INEXACT INFERENCE FOR RULE-BASED DAMAGE ASSESSMENT OF EXISTING STRUCTURES[1]"

Mitsuru Ishizuka, K. S. Fu and James T. P. Yao

School of Electrical Engineering
Purdue University
West Lafayette, Indiana 47907

School of Civil Engineering
Purdue University
West Lafayette, Indiana 47907

ABSTRACT

The knowledge organization of a rule-based damage assessment system of existing structures subjected to earthquake excitation is outlined in this paper. A principle of inexact inference to obtain a rational solution is presented. The fuzzy set theory and the production system with certainty factor are employed jointly in the inexact inference to deal with the continuous nature of the damage state and to attain the modularity of uncertain knowledge, respectively.

I- INTRODUCTION

The role of damage assessment of existing structures has received increasing attention recently [32,33,343. Existing structures refer to those already built and in existence. Frequently, there exists a need to evaluate the safety and reliability of a particular structure or a number of existing structures either as a part of periodic inspection program or immediately following a given hazardous event [5,313. As an example, consider the aftermath of a strong-motion earthquake in a metropolitan area.

prior to construction, each structure is analyzed and designed on the basis of some mathematical formulations, which are the results of idealization and generalizations from available knowledge and past experience. Once a structure is built, it has its own characteristics, which can no longer be precisely described by the same initial mathematical models used in the design phase [8,17,303. More realistic behavior of existing structures can be obtained during earthquakes. For this purpose, accelerometers and other instruments have been installed to record the dynamic behavior of certain building structures [373. System identification techniques [4,6,243 and damage assessment can be employed jointly to examine the real behavior and to assess the safety state of these existing structures so that a correct decision may be reached in terms of any immediate alarm, the need of repairing, the prediction of future damage and the improvement of technologies for aseismic structures.

The state-of-the-art in damage assessment of existing structures is that only very small number of experienced engineers are well qualified to practice it. Moreover, the transfer of this complex decision-making practice to younger engineers depends primarily on many years of close working relationship with these experienced and qualified engineers [33]. To-date, several methods of structural damage assessment have been proposed [32], and some related works on the failure resistance evaluation or estimation of existing buildings have been reported [2,5,23,29]. However, a complete and rational solution of the damage assessment problem is not yet available.

Fu and Yao C113 suggested that the problem of the damage assessment can be considered in terms of the theory of pattern recognition. In pattern recognition C123, when using decision-theoretic C143 or syntactic approaches [10], it requires a description of the patterns under study in terms of a certain mathematical model, which requires a fairly clear or statistical knowledge about the patterns. Such complete knowledge is frequently unavailable in complex or ill-defined problems, or problems involving subjective human factor, such as damage assessment and medical diagnosis [21,273. Accordingly, a recent damage assessment study [183 suggested the use of a rule-based production system to realize a highly effective knowledge utilization of the structural experts and an inexact inference procedure. Relation between pattern recognition and some AI approaches has been discussed in C203.

This paper describes a rule-based damage assessment system of the existing structures subjected to earthquake excitation, called SPERIL Structural <u>Peril</u>). After a brief description of the relevant knowledge organization, the principle of an inexact inference employed in SPERIL is described.

11' KNOWLEDGE ORGANIZATION

Structures are commonly classified according to their structural materials into following types [8,17,303: (a) wooden, (b) masonry, (c) reinforced concrete, and (d) steel. During construction, certain parts of the structure can be prefabricated for economical reasons. In particular, reinforced concrete can be further classified into (C-1 poured-in-place (or in-situ) reinforced-concrete and (C-2) precast (or prestressed) reinforced-concrete. As a structure with a mixed property of reinforced concrete and steel frame, (e) steel-framed reinforced-concrete structures are built in Japan [17]. Among these types, because wooden and masonry construction are frequently limited to low-rise buildings, we will concentrate our attention on reinforced concrete

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and steel structures herein.

Generally speaking, for high-rise structure, steel frame is usually preferable because of its high strength, high ductility and uniform quality. The construction cost of steel structure, however, is frequently higher than that of reinforced concrete.

As the first step to the system design, define the grade of the damage state of existing structures in terms of a numerical quantity between 0 and 10, where 0 and 10 correspond to "no damage" and "total collapse", respectively. In addition, define the damage state in terms of verbal interpretation as shown in Fig. 1- This classification is not strict. However, each class is assumed to be associated with a suitable recommendation and the cost for proper repair action.

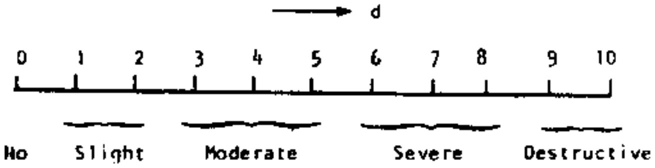

Fig. 1. Grades of damage states and its verbal expressions.

Now the problem is one to construct a rational decision-making system for confirming the hypothesis that the structure in question is severely damaged, to be true or false, or to be more reasonable than other hypotheses from possible observations. The observations may come from (i) visual inspection at various portions of the structure, (ii) reading of accelerometer records during the earthquake, (iii) nondestructive testing, and (iv) loading tests before and after the earthquake. Although we will primarily consider the observations (i) and (ii) in this paper, acceptability of other observations should be considered in the design.

Available features for damage classification from the visual inspection may include the detection of deformations and cracks in columns, beams, joints, floors, ceilings, external & internal walls, doors, windows, stairs, nonstructural par-

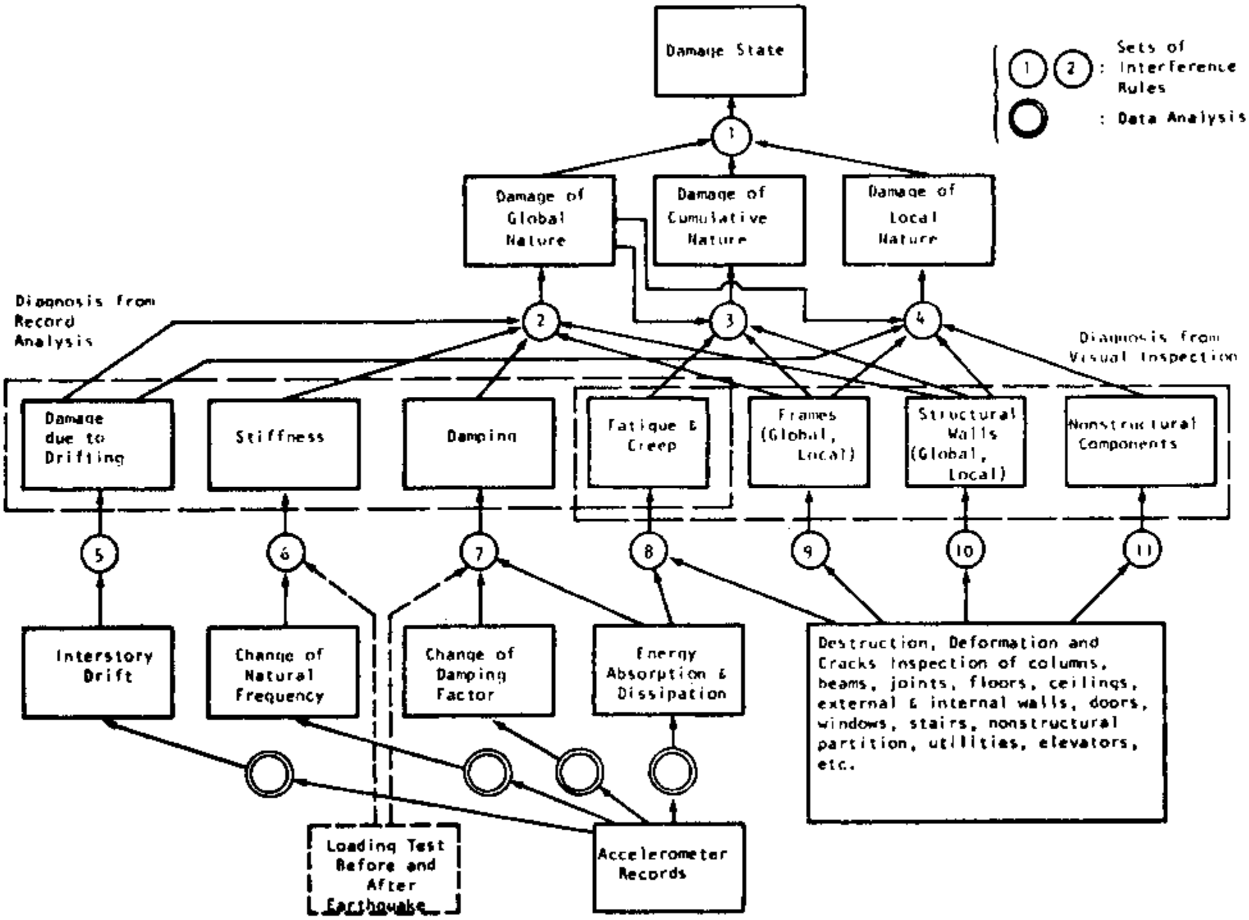

Fig. 2. Inference Network for the Damage Assessment of Existing Structures.

titions, utilities, elevators, etc. Features to be derived from the accelerometer records by using system identification techniques may include the change of natural frequency of the building vibration, the change of damping factor, the maximum interstory drift and the total energy absorption and dissipation during the earthquake. (Time histories of above changes are sometimes also good information for experts.) in addition, when we try to infer the damage state from above-mentioned features, we should consider many other conditions regarding the structures, such as structural material, height or number of stories, areas of floors, shapes, soil condition and foundation, the *year* that the building was built, building use, design parameters if available, existence *oi* walls, experience of human inspector, etc. which *are* stored as reference data apart from inspectior data and utilized for the inference.

The approach of production system [6,26,281 allows us to decompose a complex problem into a number of simpler sub-problems, the relations among which are hierarchical (parent and son) or parallel (brothers). In addition, in order to accommodate knowledge efficiently from human experts, these sub-problems are fit into knowledge units of the experts. With this in mind, the framework for knowledge representation is determined and is shown in Fig. *2,* where several intermediate diagnostic states *are* introduced. Each numbered node corresponds to a set of rules in the productior system for inference. Each double circled node denotes the data analysis process for obtaining the feature from the accelerometer records.

III. PRODUCTION SYSTEM WITH CERTAINTY FACTOR

Before going into the description of SPERIL's inexact inference mechanism, let us see why a direct application of existing methods is inconvenient .

The certainty factor was first introduced int(the production system of MYCIN [25,26] to deal with the uncertainty of knowledge expressed by various experts. The combining function of certainty factor plays an important role in the production system to keep knowledge modularity even in uncertain situations.

Production rules with uncertainty are expressed, for example, as,

Rule 1 IF: X
THEN: there is indication ($C_{h,x}$) that H,

Rule 2 IF: Y
THEN: there is indication ($C_{h,y}$) that H,

where $C_{h,x}$ and $C_{h,y}$ are certainty factors of the hypothesis H when the premises are absolutely satisfied.

The definition of this certainty factor and its relation to probabilities is as follows,

$$C_{h,x} = \begin{cases} 1 & \text{if } P(H) = 1, \quad (1\text{-}1) \\ \dfrac{P(H|X) - P(H)}{1-P(H)} & \text{if } P(H|X) \geq P(H), \quad (1\text{-}2) \\ \dfrac{P(H|X) - P(H)}{P(H)} & \text{if } P(H|X) < P(H), \quad (1\text{-}3) \\ -1 & \text{if } P(H) = 0, \quad (1\text{-}4) \end{cases}$$

where P(H) and P(H|X) are a priori and conditional probabilities, respectively.

When a hypothesis H is confirmed from two different rules, say Rule 1 and Rule 2, the resultant certainty factor $C_{h,(x,y)}$ can be calculated by the combining function. Unlike the heuristic combining functions employed in MYCIN or EMYCIN which is a problem-domain-independent version of MYCIN, a consistent combining function is derived in [19] theoretically based on Bayes' theorem providing that the two evidences are independent in the confirmation of H.

Table 1 - An example of rules

RULE#	
201	IF: 1) STI is severe, and 2) MAT is reinforced concrete, THEN: there is considerable indication (0.6) that GLO is severe.
202	IF: 1) STI is severe, and 2) MAT is steel, THEN: there is strong indication (0.7) that GLO is severe.
203	IF: STI is moderate or destructive THEN: there is weak indication (0.3) that GLO is severe.
204	IF: STI is no, THEN: there is weak <u>negative</u> indication (-0.3) that GLO is severe.
205	IF: FRG is severe, THEN: there is considerable indication (0.4) that GLO is severe.
207	IF: 1) WAG is severe, and 2) MAT is reinforced concrete, THEN: there is considerable indication (0.5) that GLO is severe.

Abbreviations

GLO	damage of global nature
STI	diagnosis of stiffness
FRG	diagnosis of global nature of frames from field inspections
WAG	diagnosis of global nature of structural walls from field inspections
MAT	structural material

$$C_{h,(x,y)} = \begin{cases} \dfrac{\alpha(C_{h,x}+C_{h,y}) - (1-\alpha)C_{h,x}C_{h,y}}{\alpha + C_{h,x}C_{h,y}} & \text{if } C_{h,x} \geq 0,\ C_{h,y} \geq 0, \quad (2\text{-}1) \\ \dfrac{Q}{1 + C_{h,x}C_{h,y}} & \text{if } C_{h,x} \geq 0,\ C_{h,y} < 0,\ Q \geq 0, \quad (2\text{-}2) \\ \dfrac{Q}{\alpha(1+C_{h,x}C_{h,y})} & \text{if } C_{h,x} \geq 0,\ C_{h,y} < 0,\ Q < 0, \quad (2\text{-}3) \\ \dfrac{C_{h,x} + C_{h,y} + (1-\alpha)C_{h,x}C_{h,y}}{1 + \alpha C_{h,x}C_{h,y}} & \text{if } C_{h,x} < 0,\ C_{h,y} < 0, \quad (2\text{-}4) \end{cases}$$

where

$$Q = C_{h,x} + \alpha C_{h,y} + (1-\alpha)C_{h,x}C_{h,y} \qquad (3)$$

and α is a parameter defined by

$$\alpha = P(H)/\{1-P(H)\} \ . \qquad (4)$$

Because X and Y are interchangeable, the case of $C_{h,x} < 0$ and $C_{h,y} \geq 0$ is omitted in Eq. (2). It is worth noting that Eq. (2) reduces to one expression in the particular case of a = 1.

Suppose that the same grade expressions as the final damage state of Fig. 1 are used for the intermediate diagnostic states. For the purpose of illustration, consider node No. 2 in Fig. 2. According to the approach of production system with certainty factor, a set of rules for confirming that structural damage of global nature (GLO) is severe may be listed like RULE 301-207 of Table 1.

The combining function of the certainty factor can work well only in the case that the rules to be combined are mutually independent in confirming a sub-goal. Thus, a problem arises. Although the combining function may work well, for example, among RULE 201, 205, and 207, it does not work well and sometimes leads into incorrect results such as an overestimation in the confirmation, among RULE 201, 203, and 204. The reasons are: 1) the decision is preserved until the final goal in the production system and therefore there exists several possibilities of different hypotheses at one time in an intermediate state, and 2) the inferred sub-goal is continuous in nature in the damage assessment of existing structures. Some minor changes to solve the above problem are possible, but they tend to lose the consistency and knowledge modularity of the production system.

11' FUZZY SET THEORY

in the fuzzy set theory [9,15,35,363, a membership function and its operations play a major role in the expression of ambiguous facts and inferences. Maximum and/or minimum are fundamental operations for the manipulation of the membership function. The theory of fuzzy set could provide a convenient tool to the inference of damage assessment which is continuous in nature. Moreover, recent applications of fuzzy set theory to civil or structural engineering problems [1,3,7,13,333 have shown that fuzzy membership functions provide a good measure for the interpretation of low-level features in damage assessment.

Consider the inference example in Section III in terms of fuzzy set theory under the framework of production system. First of all, we define the damage grades as shown in Fig. 1 as fuzzy linguistic variables. For example, let F denote the severe damage state. Then the membership function can be specified as follows:

$$\mu_F(d) = \sum_d \mu_F(d)/d$$

$$= .2/4+.5/5+.8+/6+1.0/7+.8/8+.4/9 \qquad (3)$$

where d denotes the numerical grade of the damage state.

Suppose that we have a rule

Rule 3. IF: S_x is F

THEN: there is indication ($C_{h,x}$) that S_h is G,

where F and G are fuzzy subsets of universe sets D_x and D_h respectively, and $C_{h,x} > 0$. Let

$$\mu_{G'}(d_h) = C_{h,x} \cdot \mu_G(d_r) \ . \qquad (4)$$

Then we can use the following composition [22] to generate a fuzzy relation R from Rule 3, because it satisfies the inference of modus ponens;

$$R = \mu_R(d_x,d_h),$$
$$= \int_{D_x \times D_h} (\mu_F(d_x) \wedge \mu_{G'}(d_h)/(d_x,d_h), \qquad (5)$$

where $\wedge$ denotes min. operation. If the evidence that S_x is F' which is somewhat different from F is found, then the fuzzy set G'' of S_h can be calculated through a fundamental fuzzy inference as,

$$G'' = R \circ F'$$
$$= \int_{D_h} \bigvee_{d_x \in D_x} [\mu_R(d_x,d_h) \wedge \mu_{F'}(d_x)]/d_h, \qquad (6)$$

where V denotes max. operation.

Several fuzzy sets of <GL0>, for example, can be inferred in this way from Rule 201, 203, 205, 207. According to the elementary operations of the fuzzy set theory, the final <GL0> is eventually obtained by taking the maximum membership function of these {GL0>s at each d.

The advantages of using fuzzy set theory in this application are that, 1) the range covered by a rule is broad, 2) redundant rules are allowed because only one effective element is selected through the max. and/or min. operations, and 3) the inference is realized for the continuous variables by a smart mapping calculations of fuzzy relations. Hence, the problem described in the previous section would not occur.

However, because a strong rule acts to mask the other rules, the property of accumulating several confirmations from different evidences cannot be expected. To attain the accumulation effect, we have to combine the rules to create a new rule. This implies the loss of knowledge modularity.

V- CONFIRMATION BY FUZZY INFORMATION

We have seen that while the production system with certainty factor and the fuzzy set theory in production system have interesting properties in some respects, their direct applications are not necessarily appropriate in damage assessment because of their critical drawbacks.

The idea of inference mechanism employed in SPERIL is simple but very important. That is, the premise and/or conclusion of the rule are regarded as fuzzy sets along the degree of damage state d. individual inference with a rule is conducted in terms of fuzzy information, which will be described subsequently. After this individual inference, several resultant certainty factors of the damage state from different rules *are* combined by using the consistent combining function of Eq. (2).

Suppose that we have the abovementioned Rule 3. The probability of fuzzy state that S_h is G is defined by,

$$P(G) = \sum_{d_h} \mu_G(d_h)p(d_h), \tag{7}$$

where $p(d_h)$ is the probability density at d_h. A posterior probability of fuzzy state S_h after the acquisition of fuzzy state that S_x is F can be calculated by,

$$P(G|F) = \sum_{d_h} \mu_G(d_h)p(d_h|F), \tag{8}$$

Using these definitions, Rule 3 can be interpreted as that if the premise is completely satisfied, $P(G|F)$ is associated with $P(G)$ and $C_{h,x}$ as follows,

$$C_{h,x} = \frac{P(G|F) - P(G)}{1 - P(G)} \quad \text{if } C_{h,x} \geq 0 . \tag{9}$$

A posterior probability density $p(d_h|F)$ is then calculated to satisfy Eqs. (8) and (9); however, this solution is not unique. Therefore we impose a heuristic restriction such that $p(d_h|F)$ is increased over $p(d_h)$ in proportion to $\mu_G(d_h)$ if $C_{h,x} > 0$. Then we can have

$$p(d_h|F) = p(d_h) + \frac{C_{h,x}\{1 - P(G)\}}{\sum_{d_h} \mu_G^2(d_h)p(d_h)} \mu_G(d_h)p(d_h) \ . \tag{10}$$

This implies that the certainty factor at d_h can be inferred by

$$c_{h,x}(d_h) = \frac{p(d_h|F) - p(d_h)}{1 - p(d_h)}$$
$$= C_{h,x}\mu_G(d_h) \frac{1 - \sum_{d_h} \mu_G(d_h)p(d_h)}{\sum_{d_h} \mu_G^2(d_h)p(d_h)} \cdot \frac{p(g_h)}{1 - p(g_h)} \tag{11}$$

$C_{h,x}$ in Eq. (11) will be replaced by $C'_{h,x}$ as described subsequently if the machining of the premise is not perfect.

The certainty factor of the premise part can be calculated as follows,

$$C_x = \frac{P(F|\cdot) - P(F)}{1 - P(F)}$$
$$= \frac{\sum_{d_x} \mu_F(d_x)c_x(d_x)\{1 - p(d_x)\}}{1 - \sum_{d_x} \mu_F(d_x)p(d_x)} , \quad \text{if } c_x(d_x) \geq 0 \tag{12}$$

where $c_x(d_x)$ is the inferred density of certainty factor of S_x. Consequently, $C_{h,x}$ in Eq. (11) is replaced by,

$$C'_{h,x} = C_{h,x}(C_x \vee 0) , \tag{13}$$

where the lower limitation is introduced to eliminate the effect of disconfirmed states. Similarly, equations for $C_{h,x} < 0$ can be derived; they are omitted in this paper.

Both the modularity of the knowledge and the capability of expressing continuous nature can be achieved by taking advantages of the certainty factor and fuzzy membership function, respectively.

VI. CONCLUSIONS

The knowledge organization of a rule-based damage assessment system of existing structures subjected to earthquake excitation is outlined. A principle of inexact inference to reach a rational solution has been described. Fuzzy set theory and production system with certainty factor *are* employed jointly in the inexact inference to deal with the continuous nature of the damage state and to attain the modularity of uncertain knowledge, respectively.

No special strategy to speed up the inexact inference process is adopted at present. It is important for the system to build up gradually by accepting new knowledge. Particularly, recent full-scale dynamic tests of buildings are expected to provide useful information to this problem.

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