PRERDICTION OF THE PROBABILITY OF EARTHQUAKE DAMAGE TO EXISTING BUILDINGS IN CHINA

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SUMMARY

In this paper, considering the seismic design code of buildings in China and some experimental results, using the simplified nonlinear static analysis method, an analytical method of vulnerability analysis is studied to estimate the vulnerability of multistory or high-rise reinforced concrete. Analyzing the relationships among the initial yielding point, significant yielding point, ultimate point and other key point in parameterless pushover curves, considering the seismic design level, the parameterless pushover curves are transformed to general pushover curves. Then the general pushover curves are converted to a spectral capacity curves for the building, using the simplified nonlinear static analysis method to estimate the seismic vulnerability of multistory or high-rise reinforced concrete As example, the fragility curves and damage probability matrices of a six-story reinforced concrete are calculated. The simplified method of seismic vulnerability evaluation can be used to estimate vulnerability of multistory and high-rise reinforced concrete structures which have few earthquake damage data but are normally designed. It will overcome the earthquake damage data limitation on vulnerability estimation.

INTRODUCTION

Information on structural damage is of critical importance for reliable economic loss evaluation for a structure or a region that has been or that might be affected by an earthquake. Relations between earthquake ground motion severity and structural damage are most frequently used in seismic risk assessment and earthquake scenario simulation. These motion-damage relationships are in the form of probability distributions of damage at specified ground motion intensities and are usually expressed by means of fragility curves or damage probability matrices. In most cases, such as in seismic risk evaluations developed in California (ATC-13, 1985) and in China (Yin, 1995), they make use of the macroseismic intensity as ground motion parameter. The utilization of intensity presents however several drawbacks: limited experienced damage data, especially for new kind and high-rise buildings, discrete values of intensity, subjective assessment in intensity, logical round-error (assessing a intensity according to damage state, then predicating damage state according to the intensity). Using the macroseismic intensity as ground motion parameter, it is very difficulty to consider the site effect and frequency content on damage, further more it is also difficulty to consider the earthquake type (near earthquake, far earthquake, small earthquake and large earthquake) effect on damage.

On the other side, fragility curves related to ground motion or spectral acceleration are generally based on mathematical models of structural behavior or test data. This analytical approach can overcome drawbacks in using the macroseismic intensity as ground motion parameter. It is very easy to consider the type of earthquake, frequency content and site effect on the damage of buildings.

This paper presents a simplified method of evaluation for fragility curves of buildings in China, which does not rely either on heuristics or on empirical data. The fragility curves which predict the probability of reaching or exceeding specific damage states are estimated by quantifying the response of structure subjected to ground

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motion. The probability of being in particular state of damage is calculated as the difference between fragility curves. They will be used to demonstrate the methodology for estimation seismic losses in China.

SEISMIC EVALUATION

The capacity spectrum method (CSM) was originally developed as a rapid evaluation method. It was later used as a procedure to correlate earthquake ground motion with observed building performance (Freeman,1978,1987 & ATC-10,1982). The method combines a nonlinear step-by-step "pushover" analysis of the structure, the Acceleration-Displacement Response Spectra (ADRS) and the substitute structure approach (Mahaney 1993, ATC-40,1996). It compares the capacity of structure to resist lateral forces to the demands of earthquake response spectra in a graphical presentation that allows a visual evaluation of how the structure will perform when subjected to earthquake ground motion. It is easily to understandable and generally consistent with other methods that take into account the site effect, frequency content of strong ground motion and the nonlinear behavior of structures subjected to strong ground motion.

In the paper the capacity spectrum method is used to estimate peak response of buildings for a given level of spectral demand, fragility curves are established, and then the probability of earthquake damage to existing buildings in China is predicted. The seismic evaluation can be summarized by the followings:

Pushover curves: Conduct simplified pushover analysis of the structure, establish pushover curve of the building in terms of roof displacement and base shear.

Analyze dynamic characteristics: calculate modal vibrational characteristics such as periods of vibration, mode shapes, modal participation factors, and effective modal mass ratios.

Capacity spectrum: Convert the pushover curve to a capacity spectrum by use of dynamic characteristics.

Demand spectrum: Obtain demand spectrum-damping reduction.

Building response: Determine the building response by intersection of the demand spectrum with appropriate damping and the building capacity curve.

Building fragility curves: Established the fragility curves for different damage state and predicted the probability of earthquake damage to existing buildings.

Pushover curve

Conduct simplified pushover analysis of the structure, as described in the next section. Plots of the base shear V versus roof displacement ΔR are established until failure of the structure. Four distinct phases are identified during the pushover analysis, as follows: initial elastic stage; first yield determined by the first major transition from elastic to inelastic response; formation of an incipient mechanism determined by considerable loss of system stiffness; final failure mechanism of specified ultimate drift limit.

For as soon as possible using the experimental and calculated results of reinforced concrete pushover curves, that $V-\delta$ is a static force-deflection relation, at same time, taking the significant yielding point as reference point, the pushover curves are converted into parameterless pushover curves $V/V_{Y2}-\delta/\delta_{Y2}$. The relationships among the initial yielding point, significant yielding point, ultimate point and other key point in parameterless pushover curves are statistically analyzed. Using the these relationships, the parameterless pushover curve is transformed to pushover curve according to the seismic design level of the estimated building. As later section described, the pushover curve is converted to a spectral capacity curve for the building, using the simplified nonlinear static analysis method to estimate the seismic vulnerability of multistory or high-rise reinforced concrete. The procedure of development pushover curve and capacity curve is shown in Fig 1. In the paper the relationships of reinforced concrete are given. Taking the significant yielding point as reference point in parameterless pushover curve, providing significant yield point coordinate Y2(1, 1), then initial yield point and ultimate point coordinate are Y1(0.32, 0.51), U(2.1, 1.07) respectively. The variability associated with the pushover curve $\beta_c = 0.38$ is given too.

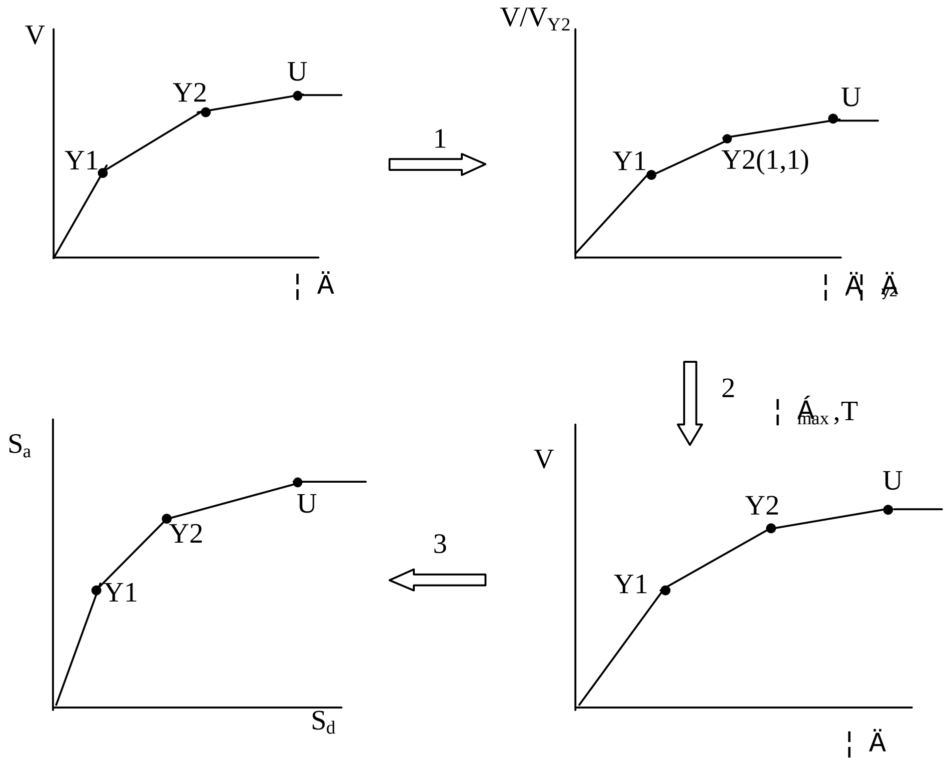

FIG. 1. Steps in development of the pushover curve and capacity curve

Analyze dynamic characteristics

A eigenvalue analysis of the system is performed to determine the fundamental-mode shape (ψ_x). A single degree of freedom (SDOF) system is used to represent a translational vibration mode of the structure. This system has an effective mass equal to $a_1 M$, where α_1 is the effective mass ratio and M is total mass of the structure. This system also has a roof participation factor α_2 that gives the ratios of the roof displacement (ΔR)to the displacement of the mass (S_d) of the SDOF system. The fundamental-mode period is determined by empirical formulas in seismic code for estimating the fundamental period.

Capacity spectrum

The conversion of the ΔR vs V pushover curve to the Sd vs Sa spectral capacity spectrum for a building can be accomplished by knowing the dynamic characteristics of the structure in terms of fundamental-mode period, (T),. the effective mass ratio, α_1 ,and fraction of building height at the elevation where pushover-mode displacement is equal to spectral displacement, α_2. The spectral acceleration and spectral displacement of the design point and initial yield point are determined by the following equations.

$$A_d = \alpha_3 \alpha_{\max} / \alpha_1 \tag{1}$$

$$D_d = A_d T^2 g / 4\pi^2 \tag{2}$$

$$A_{Y1} = \alpha_3 \alpha_{\max} \gamma / \alpha_1 \tag{3}$$

$$D_{Y1} = A_Y T^2 g / 4\pi^2 \tag{4}$$

where γ is “overstrength” factor relating initial yield strength to design strength, taking as 1.3, α_3 is a coefficient, for a single story building taking as 1.0, otherwise taking as 0.85.

Demand spectrum

The demand spectrum is a graph of spectral acceleration versus spectral displacement as modified for the level of effective damping in the structure, which can be converted from the earthquake spectrum. It is based on the 5%-damped response spectrum at the building’s site, reduced for effective damping when effective damping exceeds the 5% damping level of the input spectrum. The paper characterizes ground motion or the earthquake action using the site-specific ground demand (design response spectrum). It depends on the scenario earthquake (both magnitude M and distance R) and the site condition (soil or site classification). Both effects included in the design spectrum and site condition modification. To consider nonlinear structural response effect, modification of damping to include the hysteretic damping may easily be considered by a reduction of the demand spectrum by a damping-related factor. Spectrum reduction factors are a function of the effective damping of the building, β_{eff} .

$$R_A = 2.12/(3.21 - 0.68\ln(\beta_{eff})) \quad (5)$$

$$R_V = 1.65/(2.31 - 0.41\ln(\beta_{eff})) \quad (6)$$

the variability associated with the demand spectrum is $\beta_d = 0.71$ (Gou,1989)

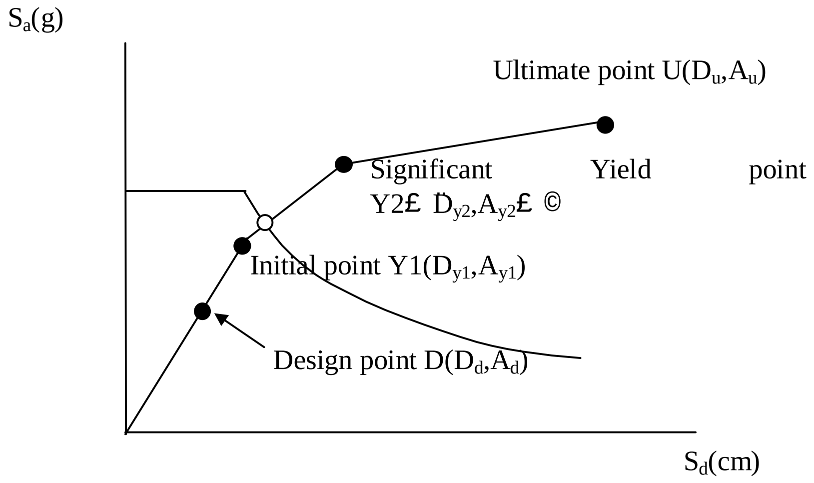

FIG. 2. Example intersection of demand spectrum and capacity spectrum

Building response

Building response is determined by the intersection of the demand spectrum and the building capacity curve. The procedure is illustrated in Fig 2. The demand spectrum curves are superimposed with the building capacity, the intersection of the capacity and appropriately damped demand curve represents the spectral acceleration and spectral displacement response of the structure.

Building fragility curves and probability earthquake damage to buildings

Because there are large uncertainty factors involved in the evaluation of both the demand spectrum of the design ground motion and the capacity curve of the structure, the seismic evaluation is always considered in a probability sense, building fragility curves are a lognormal functions that describe the probability of reaching or exceeding structural damage, given deterministic estimates of spectral displacement response. They distribute damage among slight, moderate, extensive and complete damage states.

Each fragility cures is defined by a median value of the spectral displacement that corresponds to the threshold of that damage state and by the variability associated with that damage state. The conditional probability of being in or exceeding a particular damage state, given the spectral displacement, S_d :

$$P[ds|S_d] = \Phi\left[\frac{1}{\beta_{ds}}\ln\left(\frac{S_d}{\overline{S}_{d,ds}}\right)\right] \qquad (7)$$

Where: $\overline{S}_{d,ds}$ is the median value of spectral displacement at which the building reaches the threshold of damage

state, ds,

β_{ds} is the standard deviation of the natural logarithm of spectral displacement for damage state, ds, and

Φ is the standard normal cumulative distribution function.

Median values of structural component fragility are based on inter-story drift ratios that describe the threshold of damage states. Damage-state drift ratios are converted to spectral displacement using

$$\overline{S}_{d,ds} = \delta_{ds}\alpha_2 H \qquad (8)$$

where: $\overline{S}_{d,ds}$ is the median value of spectral displacement for damage state, ds

δ_{ds} is the drift ratio at the threshold of structural damage state, ds,

α_2 is the fraction the building (roof) height at the elevation where pushover-mode

displacement equals spectral displacement, and

H is the typical roof height of the model building type of interest.

Table 1. Typical drift ratios used to define structural damage states for reinforced concrete

Drift ratio at the threshold of structural damage			
Slight	Moderate	Extensive	Complete
0.002	0.005	0.015	0.04

Table 1 summarizes typical drift ratios used to define structural damage for various building types(Zhong, 1984). The variability $\beta_d = 0.38$ associated with the damage state was given(Guao,1990)

Lognormal standard deviation values (β) escribe the total variability of fragility curve damage states. Three primary sources contribute to the total variability of any given state, namely the variability associated with the capacity curve, (β_C) ,the variability associated with the demand spectrum , (β_d), and the variability associated with the discrete threshold of each damage state, (β_T, ds), for simplicity ,the square-root-sum-of-the squares method are used to calculate the total variability.

EXAMPLE

A seismic damage assessment is performed on an uniform six-story reinforced concrete building to illustrate the seismic evaluation procedure. The building was designed according to the seismic design 89'code of China. It's seismic design level was 8 degree. The story height, story stiffness and story mass of the reinforced concrete are summarized in table 2.

Table 2. The parameters of a six-story reinforced concrete designed according to seismic code

Story number	Story height (m)	Stiffness(×108) (N/m)	Mass(×105) (Kg)
1	4.0	5.839	10.36
2	3.6	5.838	9.33
3	3.6	5.835	9.33
4	3.6	4.748	9.33
5	3.6	4.748	9.33
6	3.6	4.544	6.95

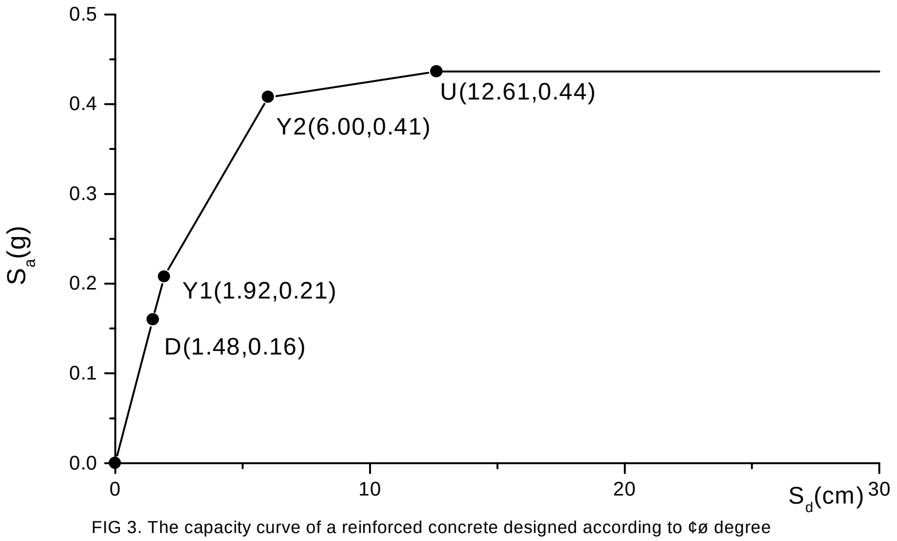

FIG 3. The capacity curve of a reinforced concrete designed according to ¢ø degree

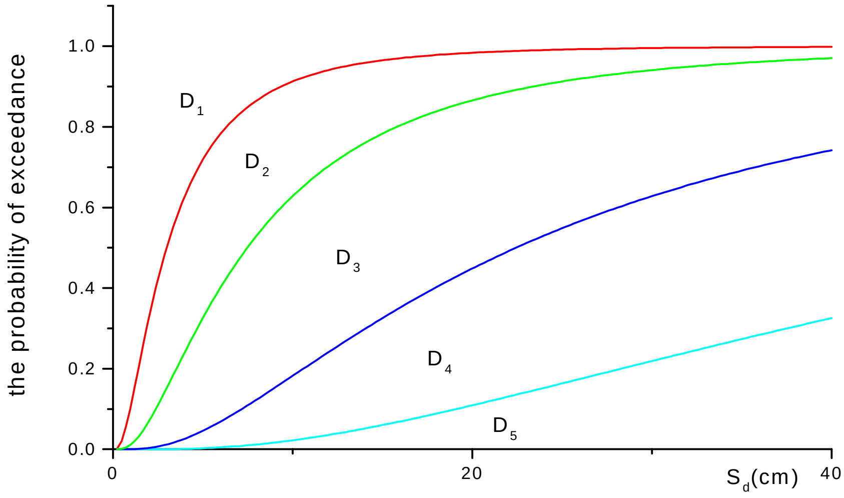

FIG.4 The fragility curves of a six-story reinforced concrete designed according to ¢ø degree

A eigenvalue analysis of the building is performed to determine the effective mass ratio $\alpha_1 = 0.85$ and fraction of building height at the evaluation where pushover-mode displacement is equal to spectral displacement $\alpha_2 = 0.68$. According to empirical formulas for estimating the fundamental period, the period is determined $T = 0.61$s. The capacity curve of the reinforced concrete was shown in Fig. 3. The fragility curves of the reinforced concrete are shown in Fig.4.

Table 3. The damage probability matrices for a reinforced concrete whose seismic design level is 8 degree (%)

Damage state	**Modified Mercalli Intensity of correspondent to Ground motion input**		
	7	8	9
Undamage	52	32	12
Slight	33	39	30
Moderate	15	25	43
Extensive	0	4	13
Complete	0	0	2

Adjusting the standard response spectra according to the value of peak ground acceleration corresponding to seismic intensity 7 degree, 8 degree, 9 degree in Chinese Macroseismic scale, the response spectra were used as seismic input to calculate the seismic response of the reinforced concrete, and then the damage probabilities of the reinforced concrete subjected the ground motion are estimated. The calculated damage probability matrices for the reinforced concrete whose seismic design level is 8 degree are summarized in Table 3.

CONCLUSION

This paper has presented a simplified method of evaluation for the probability of earthquake damage to existing buildings in China, which does not rely either on heuristics or on empirical data. It performs the vulnerability analysis based on mathematical models of structural behavior using response of structure subjected to ground motion. It will be used to estimate seismic losses based on ground motion parameter in China.

It permits vulnerability estimation to incorporate important ground motion characteristics, including site/soil amplification effects, the type of earthquake, frequency content. Further it explicitly consider the level of seismic design, vintage, nonlinear inelastic response, and effects on the structural system. It can overcome other drawbacks such as logical round-error in damage estimation, subjective assessment in intensity, discrete values of intensity and actual damage data limitation on seismic evaluation by empirical approach.

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