A Study on the Capacity Spectrum Seismic Design Method for Building with Self-centering Hydraulic Damper

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Abstract: In order to determine the reasonable mechanic parameters of the damper on the passive energy dissipation structure, which combined with the basic principle of Chinese seismic design code and capability spectrum. It is important for the self-centering hydraulic damper to fully consider their additional stiffness and the additional damping ratio. Then determining the parameters and quantities of the damper through the performance limit of the story drift. In this paper, taking a six-story steel frame structure as an example. The damper parameters of passive energy structure are designed and the nonlinear response history analysis is used in the OpenSees. The calculation and example analysis shows that the performance-based seismic method is feasible.

1. Introduction
Earthquake disasters are sudden and will cause a great threat to people's life and property safety. So the passive energy structure design has always been a hot research. With the study goes deeper, scholars found that the residual displacement has an important guiding function for the repair and use of the structure after earthquake. Therefore, Tsopelas and Constantinou[1]developed a kind of damper. It can not only consume seismic energy, but also have a self-centering capability. It can effectively reduce the residual displacement. Today, a new self-centering hydraulic damper is formed. We need to study optimization methods for this damper parameter design.

In view of this, referring to the concept of performance-based seismic design proposed by American engineers in the early 1990s. It can meet the performance target under different seismic damage states. Later, the results of Pushover analysis combined with seismic response spectrum design were developed into capability spectrum design method by Freman[2]. It was developed into a performance-based capability spectrum method through a large number of scholars studied[3]. Therefore, this method is introduced in the seismic design of the passive energy dissipation structure, which is different from the design of the ordinary structure. The former focused on the parameters design of the energy dissipation device so that the passive control structure can meet the performance target requirements. Pei Xing Zhu et al[4]studied the steel frame structure of additional metal dampers and proposed a damping performance curve method. Zhang Sihai et al[5]had proposed the intuitive design method of the viscous damper based on improving the capability spectrum. Due to the different mechanical model of energy consumption devices, the characteristics of energy consumption devices are different. According to the mechanical model[6]of the self-centering hydraulic damper, which will
produce additional stiffness on the structure. It is a non-negligible influence on the structure period and the structure total damping ratio. Based on this method, a modified seismic performance design method for the additional self-centering hydraulic damper structure is proposed.

2. Basic theory of capacity spectrum method

2.1. Establishment of the capability spectrum curve

The Pushover curve of the structure is obtained by Pushover analysis. According to the principle of equivalent energy, the Pushover curve is equivalent to a double fold line. Then the capability spectrum curve is calculated by the following Equations (1) and (2):

\[ S_a = \frac{V}{W_1} g \]  \[ S_d = \frac{u_r}{\phi \Gamma_1} \]

Where \( S_a \) is spectral acceleration, \( S_d \) is spectral displacement, \( V \) is base shear, \( u_r \) is roof displacement, \( \phi \) is orthogonal to the vertex vector value of the first modal shape after normalized 1, where \( W_1 \) is the 1th modal weight is calculated by Equation (3), \( \Gamma_1 \) is the 1th modal participation factor given by Equation (4):

\[ W_1 = \left( \sum_{i=1}^{N} \alpha_i \phi_{i1} \right)^2 \]

\[ \Gamma_1 = \frac{\sum_{i=1}^{N} \alpha_i \phi_{i1}}{\sum_{i=1}^{N} \alpha_i \phi_{i1}^2} \]

2.2. Establishment of the demand spectrum curve

The demand spectrum curve is to convert the standard acceleration response spectrum provided by seismic specification[7]to the spectral acceleration \( S_a \) - spectral displacement \( S_d \) curve by Equation (5):

\[ S_d = \left( \frac{T}{2\pi} \right)^2 S_a \]

3. The calculation on effective stiffness of the damper

According to the principle of equivalence, damper is equivalent to a line elastic support member with effective stiffness \( K_{\text{eff,j}} \), then the effective stiffness of the damper \( j \) can be calculated using Equation (6):

\[ K_{\text{eff,j}} = \frac{F_{0,j} + u_{y,j} \times K_0 \times \cos \theta_{j}}{u_{y,j} \times \cos \theta_{j}} \]

Where \( F_{0,j} \) is the preload of single damper on the level \( i \), \( u_{y,j} \) is yield displacement of level \( i \), \( K_0 \) is elastic recovery stiffness of damper, \( \theta_{j} \) is the installation angle of damper.

4. Calculation of the equivalent damping ratio on the passive control structure

The equivalent damping ratio of the structure can be divided into three parts including the structural inherent damping ratio, the hysteresis damping ratio and the additional damping ratio of the damper, which is described by Equation (7):

\[ \xi_{\text{eff}} = \xi_{0} + \xi_{\mu} + \xi_{v} \]

4.1. Inherent damping ratio \( \xi_{0} \)

According to code for seismic design of buildings[7], the elastic damping ratio \( \xi_{0} \) of steel structure with a height of less 50m is 0.04, while the structure of under 200m is 0.03.

4.2. Hysteresis damping ratio \( \xi_{\mu} \)

The hysteresis damping ratio can be calculated by Equation (8) in the elastic-plastic phase, which is proposed by scholars[8].

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$\xi_\mu = \frac{1}{\pi} \left[ 1 - \frac{1 - \alpha_s}{\sqrt{\mu}} - \alpha_s \sqrt{\mu} \right] \quad (8)$

Where $\alpha_s$ is the stiffness yield ratio, $\mu$ is the displacement ductility ratio.

4.3. Additional damping ratio $\xi_v$ for the self-centering hydraulic damper

Linear viscous damping ratio is given Equation (9):

$$\xi_v = \left( \frac{T}{4\pi} \right) \frac{\sum C_j \cos \theta_j \phi_j^2}{\sum \left( \frac{\alpha_j}{g} \right) \phi_i^2} \quad (9)$$

Where $C_j$ is the damping coefficient of the $j$ damper, $\phi_j$ is the vector difference of the $j$ damper at the degrees of freedom $i$.

5. Example analysis

Only taking the rare earthquake analysis results as an example because of given the limited space.

5.1. Project overview

The calculation example used in this paper is a 6-story steel frame structure. The building site category is III and design seismic group is 3th group. Grade 7 with seismic intensity of 0.15g. The plane and elevation drawings are shown in Figure 1. The plane size is 41.15m × 41.15m with 5 span every direction. First floor height is 4.42m and 2th~6th floor height is 4.304m. The steel beam and column yield strength is 345MPa. Response modification factor is 8 and deflection amplification factor is 5.5. Due to the regular symmetry of structure, an middle frame was taken for analysis.

According to the relevant references[9-10], the extreme value of the performance story drift under fortification seismic action is taken as 1/100 and 1 / 150 under rare earthquake action.

5.2. Seismic wave selection

According to the specification requirements, two natural and one artificial waves are selected. Then fitting to the specification reaction spectrum as shown in Figure 2. It can be seen from the picture that the mean spectrum is in good agreement with the standard response spectrum and the error is within 20%.

![Figure 1. The diagram of frame construction](image-url)
5.3. Performance analysis of uncontrolled structure

Modal analysis of a steel frame structure is analyzed through using OpenSees. The first period of this structure is 1.91s. And first modal shape vector $\phi_1 = [1,0.887,0.707,0.508,0.292,0.110]$. It is important for Pushover analysis to consider P-Δ effect of column. The base shear-roof displacement curve is obtained. Then reducing to a double-fold line according to the principle of energy equivalence. And converted to a capability spectrum curve as shown in Figure 3. The structural yield point $(u_y, V_y)$ is (400 mm, 2000 kN) and the performance yield point $(S_{dy}, S_a)$ is (285.7 mm, 0.162g).

5.4. Verification of the uncontrolled structure analysis results

Enter the ground seismic acceleration selected that adjusting the ground motion peak specified on the specification under the rare earthquake to 310gal. It is analyzed by the nonlinear response history analysis method in the OpenSees. Then the average results of the story drifts and the maximum value is 0.0192, which exceeding the limit of 1/100.
Figure 4. The story drifts under the rare earthquake.

Judging from the results, the nonlinear response analysis results usually are more conservative than the value calculated by the reaction spectrum method. But they also exceed the performance limit. It shows that the calculation results of the reaction spectrum method have sufficient design authenticity within the allowable error range.

5.5. Preliminary design of the damper

The story yield shear of each floor can be obtained by Pushover analysis: $F_{y,1}=2000$ kN, $F_{y,2}=1400$ kN, $F_{y,3}=800$ kN, $F_{y,4}=500$ kN, $F_{y,5}=280$ kN and $F_{y,6}=100$ kN.

A damper is initially configured at each diagonal position along the nodes. And the preload per damper is 20% of the floor yield shear. So the preload $F_{0,i}$ on level $i$ is calculated as $F_{0,1}=500$ kN, $F_{0,2}=350$ kN, $F_{0,3}=200$ kN, $F_{0,4}=150$ kN, $F_{0,5}=100$ kN, and $F_{0,6}=50$ kN.

According to the measuring range and output of the damper, $K_{0,i}$ is given as $K_{0,1}=2000$ kN/m, $K_{0,2}=2000$ kN/m, $K_{0,3}=1800$ kN/m, $K_{0,4}=1800$ kN/m, $K_{0,5}=1500$ kN/m, $K_{0,6}=1500$ kN/m.

The additional effective stiffness of the damper is calculated according to the preliminary designed damping parameters by Equation (6). Then the dampers are replaced with the elastic units of equal stiffness. Reperforming the modal analysis and pushover analysis. Then the equivalent model's basic period is 1.74s. And first modal shape vector $\phi_1 = [0.880, 0.699, 0.501, 0.292, 0.111]$.

The yield point $(u_{ry}, V_y)$ of the structure is (287.1 mm, 1900 kN) and the performance yield point $(S_{dy}, S_a)$ of the capability spectrum is (203.6 mm, 0.153 g).

5.6. Determine the additional damping ratio

The target performance point of the structure is found according to the target performance story drift limit value under the rare earthquake. So the target performance point is (211.4 mm, 0.161 g). We can know the structure has entered the elastic-plastic working phase. Then the hysteresis damping ratio is 0.004 through calculating. Making the demand spectrum curve through the target performance point by adjusting the total damping ratio as shown in Figure 5. So the equivalent damping ratio $\zeta_{eff}=0.152$.

So the additional damping ratio required for the damper is 0.072.

5.7. Other parameters design for the damper

In this paper, linear viscous damping is used and the damping index $a=1$. The damping coefficient of the dampers on each floor is distributed equally. Then the damping coefficient $C_j$ of the single damper can be calculated on each floor. Therefore, the required damping coefficient is calculated at the large earthquake level:

$$C_j = \frac{1567 \times 1^2 + 2900 \times 0.880^2 + 2900 \times 0.699^2 + 2900 \times 0.501^2 + 2900 \times 0.292^2 + 2900 \times 0.111^2}{9.8 \times (0.120^2 \times \cos^2 27.6^\circ + 0.181^2 \times \cos^2 27.6^\circ + 0.198^2 \times \cos^2 27.6^\circ + 0.210^2 \times \cos^2 27.6^\circ + 0.181^2 \times \cos^2 27.6^\circ + 0.111^2 \times \cos^2 27.6^\circ)} \times \frac{4 \times 2404.84 \text{N} \cdot \text{s}}{1.74}$$

The viscous damping coefficient of the energy consumption group is taken at 2400 kN. (s/m). The final design parameter of the self-centering hydraulic damper is shown in Table 1.
Table 1. Self-centering hydraulic damper design parameters sheet

| Level | Quantity | C(N/(mm/s)) | a   | F0(N) | K0(kN/m) | F_min(N) |
|-------|----------|-------------|-----|-------|----------|----------|
| 1     | 1        | 2400        | 1   | 500000| 2000     | 25000    |
| 2     | 1        | 2400        | 1   | 350000| 2000     | 17500    |
| 3     | 1        | 2400        | 1   | 200000| 1800     | 10000    |
| 4     | 1        | 2400        | 1   | 150000| 1800     | 7500     |
| 5     | 1        | 2400        | 1   | 100000| 1500     | 5000     |
| 6     | 1        | 2400        | 1   | 50000  | 1500     | 2500     |

5.8. Analysis of passive energy dissipation structure
The determined damper parameters of self-centering hydraulic are set in the original structure. And the peak story drift and residual story drift of the energy dissipation damping structure is analyzed.

Peak story drift is compared in Figure 6(a) and residual story drift is compared in Figure 6(b).

![Figure 6](image_url)

(a) Story drift (b) Residual story drift
Figure 6. The peak story drift under the rare earthquake
The comparison results in the figure show that the maximum story drift of uncontrolled structure under large earthquake is 1.62% and the maximum value of shock absorption structure is 0.98%, which just meeting the performance level. So the shock absorption rate reaches 40.54%. The story drift value of each floor can meet the performance limit requirements very well. The structure will produce a large residual displacement under the action of rare earthquake, which affects the repair and normal use of the structure. Therefore, the self-centering hydraulic damper reduces the maximum residual story drift from 0.311% to 0.022% and the recovery degree reaches 92.98%. It is very good on realizing the self-centering function.

6. Conclusions
From the results above in this study, the following conclusions can be made.
(1) The improved seismic design method based on capability spectrum can easily complete the number and parameter design of dampers.
(2) The proposed method is more simple and more safe compared with the nonlinear response history analysis method, which can better reflect the nonlinearity of the damper.

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References
[1] Tsopelas, P., and Constantinou, M. C. (1994)NCEER-Taisei research program on sliding seismic isolation systems for bridges: Experimental and analytical study of a system consisting of sliding bearings and fluid restoring force/damping devices[C]. NCEER-94-0014, National Center for Earthquake Engineering Research, Buffalo, NY.
[2] Fajfar P. (1999) Capacity spectrum method based on Inelastic demand spectra[J]. Earthquake Engineering and Structural Dynamics. 28: 979-993.

[3] Qian Jia ru, Luo Wen bin. (2001) Displacement Based Seismic Design Methodology for Building Structures[J]. Building Structure. (04): 3-6.

[4] Pei Xing zhu, He Fang qian. (2012) Metal Damping Design of Energy Dissipation Structure Based on the Equivalent Linearization Theory[J]. Earthquake Resistant Engineering and Retrofitting. (03): 97-102.

[5] Zhang Si hai. (2006) A study on the capacity-spectrum seismic design method for buildings equipped with passive energy dissipation systems[J]. China Civil Engineering Journal. (07): 26-32.

[6] Tsopelas P, Constantinou M. C, Kircher C. A, Whittaker A. S. (1997) Evaluation of Simplified Methods of Analysis for Yielding Structures[C]. NCEER-97-0012, Multidisciplinary Center for Earthquake Engineering Research, Buffalo, NY.

[7] GB 50011-2010. (2010) Code for seismic design of buildings[S]. Beijing, China Architecture & Building Press.

[8] Huang Zi bin. (2017) Performance-based Seismic Design of Passive Energy Dissipation Structure with Shape Memory Alloy damper [D]. South China University of Technology.

[9] FEMA 356(2000). Pre-standard and Commentary for The Seismic Rehabilitation of Buildings[S]. Washington, D. C.: Federal Emergency Management Agency.

[10] ATC-40. (1996) Seismic Evaluation and Retrofit of Concrete Buildings[R]. Applied Technology Council, Redwood City, California.