A SIMPLIFIED PROCEDURE TO ESTIMATE SEISMIC PERFORMANCE OF BUILDING EQUIPPED WITH OIL DAMPERS

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Abstract

This study introduces a modified capacity spectrum method (CSM) to estimate the seismic performance of passively controlled structure with oil dampers. Conventionally, in CSM, the building performance estimation is carried out in acceleration-displacement response spectrum coordinates. And accordingly, the equivalent viscous damping ratio is calculated from the energy dissipated by the hysteretic behavior of system. Whereas, for a building with oil damper, additional viscous damping generates as the damper piston head moves through a low-viscosity oil inside the damper cylinder with relief mechanism, which leads the bi-linear force-velocity relation. Considering the force-velocity characteristics of the oil damper, a practical method is introduced to estimate the effective damping ratio of the structure. The modified CSM estimates the building performance point in a repetitive process. Firstly, for a certain ductility factor, the performance point is determined from the intersection of the demand curve and the equivalent stiffness line, without considering the contribution of oil damper. Then the effective damping at the performance point is estimated and the demand curve is regenerated to update the performance point. Continuing the same process for different levels of ductility factor, the locus of performance points are adjusted and connected to determine the final performance point. The proposed method is applied to 4- and 10-story steel buildings equipped with oil dampers in each story. Seismic performance of the buildings is estimated accordingly and then compared with non-linear time history analysis. The performance is studied in terms of the maximum story drift and shear force for a couple of scaled earthquake ground motions which are compatible to extremely rare design earthquakes in Japan. It is observed that the proposed CSM scheme provides satisfactory accurate results to assess the nonlinear response of passively controlled buildings with oil dampers.

Keywords: Passive Control Building; Capacity Spectrum Method; Performance Point; Oil Damper.

1. Introduction

The capacity spectrum method (CSM) which was originally developed by Freeman et al in 1975, gradually became a practical tool to evaluate the seismic performance of buildings. And for the first time in 1980, the Applied Technology Council (ATC) used the CSM concept to estimate the correlation between earthquake ground motion and building performance [1]. Later on, the revision of Building Standard Law of Japan adopted a revised Capacity Spectrum Method in 1998 [2]. Since then, many researchers have assessed the accuracy of the method and applied over a wide range of reinforced concrete and steel structures. Consequently, a number of changes have been proposed to improve the application of CSM by considering the building construction technology and new structural elements.

Dissipating the earthquake energy by implementing damping devises along the height of the building is one of the recent technology used frequently to mitigate the earthquake damage. Generally, seismic assessment and design of structure with added damping devices require non-linear time history analysis, which is extremely time-consuming. Couple of straightforward procedures, based on CSM, have been introduced by researchers to make the CSM applicable of passive control buildings.

In this paper, taking into account the force-displacement relationship in CSM and force-velocity relationship of the oil damper, a practical method is introduced to estimate the effective damping ratio of the building with oil damper by iterative way. Firstly, without considering the contribution of oil damper, for a certain ductility factor, the performance point is obtained as a result of intersection of an equivalent stiffness line and the demand curve of input earthquake ground motion. Then, equivalent circular frequency, story drift and story velocity at the performance point are estimated. The amount of hysteresis damping and viscous damping corresponding to the performance point are calculating and the effective damping ratio of the building is estimated. Secondly, the demand curve is regenerated based on the effective damping ratio to update the performance point. Continuing the same process for different levels of ductility factor, the locus of performance points are adjusted and connected to determine the final performance point.

2. Effective Damping Ratio

The effective damping ratio h_{eff} of a passive control building consists of the inherent damping ratio h_0, the hysteresis damping ratio h_e and the viscous damping ratio h_v provided additionally by the oil damper devises. The hysteresis damping ratio is calculated by the amount of hysteresis energy dissipated at the maximum displacement of nonlinear structure. Whereas, the viscous damping ratio is calculated from the energy dissipated by the oil dampers due to the damping force generated as a result of the maximum velocity at the damping devices. The equivalent damping ratio is defined as the ratio of the area of hysteresis loop and the area of potential energy as shown in Fig. 1a. Therefore;

$$h_e(\mu,\omega) = \frac{1}{4\pi}\frac{\Delta W_e}{W} \tag{1}$$

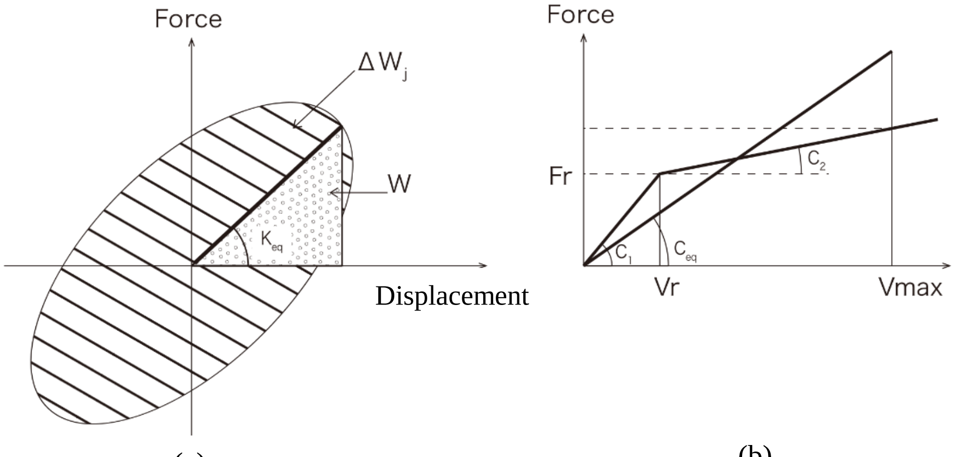
$$h_v(\mu) = \frac{1}{4\pi}\frac{\Delta W_v}{W} \tag{2}$$

where, ΔW_e is the area under one cycle of hysteresis of nonlinear structure given by Eq. (3) for a bilinear hysteresis, ΔW_v is the area of one cycle of force-velocity relation of oil damper given by Eq. (4), and W is the area of elastic strain energy given by Eq. (5), respectively.

$$\Delta W_e = 4\,K\,u_y^2(\mu-1)(1-p) \tag{3}$$

$$\Delta W_v = \pi\,C_{eq}\,\omega\,\mu^2\,u_y^2 \tag{4}$$

$$W = \frac{1}{2}\,K_{eq}(\mu)\,u_y^2\,\mu^2 \tag{5}$$



(a) (b)

Fig. 1 – Energy dissipation mechanism and definition of effective damping
a) the force-displacement relation, b) the force-velocity relation of oil damper

where, K, K_{eq} and p are the initial stiffness, the equivalent stiffness and the ratio of the secondary stiffness to the initial stiffness of the bilinear hysteresis. C_{eq} and ω are the equivalent damping coefficient of oil damper and the circular frequency. u_y and μ are the yield displacement and the ductility factor equal to the ratio of the maximum displacement to the yield displacement.

The equivalent damping coefficient C_{eq} is determined so that the area under equivalent damping coefficient should be equal to the area of bi-linear force-velocity relation of oil damper as shown in Fig. 1b [3] and derived as;

$$C_{eq} = \frac{C_1}{\mu^2} + C_2\left(1-\frac{1}{\mu}\right)^2 + \frac{2C_1}{\mu}\left(1-\frac{1}{\mu}\right) \tag{6}$$

where C_1 and C_2 are the pre-relief and post-relief damping ratio of oil damper. In addition, μ is the ratio of maximum velocity to the relief velocity.

By substituting Eq. (3) and Eq. (5) into Eq. (1), the hysteresis damping ratio can be obtained as

$$h_e = 0.8\,\frac{2}{\pi}\left(1-\frac{1}{\mu}\right)\left(\frac{1-p}{1+p(\mu-1)}\right) \tag{7}$$

In the Eq. (7), 0.8 is the modification factor adopted in the Building Standard Law of Japan[2].

By substituting Eq. (4) and Eq. (5) into Eq. (2), the viscous damping ratio can be obtained as

$$h_v = \frac{1}{2\pi}\,\frac{\pi\,C_{eq}\,\omega\,\mu^2\,u_y^2}{K_{eq}(\mu)\,u_y^2\,\mu^2} = h_{0v}\sqrt{\frac{\mu}{1+p(\mu-1)}}, \qquad h_{0v} = \frac{\omega}{2K}C_{eq} \tag{8}$$

In case that, the oil dampers are arranged in a diagonal scheme with the inclination angle (θ) for a Multi-Degree of Freedom (MDOF) system as illustrated in Fig. 2, the Eq. (4) and Eq. (5) can be reformed as follow;

$$\sum \Delta W_j = \pi \cdot \omega_{eq} \sum C_j\,\phi_{rj}^2 \cos\theta_j^2 \tag{9}$$

$$W = \frac{1}{2}\omega_{eq}^2 \sum m_j\,\phi_j^2 \tag{10}$$

where C_j, ϕ_j, ϕ_{rj}, ω_{eq} and m_j are the damping coefficient of the oil damper, the story drift of the first mode, relative story drift, equivalent circular frequency and mass of j-th floor. Substituting Eq. (9) and Eq. (10) in Eq. (2), the viscous damping ratio of oil damper can be obtained as

$$h_V = \frac{1}{2}\frac{\sum C_j\,\phi_{rj}^2\cos\theta_j^2}{\omega_{eq}\sum m_j\,\phi_j^2} \tag{11}$$

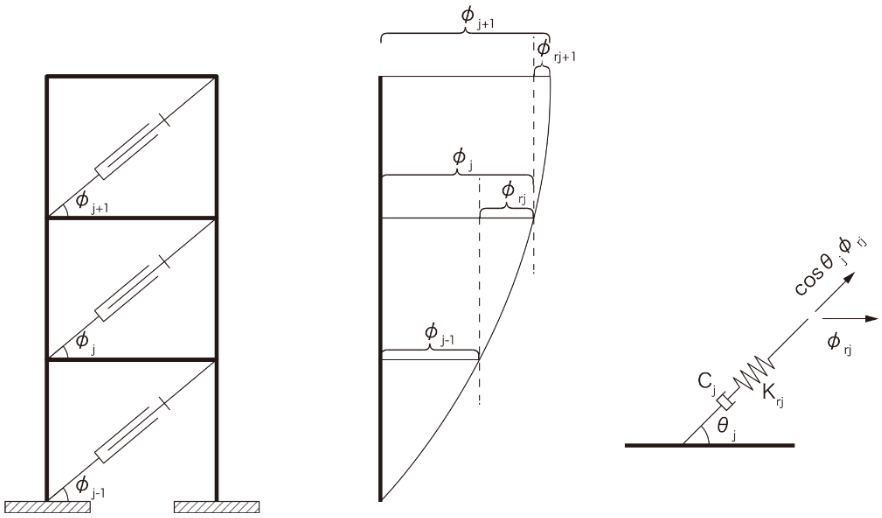


Fig. 2 – Multi Degree of Freedom (MDOF) with oil dampers corresponding to the first mode of vibration

The simple assumption to obtain the effective damping ratio h_{eff} of a passive control building is the direct sum of three types of damping as;

$$h_{eff} = h_0 + h_e + h_v \tag{12}$$

Kasai et al [4] [5] recommend the effective damping for earthquake response to be the average of equivalent damping in the range of (0 to μ) as;

$$h_{eff} = h_0 + \frac{1}{\mu}\int_0^{\mu} h_{eq}(\mu')d\mu' = h_0 + \frac{1}{\mu}\int_0^{\mu}\left(h_e(\mu') + h_v(\mu')\right)d\mu'$$

$$= h_0 + \frac{h_{0v}}{\mu}\left(\frac{\sqrt{\mu(1+p\mu-p)}+p-1}{p} + \ln\left(\frac{\sqrt{p\mu}+\sqrt{1+p\mu-p}}{\sqrt{p}+1}\right)^{\frac{p-1}{p\sqrt{p}}}\right) + \frac{2}{\mu\pi p}\ln\frac{1+p\mu-p}{\mu^{p}} \tag{13}$$

This study proposes another formula to calculate the effective damping ratio from the root square sum (RSS) of viscous and hysteresis damping ratios as;

$$h_{eff} = h_0 + \sqrt{h_e^2 + h_v^2} \tag{14}$$

The comparison of the effective damping ratio among Eqs. (12), (13) and (14) is shown in Fig. 3, where the oil damper is assumed to be a linear damper with the damping factor h_{0v} in Eq. (8). It is seen that as h_{0v} increases, the RSS estimation is getting close to the value of Kasai's formula.

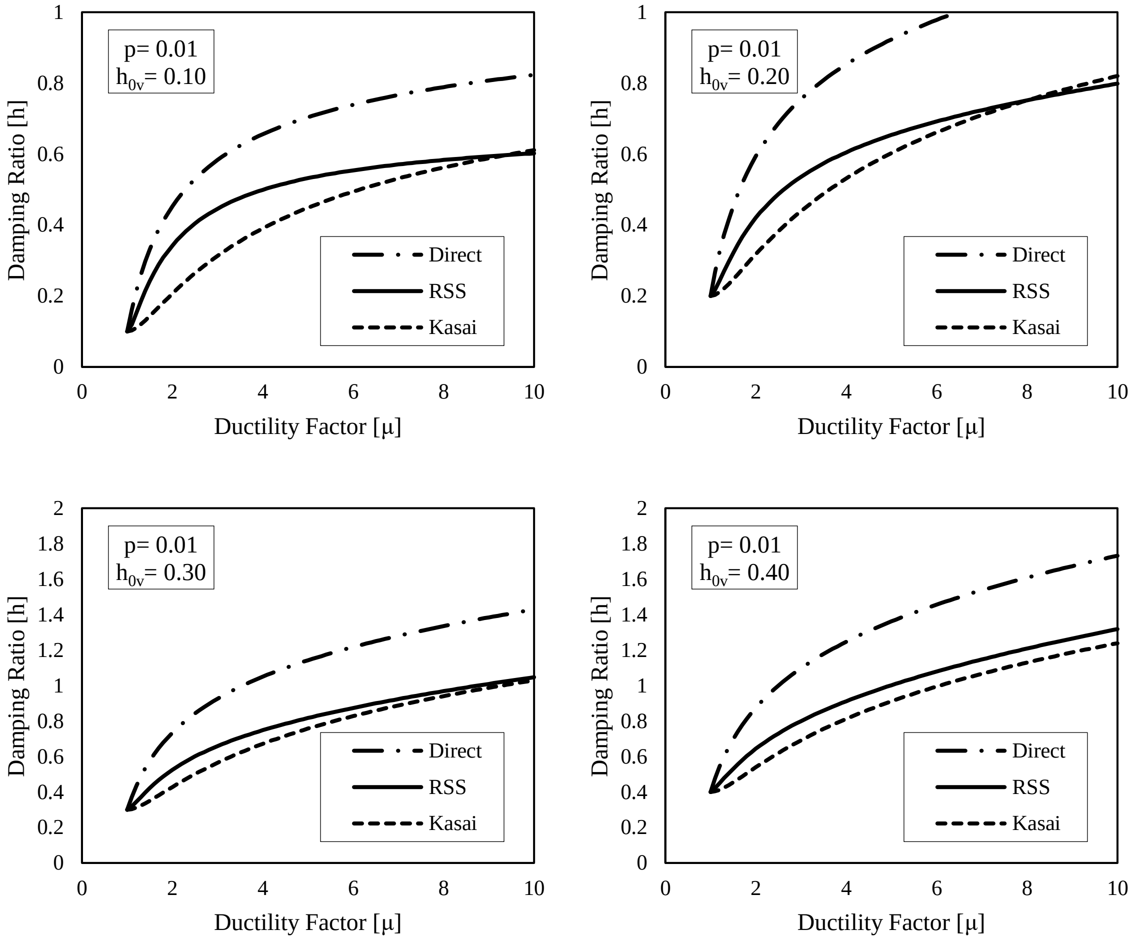


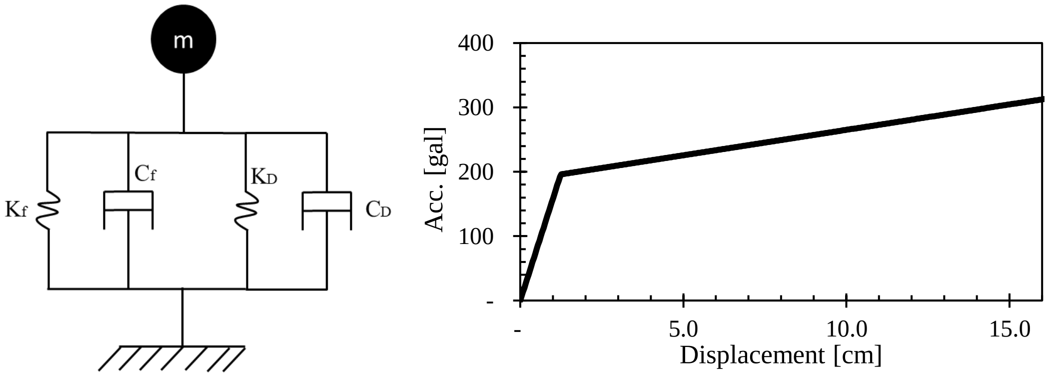
Fig. 3 – Comparison of different procedure for estimating effective damping ratio

3. Response Spectra Reduction for Higher Level of Damping

In CSM, the performance point is determined from the intersection of reduced demand curve, equivalent stiffness line and capacity curve. To generate demand curve for higher level of damping one can use the reduction factor proposed by major seismic provision or by solving the equation of motion for the appropriate damping. The study conducted by Lin et al (2003) found the reduction factory proposed by seismic design regulation are conservative in case of passively controlled buildings [6]. Therefore, in this study the demand curve is generated by solving the equation of motion to constructed demand curve of effective damping.

4. Proposed CSM calculation method

For further illustration, the peak performance of SDOF system equipped with oil damper under Scaled El Centro of 50kine Earthquake is estimated. For this purpose, the SDOF system with natural period of 0.5 sec is created to have the seismic coefficient of 0.2 as shown in Fig. 4. The amount of oil damper is estimated according to the JSSI manual and its design parameter is summarized in Tables 1 and 2 [3].



(a)

(b)

Fig. 4 – a) The SDOF with oil damper system, b) the Pushover curve of SDOF

Table 1: Technical Parameter of SDOF system

Model	**T**	**W**	**K_f**	**K_2/K_1**	**Fy**
	sec	*kN*	*kN/mm*		*kN*
1	0.50	5,000.0	80.568	0.05	1,000.0

Table 2: Technical Parameter of Supplemental oil Damper

Model	**K_D**	**C1**	**C_2/C_1**	**Vr**
	kN/mm	kNS/cm		cm/s
1	80.568	22.0	0.05	5.0

Bellow steps summarize the procedure proposed in this study to estimate the spectral performance point of SDOF system equipped with oil dampers;

Step 1: Perform the static non-linear pushover analysis of passive control building to construct the capacity curve of the structure neglecting oil dampers.

Step 2: Determine the demand curve as the S_a (acceleration response spectrum) and S_d (displacement response spectrum) curve with the inherent damping factor of h_0=5%.

Step 3: For the certain ductility factor (e.g. μ=1, 2, 3 …) estimates the hysteresis damping ratio (h_{S1}, h_{S2}, h_{S3}…) using Eq. (7). Then, reduce the demand curve to have the damping ratio of (h_{S1}, h_{S2}, h_{S3}…).

Step 4: Plot the demand curve of (h_{S1}, h_{S2}, h_{S3}…) damping together with the building capacity curve, and corresponding equivalent stiffness line of (μ=1, 2, 3 …). Up to this end, determine the spectral displacement (S_D) and acceleration (S_A) from the interstation of equivalent stiffness line of (μ=1, 2, 3 …) and demand curve of (h_{S1}, h_{S2}, h_{S3}…) damping ratio as shown in Fig. 5a. These points which represent the building performance without considering the contribution of oil damper hereafter call as initial performance points.

Step 5: For taking into account the contribution of oil damper, the amount of viscous damping added by damping device is estimate from this step forward. Thus, for each of the initial performance, estimate the equivalent circular frequencies of structure for the different level of ductility of (μ=1, 2, 3 …) from Eq. (15).

$$\omega_{eq}(\mu) = \sqrt{\frac{S_A}{S_D}} \tag{15}$$

Step 6: Determine the story drift for each floor (ϕ_{r1}, ϕ_{r2}, ϕ_{r3} ….) from pushover analysis corresponding to the initial performance point.

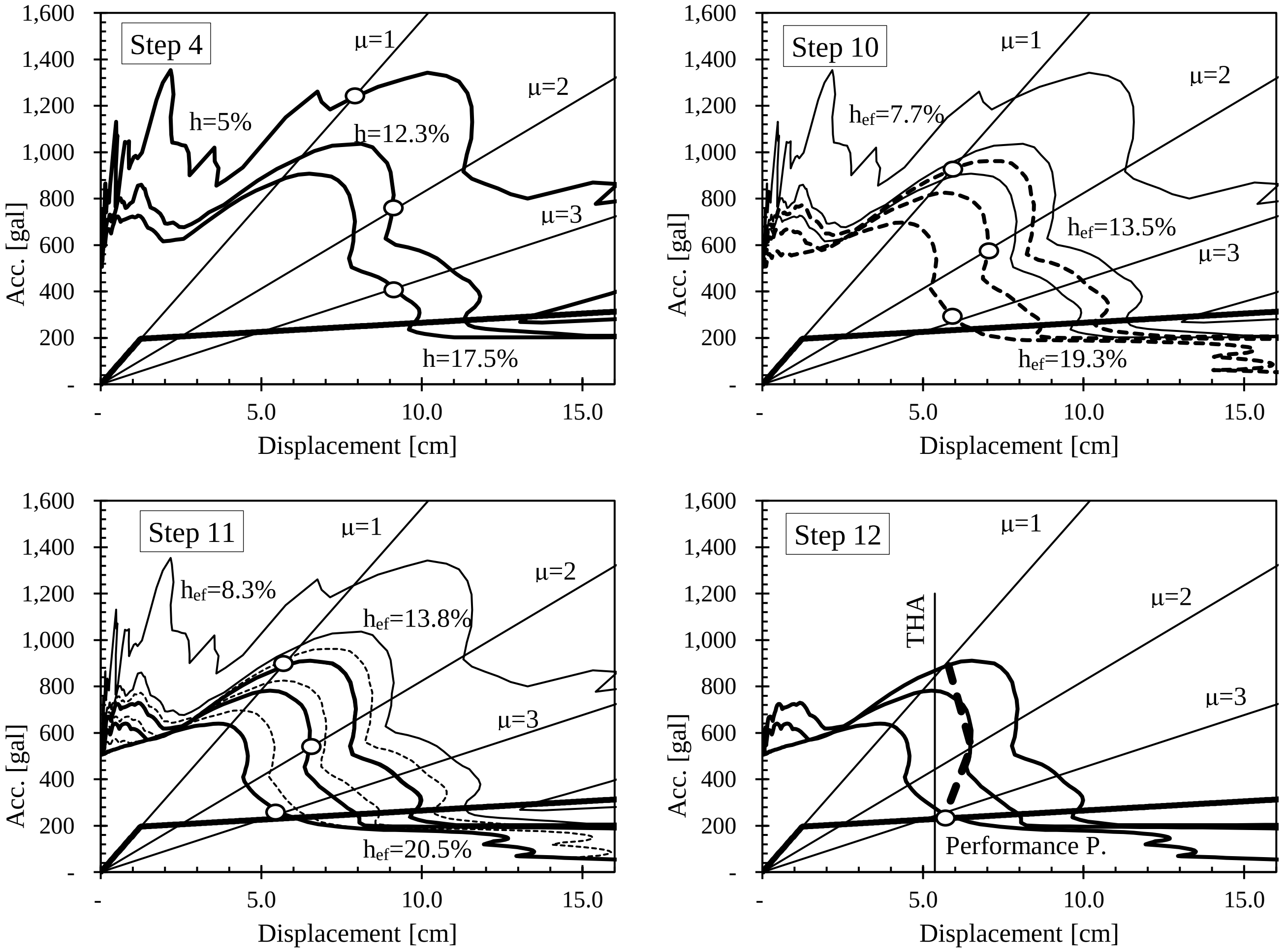


Fig. 5 – The steps of the proposed CSM application to SDOF under Scaled El Centro of Level 2 Earthquake

Step 7: Estimate the individual story maximum velocity corresponding to the initial performance point using Eq. (16).

$$V_{i-max}(\mu) = \omega_{eq} \cdot \phi_{ri} \tag{16}$$

Step 8: Estimate the equivalent damping coefficient C_{eq} of oil damper in individual story from force-velocity relation using Eq. (6).

Step 9: Determine the viscous damping ratio h_v of oil damper from Eq. (11), and then estimate the effective damping of system h_{eff} in Eq. (14).

Step 10: Construct the demand curve with higher level of effective damping (h_{eff1}, h_{eff2}, h_{eff3}…) for different ductility factor (μ=1, 2, 3 …) as shown in Fig. 5b.

Step 11: Update the initial performance point by replotting the demand curve with effective damping (h_{eff1}, h_{eff2}, h_{eff3}…) estimated in Step 10, together with the building capacity curve, and corresponding equivalent stiffness line of (μ=1, 2, 3 …) as shown in Fig. 5c. Repeat Step 4 to Step 10 to adjust the effective damping ratio (h_{eff1}, h_{eff2}, h_{eff3}…) for certain ductility factor (μ=1, 2, 3 …).

Step 12: Find out the final performance point as the intersection between the locus of performance points and the capacity curve as shown in Fig. 5d. The result of time history analysis (THA) is also shown in the figure and both results match well.

5. Verifying the proposed CSM

5.1 Target Building Description

4-story and 10-story steel buildings are selected from JSSI manual [3] [7]. The buildings are design as steel moment-resisting-frames to resist the gravity loads, while oil dampers are considered to control the response of the ground shacking loads. The yield stress of steel is 325 MPa for beam and columns whereas the element type and size for each building are presented in detail by Sekiya et al [7]. Except the ground floor which is 6 meter height, the typical floor has 4 meter for both of the target buildings as shown in Fig. 6.

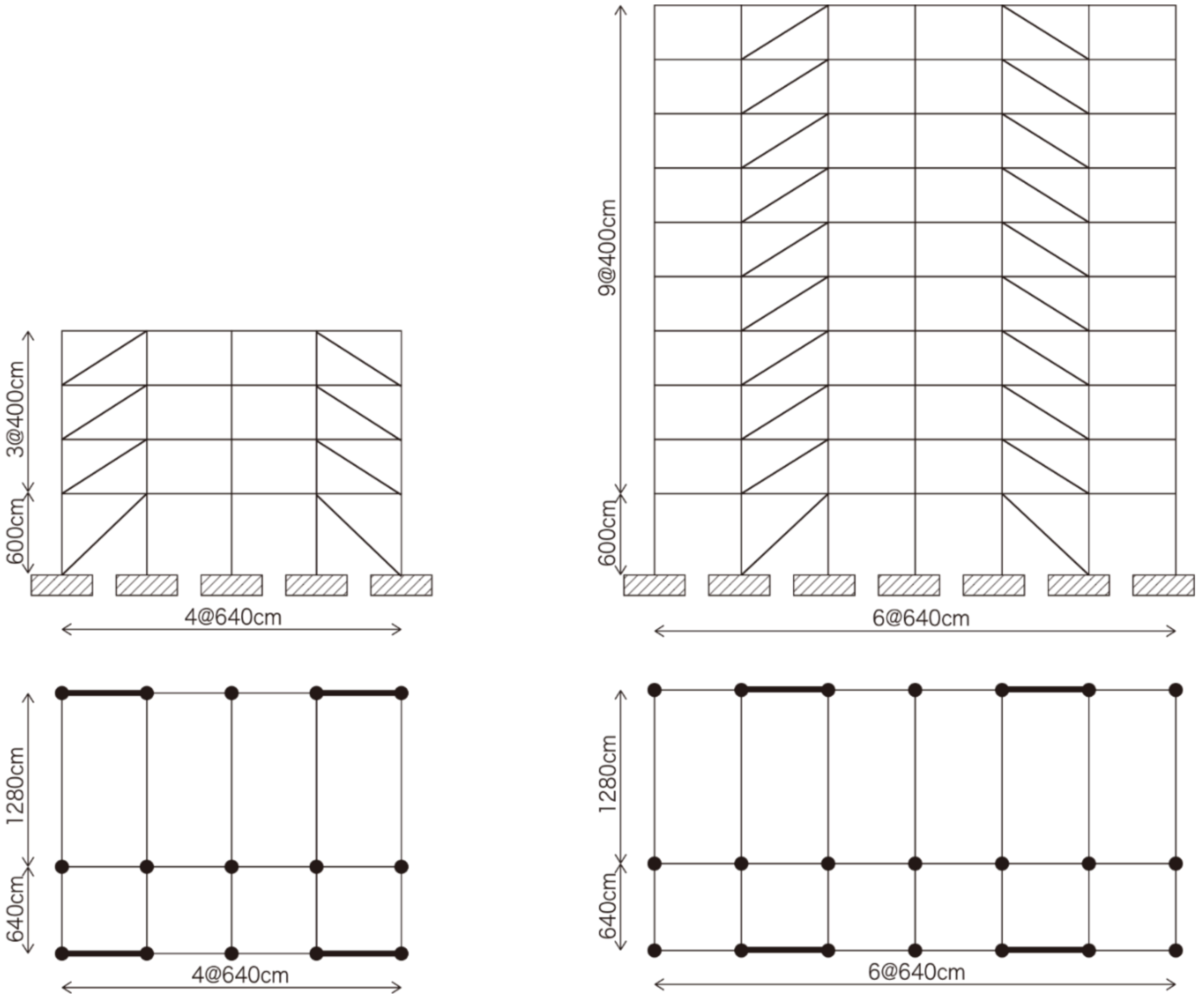
The oil dampers are diagonally installed in longitudinal direction only. Therefore, the following analysis is limited to the longitudinal direction. The number of oil dampers and configuration in plan and evaluation are shown in Fig. 6. The oil dampers stiffness, damping coefficient, relief velocity, story weighted, story height and story stiffness are presented in Tables 3 & 4, for 10-story and 4-story buildings respectively.

Table 3 – Technical parameter of oil dampers for 10-story building

Floor	W	H	K	Kb	C1	C2/C1	Vr
	kN	mm	kN/mm	kN/mm	kN*s/mm		mm/s
10	8579.00	4000.00	158.60	27.30	5.67	0.02	38.60
9	6365.00	4000.00	180.10	31.00	6.45	0.02	38.60
8	6431.00	4000.00	220.30	37.92	7.88	0.02	38.60
7	6470.00	4000.00	244.80	42.13	8.77	0.02	38.60
6	6539.00	4000.00	291.80	50.23	10.45	0.02	38.60
5	6567.00	4000.00	306.20	52.70	10.95	0.02	38.60
4	6622.00	4000.00	328.20	56.50	11.75	0.02	38.60
3	6664.00	4000.00	383.00	65.93	13.70	0.02	38.60
2	6680.00	4000.00	383.50	66.02	13.72	0.02	38.60
1	6859.00	6000.00	280.00	48.18	10.02	0.02	57.90

Table 4 – Technical parameter of oil dampers for 4-story building

Floor	W	H	K	K_b	C_1	C_2/C_1	V_r
	kN	mm	kN/mm	kN/mm	kN*S/mm		mm/s
4	4894.00	4000.00	62.70	45.58	6.13	0.02	62.80
3	3669.00	4000.00	72.90	52.98	7.13	0.02	62.80
2	3691.00	4000.00	91.00	66.18	8.90	0.02	62.80
1	3762.00	6000.00	56.20	40.85	5.50	0.02	94.00



(a) (b)

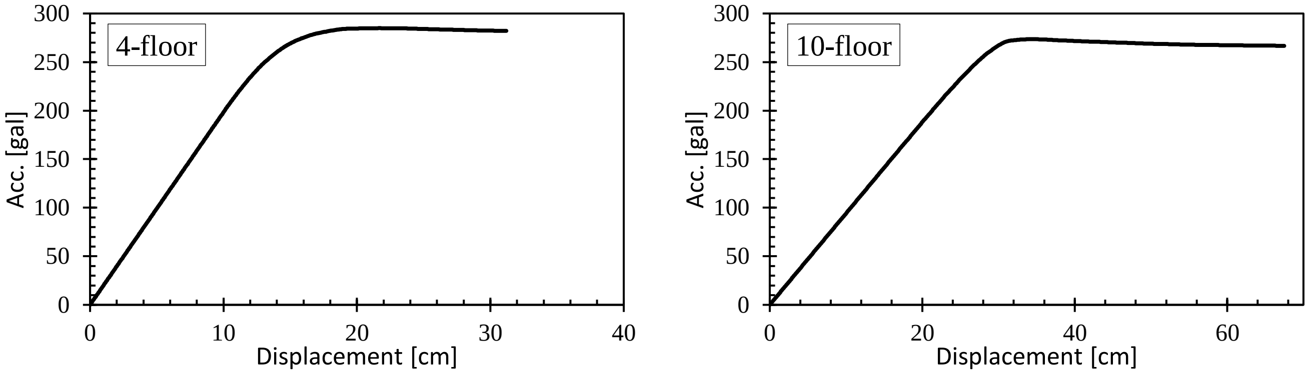
Fig. 6 – Targeted Buildings plan and elevation for Oil damper Configuration;
a) 4-story steel frame; b) 10-story steel frame

5.2 Target Building Simulation & Analysis

The targeted buildings are modeled by STERA_3D software, which is a finite element based program developed by one of the author [8]. The dynamic modal characteristics of the two target buildings is shown in Table 5. The results for non-linear pushover analysis are represented in acceleration-displacement coordinate (capacity curve) in Fig. 7.

Table 5 – Dynamic characteristics of target buildings

Building	Mode	1	2	3
4F	Natural Period (sec)	1.404	0.488	0.252
	Modal Participation Factor	3.861	-1.135	-0.326
	Effective Mass (%)	91.20%	7.90%	0.60%
10F	Natural Period (sec)	2.030	0.748	0.436
	Modal Participation Factor	7.566	-2.798	-1.534
	Effective Mass (%)	82.80%	11.30%	3.40%



(a) (b)

Fig. 7 – Targeted Buildings Capacity curve; a) 4-story steel frame; b) 10-story steel frame

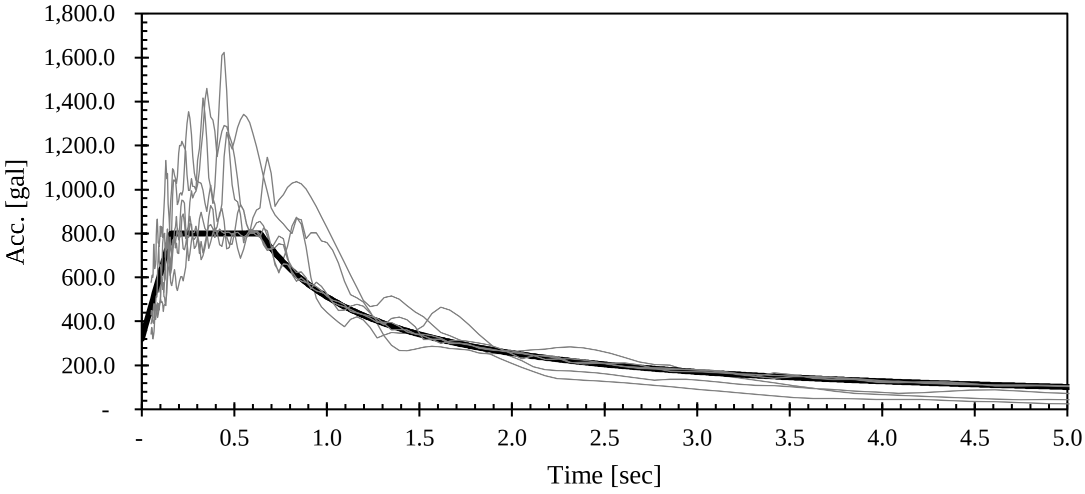


Fig. 8 – Acceleration response spectra of selected earthquakes

5.3 Demand of earthquake ground motion

Six earthquakes listed in Table 6 have been selected and scaled to be compatible of extremely rare earthquake defined by Japanese Standard [2]. According to Building Standard Law of Japan, the intensity of design earthquake motion are categorized as rare earthquake (level 1) and extremely rare earthquake (level 2) with maximum spectral acceleration of 1.6 (m/s^2) and 8.0 (m/s^2), respectively. Fig. 8, illustrates and compares the earthquake scaled to be compatible of level 2, with design spectra (thick solid line).

Table 6 – List of selected and scaled earthquakes

S. No.	Scaled Categories	Earthquake	Event Date	Recording Station
1	Scaled earthquake to be compatible of 50 cm/sec (kine)	Imperial Valley	1940	El Centro
2		Kern County	1952	Taft
3		Kobe	1995	JMA
4	Artificially generated earthquake to be compatible of Level 2	Tohoku	1978	T. University
5		Tokachi Oki	1968	Hachinohe
6		Kobe	1995	JMA

5.4 Evaluation of the maximum responses

The maximum responses of two buildings under each earthquake ground motion are calculated by the proposed CSM and nonlinear time history analysis (THA). By using the proposed CSM the targeted building performance point was estimated. The distribution of the maximum story drift and the maximum story shear force are compared in Figs. 9-12. In case of 4-story building, the difference between CSM and THA is less than 20%, however this difference is about 10% for the 10-story building.

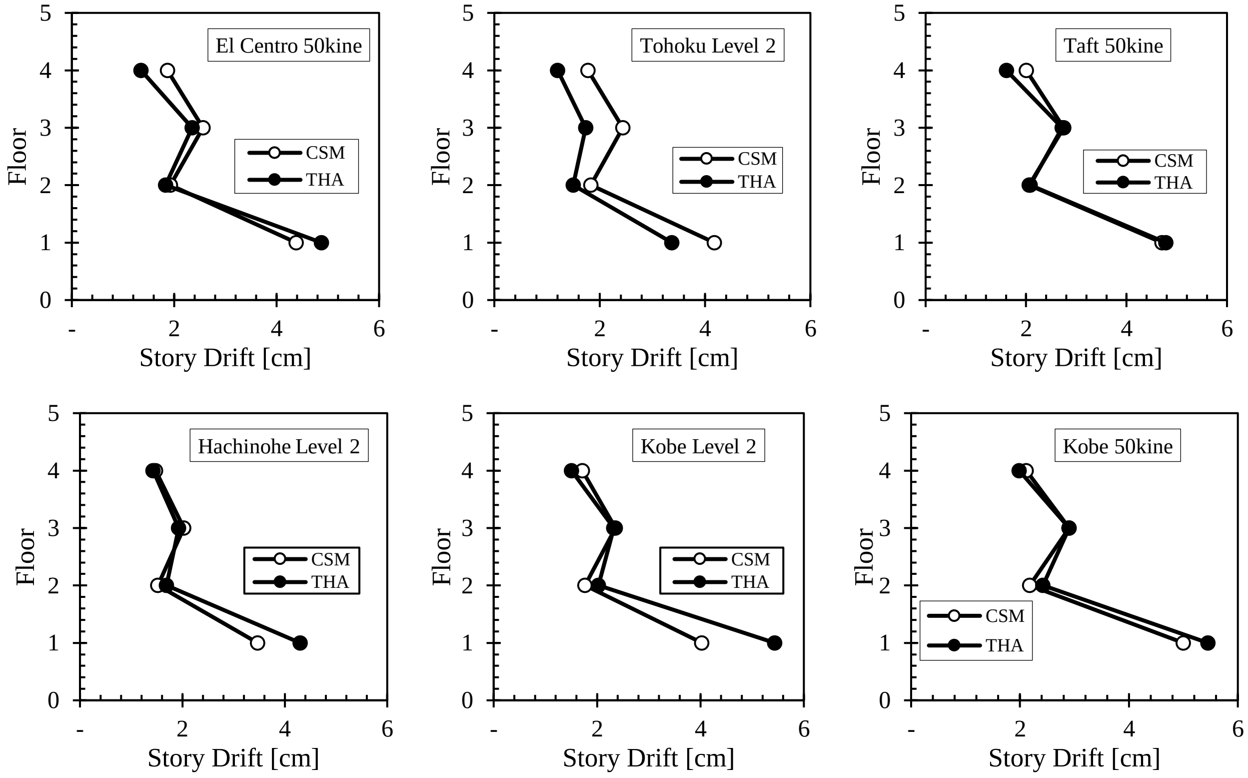


Fig. 9 – Story drift comparison of Proposed CSM and THA for 4-story building

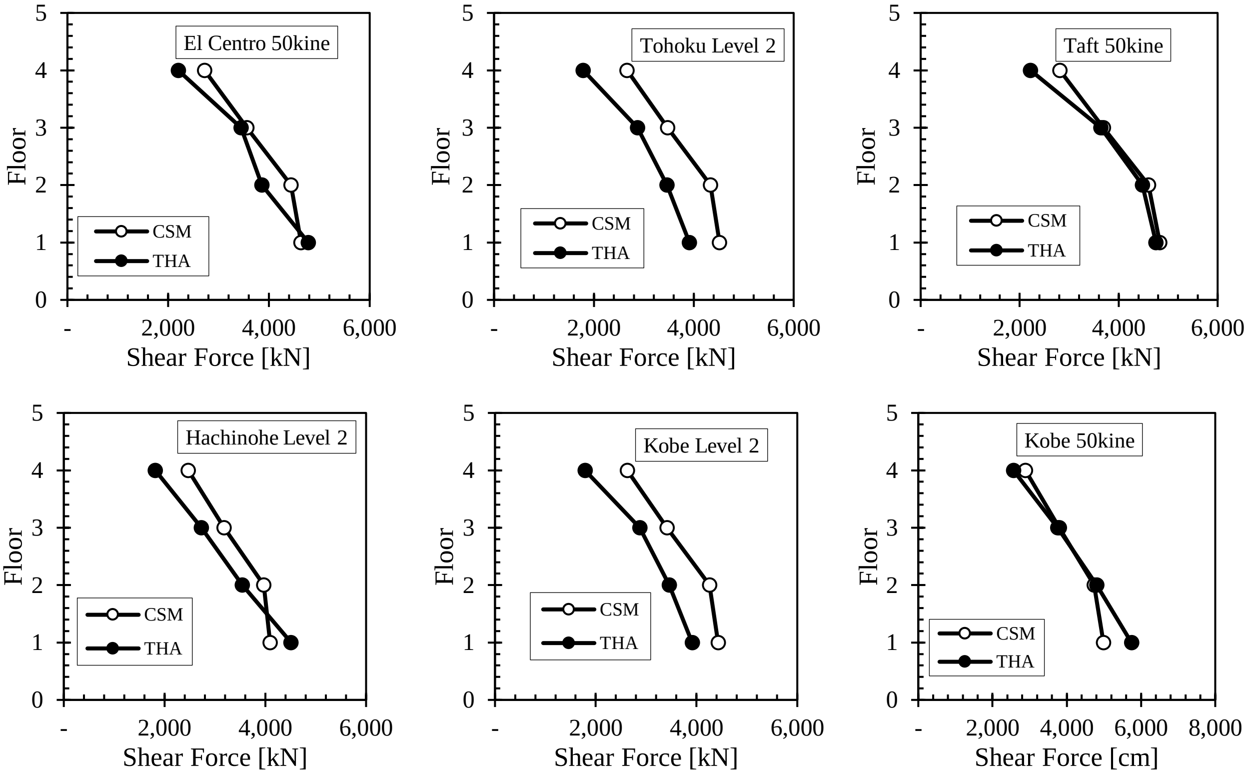


Fig. 10 – Story shear force comparison of Proposed CSM and THA for 4-story building

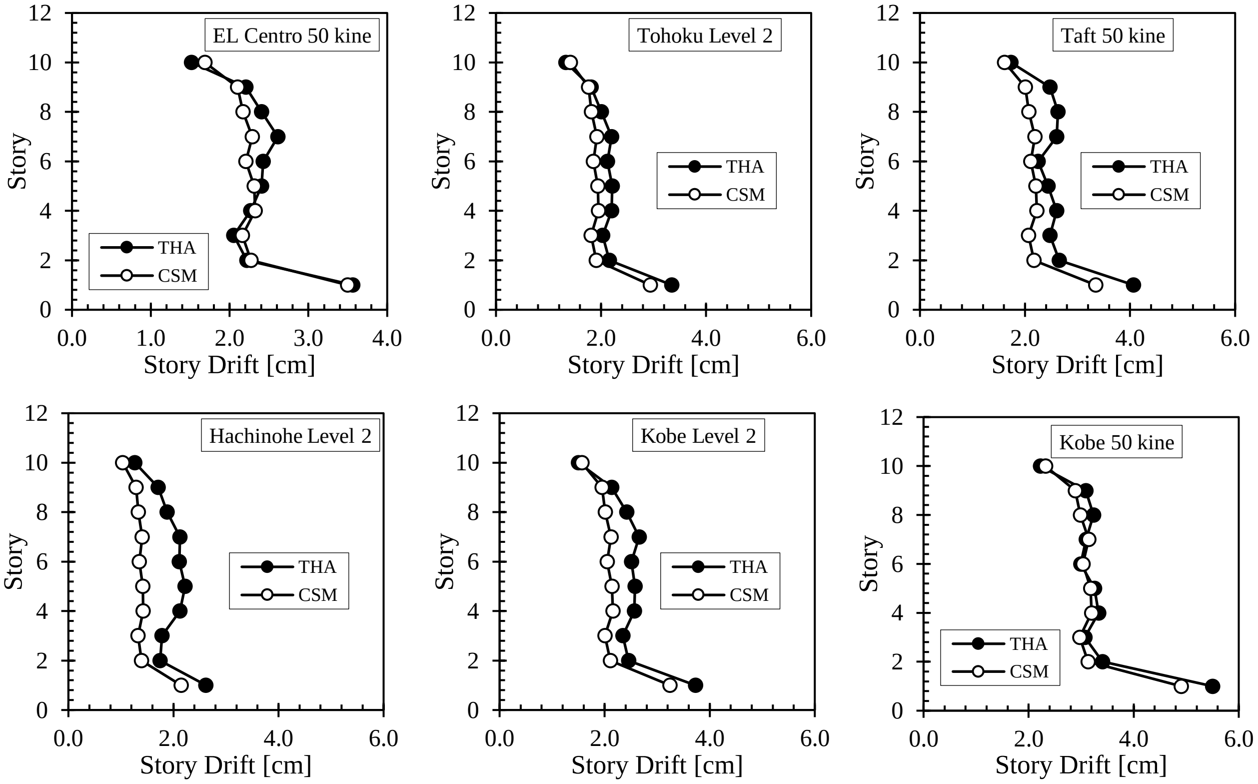


Fig. 11 – Story drift comparison of Proposed CSM and THA for 10-story building

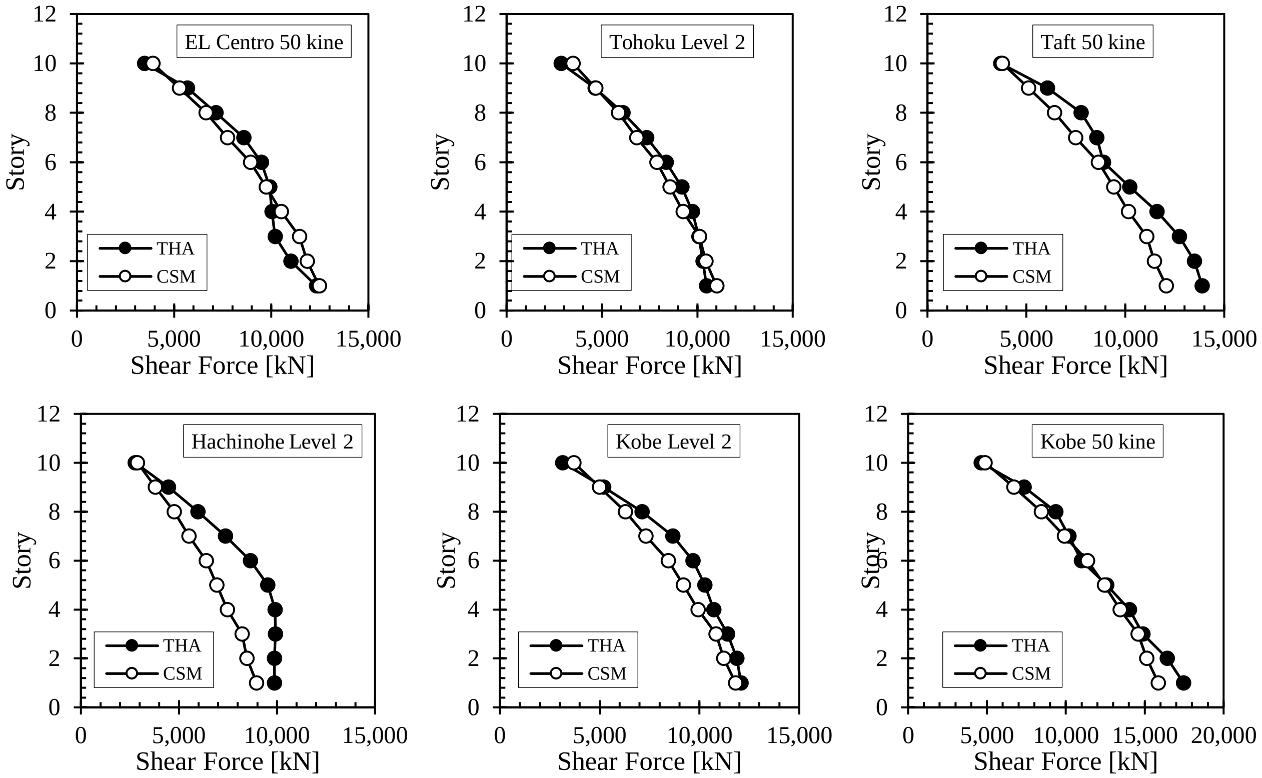


Fig. 12 – Story shear force comparison of Proposed CSM and THA for 10-story building

6. Conclusion Remarks

A CSM based procedure to estimate the maximum response of passively controlled building with oil dampers under earthquake ground motion is proposed adopting a simple formula to calculate the effective damping ratio from the root square sum (RSS) of viscous and hysteresis damping ratios. The proposed CSM is applied to two steel frame buildings of 4- and 10-story equipped with oil dampers subjected to several earthquake ground motions. From the comparison with THA, the proposed CSM technique estimates the maximum responses of buildings with excellent accuracy.

References

[1] Freeman S. A. (2004): Review of the development of the capacity spectrum method. *ISET Journal of Earthquake Technology*, Paper No. 438, Vol. 41, No. 1, 1-13.

[2] Building Standard Law of Japan (2004), published by: The building Center of Japan.

[3] The Japan Society of Seismic Isolation (JSSI) (2013*): Manual for Design and Construction of Passively-Controlled Buildings*. JSSI, 3rd edition. (in Japanese)

[4] Kasai K., Kawanabe Y. (2005): Equivalent Linearization to Predict Dynamic Properties and Seismic Peak Responses of a Structural System with High Viscous Damping an Hysteretic Damping, *Journal of Structural Construction Engineering*, Architectural Institute of Japan, No. 591. 43-51, (in Japanese)

[5] Fu Y., Kasai K. (1998): Comparative study of frames using viscoelastic and viscous dampers, *Journal of Structural Engineering*, 124, 513-522

[6] Lin Y.Y., Chang K.C. (2003): Study on damping reduction factor for buildings under-ground motions, *Journal of Structural Engineering*, 129, 206-214

[7] Sekyiya E., Mori H., Ohbuchi T., Yoshie K., Hara H., Arima F., Takeuchi Y., Saito Y., Ishii M., Kasai K. (2004): Details of 4-, 10-, and 20-story theme structure used for passive control design examples, *JSSI Response Control Committee Symposium on passive vibration control* (in Japanese)

[8] Saito T.: STERA_3D Software Ver. 10.3, TUT, Japan, (http://www.rc.ace.tut.ac.jp/saito/software-e.html)