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by

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I. Introduction

The safety of structures is one of the major concerns of structural engineers. To evaluate the safety and reliability of existing structures against future hazardous events, the current safety or damage state of each structure should be assessed as accurately as possible. Recently, Yao [1-3] reviewed the role and the state-of-the-art of damage assessment techniques. For example, following a strong-motion earthquake, those few structures which suffer total or partial collapse are easy to identify. For most structures which remain standing, however, it is difficult to assess their true damage states and to determine whether and/or how each structure should be repaired.

The state-of-the-art of damage assessment is that relatively few structural engineers are capable of making such decisions on the basis of their professional experience. Moreover, the transfer of this complex decision-making practice to younger engineers depends primarily on close working relationship with these experienced engineers. To date, several methods of structural damage assessment have been proposed [1], and some related works on the failure resistance evaluation of existing buildings have been reported [4-7]. However, a rational and systematic approach to damage assessment problem has not yet been established.

In 1979, Fu and Yao [8] suggested that the problem of the damage assessment can be considered in terms of the theory of pattern recognition [9-11]. Since 1980, the authors have chosen an expert system approach, which will be briefly reviewed in section II, as the development tool for computer-based damage assessment system. New rule-based inference procedures [12-16] have been developed for this purpose. In this paper, a rule-based damage assessment system called SPERIL version I [17] is outlined along with its theoretical basis. Although (a) the current performance of SPERIL is not yet sufficient for practical applications and (b) the implemented rules are expected to be updated with more accurate and more specific rules, it can be said that this first version demonstrates the feasibility of a systematic appraoch for the computer-based damage assessment system.

II. Methodology

Efficient knowledge utilization of human experts is the most important issue in an expert system in which artificial intelligence techniques are applied to solve complex problems in the real world. Studies relating to the construction of the expert system is called knowledge engineering [18]. The expert system basically consists of a knowledge base and an inference machine. A knowledge base is a storage in a computer, in which useful knowledge is stored in a stylized form suitable for the inference. An inference machine is a control process which deduces an answer from a given problem situation by using the knowledge stored in the knowledge base. Fig. 1 shows a simplified diagram of the expert system.

In the inference process, questions are initiated to obtain additional information in case of need. Those procedures are analogous to, for example, medical diagnosis, in which a physician draws a conclusion by integrating many observed symptoms and his/her knowledge. Expert systems for medical consultations are described, for example, in [19-22].

In a complex problem, it is an efficient way to express relevant knowledge as a collection of many small pieces of knowledge. The problem reduction method [23,24] can be used as a guideline to decompose a problem into simpler subproblems, which are futher decomposed into even simpler subproblems. Hence the whole problem can be described hierarchically, and it has its own final goal to be achieved. Likewise each subproblem has its own subgoal to be achieved form available information.

The production system approach [25,26] provides a convenient way to express a piece of knowledge for the inference process which infers a higher subgoal from observed evidences and lower subgoals. In the production system, a piece of knowledge is written as a production rule in the following basic form;

Rule: IF X,
THEN H,

where IF and THEN clauses are called premise (condition) and action (conclusion), respectifely. The function of the rule is that if the premise is satisfied, then the updating action of the subgoal state takes place.

In the real-world decision-making problems, situations are not always clear and there exist two kinds of uncertainties. One is the uncertainty associated with the observed data or evidences; the other one is the uncertainty associated with the expressed rules. Consequently, the inference procedure which can deal with uncertainties in an effective manner becomes necessary. In addition to AND/OR relations, combination relation denoted by COMB in [14] becomes important in the decision-making problems with uncertainties. The combination relation refers to such a decomposition that the goal is supported separately from more than two evidences. As a result, the problem can be described by AND/OR/COMB graph as shown in Fig. 2. Corresponding rules to Fig. 2 can be represented as listed in Table 1 where C_1, C_2,... are certainty measures between 0 and 1.

Inference for AND/OR relations is rather simple; min and max operations on a certainty measure can be adopted, respectively. Therefore, inference for COMB relation is required to be defined along with the certainty measure. Consider the fundamental case as shown in Fig. 3, where two independent evidential states X and Y are observed or inferred from preceeding inference. Suppose that we have the following rules:

Rule 1

IF: X is X_1
THEN: H is H_{X1} with C_{X1}
ELSE IF: X is Y_2
THEN: H is H_{X2} with C_{X2}
.
.
ELSE: H is H_0,

Rule 2

IF: Y is Y_1
THEN: H is H_{Y1} with C_{Y1}
ELSE IF: Y is Y_2
THEN: H is H_{Y2} with C_{Y2}
.
.
ELSE: H is H_0,

where X_1, X_2, Y_1, Y_2, H_{X1}, H_{X2}, H_{Y1} and H_{Y2} are assumed to be subsets of finite universe sets X_0, Y_0 and H_0, respectively. Now the question is that how should we infer the certainty measure of hypothetical or subgoal state H.

An intuitive combining function is employed in MYCIN [19,28] for this inference purpose. Duda, Hart and Nilsson [29] proposed an inference method for the case where subjective Bayesian probability is used as a certainty measure. The combining function for Bayesian and modified Bayesian probabilities has been reported by the authors [14]. The usefulness of Dempster & Shafer's probability [30,31] is recently recognized by the aurhors [14] and others [32,33] for the ingerence in expert systems. Dempster & Shafer's theory, which is adopted in SPERIL version-I and outlined in section III, enables us to deal with uncertain information in an effective and theoretical manner. As an alternative of the statistical inference methods which often requires idealized conditions such as independency of evidences, the inference procedure based on fuzzy logic [34-36] becomes effective [14,14,21]. Another review of the inference procedures in expert systems appeared in [37].

Once the inference procedure for the COMB relation is defined as well as that for AND/OR relations, the certainty measure can propagate through the hierarchical inference network [28]. Eventually, we can obtain the degree of certainty of the hypothesis in the final goal, which will provide a reasonable answer for decision-making purposes.

III. Dempster & Shafer's Theory and Its Extension to Fuzzy Set

The main criticism regarding the use of Bayesian probability to express uncertain subjectivity is that it cannot be used to deal with ignorance in an effective manner. In other words, the Bayesian theory cannot distinguish between the lack of belief and disbelief, because it requires the relation of $P(A)+P(\overline{A}) = 1$.

In 1967, Dempster [29] proposed a useful concept named lower and upper probabilities to deal with the subjective uncertainty. Shafer refined Dempster's theory in his book [30], in which the terminologies of belief function and plausibility are used instead of the original lower and upper probabilities, respectively. The lower and upper probabilities are defined using Dempster and Shafer's (DS's) basic probability. Dempster's rule of combination provides a way to integrate more than two DS's basic probabilities which are obtained with respect to the same hypothetical goal state from separate bodies of evidences.

According to Shafer [30], the DS's basic probability $m(A_i)$ $(i=0,1,2...)$ can be visualized as a semi-mobile probability mass which is confined to subset A_i but can move freely to every point of A_i. This can be depicted graphically as shown in Fig. 4. Let A_o be a finite universe set and $A_i(i=1,2,...)$ denote crisp subsets of A_o. Then, the DS's bacis probability can be defined formally as a function $M:2^{A_o} \longrightarrow [0,1]$ which satisfies,

$$\begin{cases} m(\phi) = 0, \; (\phi\text{: empty set}) \\ \sum\limits_{A_i \subseteq A_o} m(A_i) = 1. \end{cases} \tag{3-1}$$

The degree of ignorance is represented by $m(A_o)$. A_i is called a focal element if $m(A_i)>0$.

The lower probability is defined by using this DS's basic probability as,

$$P_*(A_i) = \sum_{A_j \subseteq A_i} m(A_j), \tag{3-2}$$

that is, the sum of the DS's basic probabilities confined within the subset A_i. The upper probability is defined by

$$\begin{aligned} P^*(A_i) &= 1-P_*(\overline{A}_i) \\ &= 1-\sum_{A_j \subseteq \overline{A}_i} m(A_j), \end{aligned} \tag{3-3}$$

where $\overline{A}_i$ is the complement set of A_i.

In short, Dempster and Shafer postulate that the distributing process of probability amount to each element as in Bayesian probability is not correct. Rather, their theory treats the probability as one belonging to sets. Then it becomes unnecessary to think about a prior probability.

If m_1 and m_2 are the DS's basic probabilities inferred from independent evidences and A_{1i} and A_{2j} $(i,j = 0,1,2...)$ are their respective focal elements, then Dempster's rule of combination tells that a new DS's basic probability can be obtained by combining m_1 and m_2 as,

$$m(A_k) = \frac{\sum\limits_{A_{1i} \cap A_{2j} = A_K} m_1(A_{1i})m_2(A_{2j})}{1-\sum\limits_{A_{1i} \cap A_{zj} = \phi} m_1(A_{1i})m_2(A_{zj})}, \quad (A_K \neq \phi) \tag{3-4}$$

The combination of more than two DS's basic probability are given, if they are inferred from independent evidences, by the sequential calculation of (3-4).

The application of this theory to the inference procedure in expert systems is rather straightforward. Consider the problem of Fig. 3, where the certainty measure of hypothesis H is supposed to be inferred from the evidential states X, Y and their associated rules Rule 1, Rule 2. The inference procedure is as follows. For Rule 1, first calculate the lower probability of each premise $P_*(X_i)$ (i = 1,2...), then multiply this by the certainty measure C_{Xi}, and assign this amount to the basic probability of H_{Xi} as,

$$m(H_{Xi}) = P_*(Xi)\cdot C_{Xi} \qquad (3\text{-}5)$$

Similarly, from Rule 2 and the evidential state Y, $m(H_{yi})$ can be deduced. These basic probability assignments regarding H from independent evidences can be integrated by using (3-4).

In addition to uncertainty, it is sometimes appropriate to express the knowledge with fuzzy sets [35,38] rather than crisp sets. For example, as will be described later, the expressions of slight moderate, or severe damage as used in SPERIL are not well defined but meaningful for human experts. Thus the Dempster & Shafer's therory was extended by the authors [14,16] to include fuzzy set without losing its essence. As a result, the restrictions X_i, H_{Xi}, Y_i and H_{Yi} in Rule 1 and Rule 2 can be fuzzy subsets characterized by membership functions. In this case, it can be said that the impreciseness of the knowledge is treated in terms of fuzzy sets.

For the extention of the Dempster & Shafer's theory, define the degree that a fuzzy subset A_1 is included in another fuzzy subset A_2 of the same universe set A_o as,

$$I(A_1 \subseteq A_2) = \min_a \left\{ 1,\ 1-\mu_{A_1}(a)+\mu_{A_2}(a) \right\} / \max_a \left\{ \mu_{A_1}(a) \right\} \qquad (3\text{-}6)$$

where $\mu_{A_1}(a)$ and $\mu_{A_2}(a)$ are the membership functions of A_1 and A_2 respectively. Define the degree of intersection of two fuzzy subsets A_1 and A_2 as

$$J(A_1, A_2) = \frac{\max\limits_{a}\left\{\mu_{A_1 \cap A_2}(a)\right\}}{\min\left\{\max\limits_{a}\left\{\mu_{A_1}(a)\right\},\ \max\limits_{a}\left\{\mu_{A_2}(a)\right\}\right\}}, \qquad (3\text{-}7)$$

where the intersection $A_1 \quad A_2$ is defined in the fuzzy set theory by

$$\mu_{A_1 \quad A_2}(a) = \min\left\{\mu_{A_1}(a),\ \mu_{A_2}(a)\right\}. \qquad (3\text{-}8)$$

The degree that the intersection of A_1 and A_2 is ϕ (empty) is defined as $1-J(A_1,A_2)$.

Using these definitions, (3-2) and (3-4) can be generalized respectively to,

$$P_*(A_i) = \sum_{A_j} I(A_j \subseteq A_i) m(A_j), \qquad (3\text{-}9)$$

$$m(A_k) = \frac{\sum\limits_{A_{1i} \cap A_{2j} = A_k} J(A_{1i}, A_{2j}) m_1(A_{1j}) m_2(A_{2j})}{\sum\limits_{A_{1i},\, A_{2j}} \left\{1-J(A_{1i}, A_{2j})\right\} m_1(A_{1i}) m_2(A_{2j})}, \quad (A_k \neq \phi) \qquad (3\text{-}10)$$

Thus the inference procedure with uncertainty and impreciseness is given theoretically.

IV. SPERIL

SPERIL is a rule-based damage assessment system of existing structures particularly subjected to earthquake excitation. In SPERIL version I, separate evidential observations are integrated on the basis of the extended Dempster & Shafer's theory for fuzzy subsets. Useful information for the damage assessment comes mainly from the following two sources; (i) the visual inspection at various portions of the structure and (ii) the analysis of accelerometer records during the earthquake. The interpretation of these data is influenced to large extent by the particular kind of structure under study, such as the material, height and design of the building. The useful pieces of knowledge have been collected under the organization of Fig. 5 and expressed in a stylized rule format in the knowledge-base.

The rule format is designed so that both human and computer can interprete it easily as exemplified in Table 2. The first two digits of four digits of each first rule line are rule set number corresponding to the node number in Fig. 5. To express the knowledge with fuzzy grade, the following fuzzy subsets are allowed:

> no, slig (slight), mode (moderate), seve (severe),
> dest (destructive), uk (unknown - universe set),

the membership functions of which are defined as Fig. 6. In rule interpretation, the fundamental function of production system, that is, "if premise is satisfied, then action takes place," is emphasized. The action in this case is an updating process of short term memory corresponding to the subgoal.

Short-term memories are working memory spaces for inference, in which input data or inferred data are stored. In SPERIL version I, the following four types of short-term memory are used:

type - 1	certainty measures of fuzzy damage grades,
type - 2	linguistic data,
type - 3	numerical data,
type - 4	yes - no data.

When the short-term memory is accessed, the type of short-term memory is referred to proceed to an appropriate interpretation of the rule statement.

Because the inference network is not deep, no heuristic or sophisticated strategy of rule invocation is adapted. The sequence of rule set invocation is pre-assigned as follows:

"05", "06", "07", "08", "09", "10", "02", "03", "04", "01".

This corresponds to bottom-up search rather than top-down or goal-oriented search.

The control & inference process finds and examines a relating rule in the rule-base. If short term memory is found in the examination of the premise to be unwritten or unanswered, a question is initiated to get data. The question is generated by referring to a question file in which an appropriate question sentence is stored for each short-term memory which has the possibility of accepting data from operator rather than the inference process. To avoid the issue of annoying and unnecessary questions, "skip pass" is provided in the control flow for the case that there is no possibility for later action statements to be taken. Thus, only a minimum number of necessary questions is initiated for the purpose of inference.

After one rule is processed, the result is used to update the short-term memory indicated in the action statement. For type-1 short-term memory, the updating is executed by the extneded Dempster & Shafer's theory to integrate independent evidences. The final decision is made according to DS's lower probabilities of the fuzzy subsets in final goal which is damage state. If no fuzzy subset has larger lower probability than a certain threshold (0.2), SPERIL selects no appropriate answer. Therefore, the answer is one of the following:

1) no damage,
2) slight damage,
3) moderate damage,
4) severe damage,
5) destructive damage,
6) no appropriate answer.

More detailed implementation of SPERIL is described in [17]. The control and inference part of SPERIL is written with language-C. SPERIL is currently running on PDP11/45 which can be accessed through Purdue EE Unix network [38].

V. Conclusion

A computer-based damage assessment system of existing structures, called SPERIL version 1, has been developed. Expert system approach and, in particular, inference procedure with uncertainty and fuzzy expression based on the extended Dempster & Shafer's theory has been employed in SPERIL to integrate separate evidential observations. The advantage of this approach is that it has large capability of dealing with the wide variety of structural conditions involved in the damage assessment problem. As is stated in section I, the current implemented rules are expected to by updated by more accurate and more specific rules for better performance in the near future. A systematic knowledge acquisition from human experts in one of the remaining important problems in the expert system approach.

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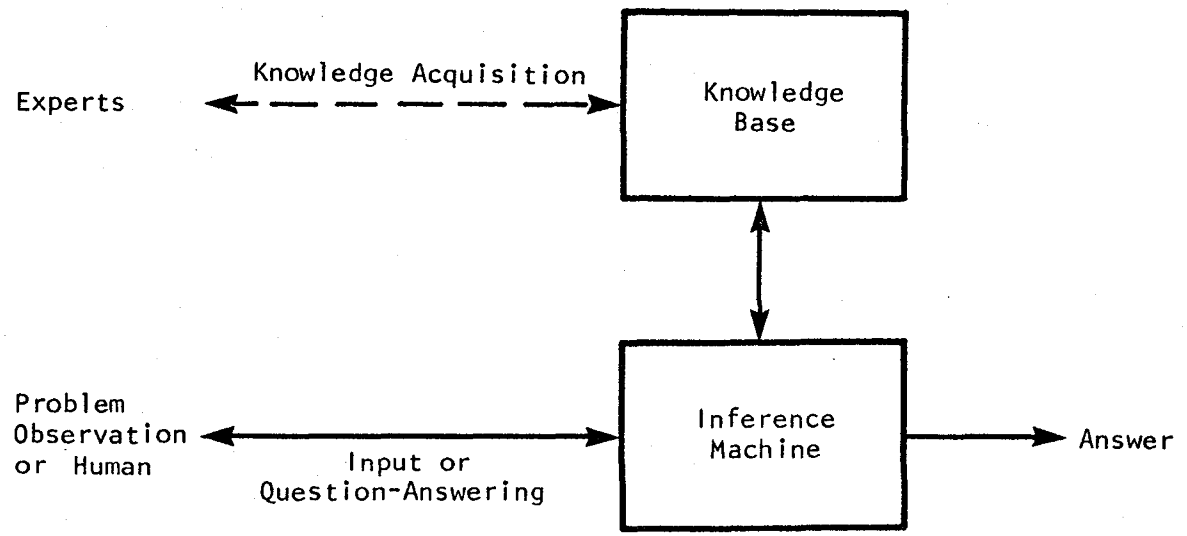

Fig. 1 Expert system.

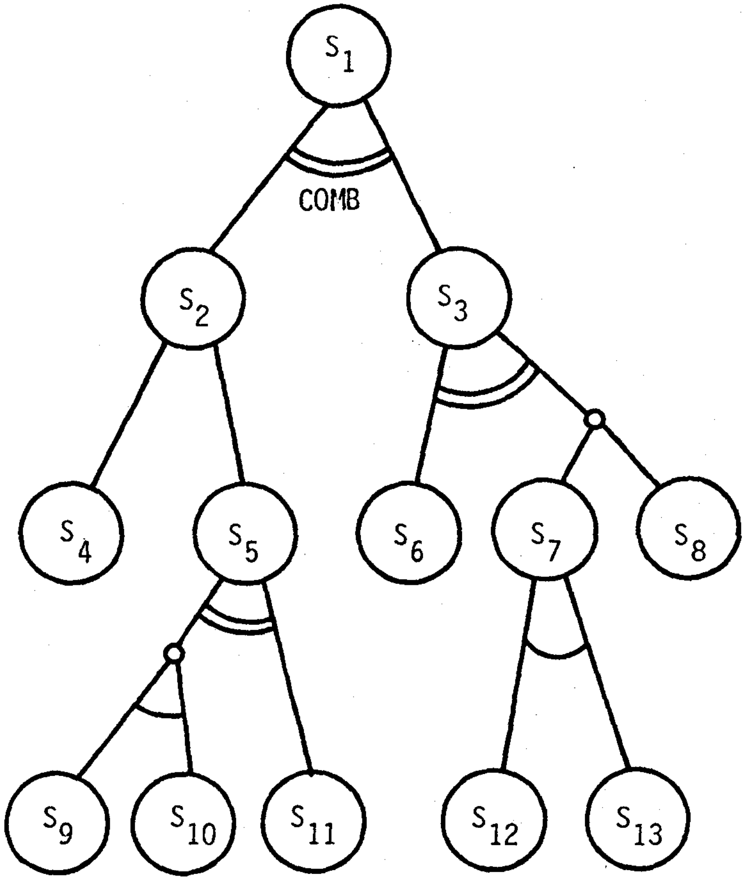

Fig. 2 An example of AND/OR/COMB graph for a problem with uncertainty.

Table 1. Rule representation for Fig. 2

Rule	IF: S_2
	THEN: S_1 with C_1
Rule	IF: S_3
	THEN: S_1 with C_2
Rule	IF: S_4 and S_5
	THEN: S_2 with C_3
Rule	IF: S_6
	THEN: S_3 with C_4
Rule	IF: S_7 *or* S_8
	THEN: S_3 with C_5
Rule	IF: S_9 and S_{10}
	THEN: S_5 with C_6
Rule	IF: S_{11}
	THEN: S_5 with C_7
Rule	IF: S_{12} and S_{13}
	THEN: S_7 with C_8

Table 2. Example of rules in SPERIL.

```
Rule0201
      IF:MAT is   r/c
THEN IF:STI is   dest
   THEN:GLO dest 0.6
ELSE IF:STI is   seve
   THEN:GLO seve 0.6
ELSE IF:STI is   mode
   THEN:GLO mode 0.6
ELSE IF:STI is   slig
   THEN:GLO slig 0.6
ELSE IF:STI is   no
   THEN:GLO no   0.6
   ELSE:GLO uk

Rule0601
      IF:MAT is   r/c
THEN IF:ISD <=   -8.9
   THEN:DRI uk    1
ELSE IF:ISD <=   0.4
   THEN:DRI no   0.9
ELSE IF:ISD <=   0.8
   THEN:DRI slig 0.9
ELSE IF:ISD <=   1.3
   THEN:DRI mode 0.9
ELSE IF:ISD <=   2.0
   THEN:DRI seve 0.9
ELSE IF:ISD >    2.0
   THEN:DRI dest 0.9
   ELSE:DRI uk

Rule0901
      IF:MAT is   steel
THEN IF:S01 is   yes      (partial collaps)
   THEN:VST dest 1
ELSE IF:S02 is   yes      (buckling of column)
   THEN:VST dest 0.5
    and:VST seve 0.5
ELSE IF:S03 is   yes      (buckling of girder/beam)
     or:S04 is   yes      (buckling of diagnal bracing)
     or:S05 is   yes      (deformation or loosing of joint)
   THEN:VST seve 0.9
ELSE IF:S06 is   yes     (spalling/crack on shear wall)
   THEN:VST mode 0.8
ELSE IF:S07 is   yes     (spalling/crack on exteria/interia wall)
     or:S08 is   yes     (spalling/crack on floor)
   THEN:VST mode 0.5
    and:VST slig 0.5
ELSE IF:S01 is   no
    and:S02 is   no
    and:S03 is   no
    and:S04 is   no
    and:S05 is   no
    and:S06 is   no
    and:S07 is   no
    and:S08 is   no
   THEN:VST no   1
   ELSE:VST uk
```

Abbreviations

dest : destructive
seve : severe
mode : moderate
slig : slight
no : no
uk : unknown
r/c : reinforced concrete

GLO : damage of global nature
DRI : damage due to drifting
ST1 : damage of stiffness
VS1 : visual damage of stractural member
MA1 : material of stracture
ISD : interstory drift

S01 : check items of visual stractural damage for steel
¦
S07

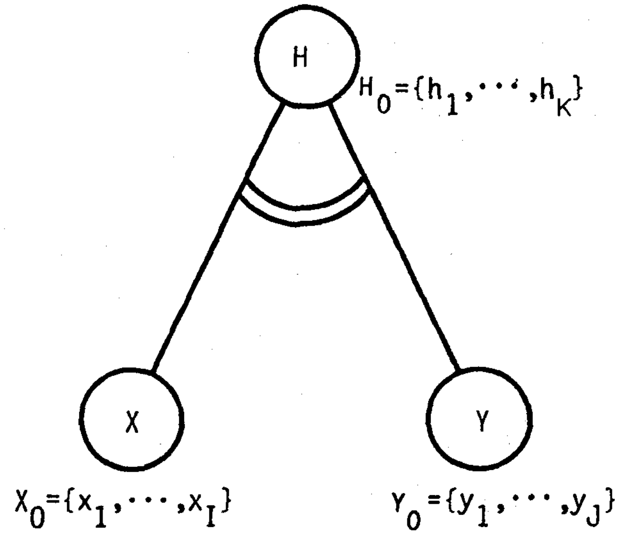

Fig. 3 Inference from the combination of two different evidences.

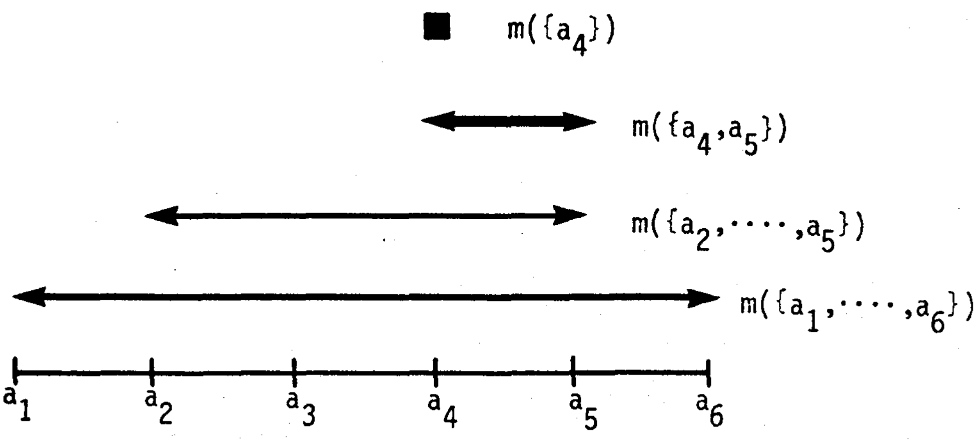

Fig. 4. An image of basic probability $m(A_i)$.
$A_0=\{a_1,\cdots,a_6\}$

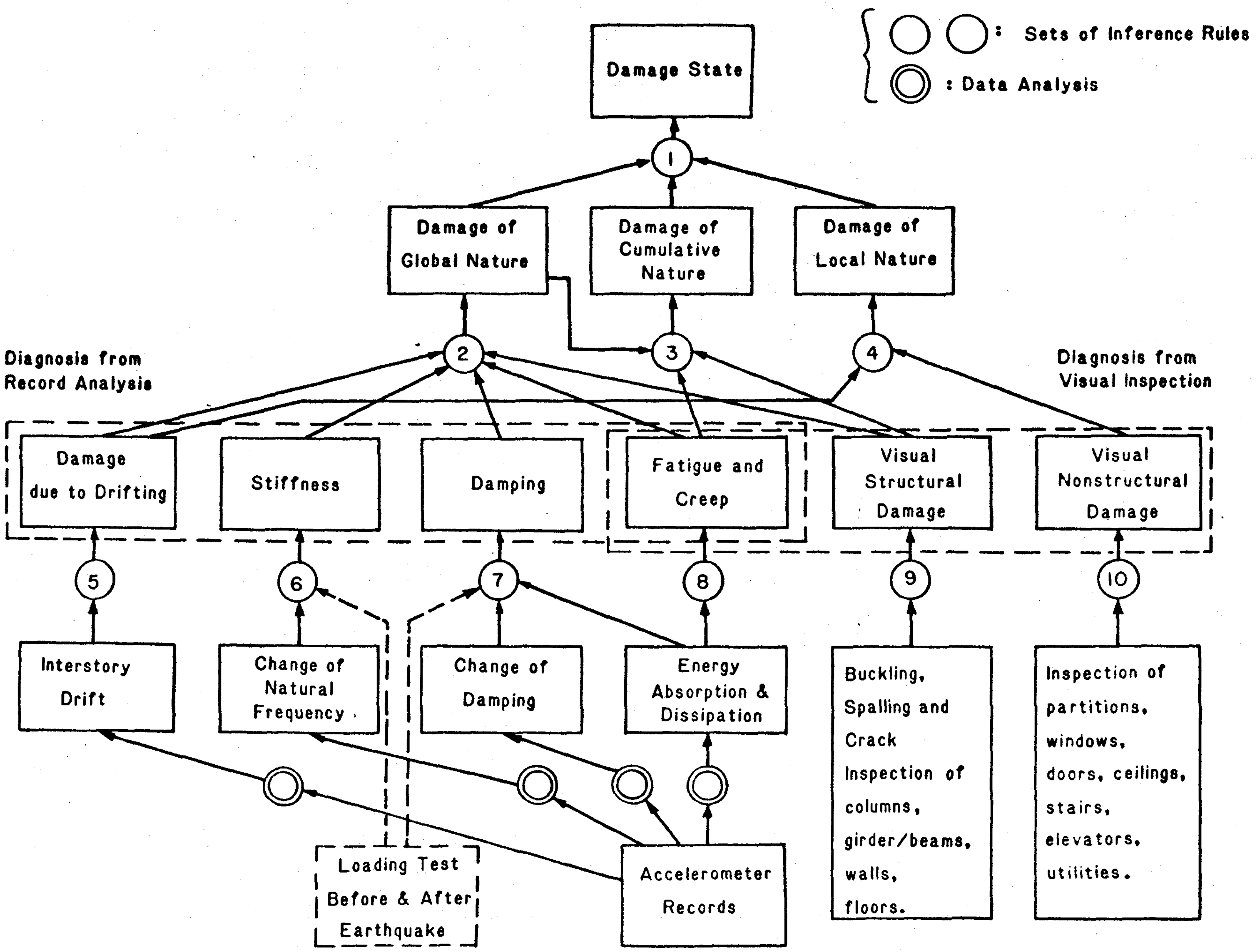

Fig. 5. Inference network of SPERIL.

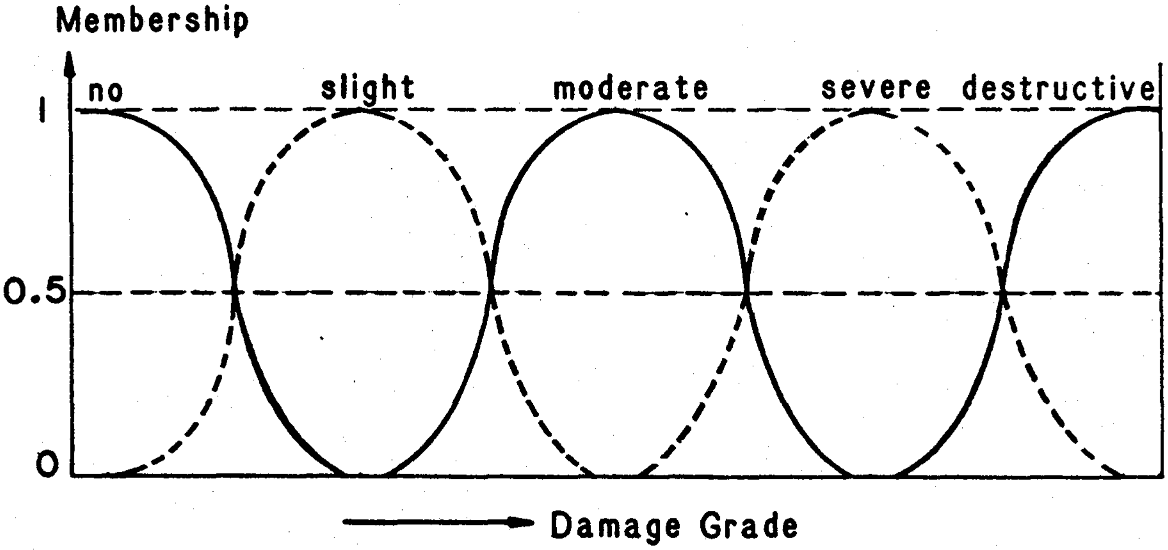

Fig. 6. Membership functions of fuzzy subset in SPERIL.

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