DISPALCEMENT BASED SEISMIC EVALUATION OF R.C. FRAME-SHEAR WALL MODEL STRUCTURES

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ABSTRACT :

By using capacity spectrum method which is related to the highly damped linear-elastic response spectra, the seismic behavior of a pseudo dynamic test model structure for R.C. frame-shear wall structure of main factory building in a heat-power plants is evaluated. The results show that some problems in capacity spectrum method, such as the equivalent linear system and equivalent viscous damping ratio etc. are to be improved further. After top displacement of structures is calculated, the displacement and force responses, location of crack and plastic hinge in every phase are analyzed according to nonlinear static push over analysis. The weak points and damage pattern of structures can be easily found by using this method. The results also show that the time history analysis method can be replaced by nonlinear static push over analysis to the displacement based seismic evaluation of R. C. structures.

KEYWORDS: capacity spectrum method, displacement based seismic evaluation, nonlinear pushover analysis, frame-shear wall model

1. INTRODUCTION

After the theory of displacement based seismic design is put forward, it is highly recognized that making use of the roof displacement as the evaluation index of the seismic performance (Bracci J. M., 1997; Nagao, T., 2000.and Tian, Y., 2001). Displacement-based seismic design mainly includes Ductility Factor-Control Design Method, Capacity Spectrum Method (CSM) and Direct Displacement-based Design Method. By changing the demand curve and structural capability curve to the same format, Capacity Spectrum Method can get the object displacement at the point of intersection of the two curves or visually evaluate structural performance in the given earthquake by the graph method. This method is also suitable to the seismic design and evaluation of earthquake resistant capability of the structure.

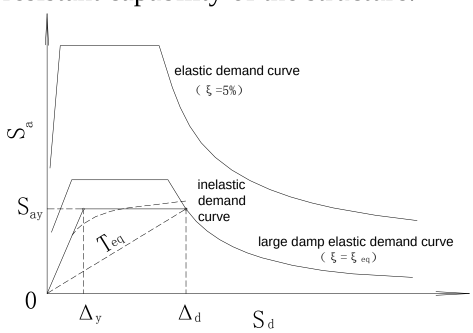


Figure 1 Capacity spectrum method (CSM)

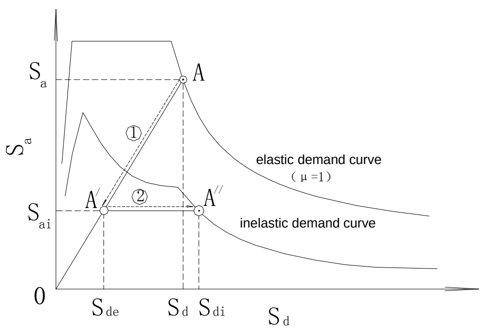


Figure 2 Improved capacity spectrum method (ICSM)

The structural demand curve in the CSM can be shown by two different ways: (1) Linear-elastic response spectrum related to the equivalent viscous damping ratio, which first establishes demand curve, namely spectral acceleration S_{ae} and spectral displacement S_{de} curve for different viscous damping ratios, for the linear-elastic single-degree of freedom system, then transform the base shear top displacement curve gained from the nonlinear push-over analysis of the structure to the acceleration S_a and displacement S_d curve of ideal equivalent

single-degree of freedom system and get the capability curve of the structure, shown as Fig.1. (2) Nonlinear response spectrum related to the ductility of structure, namely Improved Capacity Spectrum Method (ICSM), which can overcome the shortage of CSM, and establishes nonlinear demand curve using the linear-elastic design response spectrum and $R-\mu-T_n$ relation, shown as Fig.2. Calculation shows that the nonlinear demand curve can get more accurate results than the linear-elastic demand curve with equivalent viscous damping ratio, especially for bigger demand of ductility.

2. EQUIVALENT AND CAPACITY CURVE OF MULTI-DEGREE OF FREEDOM SYSTEM

2.1. Equivalent Single Degree of Freedom System

Based on the theory of earthquake response of equivalent single degree of freedom (ESDOF) can substitute for the one of multi-degree of freedom(MDOF)structural system, CSM supposes that the structural response would only be under the control of the first vibration mode whose form keeps changeless in the course of structural response(Fajfar, P., 1999). Proper mechanical model for pushover analysis of structure is selected in order to get the base shear versus top displacement curve, namely pushover curve. And then transform the pushover curve into shear versus displacement curve of ESDOF system, which will also be transformed into spectrum acceleration versus spectrum displacement curve, namely structural capacity curve.

Based on the principle of equal period of the multi-degree of freedom system and single degree of freedom system, according to the theory of structural dynamics, this paper get the follow calculation formula of the equivalent mass, equivalent displacement, equivalent shear of ESDOF freedom(Shi, Q.X.,2002).

$$M=\sum_{i=1}^{n} m_i\phi_{i1}^2\,, \qquad u=\frac{1}{\Gamma_1}u_T\,, \quad V=\frac{V_b}{\Gamma_1^2} \tag{2.1}$$

Where u_T, V_b in the formula respectively means the top displacement and base shear of the multi-degree of freedom system; ϕ_{i1} means the mode component of the first vibration mode; $\Gamma_j=\sum_{i=1}^{n} m_i\phi_{ij}\Big/\sum_{i=1}^{n} m_i\phi_{ij}^2$ means the mode participation coefficient of the vibration mode j.

2.2. Fold Line and Characteristic Parameter of the Capacity Curve

With equation (2.1), pushover curve of MDOF system can be transformed into shear versus displacement curve, which is then transformed into spectrum acceleration versus spectrum displacement curve. Then it is simplified to a polygon line commonly the double polygon line in order to compare with the demand curve of structure. And the simplification is done according to the equal principle of the two areas respectively enclosed by the shear versus displacement curve and by the double polygon line. The characteristic parameters are determined as following: k_1 is the tangent stiffness of the shear versus displacement curve whose enclosed area is A_0, and the yielding shear V_y, yielding displacement u_y, the second stiffness k_2 can be calculated as Equ. 2.2.

$$V_y=\frac{2k_1A_0-k_1V_mu_m}{k_1u_m-V_m}\,, \quad u_y=\frac{V_y}{k_1}\,, \quad k_2=\frac{V_m-V_y}{u_m-u_y} \tag{2.2}$$

Then the ductility factor of equivalent single degree of freedom system is as Equ. 2.3.

$$\mu = \frac{u_m}{u_y} = \frac{k_1 u_m^2 - V_m u_m}{2A_0 - V_m u_m} \tag{2.3}$$

The corresponding equivalent period T_{eq} and equivalent viscous damping $\hat{\xi}_{eq}$ of the ESDOF system can be calculated as Equ. 2.4.

$$T_{eq} = 2\pi\sqrt{\frac{M}{K_e}} = T_n\sqrt{\frac{\mu}{1+\mu\alpha-\alpha}}, \quad \hat{\xi}_{eq} = \frac{1}{4\pi}\frac{E_D}{E_S} \tag{2.4}$$

In the equation above, T_n is the natural period of the single degree of freedom elastic system. E_D is the area enclosed by the single cycle hysteretic loop of ESDOF system, and E_S is the corresponding strain energy of maximum displacement of ESDOF system. Without the consideration of degrading of restoring model, obviously equation (2.4) isn't applicable to the reinforced concrete structures, so the followed formula of equivalent viscous damping ratio is adopted as following (Silvia, M.,2002).

$$\xi_{eq} = \frac{1}{\pi}\left(1 - \frac{1-\alpha}{\sqrt{\mu}} - \alpha\sqrt{\mu}\right) \tag{2.5}$$

3. DEMAND CURVE OF STRUCTURE

There're two sorts of elastic demand curve related to equivalent viscous damping ratio: one is corresponding to special earthquake records, another is corresponding to response spectrum for design of the standard. To the special earthquake records, structural linear elastic demand curve corresponding to different viscous damping ratio can be established by calculations of linear elastic response spectrum. Acceleration response spectrum curve of Seismic Design Code of Building is shown as the form of acceleration period coordinate in China, so it should be transformed into spectrum acceleration spectrum displacement curve, namely structural demand curve. During the course of transformation, equivalent viscous damping of structure needs considering, and demand curve of ESDOF system with a series of equivalent viscous damping will be gained.

4. EVALUATION EXAMPLES

Take the pseudo dynamic model test of longitudinal RC frame shear wall structure of the main factory building of some heat-engine plant as the subject investigated. With the simplified polygonal line from the curve, the second stiffness will be calculated as the formula $k_2 = 0$, and at the yield point, $V_y = 100.73kN$, $u_y = 15.90mm$. Because the structure won't appear obviously plastic until the peak acceleration exceeds 200gal, analysis is only carried on when peak acceleration respectively reaches 200gal, 400gal and 800gal under the action of El-Centro wave in this paper.

4.1. Equivalent Single Degree of Freedom System

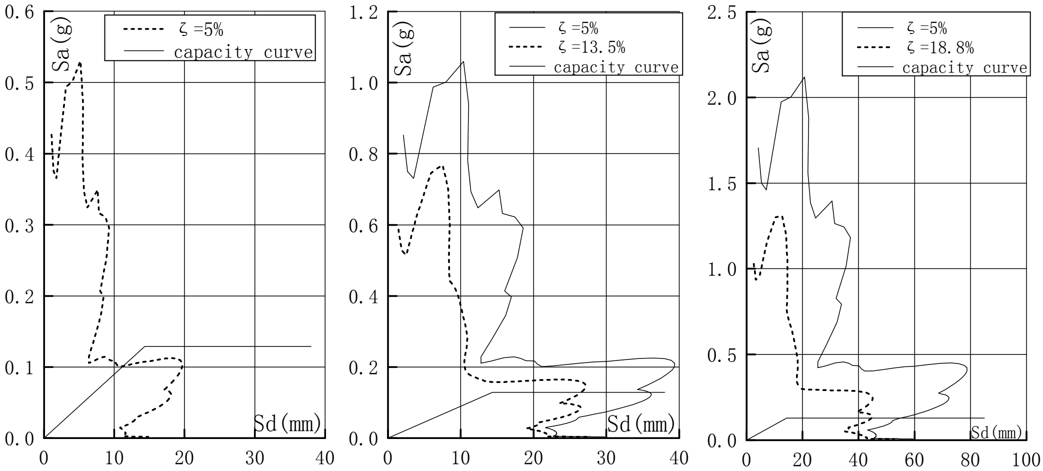
With formula (2.1), plane frame shear wall model structure of multi-degree of freedom system will be transformed to equivalent single degree of freedom system, and the equivalent mass is $M = m_i\phi_{i1}^2 = 635.57kN$, mode participation coefficient of the first mode is $\Gamma_1 = 1.109$; the yielding shear and displacement of ESDOF system are respectively $V_y = 81.90kN$ and $u_y = 14.34mm$, and the corresponding spectrum acceleration in the capability spectrum is $S_{ay} = 0.129g$; elastic stiffness, $k_1 = 5.711kN/mm$ and the corresponding elastic period is. $T_n = 0.669s$.

Table 1 Comparison of results

Roof drift of SDOF (mm)	11.25	26.52	44.67
Roof drift of MDOF (mm)	12.48	29.41	49.54
Roof drift resulted from time history (mm)	14.77	36.60	75.20
Errors (%)	-15%	-19.6%	-34.1%

4.2. Determination of Structural Capability Point

In the analysis with the CSM, the time step is 0.007s which is the same as that of El-Centro wave in pseudo dynamic test and time history analysis, and the result is shown in Fig.3. With formula (2.1), the top displacement of frame shear wall model can be calculated shown as table 1, in which the top displacement calculated by the nonlinear time history method is also shown.



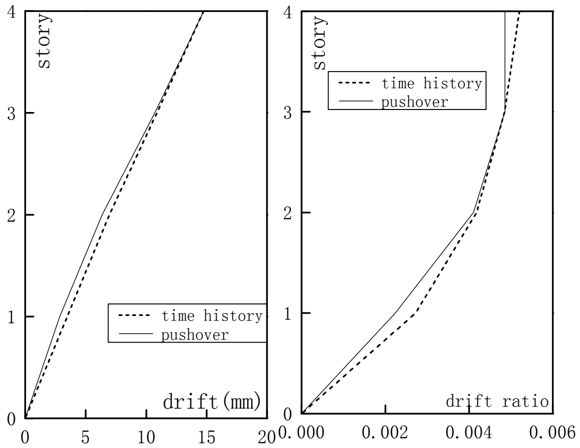
(a)PGA=200gal (b) PGA=400gal (c) PGA=800gal

Figure 3 Determination of performance points in capacity spectrum method

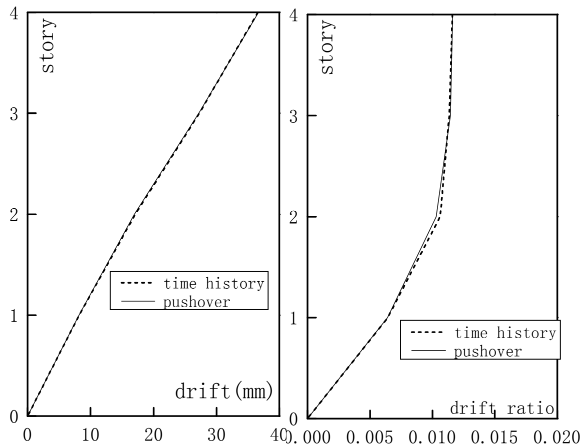
This figure shows that the difference between top displacement calculated by ESDOF system and the one calculated by time history method become larger with the damping ratio increasing. The main reason of error is that the value of equivalent viscous damping of ESDOF system is widely different from the actual value. Although a lot of research has been done with the equivalent viscous damping and many formulas have been given, the value of equivalent viscous damping in the CSM still needs further investigations and improvements, especially when the nonlinear deformation of structure is larger. The other reason is that for the structure with uniform distributed stiffness and mass, the error due to the equivalent is smaller, on the contrary, for the structure with non-uniform distributed stiffness and mass the error is larger such as this example of the structure with quite uniform distributed mass and lightly uniform distributed stiffness. Although there're many ways to structural equivalence, the same problem still exists in them. So the ESDOF system can't wholly replace the actual structure and the equivalence method needs further researches and improvements.

4.3. Evaluation of Seismic Performance

In order to contrast with the time history analysis, the nonlinear static push over analysis method is carried on with the top displacement of structural model determined by the time history analysis. The story drift curve and drift ratio curve when the top displacements of structural model are respectively 12.48mm (PGA=200gal) and 29.41mm (PGA=400gal) are shown in Fig.4 and Fig.5, together with the results of time history analysis. The two figures show that the results of nonlinear dynamic history analysis are better accorded with each other at the condition of the same top displacement of structure. So if the top displacement of structure is calculated accurately, the nonlinear static push over analysis can be used to evaluate the seismic performance of structure instead of the nonlinear dynamic history analysis.



(a)story drift curve (b)drift ratio curve

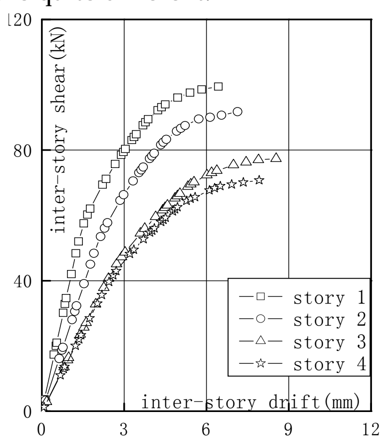


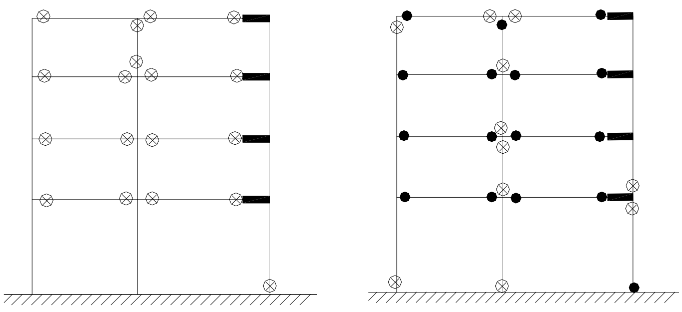
(a)story drift curve (b)drift ratio curve

Figure 4 Story drift and drift ratio curve (PGA=200ga) Figure 5 Story drift and drift ratio curve (PGA=400gal)

The calculation shows that the maximum story drift takes place in the top story. And according to the current seismic design code, when the peak acceleration is 200gal, the elastic-plastic ratio limitation of frame-shear wall structure is near to $[\theta_p]=1/100$, so the structure satisfied the requirement when the intensity of seldom occurred earthquake is 7, but the structure doesn't satisfy increased lateral rigidity in the zone of 8 intensity. The calculation also shows that the story shear gained from the nonlinear static push over analysis is less than the one gained from nonlinear dynamic history analysis, so it won't be safe if the nonlinear static push over analysis method is used in the design.

There's the story shear-story drift curve of structural model at the peak acceleration of 400gal in Fig.6, which shows that nonlinear displacements of the third and fourth stories are the maximum and the corresponding damage are the worst; however the displacements of the first and second stories are a little less and the story shear are quite different.





(a)PGA=200gal (b)PGA=400gal

Figure 6 Inter-story shear versus drift curves Figure 7 Distribution of damage and hinges

The location of crack and plastic hinge in every phase of structural members respectively at the peak acceleration of 200gal and 400gal are shown in Fig.7, which is nearly the same as the nonlinear dynamic history analysis. The requirement of strong column and weak beam of code is satisfied and the failure model of structure is beam hinged sides way mechanism.

5. CONCLUSIONS

This paper evaluates the seismic behavior of reinforced concrete model structures by using capacity spectrum method which is related to the highly damped linear-elastic response spectra. Through the comparison with nonlinear dynamic history analysis method, capacity spectrum method needs further improvement such as the equivalence of multi-degree of freedom system, value of equivalent viscous damping ratio and so on. After top displacement of structures is calculated, the displacement and force responses, location of crack and plastic hinge in every phase are analyzed according to nonlinear static push over analysis. The weak points and damage pattern of structures can be easily found by using this method. The results also show that the time history analysis method can be replaced by nonlinear static push over analysis to the displacement based seismic evaluation of R. C. structures.

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