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OPTIMUM ASEISMIC DESIGN OF BUILDINGS BASED ON PRODUCTION RULE AND FUZZY THEORY

Hiroshi KAWAMURA[1], Akinori TANI[1], Shin'ichi MATSUMOTO[2], Kouichi TSUNODA[1] and Minoru YAMADA[1]

[1]Department of Architecture, Kobe University, Kobe, Japan
[2]Kansai Electric Power Co., Ld., Osaka, Japan

SUMMARY

In this paper, an optimum aseismic design system for buildings is proposed. By applying Fuzzy Theory, this system is able to take into account subjective evaluations of users. It is also a prototype of Expert System for optimum aseismic design, and its Knowledge Base and Inference Engine are composed on the basis of the concept of Production Rule, and written in PROLOG. In this system synthetic evaluation and optimization are realized by considering various factors of the safety of structures and equipments, flexibility in architectural planning and economy.

INTRODUCTION

In aseismic design of buildings, it is necessary to take into account subjective evaluations of designers and engineers, because its objects are varied and related to many kinds of not only structural but also geophysical, architectural, economical and human factors. The application of Fuzzy Set Theory (Ref.1) to evaluating human subjectivity is considered to be one of the most appropriate methods (Refs.2-5). On the other hand, recently, the method of Expert System (Ref.6) which belongs to Artificial Intelligence (Ref.7) is rapidly developed. Using this method, it is possible to deal with many knowledges simultaneously and systematically. The most interesting and useful subject is how to combine Fuzzy Set Theory with Expert System. There are some studies on this subject in civil engineering (Refs.8-10). The purpose of this paper is to develop an Expert System for optimum aseismic design of buildings to which Fuzzy Theory is applied. The authors have already proposed Fuzzy Confluence Rule by which subjective evaluations and decision-makings are able to be formulated through some parameters (Refs.11,12). In this paper, this Fuzzy Confluence Rule is applied to the evaluation of seismic damages of buildings proposed by the authors (Refs.13,14) and to the fuzzy optimum aseismic design proposed by the authors (Ref.4).

FUNDAMENTAL CONCEPTS OF SYSTEM

DECISION-MAKING HIERARCHY The decision-making hierarchy of optimum aseismic design is shown in Fig.1. It is assumed that the synthetic evaluation of aseismic safety is derived from the following three attributes, i.e., structural safety, flexibility of architectural planning and economy, which are derived, furthermore, from lower attributes as shown in Fig.1. The evaluation of each attribute is composed of 3 grades and expressed by linguistic expressions, e.g., large/middle/small and collapse/damaged/sound, which correspond to representative numerical values [0,1] given by designers. In Fig.1, the confluence of two lower attributes at the each node(1-8) is performed by Fuzzy Confluence Rule (Refs.11,12) proposed by the authors. In this system, Fuzzy Confluence Rule quantifies subjective evaluations of users. The bottom attributes are expressed by linguistic evaluations defined corresponding to lower numerical data.

FUZZY CONFLUENCE RULE (Refs.11,12) The authors proposed Fuzzy Confluence Rule in order to take into account subjective evaluations of designers. Fuzzy Confluence Rule is expressed by the linear interpolation of intersection, union, algebraic summation and algebraic product which are combined by mutual influence, overestimating and weighting parameters, i.e., α, β, and γ_i, as shown in Eqs.1-5 and Fig.2. For example, in case of node 4 in Fig.1, Table 1 shows the linguistic evaluation of upper attribute (structural damage) derived from two lower attributes (damage of columns, damage of shear walls) according to Fuzzy Confluence Rule.

$$\mu_R = (1-\alpha)(1-\beta)\mu_I + \alpha(1-\beta)\mu_P + (1-\alpha)\beta\mu_U + \alpha\beta\mu_S \quad -(1),$$

$$\mu_I = \bigwedge_{i=1}^{n}\{\mu_{xi}(Xi)\}^{\gamma_i} \quad -(2), \qquad \mu_P = \prod_{i=1}^{n}\{\mu_{xi}(Xi)\}^{\gamma_i} \quad -(3),$$

$$\mu_U = \bigvee_{i=1}^{n}\gamma_i\mu_{xi}(Xi) \quad -(4), \qquad \mu_S = 1 - \prod_{i=1}^{n}\{1-\gamma_i\mu_{xi}(Xi)\} \quad -(5),$$

$$\mu_{xi}(Xi) : Xi \rightarrow [0,\ 1],\ x_i \in Xi\ (i=1,2,\cdots\cdots,n),$$

$$\mu_R,\ \mu_I,\ \mu_P,\ \mu_U,\ \mu_S : \prod_{i=1}^{n} Xi \rightarrow [0,\ 1],$$

$$0 \leqq \alpha,\ \beta \leqq 1, \qquad -1 \leqq \gamma_i \leqq 1\ (i=1,2,\cdots\cdots,n).$$

α : Mutual Influence Coefficent
β : Overestimating Coefficent
γ_i,(i=1,2,••••,n) : Weighting Coefficent

OPTIMIZATION INFERENCE The flow of optimization inference is composed of two parts I, II as shown in Fig.3. In the part I, the optimum synthetic evaluation of aseismic design Ai* is selected as a feasible maximum one by backward inference which is the natural function of PROLOG. In the part II, all the optimum combinations Ai^*, Bj^*, are selected by forward inference which is realized by the forced backtrack function of PROLOG. Bj shows the evaluation of lower attributes and Cj shows the procedure of checking the intersection of design parameter regions, i.e, the existence condition of the optimum solutions (Fig.4).

PRODUCTION RULE This system is an Expert System composed of Inference Engine and Knowledge Base (Fig.5). Though the both parts are constructed on the basis of the concept of Production Rule, they are written in PROLOG and consequently do not necessarily have the direct expression of Production Rule "If __ Then __ " (Ref.15). Fig.6 shows a PROLOG expression of Inference Engine used in this system and its corresponding expression as Production Rule. An expression of Knowledge Base used in this system (Fig.7) is also able to be considered as a "Frame" expression (Ref.16).

EVALUATION OF BOTTOM ATTRIBUTES BY CALCULATED DATA Linguistic evaluations of the bottom attributes (Fig.1) are derived from numerical data. Return period is calculated from earthquake magnitude M, epicentral distance Δ and earthquake type (Ref.17) by Extreme-Value Distribution Theory (Ref.18). The maximum response displacement and damage ratio of structures are calculated from given earthquake and building with design parameters by Earthquake Limit Response Analysis (E.L.R.A.) proposed by the authors (Ref.13). These calculations are performed by using BASIC included in this system.

APPLICATION

OUTLINE AS EXPERT SYSTEM The outline of this optimum aseismic design system is shown in Fig.5. By using Fuzzy Confluence Rule, Knowledge Base is constructed according to the subjective evaluations of users through the parameters of Fuzzy Confluence Rule. Furthermore by using PROLOG, extended Knowledge Base is able to be automatically produced. In this system, for simplicity, only one design parameter is employed, so the linguistic evaluations for the bottom attributes in Fig.1 are given by the design parameter (Fig.8). The boundary values a_i, b_i in Fig.4 correspond to the ones in Fig.8. After the construction of Knowledge Base according to input data by users, optimization inference is performed, and finally outputs are presented as answers on CRT.

OBJECTIVE BUILDING In this case study, an optimization on the 1st story of R/C typical school building (shown in Fig.9) is carried out. This school building is supposed to be located at Kobe City in Japan. The number of R/C shear wall units (inserted in the transverse span direction) is employed as a design parameter. That structure and the calculation processes of structural responses are almost the same as in Refs.4,13,14. The return period is given according to Ref.17.

INPUT DATA Input data used in this example are shown in Table 2. The representative numerical values for linguistic evaluations (Fig.10) enable us to perform the linguistic inference and the construction of Knowledge Base in this system through Fuzzy Confluence Rule. The parameters of Fuzzy Confluence Rule, α, β, and γ_i (Fig.11) would be able to be made more realistic with the results of questionnaire distributed to experts such as Ref.12. Input earthquake is assumed to be intraplate type one (Fig.12). The ranges of the design parameter about initial cost and flexibility of architectural planning (Fig.13) are given as temporal ones in this case study. The displays of these input data are shown in Figs.10-13.

OUTPUT DATA An example of output display is shown in Fig.14. This system answers the optimum synthetic evaluation and corresponding lower attribute evaluations followed simultaneously by the range of the number of shear wall units. In Fig.14, the optimum synthetic evaluation is "middle". However there is still the possibility of the existence of lower attribute evaluations with other ranges of design parameter. In this system, all the feasible optimum combinations of lower attributes are able to be given.

CONCLUSIONS

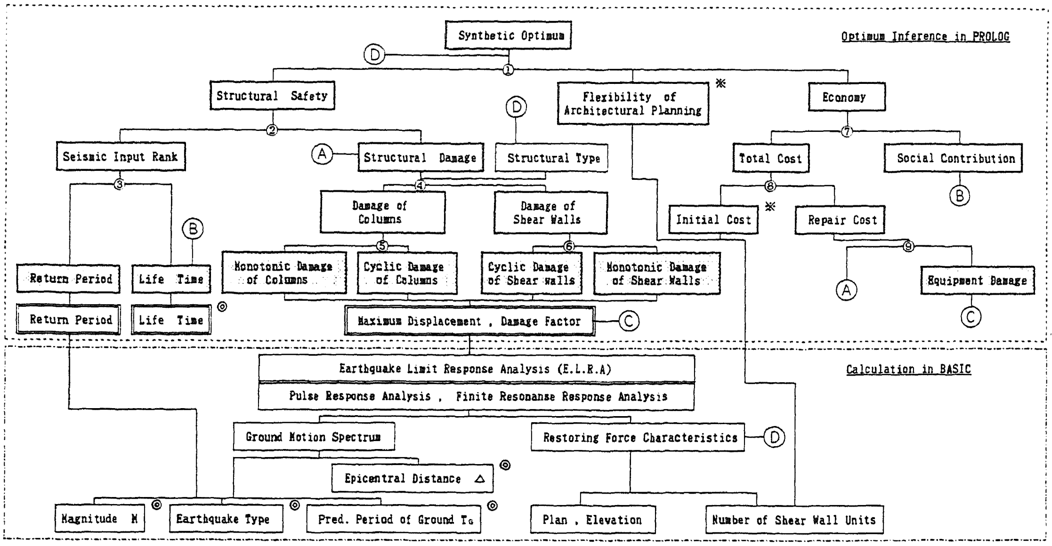
In this paper, the authors developed an expert system for optimum aseismic design of buildings based on the concept of Production Rule and Fuzzy Set Theory using PROLOG. This system has following characteristics.

(1) This system is composed of a numerical calculation part written in BASIC and a part with Knowledge Base and Inference Engine written in PROLOG, which takes advantage of the merit of each language.

(2) At each node, using Fuzzy Confluence Rule, subjective evaluations of users are able to be taken into account. Knowledge Base is automatically constructed according to the parameters of Fuzzy Confluence Rule, α, β and γ_i.

(3) In this system, not only earthquake informations but also responses and damages of structures, damages of equipments, flexibility of architectural planning, economy are able to be evaluated synthetically.

In this system, only main factors necessary for aseismic design of buildings are considered. For any practical needs, however, it is possible to increase the number of attributes, the design parameters and the parameters of Fuzzy Confluence Rule from quantitative and qualitative points of view.



Where ◎ : Input Numerical Data by Users ○ : Confluence Node (by Fuzzy Confluence Rule)

※ : Input Data by Users (The Range of Design Parameter which corresponding to Linguistic Evaluation)

▢ : Attribute (Evaluated by Linguistic Expression) ▒ : Bottom Attribute (Derived from Numerical Data)

▣ : Numerical Data

Fig.1 Decision - Making Hierarchy

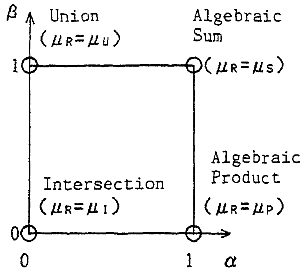


Fig.2 Fundamental Concept of Fuzzy Confluence Rule

Table 1 Combined Evaluation by Fuzzy Confluence Rule (ex. Node_4)

Linguistic Evaluation of " Structural Damage "

Damage of Columns (columns) / Damage of Shear Walls (rows)

	C	D	S
C	C	D	D
D	C	D	D
S	C	D	S

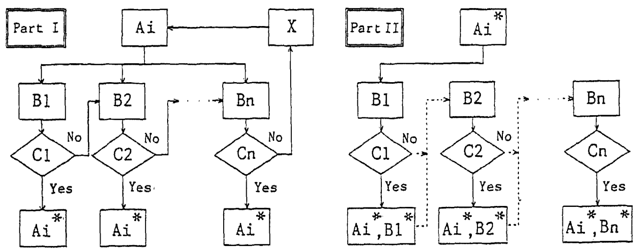
Input Parameters

C : Collapse

D : Damaged

S : Sound

Representative Value of Each Linguistic Evaluation		
Collapse : 0.9	Damaged : 0.5	Sound : 0.1
Weighting Parameters		
γ_1 (Columns) : 1.0	γ_2 (Shear Walls) : 0.8	
Mutural Influence Parameter α : 0		
Overestimating Parameter β : 1.0		



——— : Backward Inference ------- : Forward Inference

Ai	Assumed Optimum Evaluation of Top Attribute (Ai > Ai+1)
B1-Bn	Selected Combinations of Lower Attributes correspoding to Ai or Ai*
C1-Cn	Cheking the intersection of Design Parameter Ranges
X	Changing the Assumption of Top Attribute Evaluation
Ai*	Fixed Optimum Linguistic Evaluation of Top Attribute
B1*-Bn*	Fixed Optimum Combinations of Lower Attributes

Fig.3 Inference Flow of Optimum Aseismic Design

A1: $[a_1, b_1]$, A2: $[a_2, b_2]$, ・・・・, A2: $[a_n, b_n]$

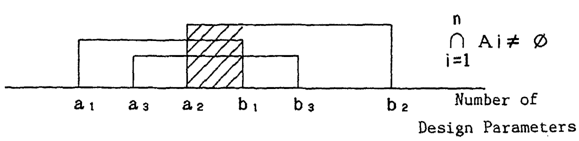


Fig.4 Existence Condition of Optimum Solution

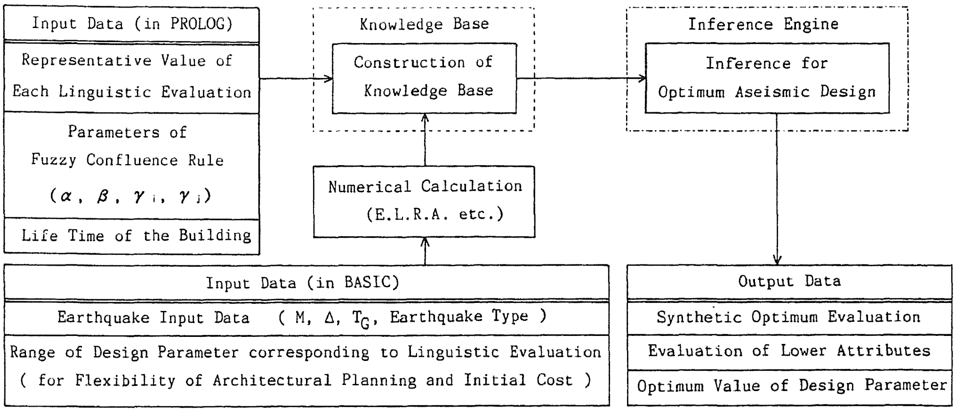


Fig.5 Block Chart of Optimum Aseismic Design System

(1) Real Expression in PROLOG

```
earthquake(X) :-
   return_period(A),  life_time(B),
   knowledge(earthquake_input_rank,X,[A,B]).
```

(2) Expression of (1) by Production Rule

```
if
  return_period = A     and
  life_time = B         and
  knowledge(earthquake_input_rank,X,[A,B])
then
  earthquake = X
```

Fig.6 Comparison between Programs in PROLOG and Production Rule in Inference Engine

(1) Real Expression in PROLOG

```
knowledge(synthetic_optimum,middle,[large,middle,middle]).
```

(2) "Frame" Expression of (1)

```
synthetic_optimum

Evaluation of Synthetic Optimum = "middle"
Evaluation of Structural Safety = "large"
Evaluation of Flexibility of A. Planning = "middle"
Evaluation of Economy = "middle"
```

Fig.7 Comparison between Programs in PROLOG and "Frame" System

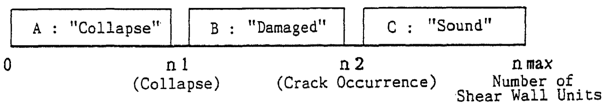
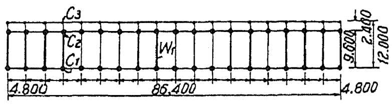


Fig.8 Linguistic Evaluation of Bottom Attribute by number of Design Parameter

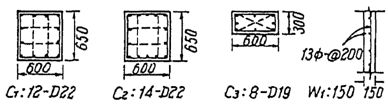
Table 2 Input Data

Representative Value of Each Linguistic Evaluation		Earthquake Input Data		Range of the number of Shear Wall Units Corresponding to Linguistic Evaluation		
1 (large,collapse,etc.)	0.9	Earthquake Type	Intraplate-T.	Flexibility of Architectural Planning	large middle small	[0, 5] [5,12] [12,19]
2 (middle,damaged,etc.)	0.5	Magunitude M	6.5			
3 (small,sound,etc)	0.1	Epicentral Distance Δ	70(Km)	Initial Cost	large middle small	[15,19] [6,15] [0, 6]
Life Time (years)	100	Pred. Period of Ground T_G	0.3(sec)			

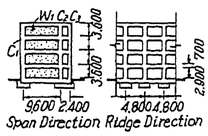
Node	α	β	Lower Attributes	γi	Node	α	β	Lower Attributes	γi
Node 1	0	0	Structural Safety Flexibility of A.Planning Economy	1.0 0.9 0.8	Node 6	0	1.0	M.Damage of Shear Walls C.Damage of Shear Walls	1.0 1.0
Node 2	1.0	0.5	Seismic Input Rank Structural Damage *	0.4 1.0	Node 7	0.5	0.5	Total Cost * Social Contribution	1.0 0.8
Node 3	1.0	0	Return Period Life Time	1.0 -1.0	Node 8	1.0	1.0	Initial Cost Repair Cost	0.8 1.0
Node 4	0	1.0	Damage of Columns Damage of Shear Walls	1.0 0.8	Node 9	1.0	1.0	Structural Damage Equipment Damage	1.0 0.6
Node 5	0	1.0	M.Damage of Columns C.Damage of Columns	1.0 1.0					



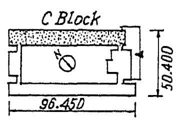
(a) Plan of C Block



(b) Sections of Columns and Shear Walls



(c) Frameworks



(d) Plot Plan of R/C School Building

Fig.9 Objective Building

```
Input Representative Value(x100) of
    Each Linguistic Evaluation.

 In Case of 3 Steps

   large      ___  |: 90.

   middle     ___  |: 50.

   small      ___  |: 10.

 Input Life Time (years)

   _______________  |: 100.
```

Fig.10 Representative Values of each Linguistic Evaluation and Life Time

```
   Upper Attribute -- structural_damage --

Input Weighting Parameter(x10) of Lower Attributes.

     damage_of_shear_walls--> |: 8.

     damage_of_columns--> |: 10.

Input Confluence Prameters(x10).

     Mutual Influence Prameter α   --> |: 0.

     Overestimating Prameter   β   --> |: 10.
```

Fig.11 Parameters of Fuzzy Confluence Rule at Node

```
Optimum Aseismic Design is Performed under the Following Condition.
          Life Time            __ 100 years
          Seismic Input Rank   __  A  Rank
          Return Period        __ 173 years
******************************************************************

     ** Optimum Aseismic Design has been Finished. **
       ** Optimum Results are shown as Follows. **

   Synthetic Optimum __ middle
   The Optimum Number of Shear-Wall-Units ___ 1~5
*************************************************************
   Structural Safety  ____ middle
   Seismic Input Rank ____  A          Structural Damage ___ damaged
   Damage of Shear Walls __ collapse   Damage of Columns ___ damaged
*************************************************************
   Flexibility of Architectural Planning ______ large
*************************************************************
   Economy __________ middle
   Total Cost _______ middle           Social Contribution __ large

If You want another Results, Push Any Key. |:

   restor debug. trace. listin halt.     save(' q      1      edit.
```

Fig.14 Result of Optimum Aseismic Design

```
Please input earthquake data

Intraplate-Type --- Epicentral distance (0(Km)-200(Km))
Interplate-Type --- Epicentral distance (150(Km)-1950(Km))

Earthquake type (1:Intraplate,2:Interplate) = ? 1
Epicentral distance (Km) = ? 70   Earthquake Magnitude  = ? 6.8
Predominant period of ground (S) = ? 0.3
```

Fig.12 Earthquake Parameters

```
Please input the boundary numbers of shear wall units (0-19)

Evaluation of the flexiblity of Architectural Planning
    The boundary n. between large and middle ---? 5
    The boundary n. between middle and small ---? 12
Evaluation of the initial cost
    The boundary n. between large and middle ---? 15
    The boundary n. between middle and small ---? 6
```

Fig.13 The Ranges of Design Parameter about Flexibility of Architectural Planning and Initial Cost

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