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Expert System for Serviceability Rating of Concrete Bridges

Système expert pour la détermination de l'aptitude au service de ponts en béton

Expertensystem für die Unterhaltungsbeurteilung von Betonbrücken

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SUMMARY

This paper describes a knowledge-based expert system for serviceability rating of concrete bridges. The present system applies the concepts of basic probability according to Dempster & Shafer's theory to deal with the subjective information related to bridge rating. The final results produced by this system are considered to be represented by five elements expressed by linguistic expressions with the fuzziness value which is the degree of subjective uncertainty.

RÉSUMÉ

Cet article décrit un système expert, de type base de données, pour la détermination de l'aptitude au service de ponts en béton. Le présent système applique les concepts des probabilités de base selon la Théorie de Dempster et Shafer pour tenir compte des informations subjectives relatives à l'évaluation du pont. Les resultats finaux obtenus avec ce système sont considérés comme étant définis pour cinq éléments exprimés par des expressions descriptives avec une valeur de divergence qui est le degré d'incertitude subjective.

ZUSAMMENFASSUNG

Dieser Beitrag beschreibt ein Expertensystem für die Unterhaltungsbeurteilung von Betonbrücken. Das vorliegende System verwendet die Konzepte der grundlegenden Wahrscheinlichkeit nach der Theorie von Dempster & Shafer zur Handhabung der mit der Brückenbewertung zusammenhängenden Information. Für die durch dieses System erhaltenen Endergebnisse wird angenommen, dass sie mit fünf Elementen charakterisiert werden, die durch sprachliche Begriffe, zusammen mit dem Verschwommenheitswert, der Grad der subjektiven Ungewissheit ist, ausgedrückt werden können.

1. INTRODUCTION

In this paper, an expert system for serviceability rating of concrete bridges (Bridge Rating Expert System) is developed based on a combination of several components which are the knowledge base including the subjective information related to the rating, the inference engine, the data reference module, the calculation module, the explanation module, the knowledge acquisition module and the I/O module. The computer system and main language which is used in the expert system are the PC-9801VX41 personal computer made by NEC Corporation, Japan and PROLOG and C languages, respectively. For the construction of the knowledge base including the subjective information related to the rating, it is an unavoidable problem in dealing with subjective informations which cannot be allotted binary codes such as true or false. As a remedy to this problem, a concept of the basic probability according to the Dempster & Shafer's theory is introduced in the present system. The upper probabilities in the Dempster & Shafer's theory to introduce experiences and knowledge accumulated into the knowledge base are obtained through questionnaires sent out to bridge experts. The results of the rating at the final stage produced by this system are considered to be represented by five elements expressed by the linguistic expressions "safe" "slightly safe" "moderate" "slightly danger" "danger" with the fuzziness value which is the degree of subjective uncertainty. A few concrete bridges on which field data have been collected are analyzed to demonstrate the applicability of this expert system. Through the application to the deteriorated reinforced concrete bridge girders and slabs, reasonable results are obtained by inference with the expert system.

2. SYSTEM DESCRIPTION

The Bridge Rating Expert System is a newly developed microcomputer knowledge based system which is capable of various inference and judgment. The expert system consists of seven main components: the knowledge base system, the inference engine, the data reference module, the calculation module, the explanation module, the knowledge acquisition module and the I/O module.

To develop a practical knowledge-based expert system for serviceability rating of concrete bridges,it is necessary not only to establish a diagnostic process model that can capture most of the available information about bridge rating but also have a rule in dealing with subjective information of bridge engineers such as professional experience, knowledge on bridge rating, etc. In order to construct a diagnostic process model in the knowledge processor of the inference engine, the relations among causes of deterioration of structural serviceability (judgment factors) are represented by a global hierarchical form which has serviceability for slabs and main girders, respectively as the final goal. The hierarchy structure consists of 11 sub goals, 23 goals and 34 basic factors for slabs and 10 sub goals, 17 goals and 30 basic factors for main girders. On the other hand, in order to develop a rule in dealing with subjective information of bridge engineers, a concept of the basic probability according to the Dempster & Shafer's theory is introduced in the knowledge base of the Bridge Rating Expert System. The upper probabilities in the Dempster & Shafer's theory[1] to introduce experiences and knowledge accumulated into the knowledge base are obtained through questionnaires consisting more than 400 questions concerning both slab and girder sent out to bridge experts[2]. The knowledge base consists of general facts, a set of production rules for storing the empirical knowledge and a series of knowledge fields[3]. In determining the value of the above-mentioned basic probabilities, $m(\{x\})$,it is deemed effective to base on opinions extracted from questionnaires sent out to bridge rating experts as the bridge engineer's knowledge is considered to be transferred to the knowledge base of the expert system. Considering the case when a group of bridge experts make a diagnosis on a structure, the scattering of individual diagnosis may be regarded as the fuzziness of diagnosis by the group, which may be measured quantitatively by the standard deviation in the case of numerical estimation of the specified factor of a target structure. The questionnaire consists of a series of more than 400 questions which corresponded to the hierarchy structure of rating process for both slab and main girder. The results of bridge rating are considered to be represented by five elements expressed by the linguistic expressions "safe", "slightly safe", "moderate", "slightly danger" and "danger", each of which is symbolized by a,b,c, d and e. The 15 kinds of basic probabilities can be obtained by solving the equations which were formed based on the properties of basic probability. In the rating process of structural serviceability conformed to the hierarchy structure, the combination of some basic probabilities retrieved from the series of knowledge fields are performed in each level of goal and sub goal by use of the Dempster's rule of combination[1]. And, the rating at the final stage will be performed by selecting the element a_i which corresponds to the maximum estimated value $M(a_i)$ given by the following equation and then the judgment is given on the screen display of the system:

$$M(a_i)=\sum_{a_i\in A_k}\frac{m(A_k)}{N(A_k)}\quad (i=1,2,\cdots n) \tag{1}$$

where, $m(A_k)$ is the basic probability for the set A_k and $N(A_k)$ is the number of elements in a set A_k.
Furthermore, since it may be considered that the degree of fuzziness is larger when a large mass of basic probability is able to move in a wider range, the fuzziness, F, of the assessment will be given by the following equation:

$$F=\sum_{A_k} m(A_k)\cdot s(A_k)=\sum_{A_k} m(A_k)\cdot[\{N(A_k)-1\}\cdot dx]$$
$$=\sum_{A_k} m(A_k)\cdot[\{N(A_k)-1\}/(n-1)] \tag{2}$$

where, $s(A_k)$ is the allotted movable distance for the basic probability of a set A_k and $dx=1/(n-1)$ is the distance between adjacent elements on the abscissa.

Both forward and backward reasoning are used as the inference engine in the present expert system. The flow of reasoning in the inference engine of the expert system is shown in Fig.1[3]. The inference is performed separately on the slab and the main girder of a target bridge aiming at the diagnosis of the serviceability as a final goal along the flow of Fig.1. Therefore, two kinds of knowledge-base system are prepared for slabs and main girders, and are read immediately before diagnosis starts. In the flow of inferences shown in Fig.1, the forward reasoning process will continue until the arrival at the data item(basic factor) stage, for which the advanced inferences are difficult to perform. For example, an answer of "yes" or "no" for the deposition of free lime in reinforced concrete bridges halts any further inference. For such items(basic factors), suitable basic probabilities are assigned as an opinion from a series of knowledge fields and are joined

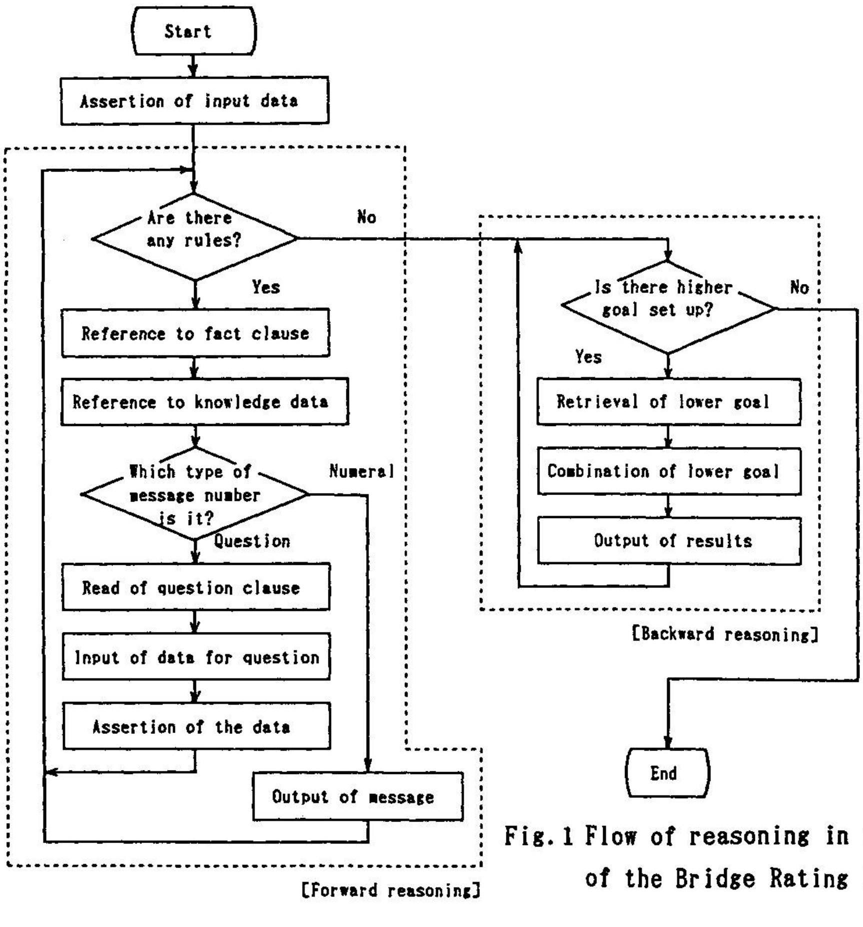

Fig.1 Flow of reasoning in inference engine of the Bridge Rating Expert System

together at each goal. When all data reaches this state, forward reasoning will be followed by backward reasoning. The basic probability is given in a set of production rules for storing the empirical knowledge according to the results of questionnaires or to the subjective judgment on them. During backward reasoning, the lower sub goal, which is necessary for inference of the higher sub goals preset previously, is retrieved, and the assigned basic probabilities are calculated and combined, and next asserted as a new fact clause. At the same time, using the new basic probabilities obtained from the higher sub goal, the estimated values for "safe", "slightly safe", "moderate", "slightly danger" and "danger" with the fuzziness value which is the degree of subjective uncertainty are calculated and picked out as outputs. Finally, the serviceability of a target bridge, which is set as a final goal, is diagnosed basing on the combination of the two highest sub goals, namely the "durability" and the "load carrying capability", and is picked out.

3.APPLICATION OF EXPERT SYSTEM TO ACTUAL BRIDGE RATING

The Bridge Rating Expert System is verified for its effectiveness through the field testing on three kinds of reinforced concrete T-beam bridges[4]. Three national highway bridges, Sakurabashi(constructed in 1933), Maenobashi(constructed in 1931) and Taitabashi(constructed in 1950), were selected for verification of the inference results because these bridges were about 40 and over 50 years old which is considered to be the design service life for concrete bridges.

The Bridge Rating Expert System is used to diagnose the three bridges described above. Table 1 shows an example of a dialog between the expert system and a user extracted from the intermediate stage of the diagnosis of reinforced concrete T-beams(main girders) in Taitabashi bridge. The first question produced by the expert system side to the user concerns the present state of cracks caused in main girders. In the case of Taitabashi bridge, the answer is chosen as "flexural crack", "corrosion crack", "bond crack" according to the observed eminent crack modes in the bridge. Generally speaking, the so-called menu format was adopted where the user selects an answer from prepared multiple-choice suggestions. The

Table 1 An example of dialog between the Bridge Rating Expert System and user (for main girder of Taitabashi bridge)

Question and explanation from the Bridge Rating Expert System	Answer from user
What kind of cracks are there in main girders?	Frexural crack Corrosion crack Bond crack
[C: Vertical cracks are inferred as caused by bending moment]	
What level is the bending cracks?	3rd stage; a few cracks
What is the maximum crack width?	1.0 mm
[C: Cracks over 0.3mm wide are recommended to be repaired]	
Are there any water leakage & free lime near the cracks?	Occurred considerably
Are there any spalling of cover concrete near the cracks?	Occurred slightly
What degree of reinforcement corrosion is there near the cracks?	Severely corroded
What level is the corrosion cracks?	3rd stage; a few cracks
[C: Horizontal cracks parallel to longitudinal direction are inferred as caused by volume expansion of steel corrosion]	
What is the maximum crack width?	0.5 mm
[C: Cracks over 0.3mm width are recommended to be repaired]	
Are there any water leakage & free lime near the cracks?	Occurred considerably
Are there any spalling of cover concrete near the cracks?	Occurred moderately
What degree of reinforcement corrosion is there near the cracks?	No exposure of steel
Are there any rust deposition?	Nothing
What level is the bond cracks?	3rd stage; a few cracks
[C: Small diagonal cracks along reinforcement sometimes occur when steel ratio is relatively large and round bars are used]	
What is the maximum crack width?	0.5 mm
[C: Cracks over 0.3mm width are recommended to be repaired]	
Are there any water leakage & free lime near the cracks?	Occurred considerably
Are there any spalling of cover concrete near the cracks?	Occurred moderately
What degree of reinforcement corrosion is there near the cracks?	No exposure of reinforcing bars
Are there any rust deposition?	Nothing

Table 2(a) Inference results for Sakurabashi bridge

	Judgement factor	safe	slightly safe	moderate	slightly danger	danger	fuzziness
Main girder	Design	0.132	0.313	0.437	0.115	0.003	0.466
	Execution of work	0.049	0.445	0.478	0.028	0.000	0.245
	Service condition	0.345	0.549	0.105	0.002	0.000	0.159
	Flexural crack	0.000	0.000	0.030	0.890	0.081	0.008
	Shear crack	0.000	0.000	0.000	0.081	0.919	0.002
	Corrosion crack	0.000	0.000	0.008	0.748	0.244	0.034
	Whole damage	0.000	0.000	0.000	0.929	0.071	0.000
	Load carrying capa.	0.000	0.000	0.000	1.000	0.000	0.000
	Durability	0.000	0.000	0.000	1.000	0.000	0.000
	Serviceability	0.000	0.000	0.000	1.000	0.000	0.000

Table 2(b) Inference results for Maenobashi bridge

	Judgement factor	safe	slightly safe	moderate	slightly danger	danger	fuzziness
Slab	Design	0.032	0.395	0.523	0.049	0.000	0.113
	Execution of work	0.248	0.248	0.248	0.248	0.008	0.760
	Road condition	0.993	0.007	0.000	0.000	0.000	0.003
	Service condition	0.985	0.015	0.000	0.000	0.000	0.003
	The worst slab	0.026	0.459	0.486	0.029	0.000	0.019
	Crack along haunch	0.277	0.581	0.131	0.011	0.000	0.285
	Crack at slab center	0.056	0.319	0.458	0.167	0.000	0.221
	Whole damage	0.007	0.634	0.357	0.001	0.000	0.006
	Load carrying capa.	0.000	0.442	0.558	0.000	0.000	0.001
	Durability	0.808	0.192	0.000	0.000	0.000	0.001
	Serviceability	0.001	0.999	0.000	0.000	0.000	0.000
Main girder	Design	0.132	0.313	0.437	0.115	0.003	0.466
	Execution of work	0.248	0.248	0.248	0.248	0.008	0.760
	Service condition	0.626	0.357	0.018	0.000	0.000	0.196
	Flexural crack	0.138	0.683	0.176	0.003	0.000	0.084
	Corrosion crack	0.001	0.093	0.599	0.306	0.000	0.000
	Whole damage	0.002	0.397	0.594	0.007	0.000	0.022
	Load carrying capa.	0.001	0.675	0.324	0.000	0.000	0.007
	Durability	0.001	0.789	0.210	0.000	0.000	0.003
	Serviceability	0.000	0.000	0.883	0.117	0.000	0.000

Table 2(c) Inference results for Taitabashi bridge

	Judgement factor	safe	slightly safe	moderate	slightly danger	danger	fuzziness
Slab	Design	0.007	0.317	0.605	0.071	0.001	0.068
	Execution of work	0.407	0.495	0.092	0.006	0.000	0.241
	Road condition	0.058	0.199	0.421	0.321	0.001	0.448
	Service condition	0.865	0.134	0.002	0.000	0.000	0.015
	The worst slab	0.000	0.000	0.001	0.515	0.484	0.003
	Crack along haunch	0.002	0.123	0.815	0.060	0.000	0.076
	Crack near support	0.000	0.007	0.173	0.794	0.026	0.068
	Crack at slab center	0.000	0.000	0.001	0.528	0.471	0.004
	Whole damage of slab	0.000	0.000	0.000	1.000	0.000	0.000
	Load carrying capa.	0.000	0.000	0.006	0.994	0.000	0.000
	Durability	0.000	0.000	1.000	0.000	0.000	0.000
	Serviceability	0.000	0.000	1.000	0.000	0.000	0.000
Main girder	Design	0.264	0.479	0.196	0.060	0.002	0.421
	Execution of work	0.049	0.445	0.478	0.028	0.000	0.245
	Service condition	0.511	0.455	0.034	0.000	0.000	0.178
	Flexural crack	0.000	0.000	0.000	0.009	0.991	0.001
	Corrosion crack	0.000	0.000	0.007	0.832	0.161	0.006
	Bond crack	0.000	0.000	0.078	0.915	0.007	0.020
	Whole damage	0.000	0.000	0.000	0.959	0.041	0.000
	Load carrying capa.	0.000	0.000	0.000	1.000	0.000	0.000
	Durability	0.000	0.000	0.000	1.000	0.000	0.000
	Serviceability	0.000	0.000	0.000	1.000	0.000	0.000

following question is on the flexural cracks on which the observation from the most severely cracked girder was chosen as input. The feature of the cracks pointed out in this case are generally unidirectionally spread out, which leads to the answer "3rd stage" out of a choice of 8 stages presented in a menu format. For the input of a maximum crack width of "1.0mm", which surpasses well above the allowable limit, the system recommends that the cracks be repaired. In the following step, the target of questions is directed to the "condition of cracks along the flexural crack", and answers concerning the severe deterioration around the bottom and both side surfaces are required: "Are there any water leak and free lime deposited? " or "Are there any spalling of cover concrete?". The answers for these are "considerably occurred" and "slightly occurred", respectively. Based on the answer for level of spalling, a further question is produced by the expert system: "What degree of reinforcement corrosion is there". By answering "severely corroded",the questions on the flexural cracks comes to an end. In the next steps, the target of questions is moved forward from "corrosion crack" to " bond crack", and the answers are requested to be prepared on the same manner as that of flexural crack. When all questions are filled up the data(basic factors), and the assigned basic probabilities are combined, the inference results with the inferred causes at the final goal and each sub goal are listed on the screen display through the forward and backward reasoning as shown in Table 2(a)-(c). From these tables, the "slab serviceability" as the final goal inferred from the "load carrying capability" and the "durability" is estimated to be support of the element of "slightly safe" for Maenobashi bridge and "moderate" for Taitabashi bridge. On the other hand, the "girder serviceability" is estimated to be support of the element of "slightly danger" for Sakurabashi bridge, "moderate" for Maenobashi bridge and "slightly danger" for Taitabashi bridge. To illustrate further, we investigate and analyze the estimated values at the sub goals(judgment factors) where the items related to the deterioration of serviceability along the rating process for main girder are as follow: The estimated results for the "flexural crack", "shear crack" and "corrosion crack" in Sakurabashi bridge are support of the element of "slightly danger" and "danger". Then, such estimation affects those for the "whole damage of main girder(element value =0.93)", and the "load carrying capability" and the "durability", which are the highest sub goals and the "girder serviceability" which is the final goal are estimated to be support of the element of "slightly danger(element value =1.0)" without "fuzziness" (see Table 2(a)). On the contrary, for Maenobashi bridge, the estimated results for all judgment factors except for "service condition" have a tendency to support the element of "slightly safe" and "moderate". Then, the "load carrying capability" and the "durability" are estimated to be support of the element of "slightly safe"(see Table 2(b)). Finally, for Taitabashi bridge, the judgment factors except for "design", "execution of work" and "service condition" are estimated to be support of the element of "slightly danger" and "danger". Because such estimation affects those for the abovementioned three factors, both the "load carrying capability" and the "durability" are estimated to be support of the element of "slightly danger (element value =1.0)" without "fuzziness"(see Table 2(c)). These conclusions coincide well with the results obtained through the field testing[4].

4. CONCLUDING REMARKS

By introducing the expert system and constructing the knowledge-base system of experiences and knowledge of experts through questionnaires to them, the systematization of the bridge serviceability diagnosis which is comparatively easy to modify and to renew is shown possible. Through the application to actual bridges, reasonable results were obtained by inference with the system. The certification of the present system will be continued by accumulating data on actual bridges.

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