16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 3031

Registration Code: S-U1465779382

Equivalent SDOF System Model for Estimating the Seismic Response of Building Structures with Displacement-Dependent Passive Dampers

JD. Kang[(1)], T. Furukawa [(2)], and Y. Mori [(3)]

[(1)] *Research Fellow, National Research Institute for Earth Science and Disaster Resilience, kang@bosai.go.jp*
[(2)] *Graduate Student, Nagoya University, Nagoya, Japan, furukawa.taishi@g.mbox.nagoya-u.ac.jp*
[(3)] *Professor, Nagoya University, Nagoya, Japan, yasu@sharaku.nuac.nagoya-u.ac.jp*

Abstract

In this paper, an equivalent SDOF system model of a multi-story frame with displacement-dependent dampers is proposed to estimate the seismic response. The proposed equivalent SDOF system model has multi-spring to take into account the hysteretic behaviors of frame and damper elements. The properties of multi-spring converted from dampers are defined by an elastic mode vector obtained from the eigenvalue analysis of the frame with dampers and properties of dampers. To confirm the validity of the proposed model, seismic responses of elaborate analytical models of three-story steel moment resisting frames with displacement-dependent passive dampers and their corresponding equivalent SDOF system models were compared. The drift demands in the SDOF system are mapped back to building structures with damper based on the performance-based design method in Japan. According to the results, the proposed equivalent SDOF system model has sufficient accuracy for evaluation of the seismic responses.

Keywords: displacement-dependent damper, inelastic seismic response, calculation of response and limit strength

1. Introduction

Energy dissipation systems such as displacement- and velocity-dependent dampers have been proposed and used increasingly in new and retrofit construction. To estimate seismic responses of a structure with energy dissipation system, nonlinear time-history analysis (NTHA) using an elaborate analytical model is conducted. However, the seismic responses computed via NTHA using an elaborate analytical model require intensive computational exertion. Therefore, simplified methodologies to estimate the seismic demands have been adopted in many building codes under performance-based design frameworks [1~5]. These methodologies are the use of an equivalent single-degree-of-freedom (SDOF) systems converted from the building structure. In mostly equivalent SDOF systems, a single skeleton curve is adopted to represent characteristics of the building structure [6-8]. For considering the behavior of the dampers, a two-spring equivalent SDOF system model is proposed [9]. However, this model might require the time and effort for approximating the behavior of spring for dampers.

In this paper, the equivalent SDOF system model of a multi-story frame with displacement-dependent dampers is proposed to estimate the seismic responses. The proposed equivalent SDOF system model has multi-spring to take into account the hysteretic behavior of dampers. The properties of multi-spring equivalent to dampers are defined by the properties of dampers and the elastic mode vector obtained from the eigenvalue analysis (EVA) of the frame with dampers. To confirm the validity of the proposed model, seismic responses of elaborate analytical models of three-story steel moment resisting frames with displacement-dependent passive dampers and their corresponding equivalent SDOF system models were compared. The drift demands in the SDOF system are mapped back to building structures with damper based on the performance-based design method in Japan (Calculation of Response and Limit Strength) [5, 6]. According to the results, the proposed equivalent SDOF system model has sufficient accuracy for evaluation of the seismic responses.

2. Proposed Equivalent SDOF System

To describe an inelastic behavior of the equivalent SDOF system of general building structures, as shown in Fig. 1 (a), a skeleton curve of a single spring can be defined using the base shear force versus roof displacement curve obtained from a nonlinear static pushover analysis (NSPA) as shown in Fig. 1 (b). When all structural components of the building behave similarly, this equivalent SDOF system with assumed single skeleton curve can estimate an inelastic seismic performance of the building structure. However, if the behaviors of each structural member such as damper and frame members are very different, this assumed single skeleton curve and the hysteresis rule would lead to the loss of accuracy in the estimation of a seismic performance because the assumed tri-linear (or bilinear) single skeleton curve may not be enough to consider the behavior of dampers.

In multi-degree-of-freedom (MDOF) systems with displacement-dependent dampers, as shown in Fig. 2 (a), frame and damper elements are described using shear springs which depend on a story drifts. In the MDOF system with dampers, a base shear force can be divided into two forces: lateral force resisted by frame elements and one by damper elements as shown in Fig. 2 (b). Therefore, as shown in Fig. 2 (c), the equivalent SDOF system of the shear frame with dampers can be described using multi-spring with the skeleton curve approximated by the base shear force versus roof displacement curve as shown in Fig. 2 (b). In this paper, an equivalent SDOF system with multi-spring for considering the hysteretic behaviors of frame and dampers is proposed.

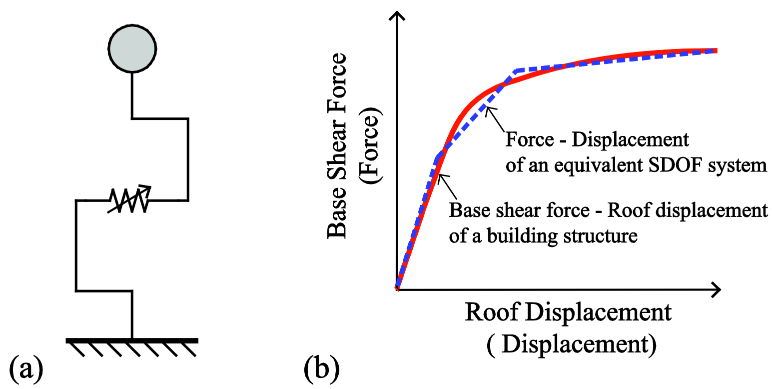

Fig. 1 – Equivalent SDOF system of general building structures: (a) equivalent SDOF system and (b) force-displacement curve.

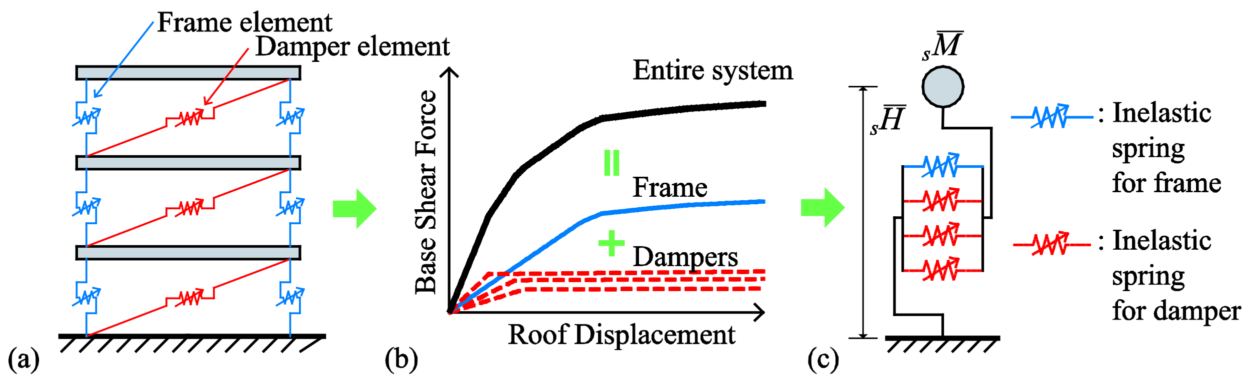

Fig. 2 – Multi-story frame with displacement-dependent dampers: (a) shear frame with dampers, (b) base shear force-roof displacement curve, and (c) proposed equivalent SDOF system.

2.1 Effective Mass and Effective Height

An effective mass, ${}_{S}\overline{M}$, and effective height, ${}_{S}\overline{H}$, of the proposed equivalent SDOF system of a multi-story frame with dampers (hereafter referred to as entire system) can be defined as

$$ {}_{S}\overline{M} = \frac{\left(\sum_{i=1}^{n} m_i \cdot {}_{S}\phi_{1,i}^{E}\right)^2}{\sum_{i=1}^{n} m_i \cdot {}_{S}\phi_{1,i}^{E}} \tag{1} $$

$$ {}_{S}\overline{H} = \frac{\sum_{i=1}^{n}\left(m_i \cdot {}_{S}\phi_{1,i}^{E} \cdot \sum_{k=1}^{i} h_k\right)}{\sum_{i=1}^{n} m_i \cdot {}_{S}\phi_{1,i}^{E}} \tag{2} $$

where ${}_{S}\phi_{1,i}^{E}$ is the first elastic mode vector of the ith story obtained from the EVA of the entire system; m_i and h_i are the mass and height of the ith story, respectively.

2.2 Inelastic Spring Equivalent to Bare Frame

In the proposed equivalent SDOF system, properties of the inelastic spring equivalent to the multi-story frame without dampers (hereafter referred to as bare frame) can be defined by the following.

As shown in Fig. 3 (a), a skeleton curve can be defined by a bi-linear or tri-linear skeleton curve into the base shear force, Q_1, versus roof displacement, Δ_N, curve obtained from the NSPA of the bare frame with lateral load distribution based on first mode vector. Then, this skeleton curve is normalized by the gravity, effective mass, effective height, and participation factor of the bare frame for the elastic first mode. The effective mass, ${}_{F}\overline{M}$, and effective height, ${}_{F}\overline{H}$, of the bare frame is defined using Eqs. (1) and (2) with ${}_{S}\phi_{1,i}^{E}$ replaced by ${}_{F}\phi_{1,i}^{E}$ which is obtained from the EVA of the bare frame; the participation factor of the bare frame can be defined as

$$ {}_{F}\Gamma = \frac{\sum_{i=1}^{n} m_i \cdot {}_{F}\phi_{1,j}^{E}}{\sum_{i=1}^{n} m_i \cdot \left({}_{F}\phi_{1,j}^{E}\right)^2}. \tag{3} $$

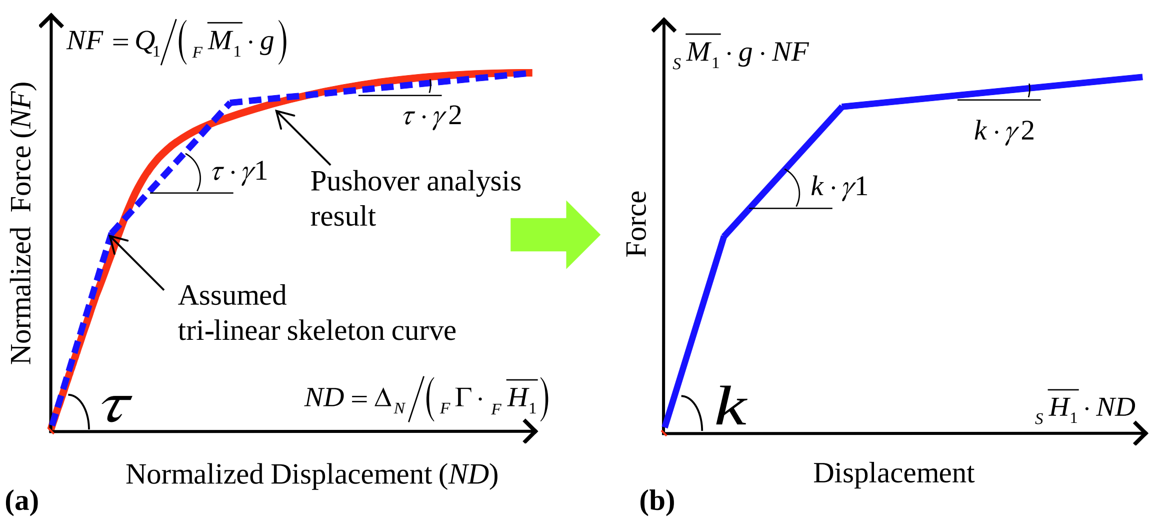

Fig. 3 – Skeleton curve of bare frame: (a) Normalized skeleton curve and (b) Force-displacement curve of an inelastic spring on the proposed equivalent SDOF system.

In the Fig. 3 (a), an initial slope, τ, of the normalized curve is equivalent to the effective elastic stiffness of the bare frame; $\gamma 1$ and $\gamma 2$ are the first and second post-elastic stiffness ratio, respectively.

By using the initial slope, τ, gravity, effective mass, and effective height of the entire system for the first mode, the effective elastic stiffness of the inelastic spring in the propose equivalent SDOF system is approximated by

$$k = \tau \frac{{}_s\overline{M} \cdot g}{{}_s\overline{H}} . \tag{4}$$

In the proposed SDOF system, the skeleton curve of the inelastic spring equivalent to the bare frame can be defined using the effective elastic stiffness and post-elastic stiffness ratios as shown in Fig. 3 (b).

2.3 Inelastic Spring Equivalent to Dampers

This section describes the methodology to estimate the hysteresis rule of inelastic spring equivalent to the damper in the proposed equivalent SDOF system.

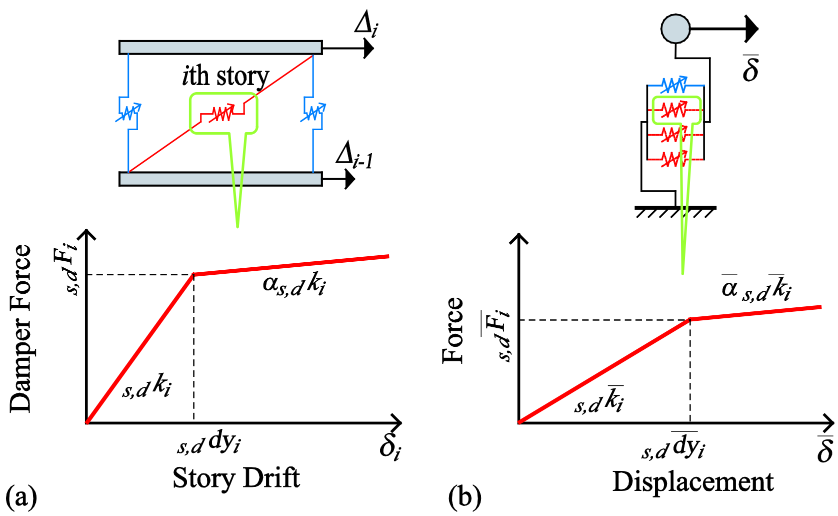

Fig. 4 – Skeleton curve of dampers and inelastic springs: (a) damper force-story drift curve of damper at *i*th story and (b) damper force-displacement curve of *i*th spring.

As shown in Fig. 4 (a), considering only the first mode, a relative displacement of the *i*th story of the MDOF system, Δ_i, can be expressed using the displacement of the equivalent SDOF system, $\overline{\delta}$, as

$$\Delta_i = {}_s\phi_{1,i}^E \cdot {}_s\Gamma \cdot \overline{\delta} \tag{5}$$

where ${}_s\Gamma$ is the participation factor of the entire system can be defined using Eq. (3) in which ${}_F\phi_{1,i}^E$ is replaced with ${}_s\phi_{1,i}^E$ obtained from the EVA of the entire system.

Using Eq. (5), the inter-story drift of the *i*th story of the MDOF system can be expressed as

$$\delta_i = \Delta_i - \Delta_{i-1} = \left({}_s\phi_{1,i}^E - {}_s\phi_{1,i-1}^E\right) \cdot {}_s\Gamma \cdot \overline{\delta}. \tag{6}$$

The force-displacement curve of the *i*th story damper of the MDOF system and the *i*th inelastic spring of the proposed SDOF system are shown in Fig. 4 (a) and (b), respectively. Here, it is assumed that the dissipative energy by the *i*th story damper of the MDOF system is equivalent to that by the *i*th inelastic spring of the proposed SDOF system. According to this assumption and Eq. (6), properties of the *i*th inelastic spring of the proposed SDOF system can be expressed as [10]

$$\overline{k}_{d,i} = k_{d,i}\left({}_s\phi_{1,i}^E - {}_s\phi_{1,i-1}^E\right)^2 \left({}_s\Gamma\right)^2 \tag{7}$$

$$\overline{dy}_{d,i} = dy_{d,i} \Big/ \left({}_s\phi_{1,i}^E - {}_s\phi_{1,i-1}^E\right){}_s\Gamma \tag{8}$$

$$\overline{\alpha}_{d,i} = \alpha_{d,i} \tag{9}$$

where $\overline{k}_{d,i}$ and $k_{d,i}$ respectively denote the elastic stiffness of the *i*th inelastic spring and the *i*th story damper; $\overline{dy}_{d,i}$ and $dy_{d,i}$ respectively denote the yield displacement of the *i*th inelastic spring and the *i*th story damper; $\overline{\alpha}_{d,i}$ and $\alpha_{d,i}$ respectively signify post-elastic stiffness ratio of the *i*th inelastic spring and the *i*th story damper.

3. Analytical Step for Estimating the Seismic Response

This section describes the methodology to estimate the inelastic seismic responses of the multi-story frame with displacement-dependent dampers based on the performance-based design method in Japan (Calculation of Response and Limit Strength) [5, 6]. The inelastic seismic responses can be estimated taking the following steps:

1. Perform the EVA of the bare frame. Then, define the effective mass, ${}_F\overline{M}$, and the effective height, ${}_F\overline{H}$, of the bare frame for the first mode using Eqs. (1) and (2).
2. Perform the EVA of the entire system. Then, define the effective mass, ${}_s\overline{M}$, and the effective height, ${}_s\overline{H}$, for the first mode that are the mass and height of the proposed SDOF system.
3. Determine the skeleton curves of the inelastic springs equivalent to dampers in the proposed equivalent SDOF system using Eqs (7)~(9), and the first elastic mode vector, ${}_s\phi_1^E$.
4. Perform the NSPA of the bare frame with a lateral load distribution based on the first mode vector.
5. Determine the skeleton curve of the inelastic spring equivalent to the bare frame using the base shear force versus roof drift ratio curve obtained from the NSPA result in Step (3) and mode vectors obtained from the EVA result in Step (1) and (2) as show in Fig. 3.
6. Perform the NSPA of the entire system with a lateral load distribution based on the first mode vector.
7. Define the shear force versus story drift curve of each story using the NSPA result in Step (6).
8. Determine the spectral acceleration and displacement (S_a-S_d) curve using the base shear force versus roof drift ratio curve using the NSPA result in Step (6). Further details on the S_a-S_d curve can be found in reference [6].
9. Generate the proposed equivalent SDOF system using the effective mass, ${}_s\overline{M}$, effective height, ${}_s\overline{H}$, and inelastic springs with the skeleton curves determined in Steps (3) and (5). Then perform NTHA of the proposed equivalent SDOF system to evaluate the maximum drift, $\delta_{\max}$.
10. Find the step number, *N*, at which response corresponds to $\delta_{\max}$ obtained from Step (9), in the S_a-S_d curve obtained from Step (8).

11. Find the displacement at each story on the shear force versus story drift curve obtained from Step (7) at the *N*th step obtained from Step (10).

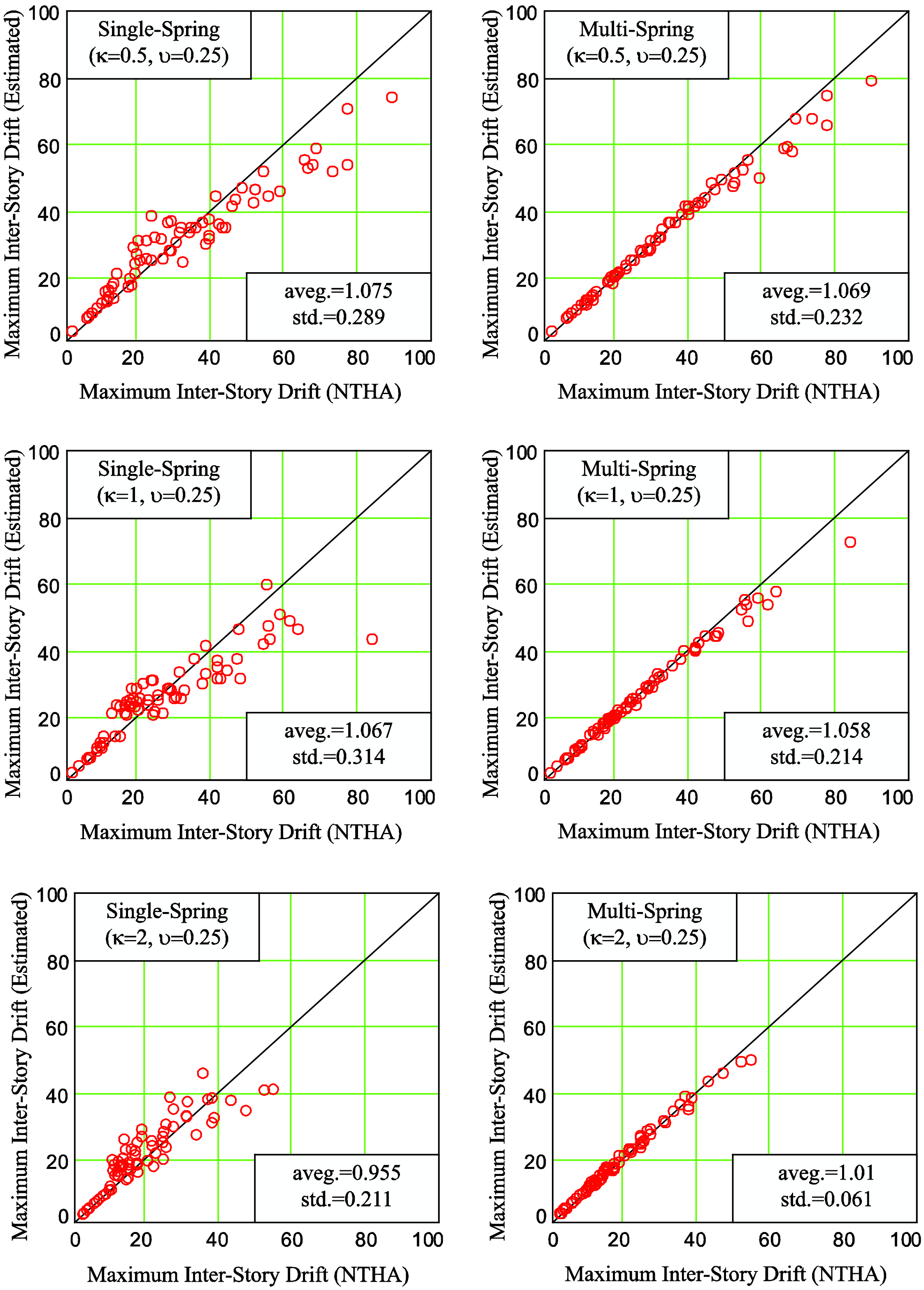

Fig. 5 – Comparison of maximum inter-story drifts obtained using equivalent SDOF system models with those obtained using the elaborate analytical models (Unit: mm).

4. Numerical Examples

In order to investigate the accuracy of the proposed model, two-dimensional steel moment resisting frames are considered for numerical examples.

4.1 Building models and earthquake ground motion records

The three-story steel moment resisting frame is designed to meet the current Japanese seismic requirements for both strength and inter-story drift. According to the EVA, the natural period for the first mode is 0.758s. Further details on the steel moment resisting frames can be found in reference [11]. Properties of dampers are determined using two parameters which are a stiffness ratio and a drift ratio. The damper stiffness of *i*th story is determined by a story stiffness of the frame and a stiffness ratio, κ, which is ratio of the damper stiffness to the story stiffness of the frame. In this paper, three values (0.5, 1, and 2) was used for the stiffness ratio. The yield deformation of the damper at *i*th story is determined by a yield story drift of the frame and a drift ratio, υ, which is the ratio of the yield deformation of the damper to the story yield drift of the frame. In this paper, only one value (0.25) was used for the drift ratio.

NTHA was performed using the nonlinear dynamic analysis program SNAP ver.5 [12]. Stiffness-proportional damping is considered for frame with a 2% damping ratio. 73 ground motion records are used to investigate the proposed method. These records include ground motions at both near- and far-field sites in the U.S. and Japan. A detailed list of the earthquakes can be found in reference [13].

4.2 Results and discussion

Fig. (5) shows the comparison of maximum inter-story drifts, which are one of the most influential indexes for evaluating the seismic performance of building structures, estimated using equivalent SDOF system models with those estimated using elaborate analytical models. For comparison, NTHAs were also performed using single-spring equivalent SDOF system models. The vertical axis is the maximum inter-story drifts estimated using equivalent SDOF system models and the horizontal axis denotes that obtained from NTHA using elaborate analytical models. In the Fig. (5), “aveg.” signifies its bias defined by the mean of the ratio of the seismic responses estimated using equivalent SDOF system models to those obtained from NTHA using elaborate analytical models. Also, “std.” represents the standard deviation of the ratio of the seismic responses estimated using equivalent SDOF system models to those obtained from NTHA using elaborate analytical models. The biases and standard deviations of the seismic responses estimated using the single-spring model are in the range of 0.955-1.075 and 0.211-0.314, respectively. The biases of estimated seismic responses varies with decreasing the stiffness ratio. On the other hands, the biases and standard deviations of the seismic responses estimated using the proposed model are in the range of 1.01-1.069 and 0.061-0.232, respectively. Regardless of the value of the stiffness ratio, the seismic responses estimated by using the proposed equivalent SDOF system model agrees fairly well with those computed via NTHA using the elaborate analytical model. This clearly demonstrates that the proposed equivalent SDOF system model can accurately estimate the seismic responses of multi-story frame with displacement-dependent dampers.

5. Conclusions

The equivalent SDOF system model of a multi-story frame with displacement-dependent dampers was proposed to estimate the seismic responses. The proposed equivalent SDOF system model has multi-spring to take into account the hysteretic behavior of dampers. To confirm the validity of the proposed model, nonlinear time-history analysis were performed using elaborate analytical models of three-story steel moment resisting frames with displacement-dependent passive dampers and their corresponding equivalent SDOF system models. The single-spring equivalent SDOF system model was also used for analysis model to comprise with the proposed equivalent SDOF system model. The drift demands in the SDOF system were mapped back to building structures with damper based on the performance-based design method in Japan (Calculation of Response and Limit Strength). According to the results, the proposed equivalent SDOF system model has sufficient accuracy for evaluation of the seismic responses.

References

[1] FEMA (1997): NEHRP Guidelines for the seismic rehabilitation of buildings. *FEMA-273*, Federal Emergency Management Agency, Washington DC, USA.

[2] FEMA (2000): NEHRP Guidelines for Recommended Seismic Design Criteria for New Steel Moment-Frame Buildings. *FEMA-350*, Federal Emergency Management Agency, Washington DC, USA.

[3] ATC (1996): Seismic evaluation and retrofit of concrete buildings. *report ATC-40*, Applied Technology Council , Redwood City, CA, USA.

[4] MLIT (2000): Technical standard for structural calculation of response and limit strength of buildings. *Notification No. 1557-2000*, Ministry of Land, Infrastructure and Transport, Tokyo, JAPAN. (in Japanese).

[5] Midorikawa M, Okawa I, Iiba M, Teshigawara M (2003): Performance-based seismic design code in Japan. *Earthquake Engineering and Engineering Seismology*, **4** (1):13–25.

[6] Kuramoto H, Teshigawara M, Okuzono T, Koshika N, Takayama M, Hori T (2000): Predicting the earthquake response of buildings using equivalent single degree of freedom system. *12th World Conference on Earthquake Engineering*, Auckland, New Zealand.

[7] Chopra AK, Goel RK. (2002): A modal pushover analysis procedure for estimating seismic demands for buildings. *Earthquake Engineering & Structural Dynamics*, **31** (3), 561-582.

[8] Mori Y, Yamanaka T, Luco N, and Cornell CA (2006): A static predictor of seismic demand on frames based on a post-elastic deflected shape. *Earthquake Engineering & Structural Dynamics*, **35** (10), 1295-1318.

[9] Oviedo A, Andres J, Midorikawa M, Asari T. (2011): An equivalent SDOF system model for estimating the response of R/C building structures with proportional hysteretic dampers subjected to earthquake motions. *Earthquake Engineering & Structural Dynamics*, **40** (5), 571-589.

[10] Kang JD, Mori Y (2014): Simplified method for estimating inelastic seismic demand of multi-story frame with displacement-dependent passive dampers. *5th Asia Conference on Earthquake Engineering*, Taipei, Taiwsan.

[11] Kang, JD, Tagawa H (2013): Seismic performance of steel structures with seesaw energy dissipation system using fluid viscous dampers. *Engineering Structures*, 56, 431–442.

[12] Kozo System (2009): SNAP Technical manual, ver.5.

[13] Luco, N (2002): Probabilistic Seismic Demand Analysis, SMRF Connection Fractures, and Near-Source Effects, *Ph.D. Thesis*, Stanford University, Stanford, California, USA.