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INEXACT INFERENCE FOR RULE-BASED DAMAGE ASSESSMENT OF EXISTING STRUCTURES

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16. Abstract (Limit: 200 words)
A rule-based damage assessment system of existing structures (SPERIL) subjected to earthquake excitation is described. The principal of inexact inference is applied to obtain a rational solution. Both the fuzzy set theory and a production system, with a certainty factor, are used jointly in the inexact inference to deal with the continuous nature of the damage state and to attain the modularity of uncertainty. An inference network diagram for the damage assessment of existing structures is included.

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Abstract

The knowledge organization of a rule-based damage assessment system of existing structures subjected to earthquake excitation is outlined first. Then the application of the 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.

1. Introduction

The role of damage assessment of existing structures is discussed recently [31,32,33]. Existing structures in this paper 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 [5,30]. As an example, consider the aftermath of a strong-motion earthquake in a metropolitan area.

Prior to construction, each structure is analyzed and designed with the use of mathematical formulations, which are results of idealization and generalizations from available knowledge and past experience. Once the structure is built, each structure has its own characteristics, which can no longer be precisely described with the same initial mathematical models used in the design phase [8,16,29]. 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 [36]. System identification techniques [4,15,23] 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 for the immediate alarm, the repair action, 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 such that relatively few 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 very few experienced and qualified engineers [32]. To-date, several methods to assess the structural damage have been proposed [31], and some related works on the failure resistance evaluation or estimation of existing buildings have been reported [2,5,22,28]. However, a complete and rational solution of the damage assessment problem is not yet available.

Fu and Yao [10] suggested that the problem of the damage assessment can be considered in terms of the theory of pattern recognition. In pattern recognition [11], when using decision-theoretic [13] or syntactic approaches [9], it requires to describe 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 pre-matured problems, or problems involving subjective human factor, such as in this damage assessment and medical diagnosis [20,26]. Accordingly, a recent damage assessment study [17] indicates the use of rule-based production system with certainty factor in order to realize a highly effective utilization of the knowledge of structural experts and an inexact inference procedure. A relation between pattern recognition and some AI approaches is discussed in [19].

This paper describes a rule-based damage assessment system of the existing structures subjected to earthquake excitation, the name of the system is SPERIL (Structural Peril). After a brief description of the relevant knowledge organization, the principle of an inexact inference employed in SPERIL is described. Fuzzy set theory [14,34,35] and production system with certainty factor [18,24,25] are utilized jointly in this inexact inference to deal with the continuous nature of the damage state and to attain the modularity of uncertain knowledge respectively.

2. Knowledge Organization

Structures are commonly classified according to their structural materials into following types [8,16,29]: (a) wooden, (b) masonry, (c) reinforced concrete, and (d) steel. During construction, certain parts of the structure can be pre-fabricated for economical reason. 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 [16]. Among these types, because wooden and masonry construction are frequently limited to low-rise buildings, we will concentrate our attention on reinforced concrete and steel structures herein.

Generally speaking, for the high-rise structure, the 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. Maximum height of existing reinforced-concrete structures is limited, for instance, to about 60 stories in United States and 18 stories (7 stories before 1974) in Japan.

As the first step to the system design, define the grade of the damage state of existing structures as a numerical quantity between 0 and 10, where 0 and 10 correspond to no damage and total collapse, respectively. In addition, define its 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. If a structure is classified into destructive damage which is often obvious from visual inspection, its recommendation will be demolition and rebuilding. In the case of severe, moderate and slight damages which are very difficult for inexperienced engineers to determine in precise manner, the recommendation will be major, considerable and minor repairs, respectively.

Now the problem is one to construct a rational way 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 or assessment from the visual inspection may include the detection fo deformations and cracks in columns, beams, joints, floors, ceilings, external & internal walls, doors, windows, stairs, nonstructural partitions, 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 abovementioned features, we should consider many other conditions regarding the structures in question, 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 of walls, experience of human inspector, etc. which are stored as reference data apart from inspection data and utilized for the inference in SPERIL.

To formulate the problem, the approach of production system [6,25,27] allows us to decompose a complex problem into a number of simpler subproblems, 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 fitted to knowledge units of the experts. Keeping this in mind, the framework** for knowledge representation or inference is determined and is shown in Fig. 2, where several intermediate diagnostic states or sub-goals are introduced, the grades of which are inferred from their lower level nodes or sons.

Each numbered node corresponds to a set of rules in production system for the inference, the principle of which is discussed later. Each double circled node denotes the data analysis process to obtain the feature from the accelerometer records. We will not go into further details in this paper except one comment that one of the important things in the interpretation of the visual inspection is to tell inexperienced inspectors what is structural component or non-structural. For example, interpretations of

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*Sozen, M. A., private communication.

**This pre-formation of knowledge or inference framework is not required in some other knowledge representation schemes.

cracks appearing on shear walls, infill walls and non-structural walls are often quite different.

3. Production System with Certainty Factor

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

The certainty factor was first introduced into production system in MYCIN [24,25]. The combining function of certainty factor plays an important role for the production system to keep knowledge modularity even in uncertain situations. For the recent theoretical development of the certainty factor in production systems, see [18].

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 201-207 of Table 1, where the numerical certainty factors of the rules are indicated in parenthesis.

Combining function of the certainty factor can work well only for the case that the rules to be combined are mutually independent in confirming a hypothesis. 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 hypothesis has a continuous 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.

4. Fuzzy Set Theory

In fuzzy set theory [14,34,35], a membership function and its operations play the key role in the expression of ambiguous facts and inferences. One important thing to understand the fuzzy set theory is, in authors' opinion, to know why maximum and/or minimum operations are used. There is no rigid justification for this, except that a) the max. and/or min. operations are the most natural extension of binary logic from a viewpoint of satisfying most of the algebraic axioms in binary logic, and b) the results of these operation are compatible with human intuition. The difference between the probability and the membership function can be understood through the property of the max. and min. operations.

This fuzzy set theory seems to give a convenient tool to the inference of our damage assessment having continuous nature. Moreover, recently its applications in civil or structural engineering [1,3,7,12,32] are believed to provide a good measure for the interpretation of low-level features in damage assessment.

Consider the same inference example as in the previous section 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 B denote the severe damage state. Then the membership function may be specified as follows:

$$\mu_B(d) = \begin{cases} 0.2\ , & \text{if } d = 4 \\ 0.5\ , & d = 5 \\ 0.8\ , & d = 6 \\ 1.0\ , & d = 7 \\ 0.8\ , & d = 8 \\ 0.4\ , & d = 9 \end{cases} \tag{1}$$

where d denotes the numerical grade of the damage state.

Let us use th. following composition [21] to generate a fuzzy relation R from the conditional statement (IF:F, THEN:G), because it satisfies the inference of modus ponens;

$$R = \int_{U \times V} (\mu_F(u) \wedge \mu_G(v))/(u,v), \tag{2}$$

where F and G are fuzzy subsets of universe sets U and V, respectively, and $\wedge$ denote min. operation. Then G' inferred from F' which is somewhat different from original premise F can be calculated as,

$$\begin{aligned} G' &= R \circ F' \\ &= \int_V \bigvee_{u \in U} [\mu_R(u,v) \wedge \mu_F(u)]/v, \end{aligned} \tag{3}$$

where $\vee$ denotes max. operation.

Consider RULE 201 of Table 1 ignoring the second premise which is a non-fuzzy variable. if we treat the certainty factor to proportionally decrease the membership function of the conclusion,* fuzzy sets $\{STI_1\}$ and $\{GLO_1\}$ of the first premise and conclusion, respectively, and the relation R_1 are given,

*This treatment is selected in connection with the following section. Truth qualification can be another approach.

$$\{STI_1\} = \begin{cases} 0.2, & \text{if } d = 4 \\ 0.5, & d = 5 \\ 0.8, & d = 6 \\ 1.0, & d = 7 \\ 0.8, & d = 8 \\ 0.4, & d = 9 \end{cases} \tag{4}$$

$$\{GLO_1\} = \mu_B(d) \times 0.6 = \begin{cases} 0.12, & \text{if } d = 4 \\ 0.3, & d = 5 \\ 0.48, & d = 6 \\ 0.6, & d = 7 \\ 0.48, & d = 8 \\ 0.24, & d = 9 \end{cases} \tag{5}$$

$$R_1 = \{STI_1\} \cap \{GLO_1\} =$$

$$\{GLO\} \begin{array}{c} \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \end{array} \overset{\{STI\}}{\begin{array}{cccccc} 4 & 5 & 6 & 7 & 8 & 9 \\ \end{array}} \begin{bmatrix} .12 & .12 & .12 & .12 & .12 & .12 \\ .2 & .3 & .3 & .3 & .3 & .3 \\ .2 & .48 & .48 & .48 & .48 & .4 \\ .2 & .5 & .6 & .6 & .6 & .4 \\ .2 & .48 & .48 & .48 & .48 & .4 \\ .2 & .24 & .24 & .24 & .24 & .24 \end{bmatrix} \tag{6}$$

After the membership of decendent state {STI} is determined, the membership of {GLO} is obtained or inferred by Eq. (3) and (6).

Likewise, other {GLO}s can be inferred through RULE 203, 204, 205, 207. According to the calculus of fuzzy set theory, the final {GLO} is eventually obtained by taking the maximum membership function of these {GLO}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 previous section would not exist.

However, because a strong rule acts to mask the other rules, the property of inference accumulating several confirmations from different evidences cannot be expected. For example, for the case that both premises of RULE 201 and 205 are satisfied, we must add a new rule;

RULE 2** IF: 1) STI is severe,
2) MAT is reinforced concrete, and
3) FRG is severe,
THEN: there is strong indication (0.7) that GLO is severe.

Otherwise, the contribution of RULE 205 is ignored. The necessity of using this kind of rule addition implies the loss of knowledge modularity.

The other problem of fuzzy set is how should we treat the rules indicating disconfirmations of the consequence like RULE 204. This consequence clause may be replaced by

THEN: there is a weak indication (0.3) that GLO is not severe.

Because the fuzzy set of not-severe is defined by $1 - \mu_B(d)$ (see Eq. (1)), RULE 204 becomes to contribute the confirmation of no and slight damage states. This effect itself is not unconvenient, but the expecting disconfirmation of severe damage state cannot be attained.

5. Membership Function of Certainty Factor

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

The idea of the knowledge representation or inference mechanism employed in SPERIL is simple but very important. That is, the certainty factor rather than the damage grade itself is regarded as a fuzzy set along the degree of damage state d. Individual inference with a rule is conducted by fuzzy inference using the fuzzy relation. After this individual inference, several resultant fuzzy sets of certainty factor from different rules are combined to generate a fuzzy set of certainty factor confirming or disconfirming a hypothesis by using a consistent combining function of certainty factors [18].

Suppose that we have

RULE IF: H_A is $\mu_A(d)$,

THEN: there is indication ($C_{b,a}$) that H_B is $\mu_B(d)$,

where $\mu_A(d)$ and $\mu_B(d)$ are membership functions characterizing no, slight, moderate, severe or destructive damaged state, and $C_{b,a}$ is a certainty factor of the rule. Since $C_{b,a}$ takes a value between -1 and 1 while $\mu_A(d)$ and $\mu_B(d)$ are in the range between 0 and 1, the fuzzy inference of Eq. (2) and (3) is changed to,

$$R = \mathrm{sgn}(C_{b,a}) \int \{\mu_A(d_1) \wedge (|C_{b,a}| \cdot \mu_B(d_2))\}/(d_1,d_2), \tag{7}$$

and

$$\mu_B'(d_2) = \mathrm{sgn}(C_{b,a}) \int \vee \, [|\mu_R(d_1,d_2)| \wedge \{\mu_A'(d_1) \vee 0\}]/d_2, \tag{8}$$

where $\mu_A'(d_1)$ is the determined membership function of certainty factor of H_A in the inference.

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.

6. Conclusions

The outline of the knowledge organization of a rule-based damage assessment system of existing structures subjected to earthquake excitation is described. Then the 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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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 negative 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

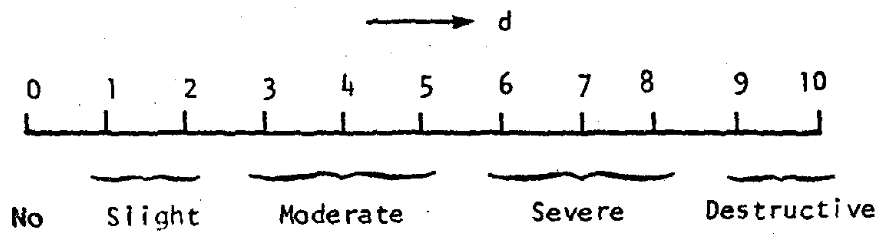

Fig. 1. Grades of damage states and its verbal expressions.

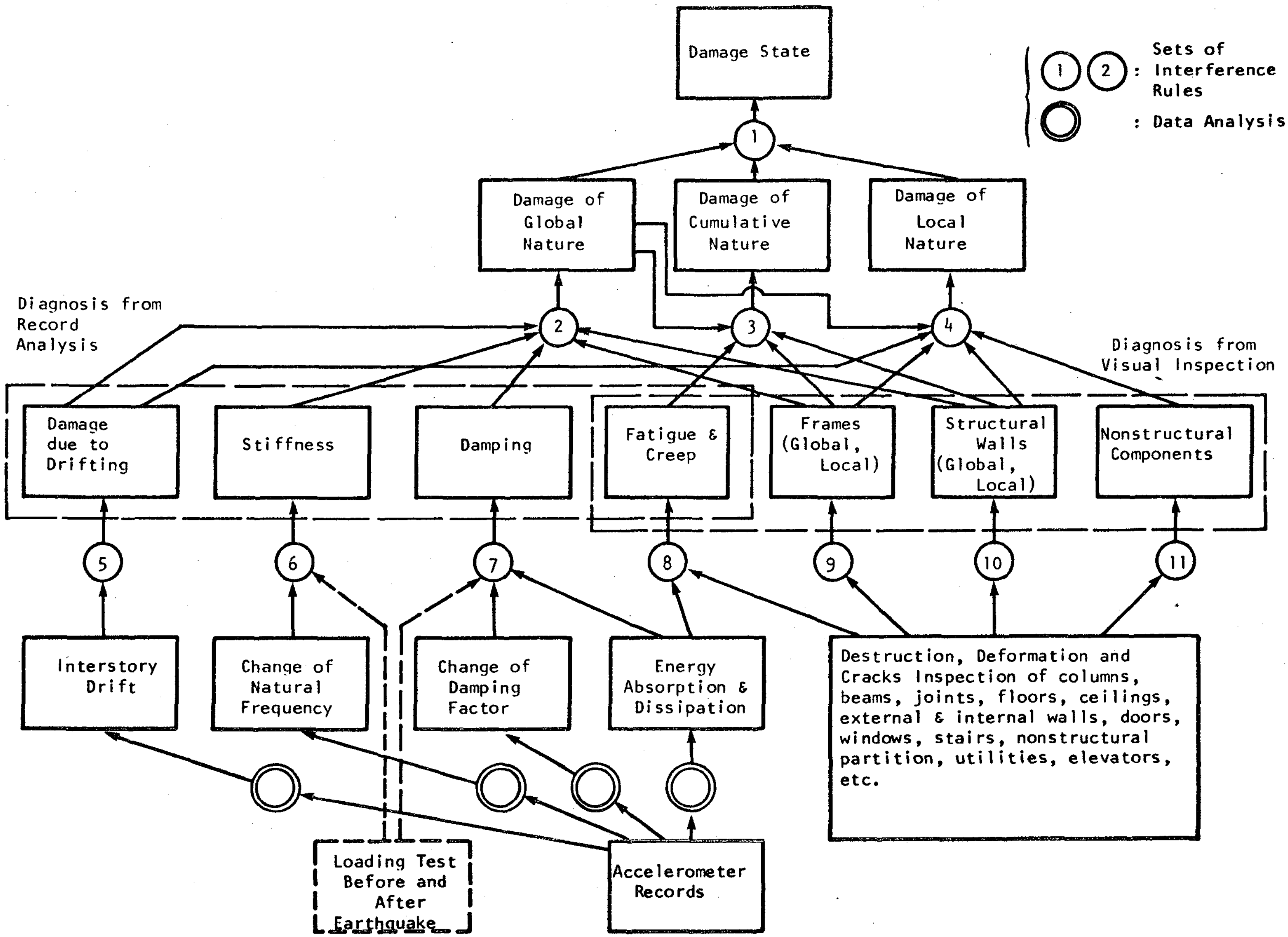

Fig. 2. Inference Network for the Damage Assessment of Existing Structures.

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