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# An expert system for damage assessment of a reinforced concrete bridge deck

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*Abstract:* This paper attempts to develop an expert system for assessing damage states of bridge structures, where the focus is put on the reinforced concrete bridge deck, because its failures have occasionally been reported. The expert system consists of an interpreter, data-base and rule-base. All the rules involved are described through production rules with certainty factors. An example is presented to demonstrate the expert system developed.

*Keywords:* Expert system; damage assessment; production rule; certainty factor; Lisp.

## Introduction

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. When a structure is severely damaged due to corrosion, defects or cracks, the damage state can be obviously evaluated from visual inspection and its demolition and alteration will be suggested without hesitation. On the contrary, when exact evaluation is difficult from the visual inspection, our decision making for the maintenance operation becomes very difficult. So far daily maintenance has been carried out on the basis of intuition and the 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 a reinforced concrete (RC) bridge deck. Many failures have occurred in the RC bridge deck which directly resists the applied loads. The damage assessment system consists of three main parts; interpreter, data-base, and rule-base. All knowledge necessary for the inference process is represented by means of production rules [3].

## Expert system for evaluating RC deck damage

### *Overview*

In this system, the inspection results are used as the input data. Supposing that the inspection results regarding cracks are firstly input into the system, rules concerning their damage degree, cause and expanding speed are implemented to provide a solution for the damage assessment. This inference procedure is performed as shown in Figure 1. The total number of available rules is 848: 92 rules for damage degree; 258 rules for occurrence time of damage; 365 rules for damage cause; 65 rules for expanding speed; 9 rules for description of damage state; 30 rules for damage pattern; and 29 rules for proceeding pattern of damage. Those rules are stored in 12 divided rule-bases. In this system, the following improvements are done compared with the previous system [3]:

(1) The number of available rules is larger than that of the previous system. This enables us to obtain a reasonable damage assessment.

(2) By dividing the data-base and rule-base into several groups, it becomes possible to reduce the execution time which is proportional to the number of available rules.

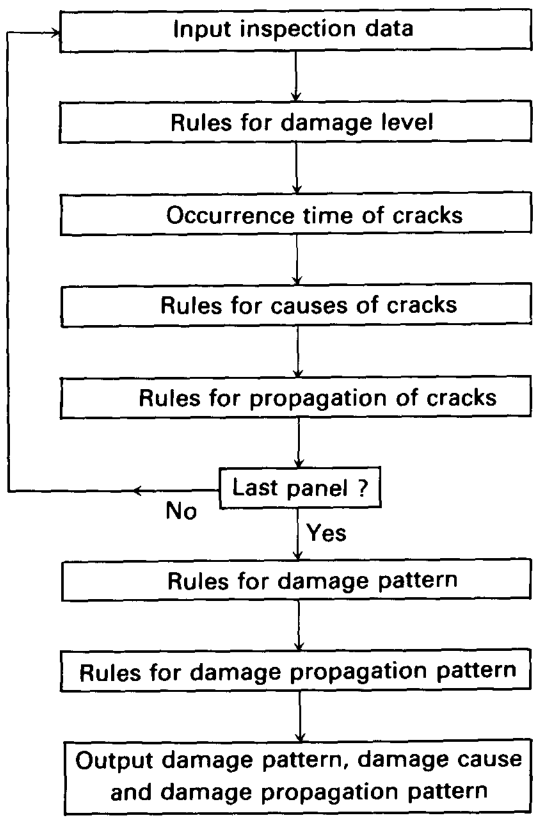


Fig. 1. The inference process.

(3) The uncertainties involved in the input data and rules can be taken into account by introducing certainty factors.

(4) Damage pattern, damage cause and deterioration speed are employed to interpret the inspection data from the multi-aspect point of view.

*Certainty factor*

Most of the data available in the damage assessment generally include certain kinds of uncertainty and experience-based knowledge may be vague and ambiguous. An expert system should, thus, have an ability to treat these uncertainties in a logical manner. The certainty factor is calculated hereafter. Input data and production rules are written as follows, with certainty factors:

Data 1: $C_1$, Data 2: $C_2, \ldots,$ Data $p$: $C_p$

IF Ant. 1, Ant. 2, . . . , Ant. $m$

THEN Con. 1: $C_1'$, Con. 2: $C_2', \ldots,$ Con. $n$: $C_n'$

where Ant. and Con. denote antecedent and conclusion, respectively, and $C_i$ and $C_j'$ are certainty factors. $p$, $m$ and $n$ are the numbers of input data, antecedents and conclusions, respectively.

At execution of the inference procedure using the rules, including the certainty factors, the following must be done:

(1) calculate the certainty factor for the resultant antecedent;

(2) calculate the certainty factor for the resultant conclusion;

(3) determine the final conclusion and calculate its certainty factor for more than two rules which provide the same conclusion.

We employ the following calculating methods corresponding to the items above:

(1) $$C_{in} = \min(C_1, C_2, \ldots, C_m) \tag{1}$$

where $C_{\text{in}}$ is the certainty factor for the resultant antecedent.

(2) $$C_{\text{out},k} = C_{\text{in}} \times C_k' \tag{2}$$

where $C_k'$ is the original certainty factor for the $k$-th conclusion. $C_{\text{out},k}$ is the certainty factor of the $k$-th output.

(3) The certainty factor $C$ for the final conclusion is calculated as follows, using $C_{\text{out},k}$:

$$C = \max(C_{\text{out},1}, C_{\text{out},2}, \ldots, C_{\text{out},k}). \tag{3}$$

Suppose that inspection data are as given in Table 1. Figure 2 shows examples of rules for the inference process. In practice, the values of the certainty factors involved in the input data and production rules are given by an expert who has been engaged in maintenance work for more than 20 years. First, matching succeeds in the rule (damage degree 2-1), where 0.9, 0.5, and 0.7 are prescribed for =CF1, =CF2, and =CF3, respectively. The symbol = denotes CF*i* is a variable. Second, $C_{\text{in}}$ is calculated as 0.7, using (1), i.e., $C_{\text{in}} = \min($=CF1,

Table 1. Inspection data

| Inspection item | Result | CF |
|---|---|---|
| Direction of cracks | 2 directions | 0.9 |
| Width of cracks | Middle | 0.5 |
| Interval of cracks | Small | 0.7 |
| Fracture | Large | 0.5 |

=CF2, =CF3). According to (2), $C_{\text{out},k}$ is obtained as 0.7 from $0.7 \times 1.0$. This leads to the conclusion that damage state is A with CF = 0.7. Similarly, the rule (damage degree 4-1) leads to another conclusion that the damage state is A with CF = 0.5. From these two conclusions, the final conclusion is judged as that damage state is A with CF = 0.7, using (3).

*Evaluation method*

Usual damage state evaluation is based only on the information obtained from visual inspection. If one desires a high accuracy in its evaluation, the damage degree ought to be classified into several categories, where too many categories may often induce a contradiction among them derived by each individual and make classification meaningless. To increase the evaluation accuracy, we introduce three damage measures; damage pattern, damage propagation pattern and damage cause. An appropriate damage pattern is chosen among prescribed basic damage patterns. Similarly, the most probable damage propagation pattern is determined by using the inference results of the crack occurrence time, crack pattern, cause of crack, and serviceability of the concrete deck. Basic damage patterns are determined by considering the following:

Pattern 1: Severe damage is seen all over the concrete deck.
Pattern 2: Severe damage is concentrated at the deck edges.
Pattern 3: Severe damage is concentrated at both ends of a deck.
Pattern 4: Severe damage is concentrated at the overhang portions of the deck.
Pattern 5: Severe damage is concentrated in the deck's center region.
Pattern 6: Severe damage is not seen all over the deck.

```
(damage-degree-2-1
  if
    (direction-of-cracks 2-directions =CF1)
    (width-of-cracks middle =CF2)
    (interval-of-cracks small =CF3)
  then
    (*deposit (damage-degree A (*times 1.0 (*min =CF1 =CF2 =CF3)))))
(damage-degree-4-1
  if
    (fracture large =CF1)
  then
    (*deposit (damage-degree A (*times 1.0 (*min =CF1)))))
```

Fig. 2. Examples of rules for the damage degree of RC decks.

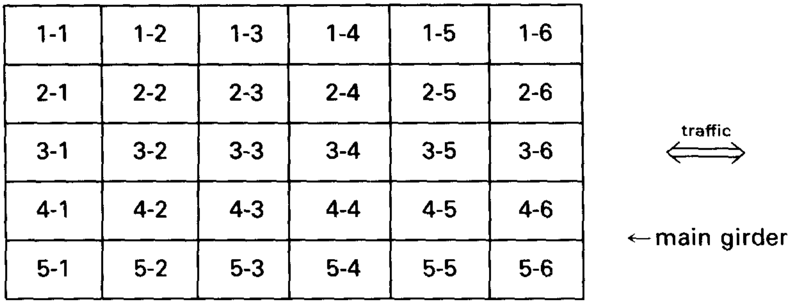


Fig. 3. Panel numbers of the RC deck.

The damage causes are estimated on the basis of damage degree, damage pattern, and loss of serviceability and the estimation is important to clarify the occurrence mechanism of damage as well as useful for establishing an efficient repair and maintenance program.

## Application and discussion

To demonstrate the usefulness of the present expert system, a plate-girder bridge with four main girders and seven cross beams is employed, where a region surrounded by main girders and cross beams is called a 'panel'. Actual inspection is carried out panel by panel. Figure 3 shows the panel numbering to identify the panel location. The inspection data shown in Table 2 are given, for example, for Panel 1-1. Using these input data, our expert system provides the distribution of damage degree and damage propagation speed, as shown in Figures 4 and 5. In these figures, the numbers in parentheses denote the values of the certainty factor. The symbol ? means that the evaluation is impossible from the given inspection data.

Figure 6 presents the rules for evaluating the damage degree of panel 1-1. From

Table 2. Inspection result for panel 1-1

| Inspection item | Result | CF |
|---|---|---|
| Width of cracks | 0.1 mm | 0.8 |
| Interval of cracks | 0.45 cm | 0.7 |
| Direction of cracks | 2-directions | 0.7 |
| Separation from cross beams | Exist | 0.5 |
| Separation of lime | 0.24 $m^2$ | 0.6 |
| Separation of cracks | Lens-like | 0.4 |
| State of cracks | Continuous | 0.4 |
| Mud in cracks | Much | 0.9 |
| Damage degree of steel | *A* | 0.8 |
| Separation of lime | Much | 0.3 |

| | | | | | |
|---|---|---|---|---|---|
| A (0.50) | A (0.90) | B (0.70) | B (0.40) | B (0.60) | A (0.40) |
| B (0.80) | B (0.70) | A (0.80) | ? | A (0.30) | A (0.50) |
| A (0.90) | C (0.80) | A (0.80) | ? | B (0.80) | C (0.80) |
| C (0.20) | A (0.50) | B (0.50) | ? | A (0.70) | A (0.60) |
| B (0.60) | B (0.80) | C (0.40) | A (0.60) | A (0.90) | A (0.30) |

Fig. 4. Damage degree.

this figure it can be seen that

Damage degree B with CF = 0.7 from the rule (damage degree 2-8),
Damage degree B with CF = 0.6 from the rule (damage degree 4-13),
Damage degree A with CF = 0.5 from the rule (damage degree 4-20).

As mentioned previously, when multiple candidates for the conclusion are obtained for the damage degree, the highest rank with the maximum CF is chosen as a final conclusion. Therefore, the final evaluation for the damage degree of panel 1-1 becomes "damage degree A with CF = 0.5". This kind of evaluation is carried out for all the panels. Figure 5 shows the distribution of damage degree for each panel. Using this result, the damage pattern is determined. At first, the whole deck is divided into three zones, zone 1, zone 2 and zone 3, as shown in Figure 7. Next, the following six damage patterns are considered as representative, corresponding to the basic patterns described before. These damage

| | | | | | |
|---|---|---|---|---|---|
| B (0.08) | A (0.34) | A (0.12) | C (0.04) | A (0.10) | B (0.22) |
| A (0.36) | C (0.06) | A (0.22) | ? | B (0.17) | A (0.36) |
| A (0.08) | ? | A (0.16) | ? | C (0.10) | B (0.02) |
| B (0.06) | A (0.26) | A (0.07) | B (0.06) | B (0.16) | B (0.23) |
| C (0.04) | A (0.10) | B (0.04) | B (0.06) | A (0.08) | A (0.13) |

Fig. 5. Damage propagation.

```
(damage-degree-1-2
  if
    (width-of-cracks =x =CF1)
    (<=x 0.2) (>= =x 0.1)
  then
    (*deposit (width-of-cracks middle =CF1)))

(damage-degree-1-5
  if
    (interval-of-cracks =x =CF1)
    (<=x 60) (>= =x = 40)
  then
    (*deposit (interval-of-cracks middle =CF1)))

(damage-degree-2-8
  if
    (direction-of-cracks 2-direction =CF1)
    (width-of-cracks middle =CF2)
    (interval-of-cracks middle =CF3)
  then
    (*deposit (damage-degree B (*times 1.0 (*min =CF1 =CF2 =CF3)))))

(damage-degree-3-10
  if
    (separation-lime =x =CF1)
    (<=x =0.3)
  then
    (*deposit (separation-lime small =CF1)))

(damage-degree-4-13
  if
    (separation-lime small =CF1)
then
    (*deposit (damage-degree B (*times 1.0(*min =CF1)))))

(damage-degree-4-20
  if
    (separation-of-deck-from-cross-beam =CF1)
  then
    (*deposit (damage-degree A (*times 1.0 (*min =CF1)))))
```

Fig. 6. Example of rules for damage degree.

patterns are specified on the basis of the opinion and suggestion of an expert of bridge maintenance work.

Pattern 1: There are more than 70% of panels having damage rank A or B in all zones 1, 2 and 3.

Pattern 2: There are more than 70% of panels having damage rank A or B in at least one zone among 1, 2 or 3.

Pattern 3: There are more than 70% of panels having damage rank A or B in zone 1 only.

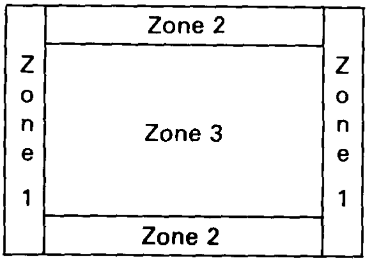


Fig. 7. Three zones.

Pattern 4: There are more than 70% of panels having damage rank A or B in zone 2 only.

Pattern 5: There are more than 70% of panels having damage rank A or B in zone 3 only.

Pattern 6: There are less than 70% of panels having damage rank A or B in all zones, 1, 2 and 3.

According to the above patterns, the damage pattern was concluded as "Pattern 2 with CF = 0.9", where the value of CF was determined as the maximum value of CFs. Similar to this procedure, the damage propagation pattern is obtained as "Pattern 2 with CF = 0.36". It is noted that almost the same basic patterns as the above are prepared for the damage propagation pattern. Finally, the damage cause is estimated using rules regarding the damage causes. For each zone, main damage cause is obtained as follows:

For zone 1: "poor fabrication at the joint of concrete with CF = 0.45".

For zone 2: "poor quality of cement with CF = 0.2".

For zone 3: "sink of cement ingredient with CF = 0.35".

The above results are derived as the damage cause with the maximum certainty factor from a set of possible damage causes.

From these results, this concrete deck should be reinspected and repaired because severe damage is seen at the edges and the damage is still in progress. For its repair, the damage causes estimated above may be worthwhile taking into consideration.

## Conclusions

This paper attempted to develop a practical method of evaluating the durability of bridge structures, which 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, an expert system for the damage assessment of the concrete bridge deck was constructed, consisting of interpreter, data-base and rule-base. This system was written in Lisp and implemented on a FACOM M-382 computer in the Data Processing Center of Kyoto University.

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 work.

(2) The use of certainty factors can lead to a reliable conclusion using vague and ambiguous data and rules.

(3) Introducing the three damage measures such as damage pattern, damage propagation pattern and damage cause, it is possible to give useful information to predict the change of structural durability in the future.

(4) This system has the following problems to be solved in the future:

(a) Although all inferences in this system are performed on the basis of forward reasoning, it is necessary to improve the system so as to use both forward and backward reasoning.

(b) Input and output systems should be improved such that users can utilize this system without any special knowledge or training.

(c) The method of calculating the certainty factors should be examined further. To treat the uncertainty and ambiguity involved in the expression in terms of natural languages, it is useful to introduce the concept of fuzzy sets.

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