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Computer-Based Systems for the Assessment of Structural Damage

Système informatisé d'estimation des dommages des constructions

Computer-System für die Einschätzung von Bauschäden

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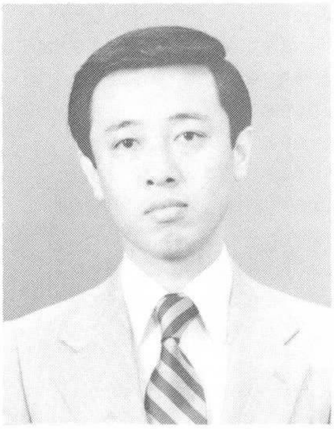

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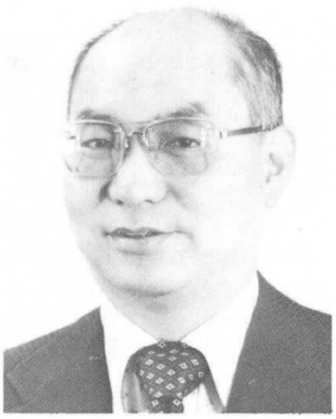

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SUMMARY
To solve the problem of assessment of structural damage, the approach of production system is used to decompose the complex problem into a number of simpler sub-problems. These sub-problems are fitted to knowledge units of human experts. A preliminary version of a program called «SPERRIL-I» is introduced herein to illustrate the feasibility of systematic computer-based damage assessment systems.

RESUME
L'évaluation des dommages d'une construction passe par une décomposition du problème, dans toute sa complexité, en sous-problèmes plus simples, selon l'approche des systèmes de production. Les sous-problèmes doivent correspondre à des domaines de connaissances et d'expérience bien délimités. La version préliminaire du programme «SPERRIL-I» est décrite afin d'illustrer la faisabilité d'un système d'évaluation faisant un usage systématique de l'ordinateur.

ZUSAMMENFASSUNG
Um das Problem der Einschätzung von Bauwerkschäden zu lösen, wird das komplexe Problem in eine Anzahl von Teilproblemen unterteilt. Diese Teilprobleme sind dem Wissensumfang menschlicher Experten angepasst. Eine vorläufige Version des Programms «SPERRIL-I» wird vorgestellt um die Durchführbarkeit eines computerunterstützten Systems für die Einschätzung von Bauwerkschäden zu illustrieren.

1. INTRODUCTION

One of the important problems in structural engineering is to decide whether and how a given structure should be repaired. To assist structural engineers in making such decisions, it is desirable to develop more rational and computer-based systems for the damage assessment of existing structures. The state-of-the-art of this subject matter was reviewed recently [1].

In this paper, several methods including those of Wiggins and Moran [2] Culver et al [3], Bresler et al [4], and Ishizuka et al [5] are critically examined and reviewed. Writers believe that all these methods are based on engineering judgement and professional experience. The correlation and calibration of these and other methods are yet to be performed.

2. METHOD OF BALANCED RISK [2]

In 1971, Wiggins and Moran developed a procedure for grading existing buildings in Long Beach, California. A total of up to 180 points is assigned to each structure according to the evaluation of the following five items:
- (a) Framing system and/or walls (0, 20, 40 points) - A well-designed reinforced concrete or steel building less than three stories in height is assigned a zero-value. On the other hand, an unreinforced masonry filler and bearing walls with poor quality mortar is assigned a value of 40 points.
- (b) Diaphragm and/or Bracing System (0, 10, 20 points) - As an example, zero values correspond to well-anchored reinforced slabs and fills. On the other hand, incomplete or inadequate bracing systems correspond to the high 20 points on the scale.
- (c) Partitions (0, 10, 20 points) - Those partitions with many wood or metal stud bearings rate zero points. On the other hand, unreinforced masonry partitions with poor mortar will draw 20 points.
- (d) Special Hazards (0, 5, 10, 15, 20, 35, 50 points) - The high hazards include the presence of non-bearing, unreinforced masonry walls, parapet walls, or appendages.
- (e) Physical Condition (0, 10, 15, 20, 35, 50 points) - The high hazards include serious bowing or leaning, sign of incipient structural failure, serious deterioration of structural materials, and other serious unrepaired earthquake damage.

For each building thus inspected, all these five numbers are added. Rehabilitation is not required if the sum is less than 50 points (low hazard). Some strengthening is required if the sum is between 51 and 100 points (intermediate hazard). Demolition or major strengthening is necessary when the sum exceeds 100 points (high hazard).

Detailed guidelines are given for the assignment of numbers in each category. Therefore, this method is relatively simple to use even for inspectors who are not trained as engineers. However, it is difficult to develop such a simple procedure to include all special cases. Moreover, the demarcation between low, intermediate, and high hazards is rather arbitrary for these verbal terms which cannot be clearly defined.

3. FIELD EVALUATION METHOD [3]

In 1975, Culver et al [3] proposed the field evaluation method (FEM) which is applicable even when building plans are unavailable. A rating of 1 through 4 is assigned for each (a) general rating, GR, for grading the materials of the frame; (b) structural system rating, s, for combining ratings of connections, roofs, and floors, etc.; and (c) Modified Marcalli Intensity I. Then a composite rating, CR, is computed as follows:

$$CR = \frac{GR + 2s}{3I} \tag{1}$$

If CR<1.0; the building is said to be in good condition, if $1.0 \leq CR \leq 1.4$; it is in fair condition, if $1.4 \leq CR \leq 2.0$; it is in poor condition, if CR>2.0; it is in very poor condition.

In addition, a more detailed methodology was also presented for survey and evaluation of existing buildings to determine the risk to life safety under natural hazard conditions and estimate the amount of expected damage. There are four major parts in this report as follows:

- (a) generation of site loads,
- (b) generation of a structural model,
- (c) computation of response, drift and ductility, and
- (d) assessment of damage.

The damage on i^{th} story, D_i, resulting from extreme natural environments is expressed in percent of total damage as follows:

- $$\mu_i = \frac{\Delta_i}{(\Delta_y)_i}, \text{ and} \tag{2}$$

- $$D_i\% = 100 \times F(\mu_i) \tag{3}$$

where $(\Delta_y)_i$ = user specified interstory drift to yield of i^{th} story.

- μ_i, Δ_i = calculated interstory ductility and drift of i^{th} story, respectively, and
- $F(\mu_i)$ = distribution function of ductility to yield of i^{th} story.

The damage is classified into three categories: structural, nonstructural and glass. It is further subdivided into frame, walls and diaphragms in the case of structural damage.

In this study, a simple method as well as a more elaborate method are proposed. However, even the more elaborate method cannot take into account all the complicated behavior of complex structures. Moreover, there exists a lack of calibration of these methods against any standard case studies.

4. STRUCTURAL AND FIRE EVALUATION MODEL [4]

In 1980, Bresler et al described their structural and fire evaluation model (SAFEM), which was developed to provide a broad overview of potential safety problems for more than 10,000 buildings for a governmental agency in the States. A building can be classified into (a) "green" requiring only routine scrutiny, (b) "yellow" requiring some attention, and (c) "red" requiring immediate attention and improvement. Authors emphatically stated that "SAFEM is not a substitute for an engineering analysis, but it directs attention to buildings which require engineering analysis on a priority basis".

The procedure consists of (a) collection of such data as building size, cost, number of occupants, address, and predetermined exposure to natural hazards; (b) ranking buildings on the basis of priorities; (c) choosing buildings which should undergo field surveys; (d) performing field surveys and recording survey results in the computer file; (e) re-ranking buildings on the basis of priorities and requesting engineering studies for buildings with the largest potential problems, (f) performing engineering studies and producing the final priority rankings, and (g) allocating funds for upgrading these structures following these priorities. A detailed computer program is developed on the basis of professional experience to combine numbers ranging from 0 to 9 for hazards (geophysical, intrinsic, and local), exposure, and vulnerability. The SAFEM profiles include one each on fire, structural, and miscellaneous (glass safety, cladding failure, electrical system, elevator system, etc.)

Writers are very much impressed by the broad scope and detailed considerations of this program. However, it is difficult to follow how the computer program is developed because of the many subjective inputs involved herein.

5. SPERIL-I [5]

Recently, Ishizuka et al suggested a rule-based damage assessment system called SPERIL version I. Although (a) the current performance of SPERIL has not yet been examined sufficiently 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 approach for the computer-based damage assessment system.

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. 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 [6-9].

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 [10,11] can be used as a guideline to decompose a problem into simpler subproblems, which are further 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 from available information.

The production system approach [12,13] 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), respectively. 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 becomes important in the decision-making problems with uncertainties. The combination relation refers to such a situation 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.

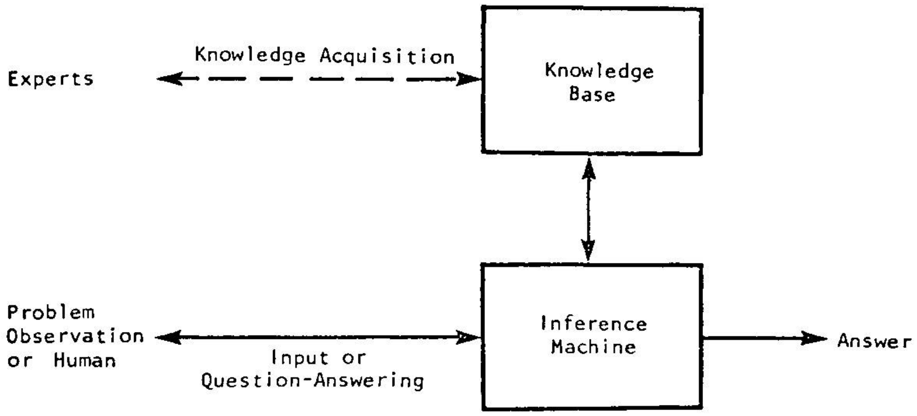

Fig. 1 Expert system.

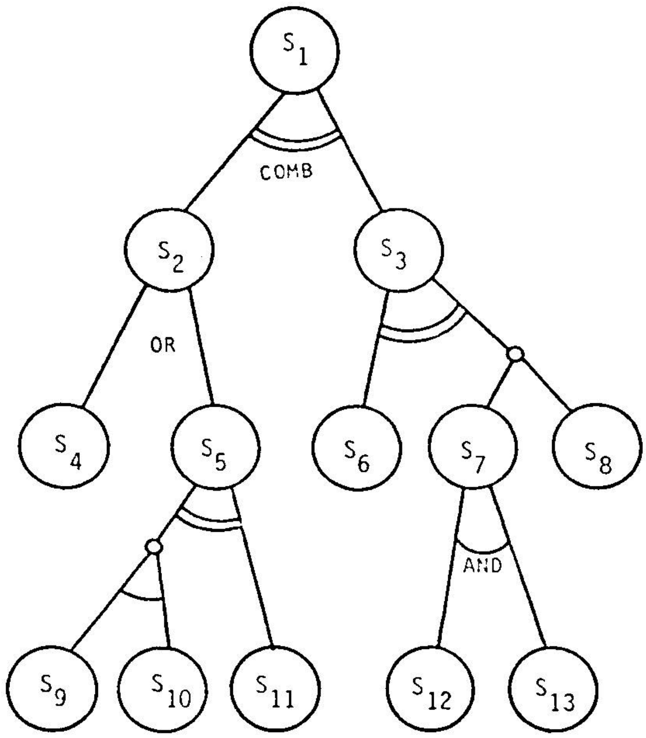

Fig. 2 An example of AND/OR/COMB graph for a problem with uncertainty.

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
ESLE IF:STI is   no
   THEN:GLO no   0.6
   ELSE:GLO uk

Rule0501
      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
ESLE 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:S03 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
STI	damage of stiffness
VST	visual damage of structural member
MAT	material of structure
ISD	interstory drift
S01 ⋮ S09	check items of visual structural damage for steel

An intuitive combining function is employed in MYCIN [6,14] for this inference purpose. Duda, Hart and Nilsson [15] 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 [16]. The usefulness of Dempster & Shafer's probability [17,18] is recently recognized by the authors and others for the handling of ignorance in expert system approach. Dempster & Shafer's theory, which is adopted in SPERIL version-I, enables us to deal with uncertain information in an effective and rigorous 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 [19,20] becomes effective.

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. Eventually, we can obtain the degree of certainty of the hypothesis in the final goal, which will provide a reasonable answer for decision-making purpose.

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 taken 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. 3 and expressed in a stylized rule format in the knowledge-base.

The rule format is designed so that both human and computer can interpret it easily as exemplified in Table 2. The first two digits of each four-digit rule label are rule set number corresponding to the node number in Fig. 3. 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 can be defined. 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 preassigned as follows:

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

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

The control and inference process finds and examines a relating rule in the

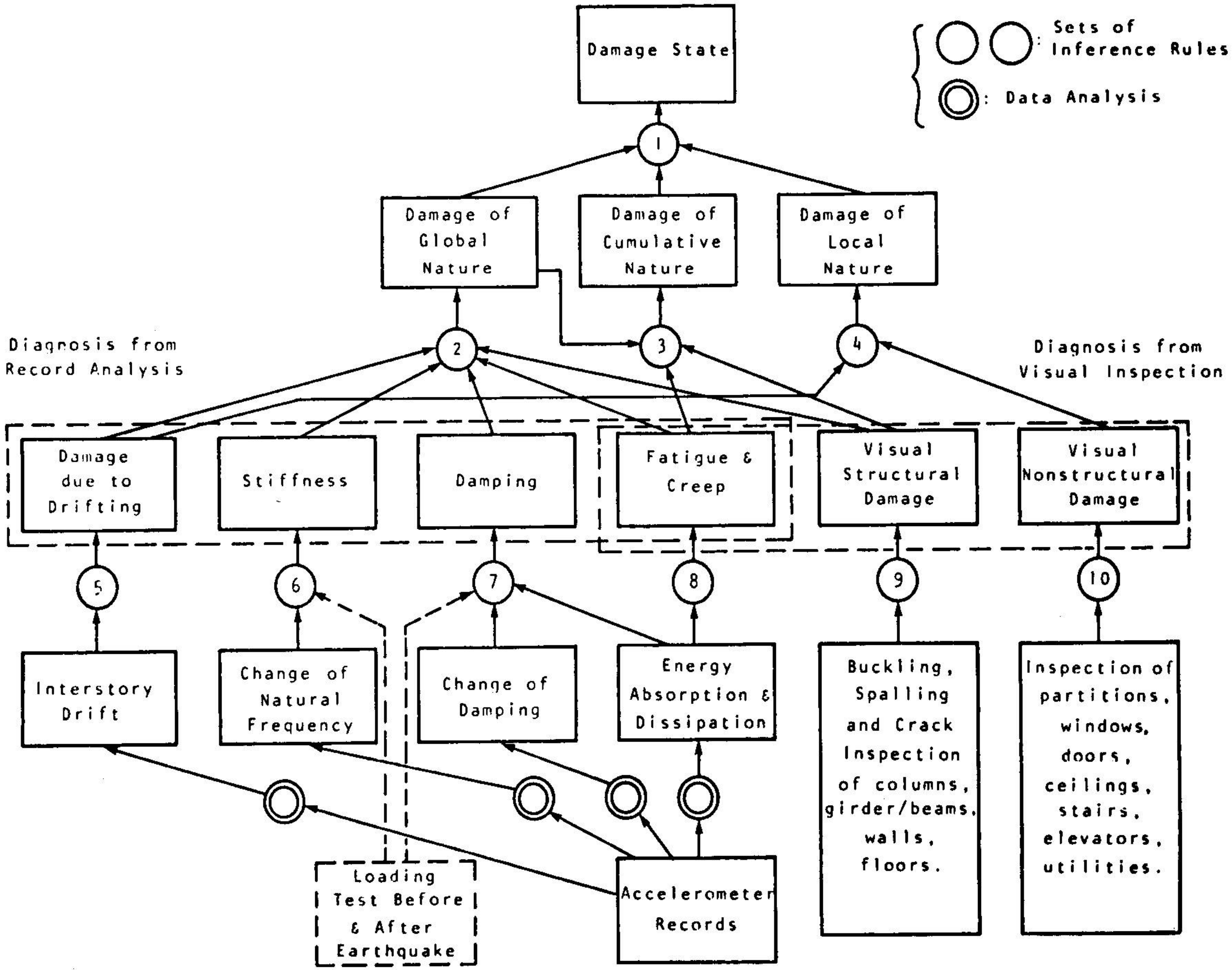

Fig. 3 Inference network of SPERIL.

rule-base. If short-term memory is found in the examination of the premise to be 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 from the inference process. To avoid the situation 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 extended 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 the damage state. If no fuzzy subset has lower probability larger 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 [5]. The control and inference part of SPERIL is written using UNIX Language-C. SPERIL is currently running on a PDP11/45 which can be accessed through the EE computer network at Purdue University.

6. SUMMARY REMARKS

With the advancement of computer technology, there have been several attempts to produce computer programs for the assessment of structural damage. Because of the complexity of the problem and the relative difficulty in summarizing the abundant information collected in such cases, all these systems are primarily based on professional experience and engineering judgment in the decision-making process. Wiggins and Moran [2] can be considered as pioneers in such efforts, and so are Culver et al [3]. The work of Bresler et al [4] is the most comprehensive one today, and it is almost entirely extracted from expert knowledge. On the other hand, Ishizuka et al [5] attempted to formulate the problem in a rational manner. At present, these latter two groups of investigators are in the process of collaborating with each other. It is hopeful that more meaningful results can be obtained in the foreseeable future.

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