available for inspection reports. The format often varies according to the private contractor. Inspection data may generally be voluminous. The bridge administrator may need much time to report/input inspection data based on the inspection report, and run the risk of making input errors. Conventional inspection procedures are inefficient because both the bridge administrator and the private contractor are separately involved in the digitization of data. An inspection report preparation support system was therefore built to help private contractors with their maintenance work. As a result, Fig. 3 shows an improved procedure for inspection data input.

First, the private contractor inspects bridges on a contractual basis, and inputs inspection results into the inspection report preparation support system. At the completion of inspection data input, the contractor outputs XML files containing inspection data and prepares an inspection report using features of the inspection report preparation support system. The contractor submits to the bridge administrator via CD or other electronic media XML files that are prepared using the inspection report preparation support system, and digital files of images of deterioration and damage obtained during inspection. The bridge administrator stores the digitized data in the database using the CD received from the contractor.

Storing inspection data in XML files enables the bridge administrator to input inspection data to the database system by simply having the database read XML files containing inspection data. Thus, work efficiency is increased.

2.2.2 Inspection report preparation support system

The inspection report preparation support system is capable of preparing inspection reports referring to inspection data input into the system, and of outputting inspection data in the XML format to facilitate data input into the database system.

The inspection report preparation function automatically generates "an inventory of photographs" and "list of deterioration cases" based on the inspection data from the inspection report preparation support system. Examples of photograph inventory and deterioration lists are given in Figs. 4 and 5, respectively.

2.2.3 Use of XML

To meet the input and output requirements described below, the database system is based on the assumption of using XML documents for bridge maintenance because XML can be used on the Internet and serve broader purposes.

(i) Data transfer to bridge maintenance support system

The diagnostic system, one of the bridge maintenance support systems described later, r equires bridge specifications and inspection data. This system requires much work to manu ally input a large volume of data, so it is not so practical. Using the XML format in the database system facilitates the transfer of bridge data to the bridge maintenance support sy stem. Each piece of data is identified by a data tag where XML is used. Thus, necessary data can be read smoothly, and data can be input automatically. This makes the bridge m aintenance support system more practical.

Photographs of damage (xx bridge)

Photograph No.	1	Spna No.	3	Member No.	3	Photograph No.	2	Spna No.	3	Member No.	3
Deformation No.	1	Type of deformation	Crack			Deformation No.	2	Type of deformation	Crack		
Deformation No.		Type of deformation				Deformation No.		Type of deformation			

Photograph No.	3	Spna No.	2	Member No.	3	Photograph No.	4	Spna No.	1	Member No.	2
Deformation No.	3	Type of deformation	Crack			Deformation No.	4	Type of deformation	Crack		
Deformation No.		Type of deformation				Deformation No.		Type of deformation			

Fig. 4 Examples of inventory of photographs

Bridge	Yamaguchi Bridge		Type of inspection	Regular inspection	Date of inspection	Feb. 3rd, 2002
Deformation No.	Beam/column No.	Type of member	inspection item	Longitudinal position	Vertical position	Orientation
1	3	Main girder	Crack	Support at the edge	Side of the girder	Longitudinal
2	3	Girder at the flared section	Crack	1/4 of span	Bottom surface of the girder	Longitudinal
3	3	Cross girder	Crack	Midspan	Bottom surface of the girder	Diagnonal
4	2	Stringer	Crack	-	-	Alligator cracking
5	1	Panel	Crack	-	-	Right angle to the horizontal axis
6	1	Cantilever slab	Crack	-	-	-
7	3	Main girder	Spalling	Throughout the main girder	Bottom surface of the girder	-
8	1	Girder at the flared section	Spalling	1/4 of span	Side of the girder	-
9	1	Cross girder	Spalling	Support at the edge	Side of the girder	-
10	2	Stringer	Spalling	-	-	-
11	2	Panel	Spalling	-	-	-

Fig. 5 List of deterioration cases

(ii) Data transfer from private contractor to bridge administrator

Authorized inspection engineers, at the request of the bridge administrator, generally inspect bridges and submit a report on inspection results to the administrator. There are concerns for errors in inputting inspection data and entering manually duplicate data into both the inspection report and the database system. To solve such problems, a system was developed to use the benefits of XML. Keeping inspection date that are input to the inspection report preparation support system in the XML format enables smooth transfer of inspection data to the database and other application systems.

(iii) Data compatibility with systems of other organizations

Bridges have a service life of approximately 100 years, longer than other structures. Bridge-related data may vary in the service life. Existing systems are therefore expected to be enhanced. What is desirable in the future about bridge data are the digitization of the documents that are prepared in the life-cycle of bridges, or in the investigation through design and maintenance phases, and the centralized control of the documents for data sharing among those concerned. Migration to new systems or integration of existing systems is therefore expected for the purpose of sharing bridge data among those concerned. Defining a uniform XML format will enable smooth systems integration or migration to new systems without re-defining bridge data.

3. Application of diagnostic system to actual bridges using a database

3.1 Outline of diagnostic system (Kawamura and Miyamoto 2003, Miyamoto et al. 2008)

3.1.1 How to represent knowledge

The diagnostic system hierarchically represents the process of experts' diagnosis of existing performance parameters of bridges such as load bearing capacity and durability. For diagnosing individual parameters, If-Then rules are used to represent knowledge. The diagnostic system also employs fuzzy membership functions to handle subjective vagueness of engineers. The diagnostic process and knowledge representation rules are outlined below.

(*i*) *Diagnostic process*

The diagnostic process hierarchically represents the thought process of engineers when they diagnose bridges by integrating various inspection results. The diagnostic process is essential to the diagnostic system that the authors are trying to develop. Fig. 6 shows a diagnostic process for the durability of a main girder.

(*ii*) *Knowledge representation rules*

Human knowledge is generally represented in natural language. For example, "if you have a slight fever and a very sore throat, then you certainly have a cold." In the diagnostic system, therefore, empirical or subjective knowledge of engineers is represented using If-Then rules.

3.1.2 Functional composition

The diagnostic system has five functions to enable accountability support and knowledg e update (Fig. 7). The functions are described below.

(*i*) *Knowledge base*

Knowledge base is a collection of experts' knowledge, experience and learning patterns.

(*ii*) *Inference engine*

Inference engine efficiently processes the knowledge in the knowledge base to solve pro blems. The diagnostic system uses hierarchical neural networks with each level having a s pecific meaning, for accountability support and knowledge update (Adeli 1995). Fig. 8 sho ws a hierarchical neural network for evaluating the durability of a main-girder.

(*iii*) *Explanation function*

The explanation function enhances the credibility of inspection and learning results. The diagnostic system has the following two explanation functions.

a) Explanation of diagnostic process

This function is aimed at explaining the path to inspection results. It supports accounta bility, one of the features of the diagnostic system. At the time of explanation of the diag nostic process, it is possible to confirm the diagnostic process and knowledge representatio n rules that are used, and what emphasis is placed on which parameters (Fig. 9).

b) Explanation of learning results

This function is performed to explain the basis on which knowledge is learned in the d iagnostic system, and helps users determine whether knowledge should be updated or not. The diagnostic system enables the verification of changes in error and difference in inspect ion results before or after learning, to provide material for decision making (Fig. 10).

(*iv*) *Knowledge update function*

Knowledge in the knowledge base is updated to increase the accuracy of inspection res ults obtained by the diagnostic system. Engineers generally have subjective and empirical k nowledge, which is very difficult to extract. In the diagnostic system, knowledge is update d through learning by error back-propagation based on the correlation between inspection a nd diagnostic results input into the neural network and training data (expert answers) colle cted through questionnaire surveys among engineers. Detailed explanations about the knowl edge update function is provided in section 4.

Table 1 Five grades of durability

Category	Point	Definition
Unsafe	0.0 to 12.5	Measures are urgently required to ensure traffic safety. Score 0.0 represents the state where the bridge should not be put into service (control limit).
Severe deterioration	12.5 to 37.5	Repair is essential. Detailed inspection is required.
Moderate deterioration	37.5 to 62.5	Deterioration is observed. Regular inspection should be made earlier than planned. Follow-up studies are required.
Mild deterioration	62.5 to 87.5	Deterioration is observed. The degree of deterioration should be recorded. Repair is not necessary.
Safe	87.5 to 100.0	Sound state with slight deterioration. Score 100.0 represents a state free from any problems.

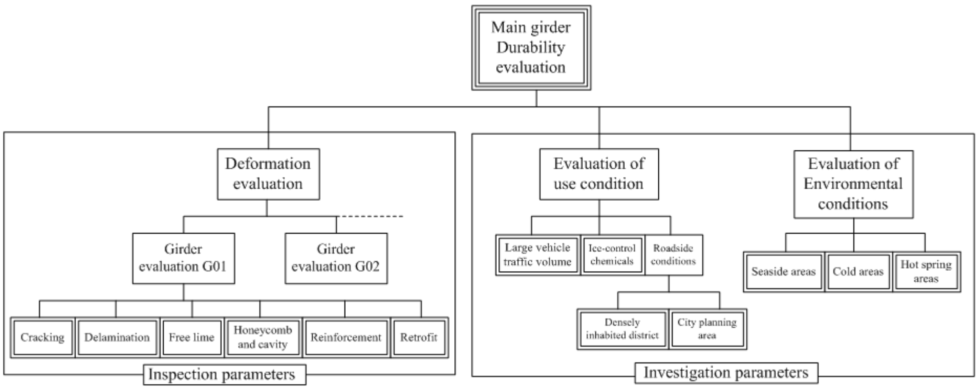

Fig. 6 Diagnostic process for evaluating the durability of main girder

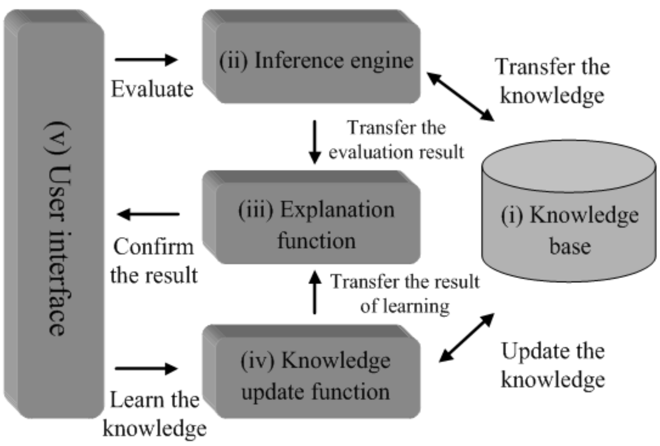

Fig. 7 Functional composition of diagnostic system

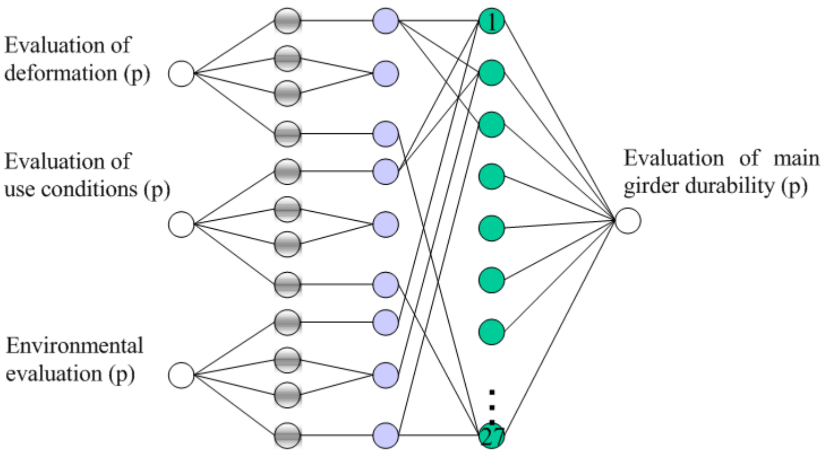

Fig. 8 Application of hierarchical neural network

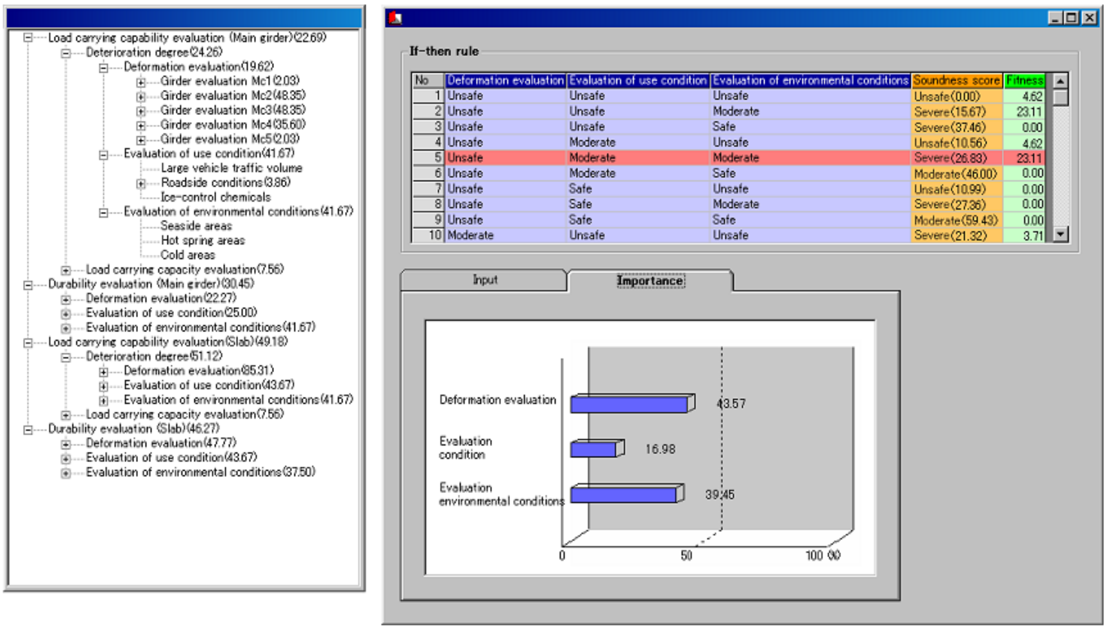

Fig. 9 Output using the explanation function in the diagnostic process

(v) User interface

User interface serves as a liaison between the system and the user to facilitate system use by the user. The user interface of the diagnostic system supports the input of inspecti on results, and enables the verification of diagnostic results and learning effects. Using the user interface in combination with the maintenance database system described in section 2 enables an efficient use of the diagnostic system

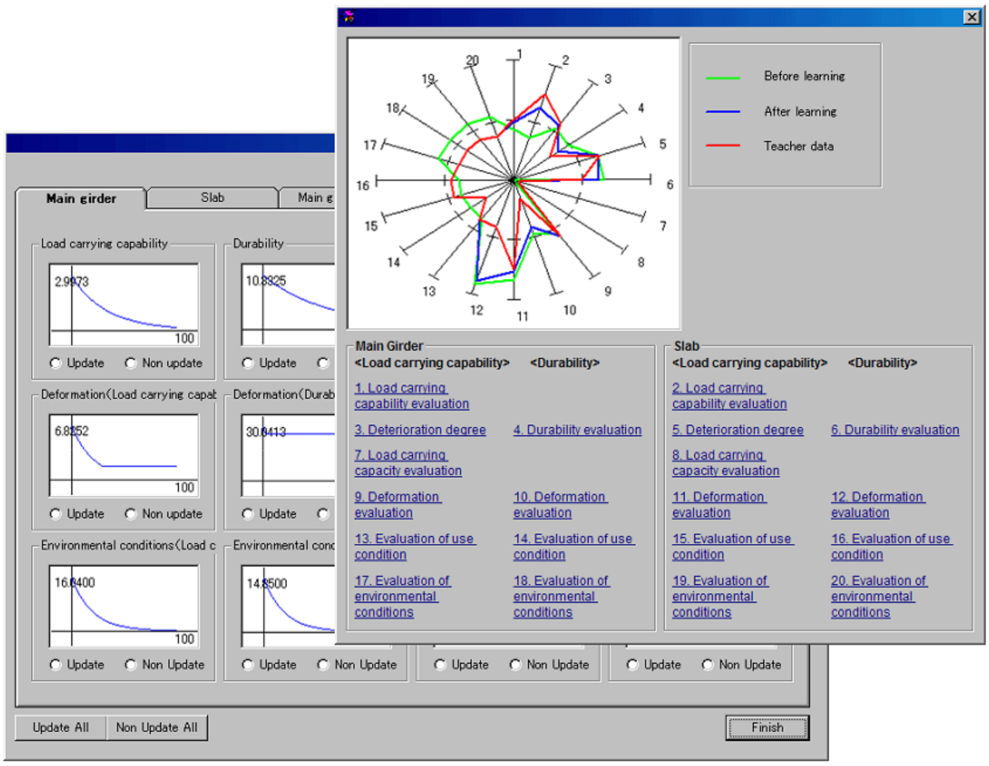

Fig. 10 Explanation of learning results

Photo 1 Deterioration of the KT-Bridge

3.2 System application to an existing bridge

Described below are the inspection results in two spans (“Span A” and “Span B”) of t he KT-Bridge, a reinforced concrete bridge, in Yamaguchi Prefecture (Photo 1), that were obtained by applying the diagnostic system.

3.2.1 Inspection results

Fig. 11 shows an example of the damage in "Span A" identified by inspection. The KT-Bridge is a reinforced concrete bridge on a national highway that has been in service for nearly 70 years. It is located along a shore and has suffered deterioration mainly due to salt damage. Numerous cracks and delaminated points were found in girders on the coastal side (upper part in Fig. 11) in particular.

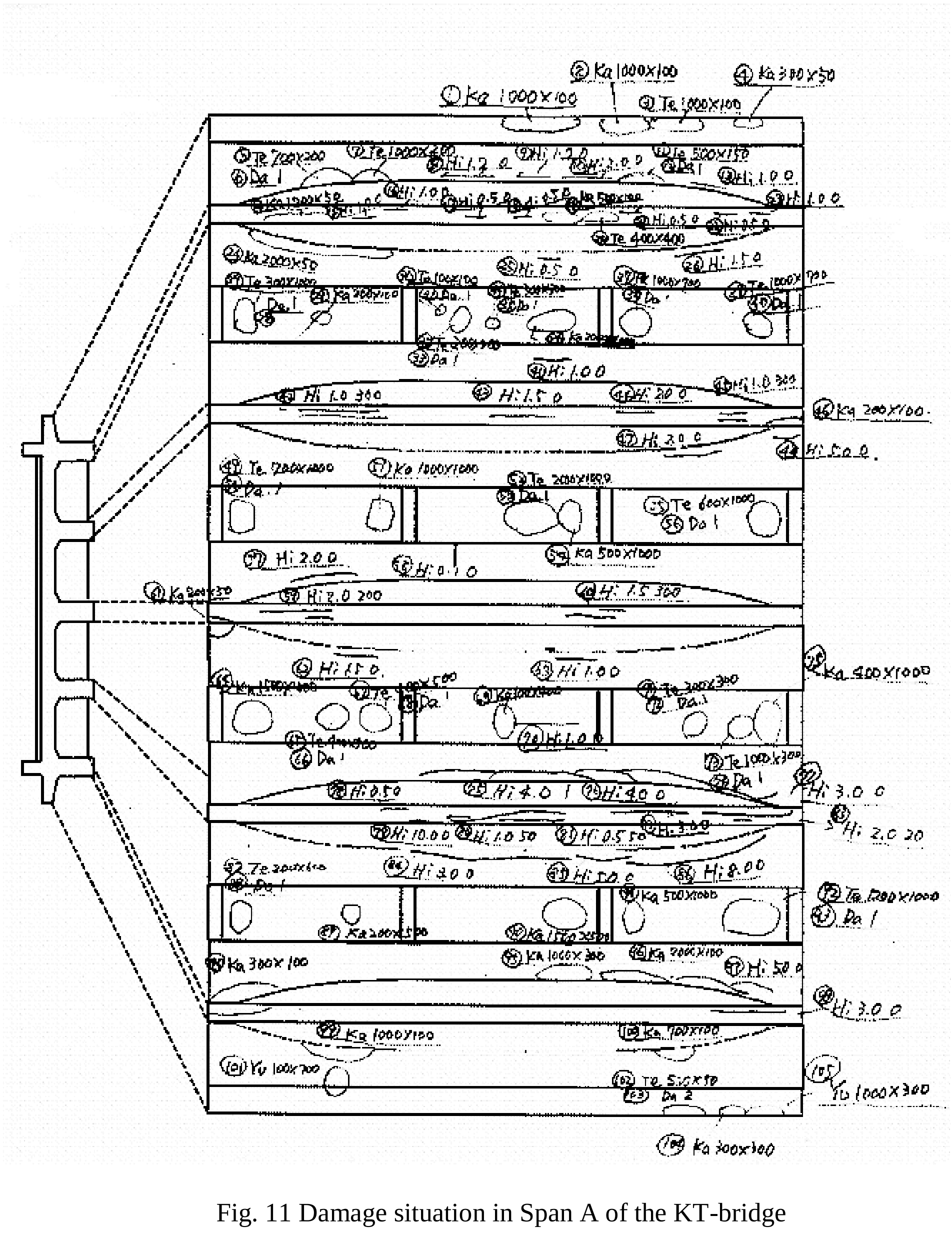

Fig. 11 Damage situation in Span A of the KT-bridge

3.2.2 Comparison with training data (expert answers)

The training data(expert answers) were calculated from answer sheets (Fig. 12)that three engineers (domain experts) provided per span in the questionnaire using a scale of 0 to 100 according to the grades in Table 1. Table 2 compares the diagnostic results for the KT-Bridge based on the initial knowledge with training data.

Table 2 shows that the score based on the output from the diagnostic system (data based on the initial knowledge) was slightly lower in “Span A” with greater deformation than in “Span B”. The variance from instructors' data is great in both “Span A” and “Span B”. This suggests the need of knowledge update. The variance is great in relation to the "evaluation of deformation". This is attributable to the fact that according to the initial knowledge, the same importance was attached to six parameters for the "evaluation of girders and panels" at a level lower than "deformation evaluation": cracking, delamination, free lime, honeycomb and cavity, reinforcement and retrofit (Fig. 6).

In the next section, the results of learning through knowledge update are presented, and the result of post-knowledge update application of the diagnostic system to an actual bridge and the effect of knowledge update are discussed.

<<Evaluation of load bearing capacity>>

Definition:
Present the degree of deterioration of load bearing capacity of main girder owing to mechanical factors e.g. loads, and determine whether retrofit is required or not.

Parameters:
Evaluation of deterioration and load bearing capacity

Criteria for determination

Unsafe:
Measures are urgently required to ensure traffic safety. Bridge should not be put into service.

Severe deterioration (Se-De):
Repair is essential. Detailed inspection is required.

Moderate deterioration (Mo-De):
Deterioration is observed. Regular inspection should be made earlier than planned. Follow-up studies are also required.

Mild deterioration (Mi-De):
Deterioration is observed. The degree of deterioration should be recorded. Repair is not necessary.

Safe:
Sound state with slight deterioration.

Enter the answer

	Unsafe	*Se-De*	*Mo-De*	*Mi-De*	*Safe*
Check appropriate box					

Fig. 12 Part of questionnaire distributed to engineers (domain experts)

Table 2 Diagnosis based on the initial knowledge and training data (in points)

	Span A			Span B		
	Based on initial knowledge	Instructors' data	Variance	Based on initial knowledge	Instructors' data	Variance
Evaluation of main girder load bearing capacity"	29.12	16.67	12.45	30.88	50.00	19.12
Evaluation of deterioration	58.23	16.67	41.56	61.77	58.33	3.44
Load bearing capacity	0.00	10.00	10.00	0.00	10.00	10.00
Evaluation of deformation	64.07	16.67	47.40	74.68	58.33	16.35
Evaluation of use conditions	43.95	41.67	2.28	43.95	41.67	2.28
Evaluation of environmental conditions	66.67	41.67	25.00	66.67	41.67	25.00
Evaluation of main girder durability	58.23	16.67	41.56	61.77	33.33	28.44
Evaluation of deformation	64.07	5.00	59.07	74.68	16.67	58.01
Evaluation of use conditions	43.95	25.00	18.95	43.95	25.00	18.95
Evaluation of environmental conditions	66.67	41.67	25.00	66.67	41.67	25.00
Evaluation of slab load bearing capacity	32.65	8.33	24.32	34.78	75.00	40.22
Evaluation of deterioration	65.31	25.00	40.31	69.56	66.67	2.89
Load bearing capacity	0.00	10.00	10.00	0.00	10.00	10.00
Evaluation of deformation	85.31	25.00	60.31	98.06	75.00	23.06
Evaluation of use conditions	43.95	45.83	1.88	43.95	45.83	1.88
Evaluation of environmental conditions	66.67	41.67	25.00	66.67	41.67	25.00
Evaluation of slab durability	65.31	25.00	40.31	69.56	50.00	19.56
Evaluation of deformation	85.31	16.67	68.64	98.06	41.47	56.59
Evaluation of use conditions	43.95	45.83	1.88	43.95	45.83	1.88
Evaluation of environmental conditions	66.67	37.50	29.17	66.67	37.50	29.17
		Total	585.09		Total	416.84

4. Knowledge Update in the Diagnostic System and Its Effectiveness (Miyamoto et al. 2008)

The diagnostic system uses visual inspection results and bridge specifications as input d ata, and the results of questionnaire surveys among engineers as training data (expert answ ers). The system enables knowledge update by error back-propagation using a neural netwo rk. In this section, inspection data are input to the system again and post-learning diagnost ic results are examined to identify the learning effect through knowledge update. When

Table 3 Post-learning output and training data (in points)

	Span A			Span B		
	Based on initial knowledge	Instructors' data	Variance	Based on initial knowledge	Instructors' data	Variance
Evaluation of main girder load bearing capacity"	22.69	16.67	6.02	40.83	50.00	9.17
Evaluation of deterioration	24.26	16.67	7.59	42.71	58.33	15.62
Load bearing capacity	7.56	10.00	2.44	7.56	10.00	2.44
Evaluation of deformation	19.62	16.67	2.95	46.54	58.33	11.79
Evaluation of use conditions	41.67	41.67	0.00	41.67	41.67	0.00
Evaluation of environmental conditions	41.67	41.67	0.00	41.67	41.67	0.00
Evaluation of main girder durability	30.45	16.67	13.78	40.62	33.33	7.29
Evaluation of deformation	22.27	5.00	17.27	41.37	16.67	24.70
Evaluation of use conditions	25.00	25.00	0.00	25.00	25.00	0.00
Evaluation of environmental conditions	41.67	41.67	0.00	41.67	41.67	0.00
Evaluation of slab load bearing capacity	49.18	8.33	40.85	63.04	75.00	11.96
Evaluation of deterioration	51.12	25.00	26.12	72.45	66.67	5.78
Load bearing capacity	7.56	10.00	2.44	7.56	10.00	2.44
Evaluation of deformation	58.42	25.00	33.42	77.45	75.00	2.45
Evaluation of use conditions	43.67	45.83	2.16	43.67	45.83	2.16
Evaluation of environmental conditions	41.67	41.67	0.00	41.67	41.67	0.00
Evaluation of slab durability	46.27	25.00	21.27	53.64	50.00	3.64
Evaluation of deformation	47.77	16.67	31.10	64.58	41.47	23.11
Evaluation of use conditions	43.67	45.83	2.16	43.67	45.83	2.16
Evaluation of environmental conditions	37.50	37.50	0.00	37.50	37.50	0.00
		Total	209.57		Total	124.71

updating knowledge, data in two spans (“Span A” and “Span B”) of the KT-Bridge and data for three spans of three bridges where inspections were made separately were used as data for learning. Table 3 compares post-learning output from the diagnostic system with the training data. Fig. 13 shows changes in importance attached to deformation parameters related to main girder load bearing capacity before or after learning.

Tables 2 and 3 show that post-learning output from the diagnostic system became closer to training data in either span by approximately 330 points on average (in terms of mean difference in variance between Tables 2 and 3). With respect to "deformation evaluation", about which initial

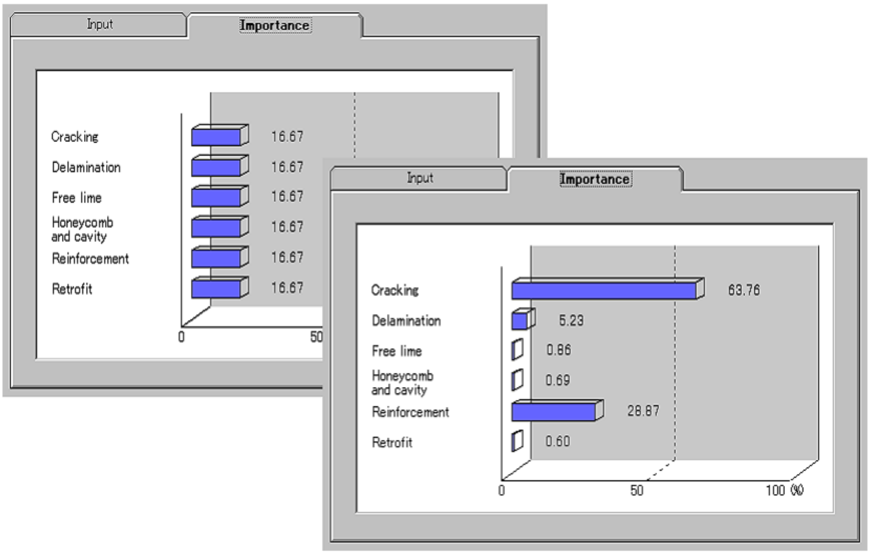

Fig. 13 Importance before (left) or after (right) learning

knowledge was greatly different from the training data, the variance also decreased substantially after learning. This indicates the effect of learning. We believe that the proposed knowledge update method in the diagnostic system based on the diagnostic data using a neural network will be able to become a generalized method for the other bridges. The data used for learning were, however, only those in five spans in four bridges. As a result of verification of the effect of knowledge update, it was still found that further knowledge update with additional learning data would make the diagnostic system more practical.

5. Concluding Remarks

This paper described a new performance evaluation system for existing concrete bridges. Namely the system evaluates performance based on load carrying capability and durability from the results of a visual inspection and specification data from an XML-based database system, and describes the necessity of maintenance. It categorizes all girders and slabs as either unsafe, severe deterioration, moderate deterioration, mild deterioration, or safe. The technique employs an expert system with an appropriate knowledge base in the evaluation. A characteristic feature of the system is the use of neural networks to evaluate the performance and facilitate refinement of the knowledge base. Generally, although a neural network is a powerful machine-learning tool, the inference process becomes a “black box,” which renders the representation of knowledge in the form of rules impossible. However, the neural network proposed in the present study has the capability to prevent an inference process and knowledge base from becoming a black box. It is very important that the system is capable of detailing how the performance is calculated since the road network represents a huge investment. The effectiveness of the neural network and machine learning method is verified by comparing diagnostic results by bridge experts.

References

Adeli, H. and Hung, S.L. (1995), “Machine learning-neural networks, Genetic algorithms, and fuzzy systems” John Wiley & Sons, Inc., New York.

Tarighat, A. and Miyamoto, A. (2009), “Fuzzy concrete bridge deck condition rating method for practical bridge management system”, *Expert Systems with Applications*, **36**(10), 12077-12085.

Elbehairy, H., Hegazy, T. and Soudki, K. (2009), “Integrated multiple-element bridge management system”, *J. Bridge Eng.*, **14**(3), 179-187.

Fan, M. and Song, S. (2010), “Study on intelligent decision patterns of maintenance for large bridges”, *ICCTP*, 3747-3752.

Furuta, H., Kayano, M. and Watanabe, E. (2007), “Current Status and Future Issues on Bridge Maintenace and Bridge Management System”, *J. Japan Society Civil Eng. F* , **63**(3), 287-294.

Furuta, H. (2010), “Bridge Management and Life Cycle Performance in Japan”, *Structures Congress*, 2757-2768.

Morcous, G., Lounis, Z. and Cho, Y. (2010), “An integrated system for bridge management using probabilistic and mechanistic deterioration models: Application to bridge decks”, *KSCE J. Civil Eng.*, **14**, (4), 527-537

Kawamura, K. and Miyamoto, A. (2003), “Condition state evaluation of existing reinforced concrete bridges using neuro-fuzzy hybrid system”, *Comput. Struct.*, Civil Comp Ltd. and Elsevier Ltd., **81**(18-19), 1931-1940.

Kawamura, K., Miyamoto, A., Frangopol, D.M. and Kimura, R. (2003), “Performance evaluation of concrete slabs of existing bridges using neural networks”, *Eng. Struct.*, Elsevier Science Direct, **25**(12), 1455-1477.

Park, K.H., Lee, S.Y., Park, C.W., Cho, H.N. and Kong, J.S. (2012), “Safety-based multi-objective life-cycle management system for steel box girder bridges”, *Structure and Infrastructure Engineering*: Maintenance, *Management, Life-Cycle Design and Performance*, **8**(3), 211-225.

Liu, M., Frangopol, D. and Kim, S. (2009), “Bridge system performance assessment from structural health monitoring: A case study”, *J. Struct. Eng.*, **135**(6), 733-742.

Miyamoto, A. (2000), “Development of a Bridge Management System(J-BMS) in Japan”, *Proceeding of the 1st US-Japan Workshop on Life-Cycle Cost Analysis and Design of Civil Infrastructure Systems*(*ASCE*), Hawaii, pp.179-221.

Miyamoto, A. and Ishida, J. (2008), “Advanced performance evaluation system for existing concrete bridges with machine learning”, *Life-Cycle Civil Engineering* (Ed. F. Biondini & D.M. Frangopol), CRC Press(A Balkema Book), Varenna, Lake Como, 843-849.

Miyamoto, A. (2010), “Development of a Practical Data Management System for Bridge Maintenance Strategies”, *Life-Cycle of Civil Engineering Systems*, IALCCE 2010, (Ed. S-S Chen, D.M. Frangopol & A.H-S. Ang), National Taiwan University of Science and Technology, Taipei, 289, (CD-ROM : pp.857-864).

Nader, M. Okashaa, D.M. and Frangopola (2012), “Integration of structural health monitoring in a system performance based life-cycle bridge management framework”, *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*, **8**(11), 999-1016.

Nakatsu, K., Furuta, H., Nomura, Y., Takahashi, K., Ishibashi, K. and Miyoshi, N. (2011),“Practical application of long-term bridge management system using genetic algorithm”, *Japan Society for Fuzzy Theory and Inteligent Infomatics*, **23**(4), 469-479.

Safi, M., Sundqutist, H., Karoumi, R. and Racutanu, G. (2012), “Integration of Life-Cycle Cost Analysis with Bridge Management Systems Case Study of Swedish Bridge and Tunnel Management System”, *Transp Res Rec*, (2292), 125-133.

Wang, N., O’Malley, C., Ellingwood, B. and Zureick, A. (2011), “Bridge Rating Using System Reliability Assessment. I: Assessment and Verification by Load Testing”, *J. Bridge Eng.,* **16,** SPECIAL ISSUE: AASHTO-LRFD Bridge Design and Guide Specifications: Recent, Ongoing, and Future Refinements,

854-862.
Yanev, B. (2007), “Bridge Management”, *John Wiley & Sons, Inc.*, New Jersey.
Yang, Y., Kumaraswamy, M., Pam, H. and Mahesh, G. (2011), “Integrated qualitative and quantitative methodology to assess validity and credibility of models for bridge maintenance management system development”, *J .Manage. Eng.*, **27**(3), 149-158.

CC