FUZZY LOGIC APPROACH IN THE PERFORMANCE EVALUATION OF REINFORCED CONCRETE STRUCTURES (FLEXIBLE PERFORMANCE)

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ABSTRACT :

For the performance evaluation of the buildings, the recommendations and related restrictions are given in different seismic codes and documents having very strict boundaries. When the approximations made in structural system modeling and in numerical analysis are remembered, generally the logical consequences of those restrictions are questionable. In this study, a new approach is presented for the performance evaluation of existing or new design buildings. It is shown that the performance levels can define to be flexible by using certain weighted values depending on the number and the deformation levels of elements (flexible performance) as used in the fuzzy set theory. In the presented method inputs are fuzzified, the rules are defined and a defuzzification process is carried out to obtain the performance level of a building from those of the structural elements. Depending on the sectional damages of columns and beams obtained from a nonlinear analysis, such as pushover analysis, under the assumptions given above, the building performance level can be determined. In the numerical treatment of the presented method, the damages and the corresponding performance levels given in FEMA 356 and Turkish Earthquake Resistant Design Code (TERDC) 2007 are considered and MATLAB Fuzzy Toolbox and Simulink options are used. The method is tested over 1600 data, the performance levels are determined and the results are given in tables and discussed, comparatively.

KEYWORDS : Fuzzy set, performance based design, non-linear analysis

1. INTRODUCTION

Aristotle's logic is used many years to describe the nature and its problems to the mathematic and computational expressions by assuming that the idea is well defined, very clear and simple to understand and apply. "It is impossible that the same thing can at the same time both belong and not belong to the same object and in the same respect." (Aristotle, *Metaphysics*, Principle of non-contradiction). This law is very helpful, if the problems are simple and linear, but the real life and the nature are not as easy as this.

Today civil engineering has many complex and non-linear problems like behavior of tall buildings, earthquake effects, wind effects, dynamic systems, uncertainties of soil behavior, obscure material behaviors etc. Simple and crisp mentality for complex systems is not enough. Some flexible systems fractal geometry, chaos and fuzzy logic can be described the complex nature better than rigid systems.

In this study, a fuzzy logic system used that gives more realistic results to determine the performance level of reinforced concrete buildings under the earthquake effect by considering the sections having plastic deformations and the level of deformation on the structural elements by using the displacement based design technique and analysis.

2. PERFORMANCE BASED ASSESSMENT

2.1. Seismic Performance and Objectives

Seismic performance is to determine of damages of a building under a specific earthquake effect and check them whether they are within the limits of the acceptable level (ATC 40a, 1996). The damages are related to ductile behavior of structural elements and premature damage occurrences have to be prevented by using the rules given in codes. Performance based design is to ensure that the damages in the elements of the buildings are under the limits that are shown in Table 2.1 for earthquakes that are probable to happen in 50 years with 2%, 10%, 50% probabilities (TERDC 2007).

Table 2.1 Description of the structural performance

Performance Levels	Description
Immediate Occupancy	No considerable damage on building. Structural system of the building maintains almost the original rigidity and capacity after the earthquake. Majority of the non-structural elements are safe and the building can be used.
Life Safety	Considerable reduction on rigidity at the structural elements having moderate damages. Structural elements are in allowable deformation limits. However, the building cannot be used before retrofitting.
Collapse Prevention	Most of the structural and non-structural elements are damaged heavily. Dramatic decrease on the building's rigidity and the capacity of the building. The building is potentially quit close to collapse.

2.2. Seismic Performance Assessment Process

The seismic performance assessment process can be summarized as follows (ATC40 and FEMA356):

a) Pushover curve force versus top displacement is obtained by considering the nonlinear behavior of the structural system.
b) Under a defined seismic condition the demanded maximum displacement is located on the force-displacement curve depending on structural behavior types and soil conditions. In this nonlinear analysis plastic hinge hypothesis (the lumped plasticity) can be used. This maximum displacement is called 'Target Displacement' (FEMA356, 'Spectral Displacement' (TERDC 2007) and this specific point is called 'Performance Point' in ATC40. The representative force-displacement curve is given Figure 2.1.
c) At the performance point the section forces and corresponding nonlinear deformations of the structural elements are checked for the performance level of the building and are decided to retrofit or not.

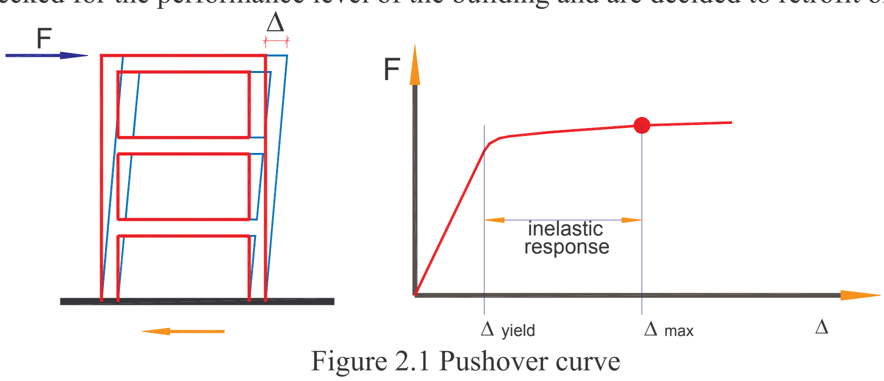


Figure 2.1 Pushover curve

The presented study introduces a new method which gives simplicity, speed and flexibility to make a decision on performance levels of the buildings.

2.3. Principles of the Process

The performance decision making of a concrete building is expressed as: '*Upon determining that concrete elements in an existing building are deficient for the selected Rehabilitation Objective, these elements shall be rehabilitated or replaced or the structure shall be otherwise rehabilitated so that the element is no longer deficient for the selected rehabilitation objective'* (FEMA356: caption 6.4.7).

The performance decision making of a concrete building is expressed as: '*If calculated response for the specified ground motion exceeds any of the global building or element and component acceptability limits given in this chapter for the appropriate performance level, than the building should be deemed to not achieve the performance objective'* (ATC40: chapter 11).

In FEMA356 and ATC40 the performance level of a structure decision making which are given above are very simple because the least performed element defines the entire structural performance. However, it is not true, according to the engineering judgment and logic. This study aims to eliminate the performance decision making deficiency.

Performance decision process of FEMA356 and ATC40 can be modified in relation to the boundaries. TERDC gives some flexibility with the percentages but it is not sufficient either. In this study, the decision criteria of flexible performance method are developed considering rules given in TERDC. The performance criteria in TERDC are given as follows (Figure 2.2):

2.3.1. Immediate Occupancy (IO) Performance Level

After carrying out the nonlinear analysis for each applied earthquake direction, max 10 percent of the beams might pass over to the damage control range (between IO-LS). However the rest of the structural elements are in the minimum damage range (between O-IO). The structural elements having brittle behavior are not allowed, if there are such elements, they must be retrofitted.

2.3.2. Life Safety (LS) Performance Level

If there are structural elements brittle behavior, they must be retrofitted then the building satisfying the following situations are supposed to be in the life safety performance level:

a) In any story, carrying out the nonlinear analysis for each applied earthquake directions, max 30% of the beams excluding the indirectly supported, and the amount of the columns in the following paragraph (b) are supposed to pass in limited safety range.
b) The total contribution of the columns in the limited safety range to the shear force that is carried by the columns should not be below 20% in each story. At the top story, the ratio of the sum of the shear forces of columns in the limited safety range to the sum of the shear forces of all columns at the same story could be maximum 40%.
c) The rest of the structural elements are all in the minimum damage range or the damage control range. However, in any story, the ratio of the shear forces carried by the columns that in the minimum damage range is exceeded at bottom and top end sections to the shear force carried by all the columns at the same story should not exceed 30%.

2.3.3. Collapse Prevention Performance Level

If there are structural elements brittle behavior, they must be retrofitted then the building satisfying the following situations are supposed to be in the collapse prevention performance level:

a) In any story, carrying out the nonlinear analysis for each applied earthquake directions, max 20% of the beams excluding the indirectly supported are supposed to pass in collapse range.

b) The rest of the structural elements are all in the minimum damage range, the damage control range and the limited safety range. However, in any story, the ratio of the shear forces carried by the columns (the minimum damage range is exceeded at bottom and top end sections) to the shear force carried by all the columns at the same story should not exceed 30%.

2.3.4. Collapse Level

If a structure does not satisfy the above given rules then the performance level of the building is at the collapse level.

2.4. Component Damage Levels and Ranges

In the nonlinear behavior of structural element, damages are described in different levels and ranges. General assumptions at levels are immediate occupancy (IO), life safety (LS) and collapse prevention (CP). Some new range labels were added to describe the pushover curve which represents the lateral behavior of a model in Figure 2.2.

According to FEMA356 and ATC40 the zone between IO and LS is called 'Damage Controlled Range' and the zone between LS and CP is called 'Limited Safety Range'. In TERDC between O and IO is called 'Minimum Damage Range' and over the CP zone is called 'Collapse'. Between the ranges of these levels shown in Figure 2.2, some new variables were defined which are BR1, BR3, BR4, CR2, CR5, BR0, CR1, CR6, BR5, BR6 and CR3. Explanations of the variables are given as follows:

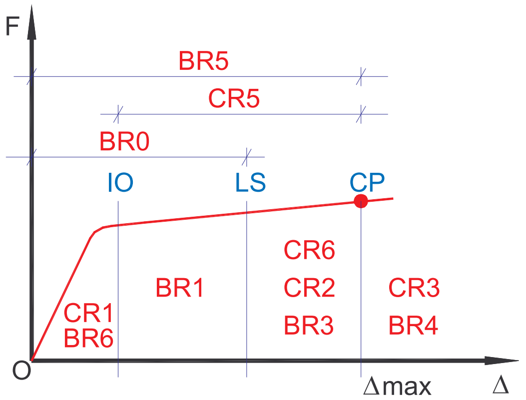


Figure 2.2 Component damage levels and ranges

BR1=(Number of between IO-LS damaged beams in any story) / (Total number of beams at the story)
BR3=(Number of between LS-CP damaged beams in any story) / (Total number of beams at the story)
BR4=(Number of over CP damaged beams in any story) / (Total number of beams at the story)
CR2=(Total shear force of between LS-CP damaged columns in any story) / (Total shear force of the story)
CR5=(Total shear force of between IO-CP damaged columns in any story) / (Total shear force of the story)
BR0=(Number of between O-LS damaged beams in any story) / (Total number of beams at the story)
CR1=(Total shear force of between O-IO damaged columns in any story) / (Total shear force of the story)
CR6=(Total shear force of between LS-CP damaged columns at top story)/(Total shear force of top story)
BR5=(Number of between O-CP damaged beams in any story) / (Total number of beams at the story)
BR6=(Number of between O-IO damaged beams in any story) / (Total number of beams at the story)
CR3=(Total shear force of over CP damaged columns in any story) / (Total shear force of the story)

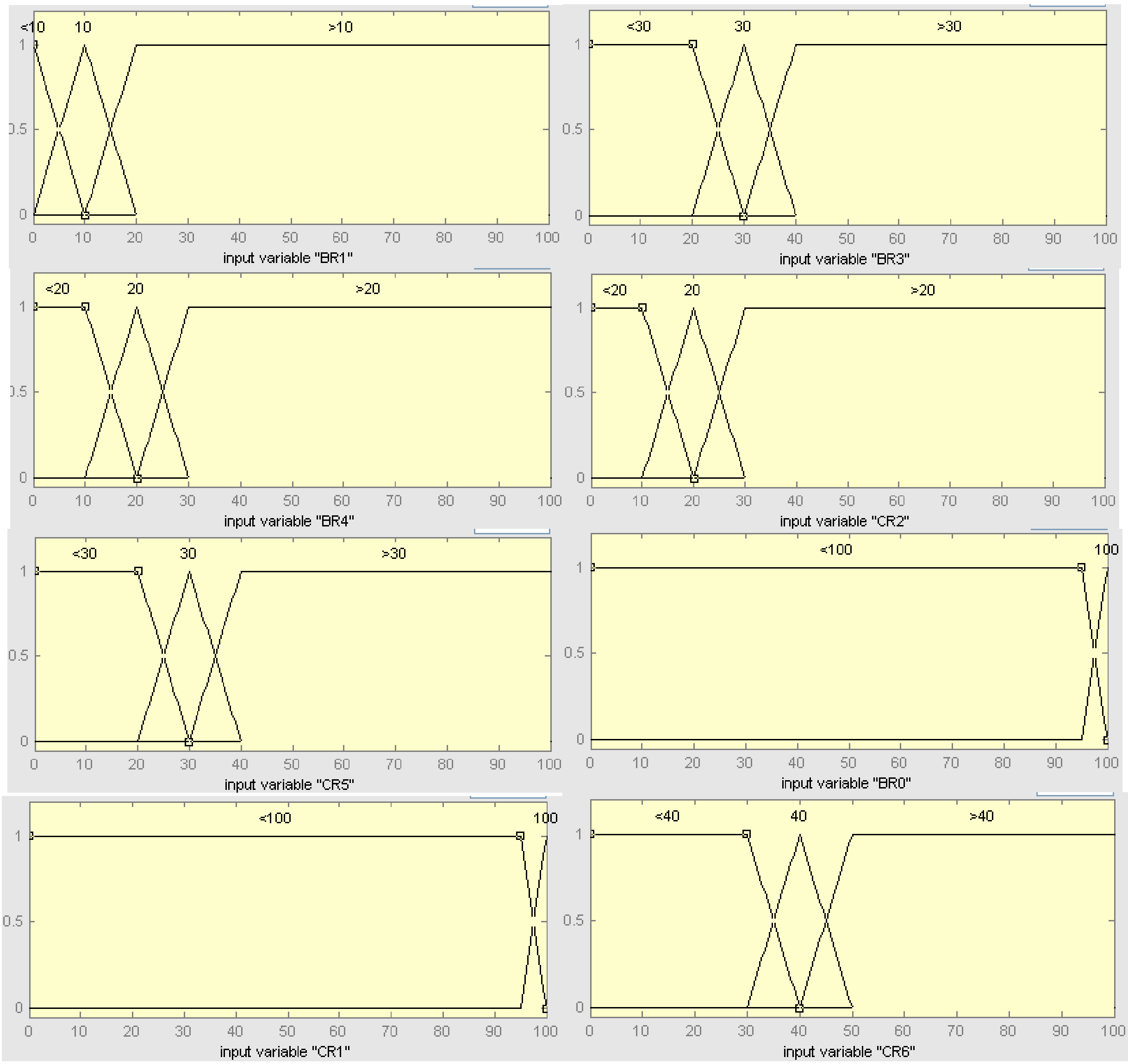
As it is clear in Figure 2.2 some variables are related to the others which reduces the input number.

BR0=BR6+BR1 (2.1)
BR5=BR6+BR1+BR3 (2.2)
CR5=100-CR1-CR3 (2.3)

3. FUZZY INFERENCE

3.1. Fuzzy Input, Output Sets, Subsets and Rules

The variables given above as damage ranges constitute fuzzy system input sets as well. Fuzzy input sets are BR1, BR3, BR4, CR2, CR5, BR0, CR1 and CR6. To get adopt TERDC and the fuzzy system, all the set members are related to ratio of column or beam damage are described in [0,100] range. Sets and subsets are given in Figure 3.1:



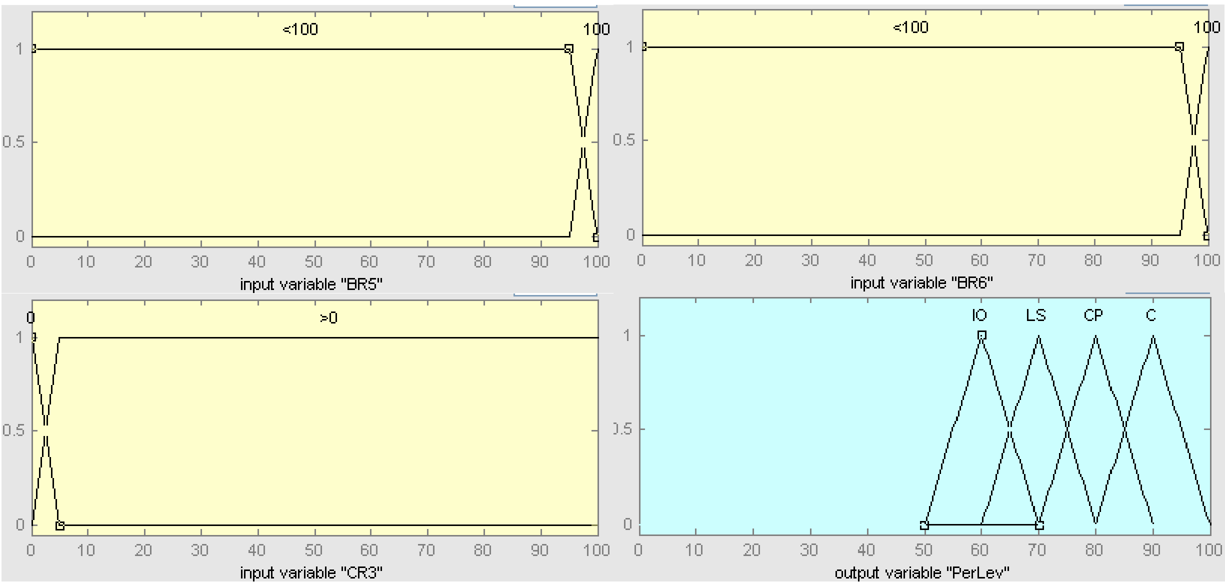


Figure 3.1 Fuzzy sets and subsets of the model

The output set have four fuzzy subsets. The fuzzy output set, PerLev, have four subsets IO, LS, CP and C. Because of some modeling problem in MATLAB, the output subsets are located in between output variables of 50-100 (Figure 3.1).

In this study, the system based on fuzzy rule is used. The relationships between input and output set are described by rules. These rules are developed by using TERDC performance criteria. Some additional rules those are not included in code to make system more stable are added. Approximately 20 rules are used to describe the system.

3.2. MATLAB Simulink Model

When the performance criteria given in TERDC are examined, it is impossible to settle the system on one fuzzy inference system. According to the rules, criteria cannot be described in the same system. Hence, three different fuzzy systems are modeled on MATLAB Simulink platform, in that model the sets are same but the rules are different. Hereby, fuzzy membership values those are cannot be transmitted to any other file by Matlab Fuzzy Toolbox can be transmitted to any numerical platform by the fuzzy flexible model. Flowing chart on the simulink is given in Figure 3.2.

Input file, in model is a $\mathfrak{R}^{11}$ vector like below:

Input11= (BR1,BR3,BR4,CR2,CR5,BR0,CR1,CR6,BR5,BR6,CR3)

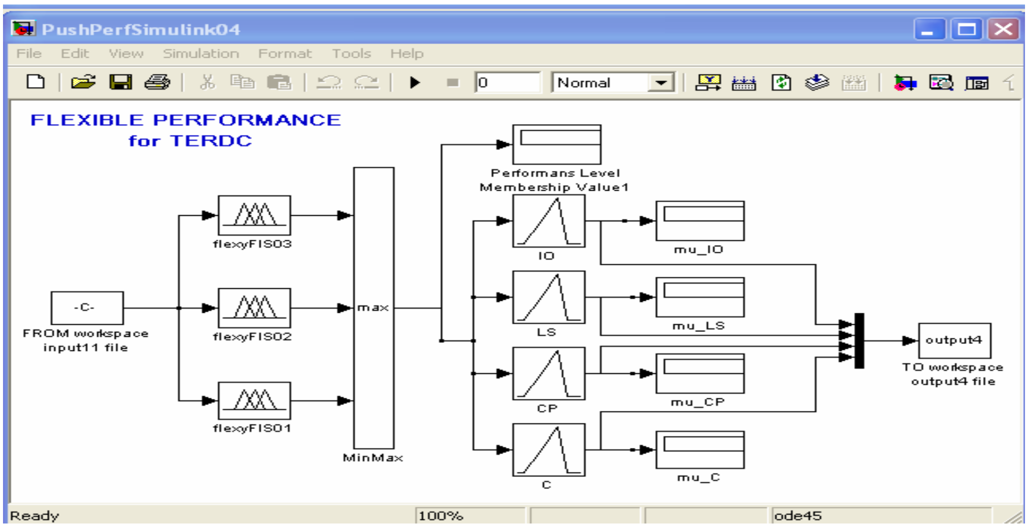


Figure 3.2 Flexible performance for TERDC model in MATLAB simulink platform

4. TESTING THE SYSTEM

Fuzzy flexible performance model are tested by using 150 sample vectors, over produced 1600 data. By the way, 20 samples are given briefly in Table 4.1, because the system shows its performance at boundaries and edge values. The rest of the data from the table give exactly the same results with the code TERDC. The last column of Table 4.1. shows the membership values for flexible performance assessment. When the results are compared, the presented fuzzy model gives more realistic results defining different performance levels for same data.

Table 4.1 Test data and results comparatively

No.	BR1 (%10)	BR3 (%30)	BR4 (%20)	CR2 (%20)	CR5 (%30)	BR0 (95-100)	CR1 (95-100)	CR6 (%40)	BR5 (95-100)	BR6 (95-100)	CR3 (0-5)	FEMA CODE Perf.	TERDC CODE Perf.	FUZZY FLEXIBLE Performance	Membership Value
1	12.5	0	0	0	0	100	100	0	100	87.5	0	LS	LS	IO	71
2	17.5	0	0	0	0	100	100	0	100	82.5	0	LS	LS	LS	71
3	0	32.5	0	0	0	67.5	100	0	100	67.5	0	CP	CP	LS	71
4	0	37.5	0	0	0	62.5	100	0	100	62.5	0	CP	CP	CP	71
5	0	32.5	0	10	10	67.5	90	0	100	67.5	0	CP	CP	LS	71
6	0	37.5	0	10	10	62.5	90	0	100	62.5	0	CP	CP	CP	71
7	0	32.5	0	12.5	12.5	67.5	87.5	0	100	67.5	0	CP	CP	LS	71
8	0	37.5	0	12.5	12.5	62.5	87.5	0	100	62.5	0	CP	CP	CP	71
9	0	32.5	0	17.5	17.5	67.5	82.5	0	100	67.5	0	CP	CP	LS	71
10	0	37.5	0	17.5	17.5	62.5	82.5	0	100	62.5	0	CP	CP	CP	71
11	0	32.5	0	20	20	67.5	80	0	100	67.5	0	CP	CP	LS	71
12	0	37.5	0	20	20	62.5	80	0	100	62.5	0	CP	CP	CP	71
13	0	32.5	0	22.5	22.5	67.5	77.5	0	100	67.5	0	CP	CP	LS	71
14	0	37.5	0	22.5	22.5	62.5	77.5	0	100	62.5	0	CP	CP	CP	71
15	0	77.5	22.5	0	0	22.5	100	0	77.5	22.5	0	C	C	CP	71
16	0	72.5	27.5	0	0	27.5	100	0	72.5	27.5	0	C	C	C	71
17	0	77.5	22.5	0	0	22.5	98.5	0	77.5	22.5	1.5	C	C	CP	70
18	0	72.5	27.5	0	0	27.5	98.5	0	72.5	27.5	1.5	C	C	C	70
19	0	77.5	22.5	0	0	22.5	96.5	0	77.5	22.5	3.5	C	C	CP	55
20	0	72.5	27.5	0	0	27.5	96.5	0	72.5	27.5	3.5	C	C	C	70

5. CONCLUSION

In this study, a fuzzy logic system is presented to give more realistic results to determine the performance level of reinforced concrete buildings under the earthquake effects by considering the plastic deformations of structural elements of the system. TERDC performance criteria are assigned to various fuzzy sets. The rules are described between the sets in combined three different fuzzy systems on MATLAB Simulink platform. For numerical treatment of the system, approximately 1600 data are used to test the fuzzy system and results are given in Table 4.1. with the results of TERDC and FEMA356, comparatively. The fuzzy flexible performance model gives different but more logical results at boundaries than the other code and proposed document. In any engineering analysis, because of uncertainties in structural components and materials, approximation cannot be avoided. The fuzzy model gives methodic flexibility to engineer on calculations and assessment of judgments. Via the flexible performance, engineering judgments will be under controlled. Conclusively, the fuzzy flexible performance model gives simplicity, speed and flexibility at the deciding building performance.

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