

JSSI MANUAL FOR BUILDING PASSIVE CONTROL TECHNOLOGY PART-8 PEAK RESPONSE EVALUATION AND DESIGN FOR ELASTO-PLASTICALLY DAMPED SYSTEM

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SUMMARY

In recent years passively-controlled building structures by incorporating elasto-plastic (EP) dampers have become common in Japan. This paper discusses a simplified theory for peak response evaluation method and design approach for elasto-plastically damped building in preliminary seismic design. The proposed theory is based on the single-degree-of-freedom (SDOF) idealization of multi-story building structure, and uses the so-called "control performance curve" which simultaneously expresses the seismic performance as a function of stiffness parameter, ductility demand and seismic response spectrum. A rule to convert a SDOF design to a multi-story design including the arrangement of damper stiffness over the height of building is also presented. The accuracy of this design approach is validated via time history simulations over a wide range of MDOF models.

INTRODUCTION

Background

In recent years passively-controlled building structures by incorporating various energy dissipation devices (dampers) have become common in Japan. In particular, the use of elasto-plastic (EP) dampers, such as buckling-restrained brace, for passively-controlled building have gained widespread practical applications. The EP dampers substantially reduce story drift and member force by adding hysteretic damping and stiffness to the primary structure (frame) under earthquake excitation. In preliminary seismic design, however, lack of comprehension of the relationship among response reduction, amount of damper and seismic ground motion induces an irrational approach, which requires numerous time history simulations.

Objectives and Scope

Objectives of this paper are to propose a simplified theory for peak response evaluation method and design approach for elasto-plastically damped building in preliminary seismic design, and to verify the accuracy of this method. The proposed theory employs the SDOF model idealization of multi-story building structure and equivalent linearization technique. A rule to convert a SDOF design to a multi-story design including the arrangement of damper stiffness over the height of building is also

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presented. The accuracy of this design approach is validated via time history simulations over a wide range of MDOF models. Basic part of this paper is adopted in "JSSI manual for design and construction of passively-controlled buildings" [1].

DYNAMIC CHARACTERISTICS OF SDOF EP SYSTEM

Damper and System

To fully comprehend the dynamic characteristics of the multi-story building structures with EP dampers, consider the idealized SDOF model of EP system as shown in Figure 1. SDOF model of EP system consists of a mass and two springs which show EP damper and frame connected in a row to the mass. EP damper is modeled as elasto-perfectly-plastic with elastic stiffness K_d and ductility demand μ_d , whereas frame behaves linearly with elastic stiffness K_f (Figure 2(a),(b)). Fundamental vibration period and damping ratio of frame are defined as T_f and h_0 . Elastic stiffness K_0 , fundamental vibration period T_0 and ductility demand μ of the EP system are given by Eq. 1(a)-(c).

$$K_0 = K_f + K_d, \quad T_0 = \sqrt{\frac{K_f}{K_0}} \cdot T_f, \quad \mu = \mu_d$$
(1a-c)

Equivalent linear (secant) stiffness of EP system K_{eq} is

$$K_{eq} = K_f + \frac{K_d}{\mu} = \frac{1 + p(\mu - 1)}{\mu} \cdot K_0, \quad p = \frac{K_f}{K_f + K_d}$$
(2a,b)

where p =ratio of post-yield stiffness to elastic stiffness of the system.







Equivalent Period and Equivalent Damping Ratio of System

According to Eq. 2(a), the equivalent vibration period
$$T_{eq}$$
 of the EP system is

$$T_{eq} = \sqrt{\frac{K_f}{K_{eq}}} \cdot T_f = \sqrt{\frac{p\mu}{1+p(\mu-1)}} \cdot T_f$$
(3)

The damping ratio of the EP system at ductility demand μ ' can be evaluated as the energy dissipated per cycle divided by 4π times the elastic strain energy obtained from secant stiffness. We define the equivalent damping ratio h_{eq} of the system as the average of the damping ratio corresponding to ductility demand μ ', considering the randomness of earthquake motion as shown in the work by Kasai et al [2].

$$h_{eq} = h_0 + \frac{1}{\mu} \int_1^{\mu} \frac{2(1-p)(\mu'-1)}{\pi [1+p(\mu'-1)]} d\mu' = h_0 + \frac{2}{\mu \pi p} \ln \left[\frac{1+p(\mu-1)}{\mu^p} \right]$$
(4)

SYMPLIFIED RESPONSE EVALUATION FOR SDOF EP SYSTEM

Response Reduction Factor of Displacement and Acceleration

Peak response of the EP system will be obtained from a linear response spectrum using T_{eq} and h_{eq} indicated above. We define S_d , S_{pv} , and S_{pa} as response displacement, response pseudo velocity and response pseudo acceleration spectra, respectively. For the frame, their values are obtained from an expected seismic response spectrum, T_f and h_0 . With the response of frame, peak response of the EP system is expressed by considering following two effects due to inserting the damper.

- 1. The effect of vibration period change (from T_f to T_{eq}) generally reduces response displacement and increases response acceleration.
- 2. The effect of hysteretic damping increase (from h_0 to h_{eq}) reduces both response displacement and response acceleration. This effect is represented by damped effect factor D_h , which is an "average" reduction of S_d , S_{pv} , and S_{pa} (Eq. 5).

$$D_h = \sqrt{\frac{1 + \alpha h_0}{1 + \alpha h_{eq}}} \tag{5}$$

where $\alpha = 25$ (for an ensemble of 31 observed earthquakes from 0.2 to 3 sec of vibration period (Kasai et al. [3])). Peak responses of the EP system S_d (T_{eq} , h_{eq}) and S_{pa} (T_{eq} , h_{eq}) normalized to those of the frame S_d (T_f , h_0) and S_{pa} (T_f , h_0) are defined as displacement reduction R_d and pseudo acceleration reduction R_{pa} (for the EP system acceleration reduction $R_a = R_{pa}$), respectively. Considered the two effects indicated above, also S_{pv} will be assumed to be period-independent as often assumed for a medium-long period structure. They are given as

$$R_d = D_h \cdot \frac{T_{eq}}{T_f}, \quad R_a = D_h \cdot \frac{T_f}{T_{eq}}$$
(6a,b)

Also, for a short period structure, S_{pa} will be assumed to be period-independent, R_d and R_a are given as

$$R_d = D_h \cdot \frac{T_{eq}}{T_f} \cdot \frac{T_{eq} + T_0}{2T_f}, \quad R_a = D_h \cdot \frac{T_f}{T_{eq}} \cdot \frac{T_{eq} + T_0}{2T_f}$$
(7a,b)

Control Performance Curve

The previous equations can clarify the complex interactive effects of stiffness parameter, ductility demand, vibration period, damping and seismic response spectrum on the response reduction of the EP system. Figure 3 shows the curves for drift reduction R_d and acceleration (base shear) reduction R_a of SDOF EP system under a period-independent S_{pv} , and S_{pa} , respectively. The initial damping ratio of frame is $h_0 = 0.02$.

The control performance curves for EP system depend strongly on two parameters: damper stiffness ratio K_d / K_f and ductility demand μ . In Figure 3, the point $K_d / K_f = 0$ gives the frame response $R_d = R_a = 1$. In case of independent-period S_{pv} , to a point, larger K_d / K_f (stiffer damper) leads to smaller drift (R_d) and force (R_a) (Figure 3(a)). Thereafter, the drift continues to decrease, but base shear increases sharply.

Also, larger μ (lower yield strength) leads to smaller drift (R_d) and force (R_a). In case of independent-period S_{pa} , larger K_d / K_f and μ lead to smaller drift (R_d) and force (R_a) (Figure 3(b)). As indicated above, the control performance curve clearly shows the trade-off between drift and base shear, and can provide readily the design solution to satisfy the desired response.





DESIGN OF MDOF EP SYSTEM

Design Conditions of MDOF Frames

Three types of frame are considered: standard type (S-Type), upper-deformed type (U-Type) and lower-deformed type (L-Type). The frames have three different heights: 3, 12, and 24-story. Member stiffness of the frames will be reduced due to incorporating the dampers, fundamental vibration period of them are $T_f = 0.040H$ (for 12 and 24-story), 0.052H (for 3-story) as shown in Table 1. *H* represents the total height of building, mass and story height are identical for every story: $m_i = 1.2 \text{ kN} \cdot \text{sec}^2/\text{cm}$ and $h_i = 4.2\text{m}$, respectively. The initial damping ratio of frame is $h_0 = 0.02$.

Consider 12-story frames for example, three types of frame stiffness distribution are shown in Figure 4(a). As Figure 4(b) shows, the frame stiffness K_{fi} at *i*th-story of S-Type is designed such that story drift becomes uniform under the A_i lateral force distribution (Architectural Institute of Japan [4]). In U-Type frame, story drift at upper stories increases, whereas in L-Type frame, story drift at lower stories increases. As mentioned above, story stiffness distributions of frames are obtained such that fundamental vibration period of them are $T_f = 2.00$ sec.

Table 1FundamentalVibration Period of the 3, 12and 24-story frames

	3-story	12-story	24-story	
T _f (sec)	0.65	2.00	4.00	
H (m)	12.6	50.4	100.8	
T _f /H	0.052	0.040	0.040	



Figure 4 Story Stiffness Distributions and Story Drift Distributions for 3 Types of 12-Story Frame

SDOF Idealization of MDOF Frames

The peak responses S_d , S_{pv} , and S_{pa} of SDOF idealized multi-story frame without damper are obtained from the seismic response spectrum, T_f and h_0 . With these response values, displacement u_0 and base shear F_0 of the SDOF frame are given by Eq. 8.

$$u_0 = S_d(T_f, h_0), \quad F_0 = M_{eq} \cdot S_{pa}(T_f, h_0)$$
(8a,b)

where
$$M_{eq} = \left(\sum_{i=1}^{N} m_i \cdot u_{0i}\right)^2 / \sum_{i=1}^{N} (m_i \cdot u_{0i}^2)$$
 (9)

where M_{eq} = equivalent mass of 1st mode and u_{0i} = deformation shape of frame, which is assumed to be linear over the height of building regardless of frame type, because desired drift angle distribution of EP system is uniform. Considered that u_0 is displacement of the MDOF frame without damper at equivalent height of 1st mode H_{eq} , drift angle of the SDOF frame θ_f is given by Eq. 10(a).

$$\theta_{f} = \frac{u_{0}}{H_{eq}}, \quad H_{eq} = \sum_{i=1}^{N} (m_{i} \cdot u_{0i} \cdot H_{i}) / \sum_{i=1}^{N} (m_{i} \cdot u_{0i})$$
(10a,b)

where H_i = height at *i*th-story level.

SDOF EP System Design

For the MDOF frames designed above, SDOF EP systems are designed to meet the performance criteria: three yield strength levels of damper corresponding to SDOF EP system ductility demands $\mu = 2$, 4, and 8, and three target drift angles $\theta_{max} = 1/200$, 1/150 and 1/125. In evaluating response and designing for each frame, BCJ-L2 artificial ground motion (The Building Center of Japan [5]) is used.

Firstly, θ_f is obtained from response spectrum of BCJ-L2 and Eq.8 - Eq.10 as mentioned above, the target displacement reduction factor R_d for each frame is given as Eq. 11.

$$R_d = \frac{\theta_{max}}{\theta_f} \tag{11}$$

Secondly, determine the damper stiffness ratio K_d / K_f at the ductility demand μ to meet the target displacement reduction factor R_d . From response spectrum of BCJ-L2 ($h_0 = 0.02$) shown in Figure5, S_{pv} will be assumed to be period-independent in the range greater than 0.7 sec, S_{pa} will be also assumed to be period-independent in the range greater than 0.7 sec, S_{pa} will be also assumed to be period-independent in the range greater than 0.7 sec, S_{pa} will be also assumed to be period- independent in the range of shorter vibration period. Therefore, displacement reduction factors R_d for the SDOF EP system in 12 and 24-story design are obtained by Eq. 6, those of 3-story designs are also obtained by Eq. 7. It is clarified that damped effect factor D_h of BCJ-L2 artificial ground motion is much lower than an ensemble of 31 observed earthquakes [3]. In this case, substitute $\alpha = 75$ (BCJ-L2 artificial ground motion) for Eq. 5.

Considering the indicated above, damper stiffness ratio K_d / K_f to satisfy the target displacement reduction factor R_d for each frame and target drift angle can be obtained.



Figure 5 Response Spectrum of BCJ-L2 ($h_0=0.02$) (a) S_{pv} and (b) S_{pa}

Conversion to MDOF EP System Design

Considering both the change of equivalent stiffness of system K_{eqi} due to yielding of damper under the earthquake excitation and the story stiffness distribution of original frame, a rule to arrange the damper stiffness K_{di} at *i*th-story is proposed by Eq. 15 (Ito et al. [6]). The following constraints are used for the conversion:

- 1. The equivalent damping, which is ratio of total energy dissipated by damper per cycle divided by 4π times total elastic strain energy obtained from the system secant stiffness, for MDOF EP system becomes the same as that of SDOF EP system.
- 2. Under the design shear force, the distributions of drift angle and ductility demand of MDOF EP system become uniform, although those of the frame without damper may be non-uniform.
- 3. Yield drift angle for each story is uniform.

Then, constraint 1 gives

$$\sum_{i=1}^{N} \left[K_{di} \cdot (\mu_{i} - 1) \cdot (\theta_{i} \cdot h_{i} / \mu_{i})^{2} \right] / \sum_{i=1}^{N} \left[(K_{fi} + K_{di} / \mu_{i}) \cdot \theta_{i}^{2} \cdot h_{i}^{2} \right] = K_{d} \cdot (\mu - 1) / \left[(K_{f} + K_{d} / \mu) \cdot \mu^{2} \right]$$
(12)

With constraint 2: drift angle θ_i and ductility demand μ_i at *i*th-story are $\theta_i = \theta$, $\mu_i = \mu$, respectively, Eq. 12 is revised by Eq. 13.

$$\frac{K_d}{K_f} = \sum_{i=1}^{N} (K_{di} \cdot h_i^2) / \sum_{i=1}^{N} (K_{fi} \cdot h_i^2)$$
(13)

where K_d / K_f = damper stiffness ratio obtained from SDOF EP system. Constraint 3 is obviously a necessary and sufficient condition for constraint 2. Also, shear drift angle is a quotient of story shear and stiffness and story height. Thus, from constraint 2

$$Q_{i} \cdot h_{i} / [(K_{di} / \mu + K_{fi}) \cdot h_{i}^{2}] = \sum_{i=1}^{N} (Q_{i} \cdot h_{i}) / \sum_{i=1}^{N} (K_{di} \cdot h_{i}^{2} / \mu + K_{fi} \cdot h_{i}^{2})$$
(14)

where Q_i = the design shear force based on A_i distribution coefficient. Substituting Eq. 13 in Eq. 14, Eq. 15 is obtained.

$$[1 + (K_{di}/\mu)/K_{fi}]/[1 + (K_{d}/\mu)/K_{f}] = \left[Q_{i} \cdot \sum_{i=1}^{N} (K_{fi} \cdot h_{i}^{2})\right] / \left[K_{fi} \cdot h_{i} \cdot \sum_{i=1}^{N} (Q_{i} \cdot h_{i})\right]$$
(15)

where $K_{di} / \mu = K_{deqi}$: equivalent stiffness of damper at *i*th-story corresponding to μ . For the frame with uniform story height as considered in this study, Eq. 15 indicates that the equivalent stiffness of system K_{eqi} at *i*th-story is proportionate to the design shear force Q_i . Consider the condition: 12-story, $\theta_{max} = 1/150$ and $\mu = 4$ for example, distributions of equivalent stiffness of damper K_{deqi} and system K_{eqi} by using the rule mentioned above are shown in Figure 6. As the frame stiffness distribution K_{fi} of S-Type is proportionate to Q_i , the ratio of equivalent stiffness of damper to frame stiffness at *i*th-story K_{deqi} / K_{fi} evidently becomes uniform value over the height of building. In both U-Type and L-Type frame, K_{deqi} / K_{fi} becomes high value at the story expected large drift of frame without damper. Whereas, no damper is inserted in the first story for U-Type, and in the top three stories for L-Type.



Figure 6 Equivalent Stiffness Distributions of Damper and System for 3 Types of 12-Story Frame $(\theta_{max} = 1/150, \mu = 4)$

Also, the yield story drift Δu_{yi} and damper force F_{dyi} at *i*th-story are given by Eq. 16.

$$\Delta u_{yi} = \frac{\theta_{max} \cdot h_i}{\mu}, \quad F_{dyi} = K_{di} \cdot \Delta u_{yi}$$
(16a,b)

NUMERICAL RESULTS

Time history simulations were carried out for 81 MDOF EP systems designed above: 3 types of frame, 3 building heights, 3 ductility demands, and 3 target drift angles. MDOF shear-bar models as shown in Figure 7 are used in dynamic simulations. Consider the condition: 3 types of 12-story frame, $\theta_{max} = 1/150$ and $\mu = 2$, 4, and 8 for example, the peak drift angle obtained from time history simulations under BCJ-L2 artificial ground motion and design target are shown in Figure 8. As you can see Figure 8, simulation results fairly meet the design target due to inserting a sufficient amount of damper. In addition, note that distributions of peak drift angle become uniform regardless of the deformation shape of each frame without damper. Table 2 summarizes the average accuracy of the drift angle for each frame type and building height. "Average" in Table 2 indicates the total average of the ratio of simulation to design target at every story for 9 cases: 3 ductility demands, 3 target drift angles. Compared 3, 12, and 24-story systems, the peak drift angle of the taller building tends to be underestimated. A most likely reason for this issue is that the present approach neglects the contribution of higher modes in evaluating

the story drift of MDOF EP system, considering first mode alone is slightly inadequate for 24-story systems.



Figure 7 Shear-bar Model

 $(\theta_{max} = 1/150, \mu = 2, 4 \text{ and } 8, \text{ under BCJ-L2 Ground Motion})$

Table 2Average Accuracy of Drift Angle

	3-Story			12-Story			24-Story		
	S-Type	U-Type	L-Type	S-Type	U-Type	L-Type	S-Type	U-Type	L-Type
AVG.	0.890	0.909	0.864	1.102	1.177	0.998	1.229	1.190	1.074
STD.	(0.102)	(0.145)	(0.112)	(0.105)	(0.167)	(0.150)	(0.176)	(0.196)	(0.235)

As a whole, the proposed response evaluation method based on SDOF can provide a good estimation for response of MDOF EP system in preliminary seismic design. It demonstrates that the simple rule to arrange the damper stiffness shown in Eq. 15 can produce the uniform distribution of peak story drift under earthquake excitation.

DESIGN PROCEDURE FOR ELASTO-PLASTICALLY DAMPED STRUCTURES

Characteristics of frame: fundamental vibration period T_{f_i} , initial damping h_0 , story stiffness distribution K_{f_i} , mass distribution m_i , and story height h_i and performance criteria: ductility demand μ , and target drift angle θ_{max} and design response spectrum are all given, design procedure for elasto-plastically damped structure is summarized in sequence of steps below:

- 1. Obtain the drift angle θ_f and base shear F_0 of SDOF frame without damper from design response spectrum, by evaluating the equivalent height H_{eq} and equivalent mass M_{eq} by Eq. 8 Eq.10.
- 2. Calculate the target displacement reduction factor R_d by Eq. 11.
- 3. Determine the damper stiffness ratio K_d / K_f at the ductility demand μ to meet the displacement reduction factor R_d by using the control performance curve.
- 4. Arrange the damper stiffness K_{di} at *i*th-story by Eq. 15.
- 5. Calculate the yield story drift Δu_{yi} and damper force F_{dyi} at *i*th-story by Eq. 16.
- 6. Determine the details of each EP damper as shown in the JSSI manual [1].

CONCLUSIONS

This research is aimed toward developing the peak response evaluation method and design approach for elasto-plastically damped structure in preliminary seismic design. The proposed method is based on the SDOF idealization of multi-story building structure, equivalent linearization technique and a rule to convert a SDOF design to a multi-story design. The evaluation of the accuracy of this method for 81 MDOF EP systems has led to the following conclusions:

- 1. The proposed response evaluation method based on SDOF can provide a good estimation for response of MDOF EP system in preliminary seismic design. Design by this approach fairly meets the performance criteria: target drift angle and ductility demand.
- 2. It demonstrates that the proposed rule to arrange the damper stiffness over the height of building can produce the uniform distribution of peak story drift under earthquake excitation.

The proposed approach neglects the contributions of higher modes in evaluating the response of MDOF EP system, considering first mode alone is slightly inadequate for tall buildings such as 24-story systems. To be further improved, the design approach including a sufficient number of modes in evaluating the drift angle is in progress.

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