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SEISMIC DAMAGE ASSESSMENT OF REINFORCED CONCRETE BUILDINGS USING FUZZY LOGIC

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SUMMARY

This paper presents a method of assessment of seismic damage of reinforced concrete buildings using fuzzy logic. Fuzzy Logic is a powerful tool in modeling uncertainties and gives a meaningful solution for the complex problem of seismic damage assessment. Uncertainties in earthquake ground motion and structure are characterized by representative values of nine damage parameters. These parameters are selected within the uncertain ranges based on engineering practices. The quality of the concrete is an important uncertain parameter in seismic damage assessment, as the material strength exhibits variation. The quality of the concrete (in-situ), which is characterized in terms of the ultrasonic pulse velocity, is considered as a parameter for damage assessment in the present study. Five limit states representing various degrees of damage have been selected for the assessment of damaged condition of reinforced concrete buildings. The fuzzy rule base is formed for assessment of seismic damage of reinforced concrete buildings. Finally, a damage index corresponding to the damage state of buildings is estimated by applying the de-fuzzification method, which converts the fuzzy linguistic variable to a real value. A program *SEISDAM* has been developed for assessment of seismic damage using fuzzy logic. The proposed method of seismic damage assessment based on fuzzy logic is simple, and hence possesses the potential for practical application.

INTRODUCTION

An earthquake is a spasm of ground shaking caused by sudden release of energy in the earth's lithosphere. Whenever a moderate or large earthquake occurs in a large metropolitan city a great majority of buildings are subjected to different degrees of damage. An assessment of the seismic damage of the reinforced concrete building requires knowledge of its strength, response characteristics, and quantitative and qualitative data concerning current state of building and a methodology to integrate various types of information into a decision making process for assessing the damage of the entire building. Important contributions in the field of seismic damage assessment have been made by Park and Ang [1], Park et al.[2], Stephens and Yao [3], Powell and Allahabadi [4], Hwang and Jaw [5], Ghobarah et al. [6].

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It is observed from the review of literatures that the seismic damage assessment of reinforced concrete buildings is a complex problem in view of vagueness and uncertainties in the available data related to both ground motion parameters and structural modeling parameters. In addition, in-situ tests established the fact that the actual concrete strengths may be different from design value and this uncertainty associated with concrete strength has not been considered in any of the available seismic damage assessment methods. The nature of uncertainties in the seismic damage assessment problem are very important points that engineers should ponder prior to their selection of an appropriate method to express the uncertainties. Fuzzy sets provide a mathematical way to represent vagueness or uncertainties in engineering systems. In this paper, simple seismic damage assessment method based on fuzzy logic is presented. Uncertainties in earthquake ground motion is characterized by predominant frequency, critical damping of soil and duration of strong motion. Uncertainties in structural parameters and material quality are characterized by viscous damping, pre-yielding stiffness ratio, post-yielding stiffness ratio, displacement ductility ratio, cyclic loading coefficient, and material quality based on the ultrasonic pulse velocity. In view of uncertainty in earthquake ground motion, structural parameters and material quality, a model with fuzzy membership function relating uncertain parameters and damage classification is more appropriate than that with a simple functional relationship for this correlation. In the proposed method, the fuzzy rule base is formed, from which the seismic damage of reinforced concrete building is assessed. The fuzzy linguistic variable corresponding to a particular damaged condition of the building is converted to a real value during de-fuzzification. The proposed method of seismic damage assessment takes into account uncertainties associated with earthquake ground motion parameters and structural parameters, but retains the simplicity of deterministic approach.

UNCERTAINTY ANALYSIS

Uncertainties in the seismic damage assessment are broadly divided into uncertainties in earthquake ground motion parameters and uncertainties in structural modeling parameters controlling behaviour of the structure during earthquake. The representative values of each of the parameters are selected with consideration of both the engineering sense and random nature of the parameters. Three values of each parameter are selected to represent the uncertainty range usually on the basis of mean value and the value of mean plus or minus one standard deviation

Uncertainties in earthquake ground motion

Uncertainties in earthquake ground motion modeling can be characterized by the parameters - *predominant frequency, critical damping of the soil* and *strong motion duration*. The predominant frequency of the ground motion, ω_g is obtained from the Fourier amplitude spectrum of the recorded accelerogram. For soft soil sites, ω_g is estimated in the range of 2.4π to 3.5π rad/sec, whereas for rock sites, ω_g ranges from 8π to 10π rad/sec [5]. As for the stiff soil sites, ω_g is between the values estimated for rock and soft soils. Thus, three values of ω_g, namely 3π, 6π and 9π rad/sec are selected as representative values. The soil damping, ξ_g is influenced by cyclic strain amplitude due to earthquake. It also depends on plasticity index, and over consolidation ratio. The damping ratio increases with increasing strain amplitude. Damping of the soil is found from the cyclic shear strain and plasticity index [7]. Representative values of are chosen as 0.05, 0.12 and 0.19. The damage to the building increases with the increase in the duration of the strong motion, d_E. The strong motion duration is found from accelerograms records. The strong motion duration is defined as the time interval between 2.5 and 97.5 per cent of the Arias intensity [8]. The representative values for duration of strong motion values are chosen as 10, 20 and 30 seconds.

Uncertainties in Structural Modeling and Material Quality

In this study, the building is idealized as a stick model. The value of lumped mass can be determined more or less accurately; thus, mass is assumed to be deterministic. The uncertainties in structural modeling and material quality are associated with the parameters - *viscous damping, pre-yielding stiffness ratio, post-yield stiffness ratio, ductility,* and *cyclic loading coefficient, material quality based on ultrasonic pulse velocity*. Viscous damping ratio, ξ for reinforced concrete structures has been recommended to be from 2 to 7 percent. Thus, three representative values of are chosen as 2, 4, and 6 percent. The initial elastic stiffness, k_e , is significantly less than the uncracked stiffness, k_0 due to the existence of cracks. Thus, k_e can be expressed as a fraction of k_0 (i.e., $k_e = \alpha_g k_0$, where, α_g is the pre-yielding stiffness ratio which can be obtained from available experimental results). Compiling the available experimental results, Hwang and Jaw [5] suggested three representative values of α_g , namely 0.1, 0.17 and 0.25, are selected. The post-yielding stiffness, k_p is expressed as a product of post-yielding stiffness ratio, α_s and k_e. Based on the available experimental data, Hwang and Jaw [5] suggested three values of α_s , namely 0.01, 0.03 and 0.05 as representative values. Displacement ductility ratio (μ) of buildings usually varies from 2 to 10 [9]. In this study, the ductility demand of the building subjected to an earthquake accelerogram is found from the nonlinear dynamic analysis of building using DRAIN-2DX program [10]. The representative values of the ductility ratio of the buildings are chosen as 3, 6 and 10. Park and Ang [1] proposed a coefficient, β, that takes into account the effect of cyclic loading on structural damage. By means of a regression curve obtained using 261 experimental results, Park and Ang [1] observed that the experimental values of β ranges between -0.3 and 1.2, with a median of about 0.15. However, theoretically this parameter cannot be negative. Therefore, the representative values of the coefficient of cyclic loading are chosen as 0, 0.4 and 1.0. The uncertainty in quality of concrete is characterized in terms of ultrasonic pulse velocity [11]. The representative values of the quality of the concrete are chosen as 2.5, 3.5 and 4.5 Km/sec.

FUZZY LOGIC

Fuzzy logic is a useful tool for expressing the professional judgments. These judgments may be verbal statements (e.g., ``the structure is moderately damaged" or ``the quality is good") with vagueness or fuzziness. Ability to make precise and significant statements concerning a given system diminishes with increasing complexity of the system. The complexity arises from the use of subjective opinion and the numerical data representing the parameter. The statement is very true in context of seismic damage assessment. The assessment of seismic damage in reinforced concrete buildings involves handling of uncertain and vague information. For example, damage can be considered as linguistic variable. The values of this variable may be moderate damage, severe damage etc., which may not be precise but they are definitely meaningful classification. Each of the uncertain parameters associated with seismic damage assessment is fuzzified by assigning a membership function [12]. The fuzzified measurements are then used by the inference engine to select the control rules stored in the fuzzy rule base. The fuzzy sets describing damaged state of the building are then converted to *damage index* (a real number) by de-fuzzification. The general scheme of fuzzy logic based decision making system is as shown in Fig.1.

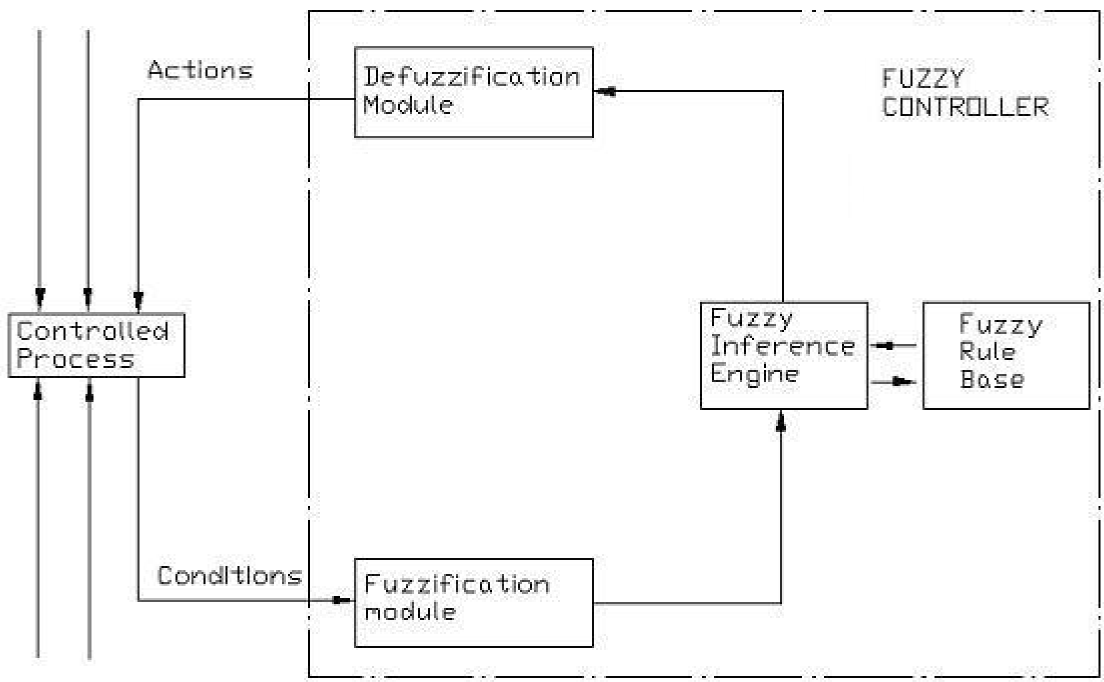


Fig.1 A General Scheme of a Fuzzy Logic Decision System

SEISMIC DAMAGE INDEX EVALUATION

The uncertainty ranges in earthquake ground motion and structural parameters are selected with the consideration of both the engineering sense and uncertain nature of parameter. Each uncertain parameter is expressed linguistically. Uncertainties in earthquake ground motion parameters are expressed as: predominant frequency of ground motion for different soil conditions - *soft soil, medium soil and rock*, critical damping of soil - *low, medium and high damping*, strong motion duration - *low, moderate and high duration*. The uncertainties in structural parameters are expressed as: viscous damping - *low, medium and high damping*, pre-yielding stiffness ratio - *low, moderate and high*, post-yielding stiffness ratio - *low, moderate and high*, ductility - *low, moderate and high*, cyclic loading coefficient - *low, medium and high*, the material quality based on ultrasonic pulse velocity - *poor, moderate and good*. The damaged conditions of buildings are expressed as *nonstructural damage, slightly structural damage, moderate structural damage, severe structural damage and collapse*. The damage classification of nonstructural damage is assumed to correlate with the damage index values close to 0. The classification of collapse was assumed to correspond to index values close to 1.0.

A triangular fuzzy surface is assigned to each of these fuzzy linguistic variables. The equation of these fuzzy surfaces are given by

$$v_x = 1 - \frac{|x-a|}{s}; \qquad (a-s) \le x \le (a+s) \tag{1}$$

where, v_x is membership value for parameter x, $(a-s)$ is the lower limit and $(a+s)$ is the upper limit of the range of each parameter. The fuzzy surfaces of these uncertain parameters are shown in Fig.2.

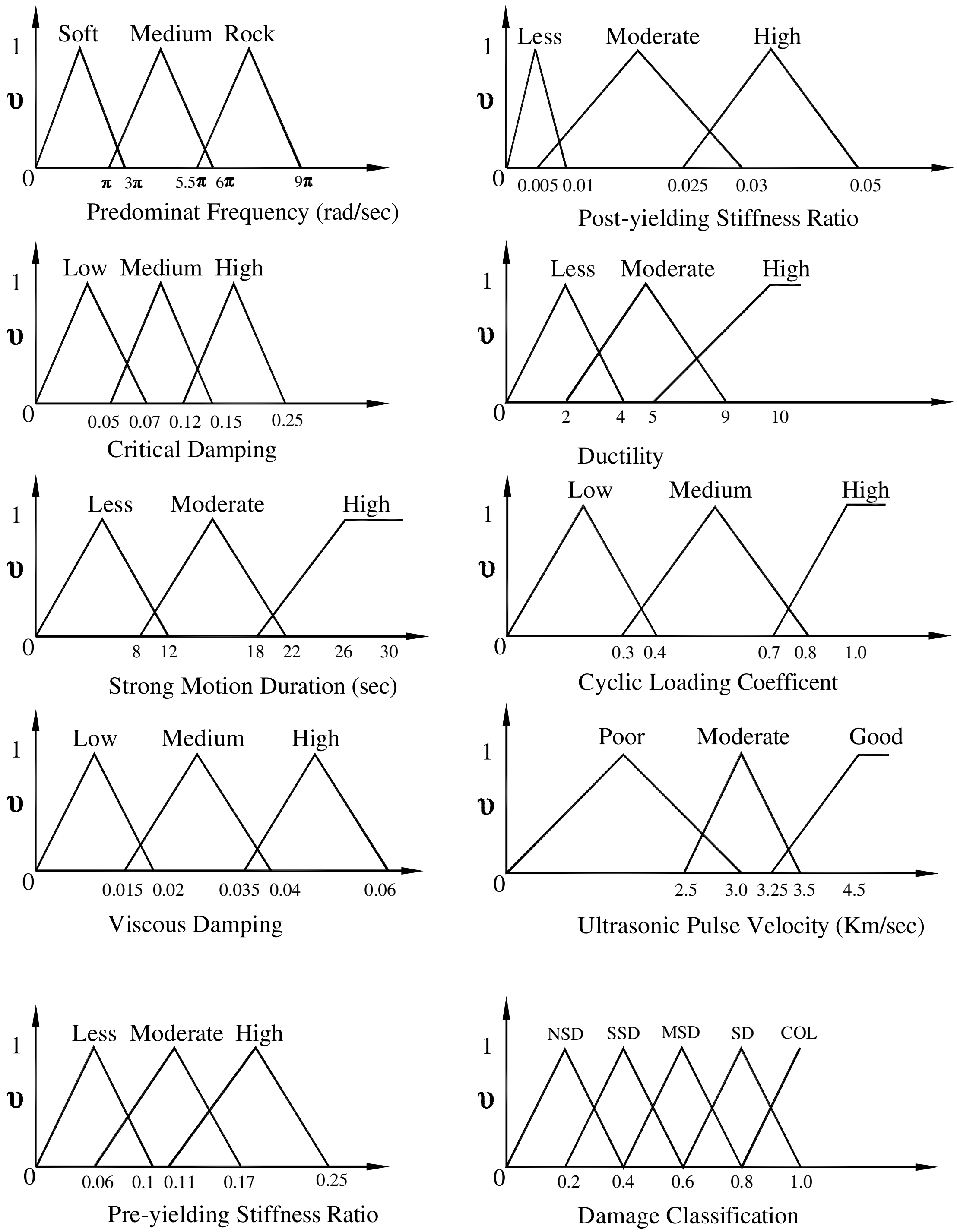


Fig.2 Fuzzy Surface of the Seismic Damage Parameters

A software *SEISDAM* has been developed for the seismic damage assessment of reinforced concrete framed buildings based on the proposed method. The rule base of the software consists of 3^9 rules. The total 3^9 rules in the rule base are due to the fact that there are 9 uncertain parameters and each of the parameters is expressed by 3 fuzzy sets.

EXAMPLE

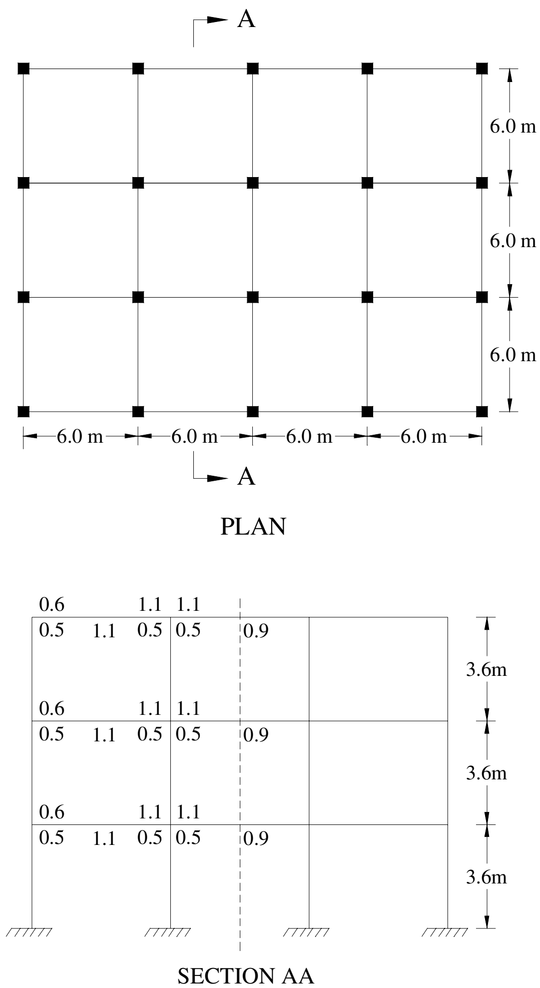
A three storey reinforced concrete frame office building designed according to ACI 318, 1963 by Ghobarah et al. [6] have been chosen as a sample building for assessment of its seismic damage by the proposed method based on fuzzy logic. The sample building has been designed for live load of 2.4 kN/mm^2. Fig.3 shows the dimensions of the building and details of reinforcements. The seismic damage index of the building, subjected to El Centro (S00E) 1940 accelerogram scaled to PGA of $0.3g$, has been evaluated for validation of the proposed method.

The uncertain parameters associated with the earthquake ground motion and the structural modeling considered for assessment of seismic damage of sample building are: $\omega_g = 2.90\pi$ rad/sec; $\xi_g = 0.08$; $d_E =$ 25 sec; $\xi = 0.04$; $\alpha_g = 0.05$; $\alpha_s = 0.005$; $\mu = 4$; $\beta = 0.25$; $p_v = 3.5$ km/sec. The output surface of the damage classification of the building considering the uncertainties of the above structural parameters and earthquake ground motion parameters is shown in Fig.4.

The damage index is calculated by finding the centroid of the output surface formed, using the *center of area method* [12]. The damage index of the building estimated using the proposed method is 0.60, which falls in the damaged condition *moderate structural damage*. The damage indices for the sample building as obtained by Ghobarah et al. [6] based on stiffness index and Park and Ang's [1] index are 0.46 and 0.61 respectively.

CONCLUSION

In this paper, a fuzzy logic based method for assessment of seismic damage in reinforced concrete buildings is presented. The damage index evaluated using the algorithm based on fuzzy logic provides reasonable measures of the damaged condition of reinforce concrete buildings. The proposed interactive method of assessment of seismic damage has potential for practical implementation because it retains the simplicity of deterministic approach for seismic damage assessment.



All beams are 250x600 mm with the shown reinforcement ratio (%)
Interior columns are 400x400 mm with 1% reinforcement ratio
Exterior columns are 300x300 mm with 1.25% reinforcement ratio

Fig. 3 Description of Structure

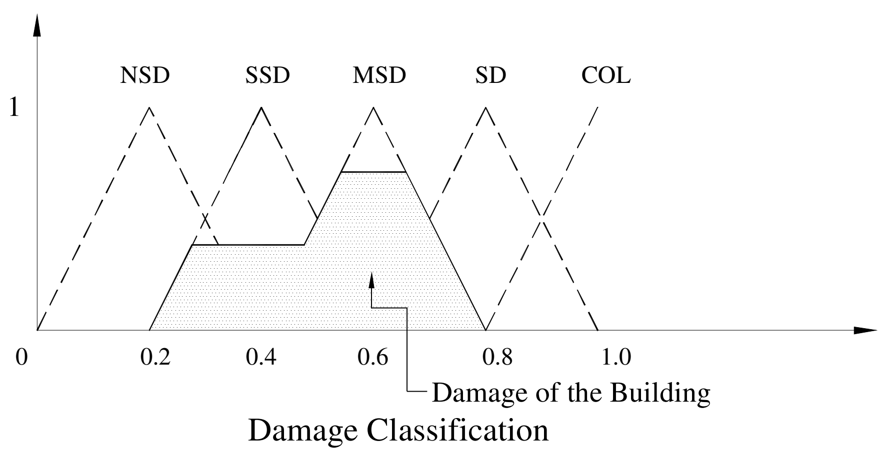


Fig. 4 Output Surface of the Damage

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