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Design of supplemental viscous dampers in inelastic SDOF system based on improved capacity spectrum method

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Abstract. A simplified yet effective design procedure for viscous dampers was presented based on improved capacity spectrum method in the context of performance-based seismic design. The amount of added viscous damping required to meet a given performance objective was evaluated from the difference between the total demand for effective damping and inherent damping plus equivalent damping resulting from hysteretic deformation of system. Application of the method is illustrated by means of two examples, using Chinese design response spectrum and mean response spectrum. Nonlinear dynamic analysis results indicate that the maximum displacements of structures installed with supplemental dampers designed in accordance with the proposed method agree well with the given target displacements. The advantage of the presented procedure over the conventional iterative design method is also highlighted.

Keywords: viscous dampers; equivalent damping; improved capacity spectrum method; nonlinear dynamic analysis; performance-based seismic design.

1. Introduction

Many modern buildings, after attacked by a severe earthquake, failed to function and required costly structural and nonstructural repairs, although they successfully protected the lives of the occupants. Thus questions could be raised regarding the traditional seismic design practice of permitting inelastic deformation of structural components to dissipate the input seismic energy.

In the past decade, the use of supplemental damping devices in building structures has become an increasingly popular approach to remedy the deficiencies inherent in conventional seismic design. These devices dissipate earthquake-induced energy through either hysteretic action (e.g., yielding of metal, sliding friction) or viscoelastic/viscous action (e.g., fluid viscous damper, solid and fluid

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viscoelastic dampers). In comparison with conventional earthquake-resistant design, the implementation of energy devices in structural systems can reduce seismic demands on structures globally or locally besides improving their capacities, thus serving the purpose of limiting or eliminating damage to the structure by dissipating most of the input earthquake energy. An additional advantage related to the use of energy dissipation devices is that they can be replaced relatively easily after a major seismic event. A review of the state of the art of energy dissipation systems for seismic protection can be found in references by FEMA-273 (1997), FEMA-274 (1997), Soong and Dargush (1997), constantinou *et al.* (1998), and Hanson and Soong (2001).

Many researchers have evaluated and improved the capacity spectrum method (CSM). An improved method using inelastic response spectrum as the demand diagram was proposed by Fajfar (1999) and Chopra and Goel (2000). Lin (2003) used the real absolute acceleration response spectrum to improve the accuracy of the CSM adopted in ATC-40 (1996). Guyader and Iwan (2004) proposed an improved CSM based on the equivalent linearization and graphical solution technology which was later incorporated in FEMA-440 (2005).

More recently, the performance-based seismic design procedure has been applied to designing and analyzing new and existing buildings installed with energy dissipation devices. Combining with nonlinear static procedure Ramirez (2001) proposed simplified methods of analysis, which was incorporated in FEMA-450 (2003), of inelastic buildings equipped with linear viscous, nonlinear viscous and hysteretic damping devices. Kim *et al.* (2003) utilized the traditional capacity spectrum method to retrofit the existing buildings using viscous dampers. Lin *et al.* (2003) presented the direct displacement-based design method for designing steel frame with various energy dissipation devices. And Kim and Choi (2006) presented a nonlinear static analysis procedure of a structure using displacement response spectrum and the capacity curve of the structure. These studies indicated that nonlinear static procedures are effective and efficient tools in designing and analyzing new and existing buildings installed with energy dissipation devices compared with nonlinear dynamic procedures. Furthermore, several code-oriented documents, provisions and guidelines, on the design, testing and incorporation of damping devices in building structures have been developed. The most up-to-date of these publications are those of Federal Emergency Management Agency (FEMA-273 Guidelines (1997) and FEMA-274 Commentary (1997), FEMA-356 Prestandard (2000) FEMA-368 Provisions and FEMA-369 Commentary (2001), and FEMA-450 Provisions (2003)), which contain the latest analysis and design guidelines for buildings with energy dissipation systems, as well as with seismic isolation systems.

The general procedure for seismic retrofit of a structure with supplemental dampers is summarized as follows: (1) evaluate the seismic behavior of the structure for given levels of earthquake ground motions; (2) assume the proper damper size and the appropriate configuration scheme (3) evaluate the target displacement of the building with added dampers (4) convert the target displacement to local response quantities and compare those with the given performance criteria to check the adequacy of the added damping. Task in step 1 and 4 can be performed by nonlinear dynamic analysis, or by more simplified approximate methods of analysis. For example, FEMA-273 (1997) suggests nonlinear static procedure based on capacity spectrum method (CSM) be used to evaluate the inelastic response of damper-added structure to the earthquake ground motion. The successful implementation of the second and the third steps, which plays a key role in the retrofitting process, largely depends on empirical estimation or iterative process performed by design professionals. After the dampers are installed in the structure, step 2 to step 4 are repeated until the amount and configuration of added dampers meet the given performance criterion.

However this conventional practice requires conducting a series of try and error analysis, which is onerous and time-consuming. Therefore a more convenient yet effective method is needed to reduce the amount of work performed in step of 2 and 3.

In this paper a simplified procedure of design for viscous dampers was developed based on improved CSM within the context of performance based seismic design. The simple method, presented in the paper, is briefly summarized as follows: first predetermine a performance objective for the damped system and second evaluate the seismic performance of the structure to be retrofitted using improved spectrum method (CSM); if the exhibited behavior of the structure can not satisfy the acceptable performance criterion the total damping required to meet the predetermined performance level can be evaluated using a single step method in combination with the design response spectrum provided in Chinese code for seismic design of building. The proposed method is simple, straightforward and non-iterative when compared with the traditional one.

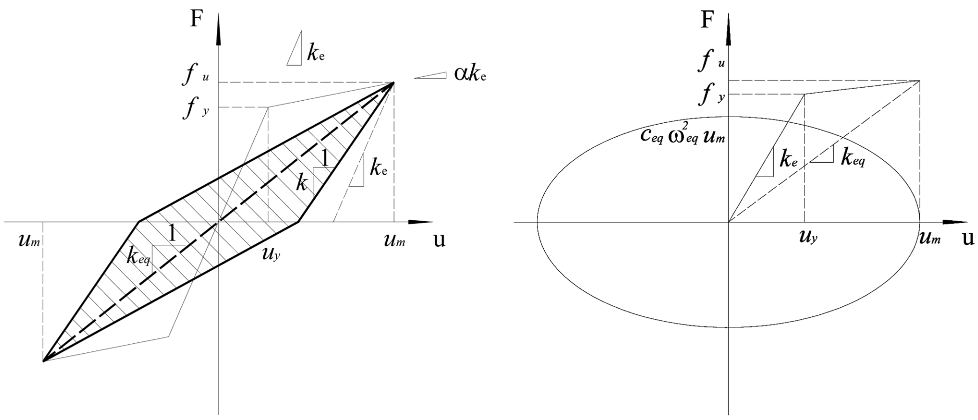
2. Design procedure of viscous dampers for inelastic system

2.1 Modeling of viscous dampers

The viscous dampers have the advantage in providing damping without changing the dynamic characteristics of structures. As stated in FEMA-274 (1997), the damping force provided by viscous damper can be modeled to be proportional to relative velocity between the two ends of the damper with the constant exponent ranging from 0.5 to 2.0. According to the study in this paper, in preliminary design stage the damper force is reasonably considered to be proportional to the velocity with a constant exponent of 1.0 (linear viscous damper) for convenience.

2.2 Effective damping of yielding system with supplemental dampers

Lin *et al.* (2004) carried out pushover tests on RC columns and employed various equivalent linearization methods to evaluate their inelastic deformation demand. Comparing the earthquake-



(1) Hysteretic energy (2) Equivalent viscous damping

Fig. 1 Equivalent damping for Kowalsky that is based on Tekeda degrading stiffness model induced demands estimated by CSM using various equivalent linearization methods, and those obtained from pushover tests, they found that the method suggested by the ATC-40 document overestimates the energy dissipation capacity of tested columns, and consequently underestimates their inelastic displacement demands. Kim *et al.* (2003) employed the bilinear hysteretic damping model, in which the effect of stiffness degradation was not accounted for when evaluating equivalent damping ratio, to estimate the inelastic deformation of a structure to be retrofitted, which may underestimate its inelastic displacement. When the Kowalsky hysteretic damping model was used and stiffness degradation slightly considered in the equivalent linearization method, the values obtained from CSM were found to be more consistent with to the experimental results. So the Kowalsky hysteretic damping model will be employed in this paper to estimate the equivalent viscous damping for the structure. Kowalsky (1994) used the Taketa model as the hysteretic model with the unloading stiffness factor of n ranging from 0 to 0.5. The unloading stiffness of $k = k_e/\mu^n$ and displacement ductility rotio of $\mu = u_m/u_y$ are shown in Fig. 1, where u_y, u_m, f_y and f_u are yield displacement, maximum displacement, yield strength and ultimate strength for bilinear system, respectively; k_e and k_{eq} are elastic stiffness and equivalent stiffness; α is the postyield stiffness ratio. The hysteretic energy, E_H, dissipated in one cycle with a deformation amplitude equal to u_m in both directions is given by (the area enclosed by the hysteretic loop shown in Fig. 1(a))

$$E_H = 2\left[1 - \mu^n\left(\alpha + \frac{1-\alpha}{\mu}\right)\right]f_u u_m \tag{1}$$

The strain energy stored in the system is

$$E_S = \frac{1}{2}f_u u_m \tag{2}$$

The equivalent damping ratio is then given by Chopra (2001)

$$\zeta_{eq} = \frac{1}{4\pi}\frac{E_H}{E_S} = \frac{1}{\pi}\left[1 - \mu^n\left(\alpha + \frac{1-\alpha}{\mu}\right)\right] \tag{3}$$

If energy dissipation devices are added, the effective damping becomes (Soong and Dargush 1997)

$$\zeta_{eff} = \zeta_i + \frac{1}{4\pi}\frac{E_D}{E_S} + \frac{1}{4\pi}\frac{E_H}{E_S} \tag{4}$$

where E_D is the energy consumed by viscous dampers in one cycle of harmonic motion. The first term on the right hand side of Eq. (4) represents the inherent damping ratio of the system, the second one describes the viscous damping ratio provided by supplemental viscous dampers, and the third one gives the equivalent damping ratio resulting from the hysteretic deformation of the system. As shown in Fig. 1(b), the energy dissipated by viscous dampers in one cycle of steady-state response of inelastic system to harmonic force excitation is expressed as follows

$$E_D = \int f_D du = \int_0^{2\pi/\omega}(c_{eq}\dot{u})\dot{u}dt = \pi c_{eq}\omega u_m^2 = 2\pi\zeta_v\frac{T_{eq}}{T_e}k_{eq}u_m^2 \tag{5}$$

where c_{eq} is the equivalent damping coefficient for a linear viscous damper ($c_{eq} = 2m\omega_{eq}\zeta_v$); u is assumed to be $u_m\sin(\omega t - \phi)$, in which ω and ϕ are circular frequency of external excitation and phase angle of system, respectively; T_e and T_{eq} are elastic period and equivalent period for system, correspondingly; ζ_v is the viscous damping ratio of the system with added dampers vibrating within the elastic range. In this study the excitation frequency is assumed to be equal to the initial elastic natural frequency of system, i.e., $\omega = \omega_e$. Substituting Eq. (5) into Eq. (4), the overall effective damping including the contribution from the dampers can then be obtained (Tsopelas *et al.* 1997)

$$\zeta_{eff} = \zeta_i + \zeta_v \frac{T_{eq}}{T_e} + \zeta_{eq} \tag{6}$$

where the relation of $f_u = k_{eq} u_m$ is utilized in the derivation process.

2.3 Determination of supplemental damping required to satisfy performance objective

When estimating the response of the structure, the total effective damping obtained from Eq. (6) can be used to reduce the seismic demand on the structure. If the desired target displacement is predetermined in seismic retrofit, the amount of supplemental damping required for structure to meet a given performance objective can then be obtained by transforming Eq. (6) to the following expression (Kim *et al.* 2003)

$$\zeta_v = (\zeta_{eff} - \zeta_i - \zeta_{eq}) \frac{T_e}{T_{eq}} \tag{7}$$

where the effective damping can be determined from the demand spectrum that crosses the capacity diagram at the given target displacement. Although Eq. (7) is derived by the simple transformation of Eq. (6), the two equations have different physical implication. Eq. (6) is intended for evaluation of the effective damping of a existing damped structure and can then be used for simplified analysis of the damped structure. In contrast, Eq. (7) implies that the added damping ratio required for the structure to be retrofitted to satisfy the given performance objective can be estimated based on the inherent damping ratio for the structure deformed within elastic range and equivalent damping ratio obtained at the target displacement using equivalent linearization method. Consequently, Eq. (7) may be employed for seismic design of supplemental dampers to a structure. The procedure for evaluation of the required added damping is detailed as follows:

(1) Set a performance objective for the system with supplemental dampers, i.e., specify the maximum response of the damper-added structure to the given level of earthquake ground motion.

(2) Perform pushover analysis of the structure to be retrofitted, transform the pushover curve to bilinear capacity diagram in the format of spectral acceleration of S_a versus spectral displacement of S_d (A-D format), and determine the performance point of the structure using design response spectrum or response spectrum for earthquake ground motions. If the displacement at performance point is less than the target one, it is implied that the effect of hysteretic damping plus inherent damping adequately limits the displacement demand of system to the given target displacement, and in this case no supplemental damping is needed. Otherwise, go to the third step.

(3) Obtain the target ductility by dividing the target displacement by the yield one, and compute the equivalent damping of system at the target ductility in conjunction with postyield stiffness ratio of α and unloading stiffness factor of n.

(4) Evaluate in A-D format the damping ratio of demand spectrum that intersects with the capacity diagram at the target displacement, according to the reduction rules of demand

spectrum. This corresponds to the total effective damping required for the structure to meet the given performance objective.

(5) Compute the supplemental viscous damping needed to limit the displacement demand to the target displacement using Eq. (7).

2.4 Determination of performance point using improved CSM

The nonlinear static procedure used by Kim *et al*. (2003) is based on the conventional CSM in which the maximum inelastic displacement of a structure to be retrofitted is estimated using an iterative method requiring analysis of a sequence of equivalent linear systems. In order to reduce the computational effort in evaluating the maximum inelastic displacement the improved CSM is employed in which no iterative computation is needed.

The improved CSM use the locus of performance points to determine the performance point. Corresponding to each point, herein termed ductility point, beyond the yield one on the capacity diagram, the equivalent period of system can be obtained for the given hysteretic damping model based on the principle of equivalent linearization. The intersection of the equivalent period radial line through the origin and the demand diagram determined by equivalent damping plus inherent damping ratio is here referred to as the demand point corresponding to the given ductility point on the capacity diagram. Increasing the value of the ductility, a series of demand points can then be

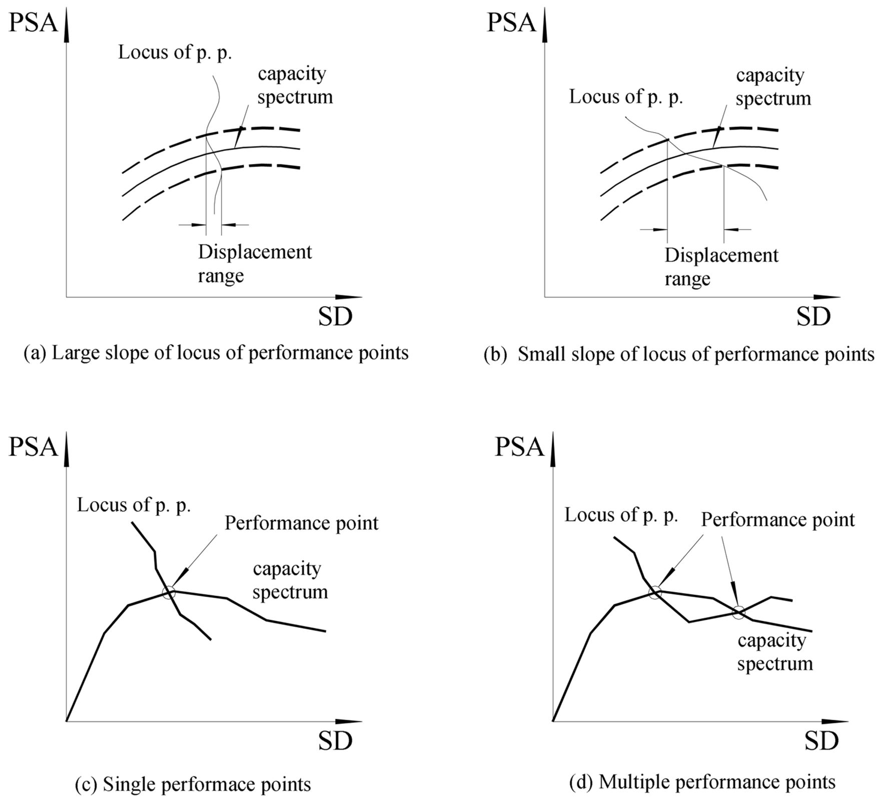


Fig. 2 Possible cases for locus of performance points

gained. The curve generated by connecting together these demand points is termed the locus of performance points (Guyader and Iwan 2004) The performance point is located at the intersection of the locus of performance points and the capacity diagram as shown in Fig. 2.

The improved CSM is a graphical solution procedure and can be used to perform the sensitivity analysis of the displacement prediction. The procedure clearly reveals how variation in both the capacity or demand will affect the location of the performance point. If the strength of capacity diagram were increased or decreased, change in the location of the performance point would occur, which depends on the slope of the locus of performance points near the performance point. Some possible cases of locus of performance points are given in Fig. 2. Fig. 2(a) shows a case where locus is nearly 90 degrees. In this case, raising or lowering the capacity diagram has very little effect on the performance point displacement. This displacement range is very small. However, Fig. 2(b) gives a case where the slope of locus is relatively small. So raising or lowering the capacity diagram has significant effect on the performance point displacement and the corresponding displacement range is large.

There may be one, several or zero intersections of the locus of performance points and capacity diagram. Extending locus beyond the first intersection will reveal if multiple intersection points exist as seen in Fig. 2(d). Serious attention should be paid to multiple performance points cases. A conservative approach is to use the performance point at the largest displacement.

The conventional iterative method for obtaining the performance point is laborious and may leads to the divergence of solution in some cases or the erroneous solution, although converged, in other cases (Chopra and Goel 2000). When using locus of performance points to evaluate performance points, the above case can be precluded, and additionally possible multiple performance points can be identified.

3. Analysis of inelastic SDOF system with supplemental dampers

This section will illustrate how to use the simplified method, in conjunction with Chinese design response spectrum (Ministry of Construction 2001) and the response spectrum of recorded ground motions, to evaluate the amount of supplemental damping required for the structure to meet a given performance objective.

3.1 Evaluation of required supplemental damping using design response spectrum

Detailed steps for determination of required added damping using Chinese design response spectrum are given as follows: (1) Set the performance objective for system with supplemental dampers. (2) Plot the elastic demand diagram with 5% damping ratio in A-D format for the given spectral acceleration, $\alpha_{\max}$, which is equal to S_a/g, and the characteristic period of the site considered. The yield displacement can be obtained by dividing the elastic demand displacement by strength reduction factor. Plot the capacity diagram in the same A-D format. (3) Compute the equivalent damping ratio at the specified ductility points on the capacity diagram. The intersection of equivalent elastic demand curve determined by the effective damping with the equivalent period radial line from the origin is here defined as the equivalent elastic demand point corresponding to the equivalent period. The locus of performance points is then developed by connecting together these demand points. (4) If the equivalent elastic demand point on the i^{th} equivalent period line is above (below) its capacity point, and the demand point on the next equivalent period line is below (above) its capacity point, then the performance point is definitely located between the two adjacent capacity points, i.e., evaluate the difference between the spectral demand acceleration and spectral capacity acceleration in i and $(i+1)^{th}$ step, respectively and check their product. If the product is less than zero the performance point exists between the two adjacent demand points. Otherwise the performance point does not exist between the two adjacent points. (5) If the demand displacement at the performance point is greater than the target one, go to the next step. Otherwise there is no need for seismic retrofit. (7) According to the spectral reduction factor of η_2, the equivalent period of T_{eq}, the characteristic period, T_g, of the site considered and spectral acceleration of $\alpha_{\max}$ in the horizontal direction, the required effective damping ratio can be computed where the demand diagram intersects with the capacity diagram at the target displacement. (8) Evaluate ζ_v from the Eq. (7).

The design response spectrum with the parameters of $\alpha_{\max} = 0.9$ and $T_g = 0.35$ sec, and the system with $T_e = 0.5$ sec, $R = 3$, $\alpha = 0.05$, and $n = 0$ were selected as an example, where R equals to the ratio of elastic demand strength to yield strength. Table 1 and Table 2 describe the detailed process for identifying the performance point and evaluating the required supplemental damping, respectively. The graphical demonstrations can be seen in Fig. 3 and Fig. 4.

The target displacement was set to be 80% of the demand displacement at the performance point. The mass was kept constant of a unit value and the inherent damping ratio was assumed as 5%.

Table 1 Evaluation of performance point for system without added damping using locus of performance points

Capacity spectrum					Elastic demand spectrum			Check for existence of solution
Step No.	Capacity ductility	Effective damping	Structural capacity point		Response demand point		Demand ductility	
i	μ_c	$(\zeta_i + \zeta_{eq})$ (%)	D_c (mm)	A_c (m/sec^2)	D_D (mm)	A_D (m/sec^2)	μ_d	$P(i+1)$ $i = 1, \ldots$
1	1.00	5.00	13.5	2.13	40.6	6.40	3.00	
2	2.00	20.1	27.0	2.24	38.6	3.20	2.86	4.10
3	3.00	25.2	**40.5**	**2.35**	**45.6**	**2.64**	3.38	0.28
4	4.00	27.7	**54.0**	**2.46**	**51.9**	**2.35**	3.84	**−0.03**
5	5.00	29.2	67.5	2.56	57.3	2.17	4.24	0.04
6	6.00	30.2	81.0	2.67	62.2	2.04	4.61	0.24
Performance point of system without added damping								
3, 4	3.72	27.1	50.3	2.42	50.3	2.42	3.72	

Note: (D_C, A_C) and (D_D, A_D) are the coordinates of capacity point and demand point in A-D format, respectively $P(i+1)$ is equal to $(A_D(i+1) - A_C(i+1))(A_D(i) - A_C(i))$

Table 2 Estimation of supplemental damping required to meet target displacement

Target displacement	Target ductility	Equivalent damping	Inherent damping	Effective damping	Supplemental damping
D_{TAR} (mm)	μ_{TAR}	ζ_{eq} (%)	ζ_i (%)	ζ_{eff} (%)	ζ_v (%)
40.2	2.98	20.8	5	50.7	15.6

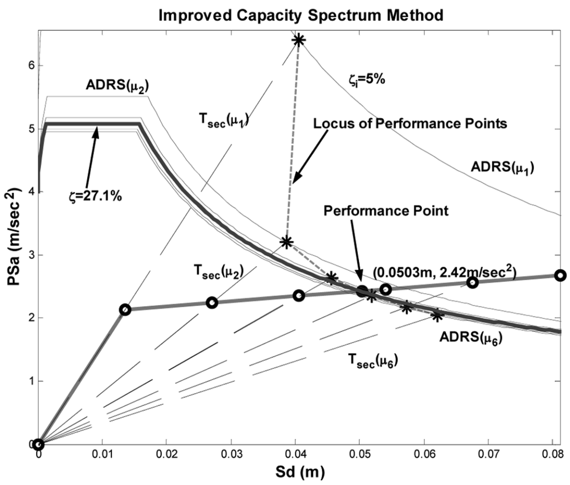


Fig. 3 Evaluation of performance point for system without added damping using locus of performance points

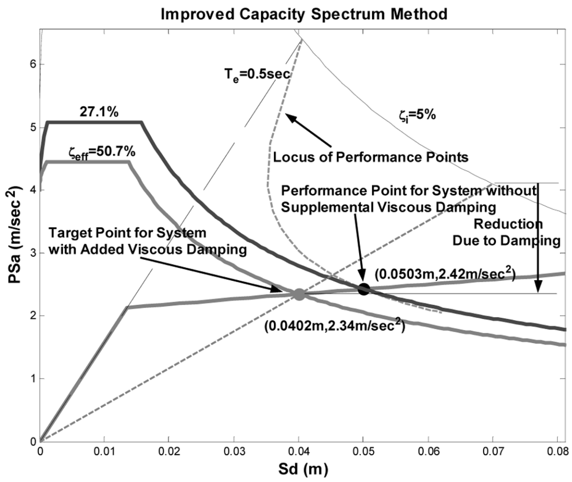


Fig. 4 Estimation of added damping for system based on improved capacity spectrum method

3.2 Evaluation of required supplemental damping employing response spectra for recorded ground motions

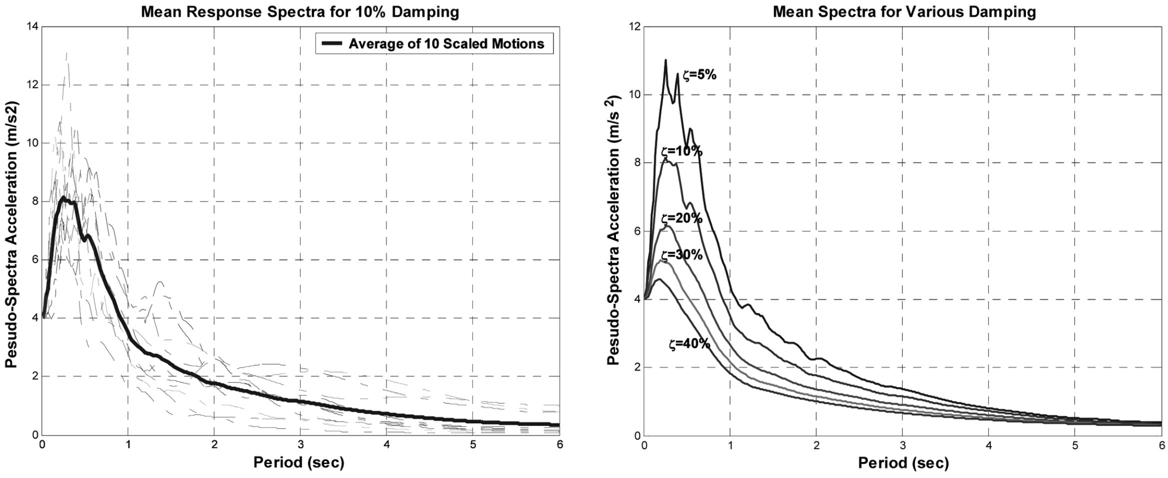
To obtain more generalized results the mean response spectra constructed from 10 horizontal earthquake records were used in the evaluation of required supplemental damping. The target displacement of a structure added with dampers was assumed to be 60% of the demand displacement of the corresponding structure without dampers. The supplemental damping needed to limit the structural response within the target displacement was estimated using Eq. (7). Finally the maximum response of the structure installed with the supplemental dampers was obtained by nonlinear dynamic analysis and the result was compared with the target value to verify the accuracy of the proposed method.

3.2.1 Model considered

The system with the following design parameters was analyzed: (1) elastic period: $T_e = 0.4$ sec; (2) strength reduction factor: $R = 4$; (3) postyield stiffness ratio: $\alpha = 0.05$; (4) unloading stiffness ratio: $n = 0$; (5) mass: $m = 1$ and inherent damping ratio: $\zeta_i = 5\%$.

3.2.2 Input ground motions

The 10 famous earthquake ground motions recorded on the site of class II and III class were taken for dynamic analysis. The selected ground motions consisted of 5 earthquake events with each one including the north-south component and the west-east component. These earthquake records are listed as follows: El centro (1940), Qian an (1976), Tang shan-Bei jing Hotel (1976), Chi-Chi (1999), and Northridge (1994). The records were scaled in such a way that the frequency content of each record was preserved and an equal contribution of these records to the mean spectrum was ensured. The detailed process of scaling can be found in the (FEMA-274 1997), Chopra and Goel 2000). The peak acceleration of these records were scaled up to 400 gal prescribed by the code for nonlinear dynamic response analysis (Ministry of Construction 2001), in the case of the rare



(a) Response spectra for 10% damping (b) Mean spectra for various damping

Fig. 5 Response spectra for the 10 earthquake records

earthquake event corresponding to the seismic fortification of intensity of 8 degrees. Fig. 5(a) shows the 10% damped response spectra for 10 scaled motions as well as their mean response spectra. Fig. 5(b) presents a family of mean response spectrum for various damping ratios, which were later converted to the A-D format together with capacity diagram to obtain the performance point.

3.2.3 Analysis of model

The procedure for obtaining the required damping ratio was the same as that presented in section 3.1, except that the design spectrum was replaced by the mean demand spectrum of recorded ground motions. For verification of the results obtained from the simplified method 10 nonlinear

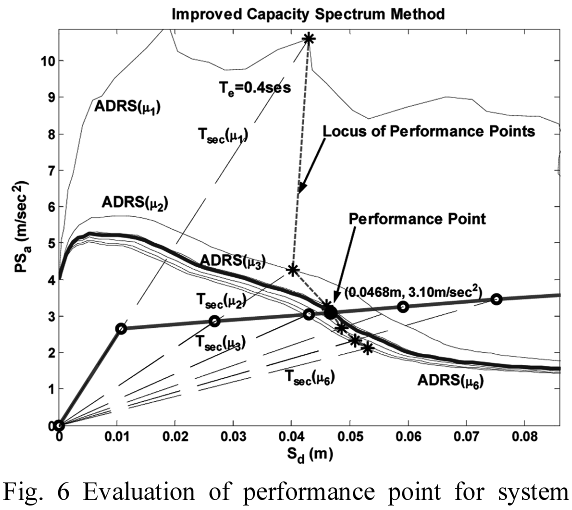


Fig. 6 Evaluation of performance point for system without added damping using locus of performance points with mean response spectra

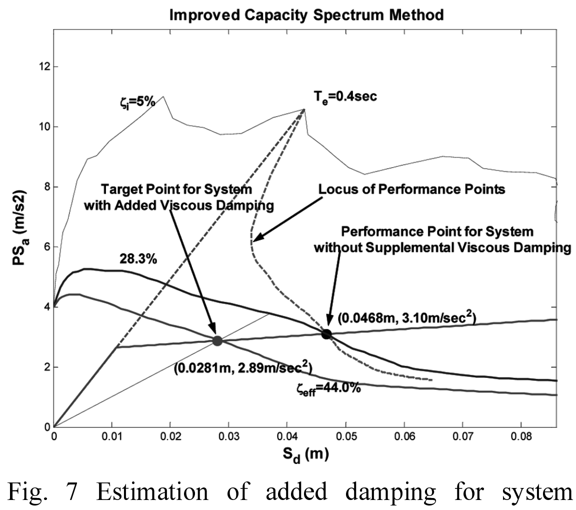


Fig. 7 Estimation of added damping for system based on improved capacity spectrum method with mean response spectra

Table 3 Evaluation of performance point for system without added damping using locus of performance points

Capacity spectrum					Mean demand spectra for 10 records			Check for existence of solution
Step No.	Capacity ductility	Effective damping	Structural capacity ductility		Response demand point		Demand ductility	
i	μ_c	$(\zeta_i+\zeta_{eq})$ (%)	D_c (mm)	A_c (m/sec^2)	D_D (mm)	A_D (m/sec^2)	μ_d	$P(i+1)$ $(i=1,\ldots)$
1	1.00	5.00	10.7	2.65	43.0	10.6	4.02	
2	1.50	15.1	26.8	2.85	40.2	4.26	3.76	11.2
3	3.00	25.2	**43.0**	**3.05**	**46.0**	**3.26**	4.30	0.30
4	4.50	28.5	**59.1**	**3.25**	**48.6**	**2.67**	4.54	**−0.12**
5	6.00	30.2	75.2	3.44	50.9	2.33	4.76	0.64
6	7.50	31.2	91.3	3.64	53.0	2.12	4.95	1.69
Performance point of system without added damping								
3, 4	4.35	28.3	46.8	3.10	46.8	3.10	4.35	

Note: (D_C, A_C) and (D_D, A_D) are the coordinates of capacity point and demand point in A-D format, respectively; $P(i+1)$ is equal to $(A_D(i+1)-A_C(i+1))(A_D(i)-A_C(i))$

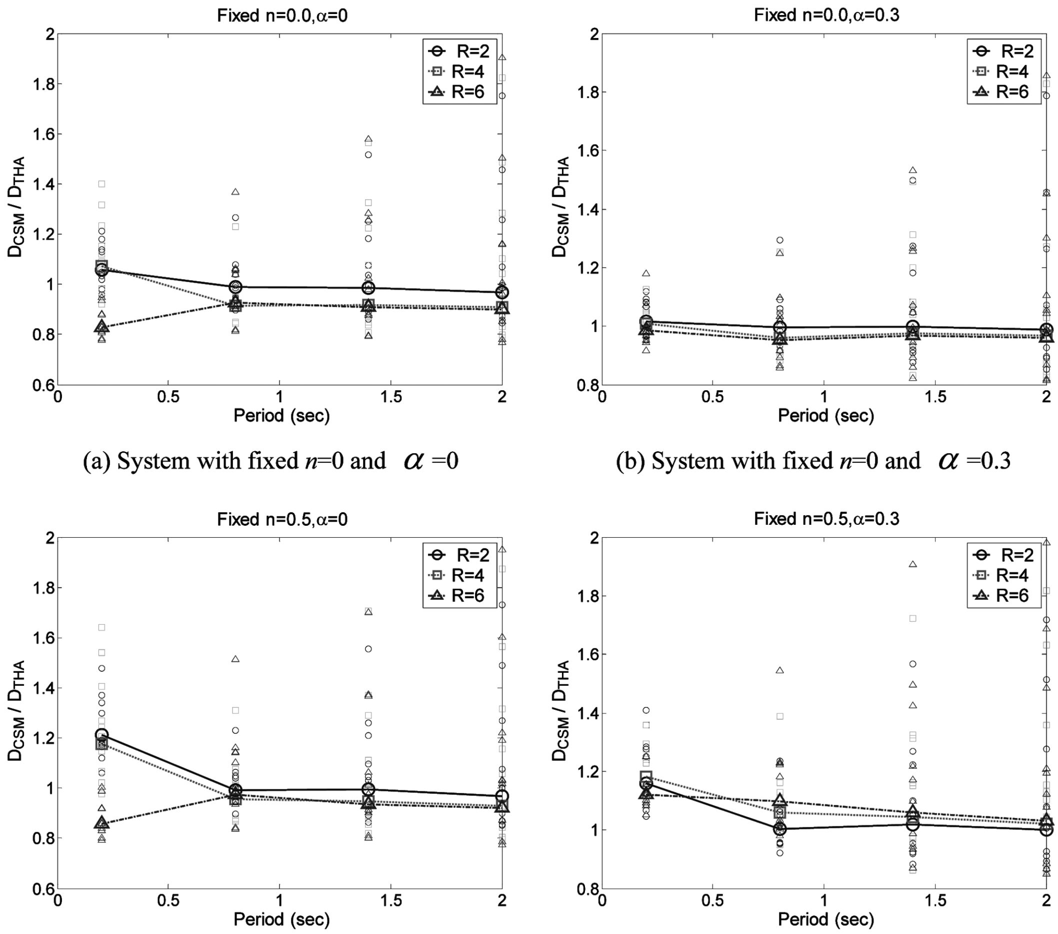
Table 4 Estimation of supplemental damping required to meet target displacement

Target displacement	Target ductility	Equivalent damping	Inherent damping	Effective damping	Supplemental damping	Total equivalent viscous damping	Mean value for THA	Comparison
D_{TAR} (mm)	μ_{TAR}	ζ_{eq} (%)	ζ_i (%)	ζ_{eff} (%)	ζ_v (%)	$(\zeta_i+\zeta_v)$ (%)	$\overline{D}_{THA}$ (mm)	$D_{TAR}/\overline{D}_{THA}$
28.1	2.63	18.7	5	44	13.1	18.1	30.0	0.94

dynamic analysis were performed on the system with the supplemental damping plus the inherent damping. The process of identifying the performance point and computing the required damping are described in Table 3 and Table 4, respectively. Graphical illustrations are given in Fig. 6 and Fig. 7. As seen from the last column in the Table 4, the result derived from the proposed method matches well with that obtained from nonlinear dynamic analysis in a statistical sense.

4. Parametric study

Structural systems with different properties, such as natural period of T, strength reduction factor of R, unloading stiffness factor of n, and post-yield stiffness ratio of α, will be analyzed and compared with nonlinear dynamic analysis results to the examine the influence of the properties of a structure on the accuracy of the proposed method. In models analyzed unloading stiffness factors of 0.0 (no stiffness degradation on unloading) and 0.5 (severe stiffness degradation on unloading) and post-yield stiffness ratios of 0.05 and 0.3 are selected, leading to four analysis cases for investigation of influence of the strength reduction factors of $R=2$, 4, and 6 and natural periods of 0.2, 0.8, 1.4, and 2.0 sec on the validity of the presented method. Each model is analyzed using 10 scaled ground motion records mentioned above and then the mean of displacement responses is



(a) System with fixed n=0 and α =0 (b) System with fixed n=0 and α =0.3

(c) System with fixed n=0.5 and α =0 (d) System with fixed n=0.5 and α =0.3

Fig. 8 Ratio of displacement obtained from nonlinear static analysis and nonlinear dynamic analysis

compared with that obtained by the proposed method. Fig. 8(a) to (d) are the plots of ratios of target displacement determined from the proposed method to the mean of nonlinear dynamic analysis results as a function of T for different strength reduction factor of R for a fixed n and α, along with all dynamic analysis results marked with circular, rectangular and triangular markers at the selected period values for R = 2, 4, and 6, respectively.

As observed from Fig. 8(a) through (d) the accuracy of the proposed method increases with decreasing R and it tends to underestimate the response of the damped system with decreasing T. For short period systems ($T < 0.4$) the presented method can lead to overestimations of their displacement responses for the smaller R and underestimations of that for the larger R, especially for the case of $n = 0.5$. For a fixed n, the accuracy of the proposed method increases with increasing α. In contrast, for a fixed α, the presented method tends to overestimate the displacement response with increasing n, which is possibly due to the fact that selecting the smaller n and/or α for systems would be lead to overestimations of their hysteretic energy dissipation capacity and thus result in underestimations of their displacement response when using the improved CSM. The degree of accuracy of the proposed method is found to be good for system with period ranging from 0.4 to 2.0 sec, particularly for the case of the fixed $n = 0$ and $\alpha = 0.3$. Furthermore, it can be found that the dynamic analysis results of the models analyzed vary widely for system with the larger period, say $T = 2$ sec.

Thus it is concluded that by observation above that the proposed method has good accuracy and hence may lead to conservative results for system with the larger n and/or α in the region of period from 0.4 to 2 sec. However, unconservative results may be obtained using the proposed method to estimate the displacement of the damped system with $R > 4$ and/or $T < 0.5$ sec.

5. Conclusions

In this paper a simplified procedure was presented using improved CSM to determine the amount of supplemental damping required to meet a given performance objective. The equivalent damping ratio was computed employing Kowalsky hysteretic model, performance point was determined using the locus of performance points, and the supplemental damping was evaluated by the simplified method. The proposed procedure have two advantages over the traditional one: (1) the graphical performance point solution procedure is a simple, straightforward, and non-iterative, and additionally can identify the possible multiple performance points; (2) the supplemental damping required to satisfy a given performance objective is evaluated through a single step without iteration. The proposed procedure has been applied to SDOF system and can also be extended to MDOF system for determination of the total amount of supplemental damping required to meet a given performance objective.

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