Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 58 (1989)

Artikel: An expert system for damage assessment of bridge structures using fuzzy production rules

Autor: Furuta, Hitoshi / Shiraishi, Naruhito

DOI: https://doi.org/10.5169/seals-44907

An Expert System for Damage Assessment of Bridge Structures using Fuzzy Production Rules

Système expert pour l'évaluation des dommages des ponts en utilisant les règles de la logique floues

Expertensystem zur Berechnung von Schäden bei Brückenstrukturen unter Verwendung von Fuzzy-Produktionsregeln

Hitoshi FURUTA
Lecturer
Kyoto University
Kyoto, Japan

Naruhito SHIRAISHI
Professor
Kyoto University
Kyoto, Japan

H. Furuta, born 1948, graduated from Kyoto University, Japan. He is Lecturer in Civil Engineering at Kyoto University. His research interests include structural safety, application of fuzzy set theory, and expert systems.

N. Shiraishi, born 1933, received Dr. Eng. Sc. from Columbia University USA. He is Professor of Civil Engineering at Kyoto University. His research interests include wind engineering, structural safety, and damage assessment.

SUMMARY
This paper attempts to develop an expert system for assessing damage states of bridge structures, where the focus is on the reinforced concrete bridge deck, because its failure has been occasionally reported. Similar to the usual expert systems, this system consists of interpreter, rule-base and working memory. Using this system, it is possible to deal with various kinds of uncertainties and ambiguities involved inherently in the data, rules and inference process in a unified and simple manner. An illustrative example is presented to demonstrate the applicability of the system developed herein.

RESUME
Cet article décrit le développement d'un système expert d'évaluation de l'état des dommages des structures de ponts. L'attention s'est portée sur le tableau en béton armé du pont, car des défauts ont été occasionnellement reportés dans cette partie de l'ouvrage. Comme pour les systèmes experts ordinaires, ce système comprend un interpréteur, une base de données et une mémoire active. Avec ce système, il est possible de traiter un nombre varié de cas incertains et d'ambiguités inhérentés aux données, aux règles et aux procédés de déduction d'une manière unique et simple. Un exemple illustre l'utilisation du système développé dans cet article.

ZUSAMMENFASSUNG
In dieser Arbeit wurde versucht, ein Expertensystem zur Schadenberechnung von Brückenstrukturen zu entwicheln, wobei der Schwerpunkt auf Stahlbeton-Fahrbahnen liegt, weil für diese Bauart öfters über Einsturzprobleme berichtet wurde. Wie bei den üblichen Expertensystemen, besteht das neuentwickelte System aus Interpreter, Rule-Base und Working Memory. Dieses System erlaubt deshalb die einfache und einheitliche Behandlung verschiedener Ungewissheiten, die in den Daten, Rules und Inference-Prozessen vorhanden sind. Ein erläuterndes Beispiel soll die Anwendbarkeit des neuen Systems klar machen.

1. INTRODUCTION

Expert Systems are relatively new and can be attractive to structural engineers. An expert system is a useful tool for solving ill-defined problems in which intuition and experience are necessary ingredients[1]. The problem of damage assessment is a typical one of ill-defined problems in the field of structural engineering[2].

In order to establish an efficient repair and maintenance program, it is important to evaluate the damage states of existing structures[4]. However, the damage assessment of structures is not easy due to the lack of available information and the complex mechanism of structural deterioration. Therefore, the daily maintenance has been so far carried out on the basis of intuition and engineering judgment of experienced engineers.

In this paper, we attempt to develop an expert system for assessing the damage states of bridge structures. As the first stage, we pay attention to the damage assessment of reinforced concrete (RC) bridge deck. This is why many failures have occurred in the RC bridge deck which directly resists the applied loads[3].

A number of problems arise when an expert system is built for the practical use. How to treat uncertainty and ambiguity is one of problems which we face occasionally. In this paper, those uncertainties or ambiguities are handled using the theory of fuzzy sets[7]. Namely, the present expert system has such a remarkable feature that it includes a fuzzy operating system which can treat fuzzy sets in the process of data handling, rule representation and inference procedure. Using this system, it is possible to deal with various kinds of uncertainties and ambiguities involved inherently in the data, rules and inference process in a unified and simple manner. Similar to the usual expert systems[5], the damage assessment system consists of interpreter, rule-base and working memory. An illustrative example is presented to demonstrate the applicability of the system developed herein.

2. FUZZY PRODUCTION SYSTEM

In order to derive a meaningful conclusion from imprecise and ambiguous information and knowledge, a special inference procedure is necessary. In this paper, a fuzzy reasoning method[8] is employed for this purpose. The outline of fuzzy reasoning and its role in the production system are described as follows.

In usual, human beings recognize and memorize knowledge and experience by such linguistic expressions as "A red apple is rape" or "A tall man has long legs". These expressions can be represented in terms of "If····, then····· " phrases; "If an apple is red, then it is rape" and "If a man is tall, then he has long legs". However, the adjectives of red, tall and long have ambiguities apparently. It may be impossible to treat those ambiguities associated with the use of natural language in terms of probabilistic methods or certainty factors. In other words, those methods can not derive a conclusion for such information as that an apple is a little bit red or a man is very tall. Fuzzy reasoning method was proposed to deal with this kind of information and therefore it is called as "approximate reasoning"[8].

Based on fuzzy reasoning, a production rule is expressed as

$$\text{If } X \text{ is } \tilde{A}, \text{ then } Y \text{ is } \tilde{B}. \qquad (1)$$

where the attributes of X and Y are defined by fuzzy sets and the symbol $\sim$

denotes a fuzzy quantity. Even if we obtain the input $\tilde{A}'$ which is somewhat different from $\tilde{A}$, we can derive a meaningful conclusion $\tilde{B}'$ using Eq. 1. Moreover, it is possible to give truth values to input data, rules and conclusions. Here, the truth values are also defined by fuzzy sets. For example, "very true" and "true" are specified as

"very-true" = {0.3/0.8, 0.8/0.9, 1/1} (2)

"true" = {0.2/0.6, 0.7/0.7, 1/0.8, 0.8/0.9} (3)

where the symbol / is a separator and the former part means the membership grade and the latter means the truth value which is defined in the range of [0,1]. The value 0 denotes the absolute false and the value 1 denotes the absolute true.

According to the expression of fuzzy reasoning, the input data and rules are written as follows:

```
(database   very-true/(temperature more-or-less-high)
                 true/(throat-pain slightly-small)
                 true/(headache more-or-less-strong)          (4)

(rules diagnosis
   rule-1
      if (temperature high)
         (throat-pain moderate)
      then (deposit (disease cold)
           (*cf times very-true =match)
   rule-2
      if (temperature high)
         (headache very strong)
      then (deposit (disease influenza)
           (*cf times =match)                                 (5)
```

where "database" is a Lisp function to register the input data and "diagnosis" is the name of rule-base and both rule-1 and rule-2 are the names of rules. The symbol = denotes a variable, and =match stores the value of matching degree between the input data and the antecedent of the firing rules. The truth value of the conclusion is calculated through a fuzzy operation between =match and the truth value of the corresponding rule. To select the calculating operator, the Lisp function *cf is employed. The phrase (*cf times =match) means that the calculating operation is the multiplication. The symbol * is used to represent a Lisp function. The detail of the matching process is referred to Ref. [6].

3. ARCHITECTURE OF THE PRESENT SYSTEM

The present expert system consists of the IO system(input and output system), interpreter(inference engine), rule-base, working memory and fuzzy operating system, as shown in Fig. 1. The input data are stored in the working memory through the IO system. The IO system is developed to make the load for data input lighter. When the amount of input data is large, they are categorized and stored in different regions of working memory. The division of working memory is useful for shortening the implementation time. The interpreter works to select adequate rules from the rule-base and implement the reasoning process. The fuzzy operating system is used when fuzzy sets appear in the implementation of the reasoning. All the above systems are written in Lisp. The present system is developed on a 32 bit engineering workstation. By using the

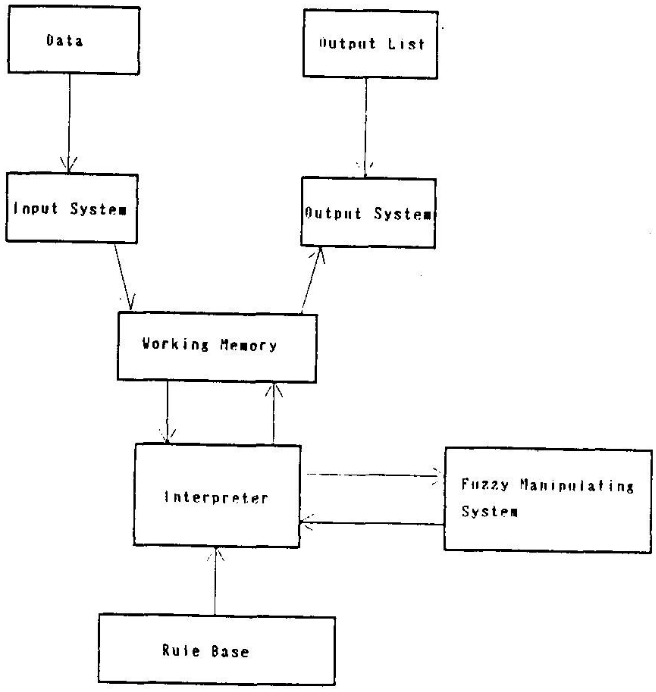

Fig. 1 Architecture of system

engineering workstation as the hardware, we can take such advantages as the easiness of transfer and the improvement of computer environment.

4. DAMAGE ASSESSMENT SYSTEM FOR REINFORCED CONCRETE DECK OF BRIDGE STRUCTURE

This paper attempts to develop an experts system for assessing the damage states of bridge structures, where the focus is put on reinforced concrete (RC) bridge deck, because its failures have been occasionally reported. The system has the following characteristics:

1) Lots of valuable expertise regarding the damage cause and damage propagation of reinforced concrete bridge deck can be acquired through a considerable number of interviews for experts of maintenance work.
2) It is possible to deal with the ambiguity and uncertainty involved in data and knowledge by introducing the fuzzy reasoning.
3) To assess the structural damage properly, the remaining life of RC bridge deck is employed as a final form of result, which is estimated on the basis of three measures; damage cause, damage degree and damage propagation speed.

In this system, the past records and inspection results are used as the input data. When the inspection results regarding cracks are firstly input into the system, the matching processes for rules concerning their damage cause, damage degree and damage propagation speed are implemented to provide a solution for the remaining life. This inference procedure is performed as shown in Fig. 2. At first, based on the inspection results, the damage is classified into cracks, damage of pavement, damage of reinforcing steel, damage of concrete, and structural damage. Followingly, using the design and environmental conditions as well as the inspection data, possible damage causes are estimated. Table 1 presents representative damage causes which are categorized by loading condition, design and structural condition, construction condition and other

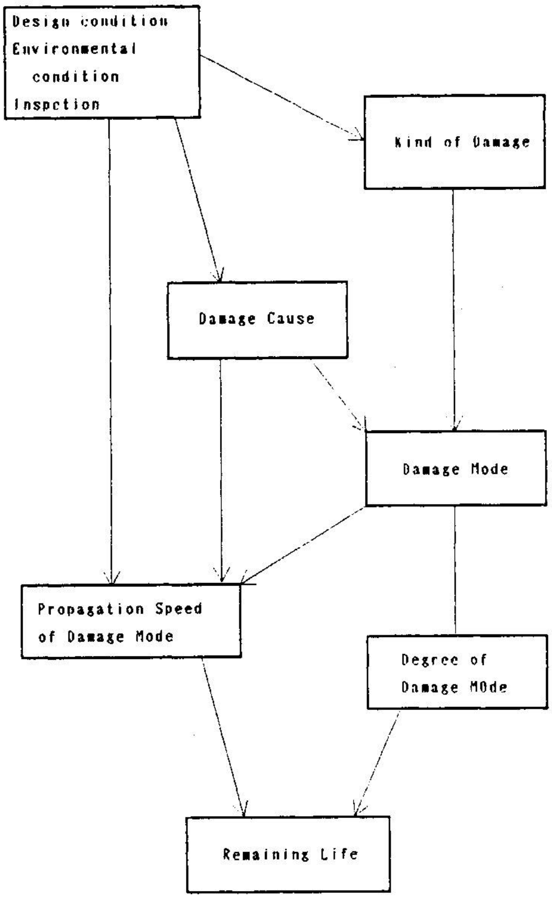

Fig. 2 Inference process

Table 1 Representative damage causes

Load	Extreme wheel load Impact effect inadequacy of girder arrangement
Design and structural factor	Short of deck depth Lack of main steel bar Lack of distribution bar Inadequacy of distributed cross beams Additional moment due to differential settlement
Construction condition	Poor quality of cement Poor compaction Inadequate curing of construction joint Lack of covering
Other Factors	Salt Poor drainage Movement of substructure

conditions. In general, multiple damage causes are estimated, to which "damage mode" is taken into consideration. The damage mode means a group of several damages resulting from the same cause. Identifying a damage mode, damage degrees are evaluated for every kinds of damage. Based on their evaluations, a damage degree to the damage mode is obtained. Similar to the process, the damage propagation speed is assessed by considering the damage causes estimated. Finally, the remaining life is estimated using the construction year and the results obtained above.

It is assumed that the relation between the construction year and the damage degree for intact structures can be expressed by S-0 curve in Fig. 3. Moreover, S-1 to S-5 curves are prepared for structures with very severe damage, severe damage, moderate damage, slight damage and very slight damage, respectively. For example, consider a structure built 20 years ago, whose damage degree is slight and damage propagation speed is slow. The present damage state of this structure is located at a point P in Fig. 4. Since the propagation speed "small" is less than the propagation speed after 30 years of the curve S-0, the propagation speed is replaced by the S-3 curve in the region larger than 30 years. Hence, the damage proceeds according to the solid line P-R-Q. Then, the remaining life is obtained as the subtraction between the abscissas of Q and P.

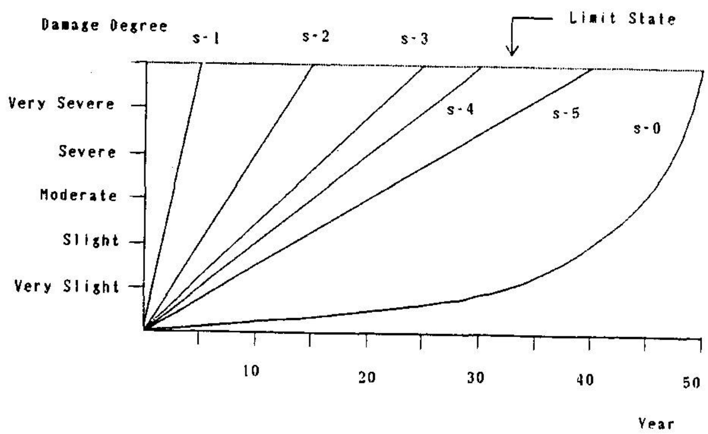

Fig. 3 Relation between construction year and damage state

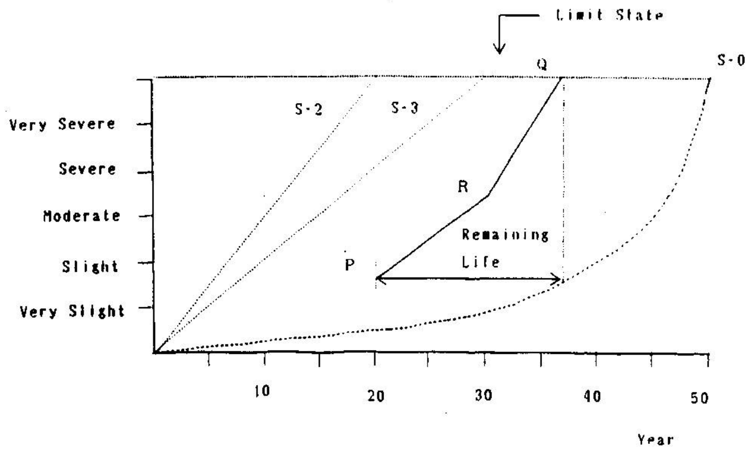

Fig. 4 Estimated remaining life

5. APPLICATION EXAMPLE

To illustrate the applicability of the present fuzzy expert system, consider a 3-spanned cantilever plate girder bridge which was built in 1938. Table 2 presents the design and environmental conditions of this bridge. The damage assessment is performed panel by panel. A panel is a region surrounded by main girders and cross beams. Employing a panel called P-1 as an example, the inference process is described in the following.

Table 2 Design and environmental conditions

Kind	Factor	State	Truth Value
Crack	Direction	Direction to bridge width	FL
	Location	Center of deck span	FL
		Haunch	M
	Density	1.72 m/mm^2	1
	Between distance	Large	FL
	Width	Medium	FL
Con-crete	Free lime	Medium	FL

Table 3 Inspection results

Kind	Factor	Data	Truth value
Design	Structural type	3-spanned cantilever girder bridge(straight)	1
	Design spe-cificastion	Before 1967	1
	Construc-tion year	Old	Large
Condi-tion	Deck width	20 cm	1
	Bridge length	69.00 m	1
	Bridge width	12.95 m	1
	Lanes	3 lanes	1
	Footway	One-side	1
	Road rank	Main road	1
Envi-ronment	Rate of heavy vehicle	Medium	FL
	Location of wheel load	Center of deck span	Large

Using the inspection results shown in Table 3 as well as the design and environmental conditions, several damage causes were estimated, as shown in Table 4. Fig. 5 shows the rules which were used to estimate the damage causes (1). From these damage causes, a damage mode is determined. Followingly, the damage propagation speed is estimated using the damage causes and the environmental conditions. These results are summarized in Table 5. Based on these inference results, the remaining life of the panel is obtained as shown in Table 6. Considering that this bridge exists in the road with large traffic volume and the adopted design code is an old version published in 1926, it is reasonable that the extreme wheel loads and the lack of distribution bars were chosen as damage causes for cracking. Moreover, the defect of surface drainage largely affects the estimation of remaining life, because the damage propagation speed of this damage cause is very quick.

```
(rule-1-1-2-2
 if   (crack configration width-direction)
      (crack location center-of-deck-span)
      (wheel-load location center-of-deck-span)
      (design-specification before-1967)
 then (deposit (damage-cause exteme-wheel-load)
      (*cf times very-true =match)))

(rule-1-3-4-5
 if   (crack configration width-direction)
      (crack location haunch)
      (design-specification before-1967)
 then (deposit (damage-cause exteme-wheel-load)
      (*cf times fairly-true =match)))

(rule-1-5-3-6
 if   (crack configration bridge-direction)
      (crack location center-of-deck-span)
      (design-specification before-1967)
      (wheel-load location center-of-deck-span)
 then (deposit (damage-cause exteme-wheel-load)
      (*cf times true =match)))
```

Fig. 5 Examples of rules for damage causes

Table 4 Estimated damage causes

	Damage cause	Truth value
Cause(1)	Extreme wheel load	Fairly Small
Cause(2)	Lack of distribution bars	Fairly Small
Cause(3)	Poor drainage	Fairly Small

Table 5 Inference results for damage propagation

Damage cause	Damage degree	Truth value	Damage propagation	Truth value
(1)	Medium	Small	Medium	Fairly Small
(2)	Medium	Small	Medium	Small
(3)	Large	Small	Fairly Large	Fairly Small

Table 6 Estimated remaining life

Damage cause	Remaining life	Truth value
Cause(1)	5 to 10 yrs.	Fairly Small
Cause(2)	5 to 10 yrs.	Small
Cause(3)	2 yrs.	Fairly Small

6. CONCLUSIONS

This paper attempted to develop a practical method of evaluating the damage states of bridge structure, that is important to establish an efficient repair and maintenance program. Considering the importance of the knowledge and intuition of experienced engineers in the daily maintenance work, a fuzzy expert system for the damage assessment of the concrete bridge deck was constructed, consisting of interpreter, rule-base and working memory. This system was written in Franz Lisp and implemented on a 32 bit engineering workstation.

The following conclusions were derived:

1) A large number of rules useful for the damage assessment could be acquired through an intensive interview with well-experienced engineers on repair and maintenance works. By introducing the fuzzy operating system into the expert system, it is possible to utilize the knowledge and rules which are expressed in terms of natural language. This enables us to acquire the expertise with ease.
2) Based on the fuzzy reasoning, it is possible to reduce the number of rules necessary for deriving a meaningful conclusion. The reduction is very useful for building a practical expert system.
3) Introducing the concept of damage mode, the reliability of the damage assessment can be increased. Furthermore, the remaining life is valuable to provide useful information to establish a future maintenance program.
4) Although any expert system including the expert systems developed herein is, even now, not completely practical, it may provide substantial assistance to more complicated or creative works which are usually not completely or well defined. In order to make the expert systems to be actually useful, some improvement is desirable on such issues as the knowledge acquisition, knowledge representation, treatment of ambiguity or uncertainty, and man-machine interface.

REFERENCES

1. FURUTA, H., K. S. Fu and J. T. P. Yao : Structural Engineering Applications of Expert Systems, Computer-Aided Design, Vol.17, No.9, pp.410-419, 1985.
2. FURUTA, H., N. SHIRAISHI and J. T. P. YAO : An Expert System for Evaluation of Structural Durability, Proc. of 5th OMAE Symp., Vol.1, pp.11-

15, 1986.

3. FURUTA, H., Y. OZAKI and N. SHIRAISHI : Fatigue Analysis of Reinforced Concrete Decks Based on Fuzzy Sets Theory, Proc. of ICASP-5, Vol. 1, pp.198-205, 1987.
4. SHIRAISHI, N., H. FURUTA and M. SUGIMOTO : Integrity Assessment of Bridge Structures Based on Extended Multi-Criteria Analysis, Proc. of ICOSSAR, Vol. 1, pp.505-509, 1985.
5. SHIRAISHI, N., H. FURUTA, M. UMANO and K. KAWAKAMI : An Expert System for Damage Assessment of Reinforced Concrete Bridge Deck, Preprints of Second IFSA Congress, Vol. 1, pp.160-163, 1987.
6. UMANO, M. : Fuzzy Set Manipulation System in Lisp, Proc. of 3rd Fuzzy System Symposium, Japan, pp.167-172, 1987 (in Japanese).
7. ZADEH, L. A. : Fuzzy Sets, Information and Control, Vol. 8, pp.338-353, 1965.
8. ZADEH, L. A. : The Concept of a Linguistic Variable and Its Application to Approximate Reasoning, Part 2, Information Science, Vol. 8, pp.43-80, 1975.