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## SEISMIC RETROFIT FOR RC BUILDINGS USING ELASTO-PLASTIC AND VISCOUS DAMPERS IMPLEMENTED WITH ELASTIC STEEL FRAMES

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### **Abstract**

Learning from the past severe earthquakes, many reinforced concrete buildings were damaged because of insufficient lateral force resistance, stiffness, ductility, or energy dissipation capacity. Seismic design specifications in many countries are being updated in order to ensure safety from future earthquakes. Recent severe earthquakes around the world have proven that retrofitting of these buildings is an urgent matter.

Seismic retrofit of a reinforced concrete building using dampers is proven to increase the energy dissipation capacity and seismic performance for the building. The available damper design approaches are required to iterate in order to calculate the required stiffness and equivalent damping ratio, which may lead to a complicated design. This study proposes a seismic retrofit design method using elasto-plastic or viscous dampers implementing with an elastic steel frame without iteration. The steel frame not only applies an interface between the dampers to the RC frame but also prevents damage concentration from limiting stories and secures the self-centering function. The proposed retrofitting method is based on the equivalent linearization approach, which efficiently distributes the dampers along with the building height in order to reduce the maximum story drift ratio of the buildings. The equations to evaluate the required dampers stiffness for elasto-plastic damper and the required damping coefficient for viscous dampers are introduced.

A four-story reinforced concrete school building is used as a benchmark model, and nonlinear response history analysis is performed to verify the proposed retrofit method. The results suggest that the proposed retrofit method is considered to be effective in the example building. The maximum story drift ratio of retrofitted reinforced concrete building using both elasto-plastic and viscous dampers is reduced significantly when compared to the bare reinforced concrete building without retrofit, and the maximum story drift ratio is close to the design target story drift ratio.

*Keywords: Seismic retrofit; Response control; Structural dampers; RC buildings; Equivalent linearization*



## 1. Introduction

Over the past centuries, many reinforced concrete (RC) buildings were damaged by severe earthquakes in multiple aspects such as insufficient lateral force resistance, stiffness, ductility, or energy dissipation capacity. Seismic design specifications across the world are regularly updated in order to ensure sufficient lateral force resistance to prevent building damages from future earthquakes. Therefore, several of the old buildings which were designed in compliance with the outdated codes are often deemed substandard. Extensive damage observed in many existing RC buildings in the recent earthquakes such as the Northridge in USA 1994, Kobe in Japan 1995, Chi-Chi in Taiwan 1999, Van in Turkey 2011, Mae Lao in Thailand 2014, and Italy in 2016, have proven that retrofitting of these buildings is an urgent matter.

Seismic retrofit of a reinforced concrete building using dampers is proven to increase an energy dissipation capacity for the building [1-4]. Elasto-plastic damper (EPD) is a displacement-dependent device, which is one of the widely used devices to improve the seismic performance of the building [4]. One of the most popular EPD is a buckling-restrained brace (BRB), which delivers the performance against tensile and compressive forces equally with stable hysteresis behavior [5]. The retrofit of RC buildings using BRB is proven to improve the seismic performance of the RC building [6-11]. Another type is fluid viscous damper (FVD), which is effective in increasing the energy dissipation capacity for the building [1-3, 12]. In order to simplify the design procedure, the study presented in past research [13] proposed a retrofit design method for RC buildings without the need for iteration by designing the BRB members when the structure reaches a target deformation based on the equivalent linearization approach [14]. This procedure is named as constant drift (CD) method.

In this study, the CD method is applied to the seismic retrofit of RC buildings using EPD or FVD implemented with an elastic steel frame (SF) based on the equivalent linearization. The RC building is simplified to a single-degree-of-freedom (SDOF) model. The seismic response of the SDOF model of the RC building, when compared to the design target story drift ratio ( $SDR_{tar}$ ), is used to judge if the building is required to be retrofitted or not. If the building is required to be retrofitted, the required stiffness of EPD or the required damping coefficient of FVD can be designed without an iterative procedure. The optimal equations to evaluate the required damper stiffness for the EPD and the required damping coefficient for the FVD are proposed. A four-story RC school building is used as a benchmark model, and nonlinear response history analysis (NLRHA) is performed to verify the effectiveness of the proposed retrofit method.

## 2. Retrofit design method

Fig. 1(a) and 1(b) show configuration and SDOF model of the retrofitted RC frame using EPD or FVD with SF. The simplification method to design damper distribution in the real RC building is presented in this section.

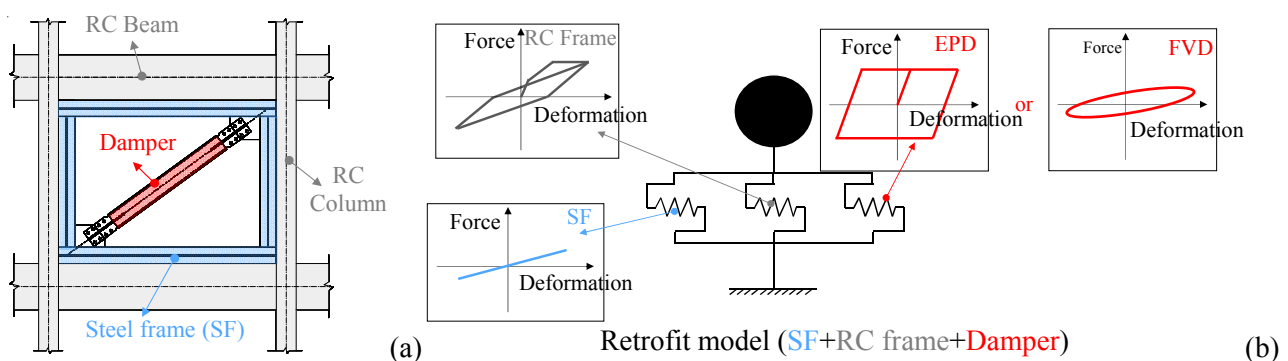


Fig. 1 –Retrofitted concept (a) Configuration and (b) Simplified SDOF model



## 2.1. Simplification of RC building

The RC building is simplified to a SDOF model, as shown in Fig. 2. The equivalent height ( $H_{eq}$ ), equivalent mass ( $M_{eq}$ ), and equivalent stiffness ( $K_f$ ) of the SDOF RC (SDOF<sub>RC</sub>) model can be calculated by Eq. (1), Eq. (2) and Eq. (3), respectively, where  $m_i$  is the mass of  $i^{\text{th}}$  story,  $u_i$  is the displacement of  $i^{\text{th}}$  story,  $H_i$  is the height of  $i^{\text{th}}$  story, and  $T_f$  is the fundamental period of the first vibration mode.

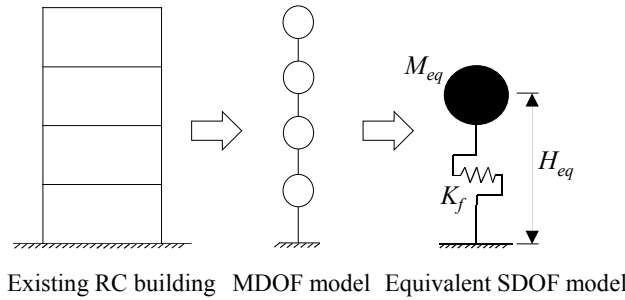


Fig. 2 – Simplification of the RC building to SDOF model

$$H_{eq} = \frac{\sum_{i=1}^N m_i \cdot u_i \cdot H_i}{\sum_{i=1}^N m_i \cdot u_i} \quad (1)$$

$$M_{eq} = \frac{\left( \sum_{i=1}^N m_i \cdot u_i \right)^2}{\sum_{i=1}^N m_i \cdot u_i^2} \quad (2)$$

$$K_f = \left( \frac{2\pi}{T_f} \right)^2 M_{eq} \quad (3)$$

Fig. 3 shows a simplified hysteretic response of SDOF<sub>RC</sub> at the pre-yielding (cracked,  $\mu_c < \mu_f \leq 1$ ) and post yielding (yielding,  $1 < \mu_f$ ) stages [10]. The secant stiffness of the SDOF<sub>RC</sub> ( $K_{f\mu}$ ) is  $pK_f$ , where  $p$  is the stiffness reduction coefficient determined from Eq. (4). Here,  $\alpha_1$  is pre-yield stiffness ratio,  $\mu_c$  is the ratio of lateral crack ( $\delta_{fc}$ ) to lateral yield deformation ( $\delta_{fy}$ ), and  $\mu_f$  is the ratio of the lateral target deformation ( $\delta_{tar}$ ) to  $\delta_{fy}$ .  $E_f$  is hysteretic energy, and  $E_{fe}$  is the strain energy of the SDOF<sub>RC</sub>.  $Q_{fc}$ ,  $Q_{fy}$ , and  $Q_f$  are the lateral force at the crack, yield, and target deformation stages, respectively. The  $E_f$  is given in Eq. 5. The unloading stiffness ( $K_{ul}$ ) is defined according to the Takeda degrading tri-linear model [15] for the cracked and yielding stages, where the unloading stiffness degradation parameter  $\lambda$  is assumed to be 0.4 [15].

$$p = \frac{\mu_c + \alpha_1(\mu_f - \mu_c)}{\mu_f} \quad ; (\mu_c < \mu_f \leq 1)$$

$$p = \frac{\mu_c + \alpha_1(1 - \mu_c)}{\mu_f} \quad ; (1 < \mu_f) \quad (4)$$

$$E_f = \frac{2K_f(\mu_f \delta_{fy})^2 \cdot (p \cdot (1 - p) \cdot \mu_c)}{\mu_c + p\mu_f} \quad ; (\mu_c < \mu_f \leq 1)$$

$$E_f = \frac{2pK_f(\mu_f \delta_{fy})^2 \cdot (p\mu_f - p(1 - \mu_c)\mu_f^{\lambda} + \mu_c)}{\mu_c + p\mu_f} \quad ; (1 < \mu_f) \quad (5)$$

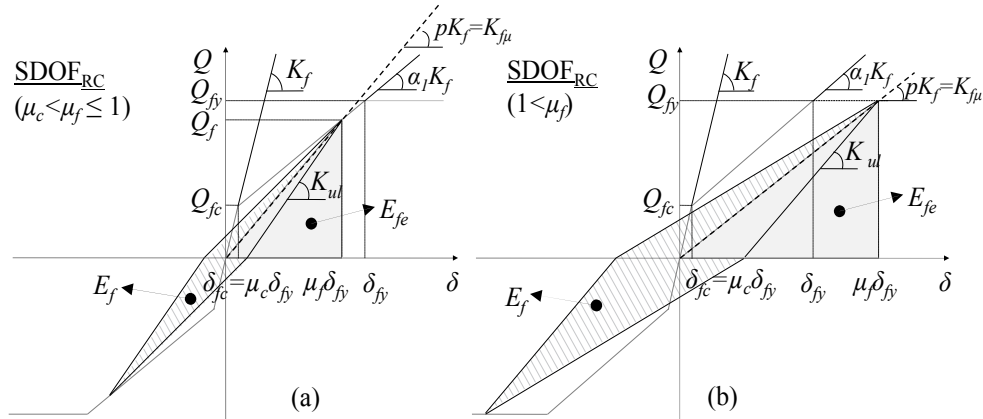


Fig. 3 –Hysteretic loops for SDOF<sub>RC</sub>: (a) Cracked ( $\mu_c < \mu_f \leq 1$ ) and (b) Yielding ( $1 < \mu_f$ )

## 2.2. Damper distribution to retrofitted RC building

This section presents the damper distribution to retrofit the RC building. The optimal equations to evaluate the required stiffness of EPD in the  $i^{\text{th}}$  story ( $K_{di}$ ) and the required damping coefficient of FVD in the  $i^{\text{th}}$  story ( $C_{di}$ ) are proposed in this section.

### 2.2.1. Elasto-plastic damper

The hysteretic response of EPD is considered on the SDOF system, which is parallel to the SDOF<sub>RC</sub>. A simple elasto-perfectly plastic force-deformation relation is assumed for the EPD, while the supplemental SF is assumed to remain elastic through the design target story drift ( $\theta_{tar}$ ), as indicated in Fig. 4. The optimal equation to evaluate the parameters is the ratio of  $K_d/K_f$ , where the EPD stiffness ( $K_d$ ) is assigned proportionally to the SDOF<sub>RC</sub> stiffness ( $K_f$ ). The proposed equation is based on the following assumptions:

(a) The hysteretic energy of the EPD ( $E_{d,EPD}$ ) is given in Eq. (6), where  $K_d$  is EPD stiffness,  $\delta_{dy}$  is lateral yield deformation, and  $\mu_d$  is damper ductility.

(b) The average equivalent hysteretic damping ratio for the retrofit system ( $h_{eq}$ ) is assumed constant at all displacement amplitudes, and the  $h_{eq}$  can be estimated by Eq. (7), where the  $E_d$  is substituted by the  $E_{d,EPD}$ .

(c) The damping response reduction factor ( $D_h$ ) was proposed in [14], as shown in Eq. (8). In this study,  $a=25$  is used for real earthquake, where the inherent damping ratio of the SDOF<sub>RC</sub> ( $h_{f0}$ ) is 3%, damping reduction factor ( $R$ ) is 0.6 [10], To evaluate equivalent damping of SDOF<sub>RC</sub> ( $h_{f\mu}$ ),  $E_d$  is substituted by zero.

(d) The target story drift at each story  $i^{\text{th}}$  ( $\theta_{tar,i}$ ) is constant ( $\theta_{tar,i} = \theta_{tar}$ ).

Therefore, the optimal ratio of the damper to frame stiffness ( $K_d/K_f$ ) can be obtained by Eq. (9), where  $\theta_{f\mu}$  is story drift of SDOF<sub>RC</sub>,  $\theta_{tar}$  is target story drift,  $h_{f\mu}$  is the equivalent damping of SDOF<sub>RC</sub>,  $\mu_d$  is ductility factor of elasto-plastic damper,  $\gamma_s$  is stiffness ratio of steel frame to damper (this study assumes  $\gamma_s = 0.05$ ).

$$E_{d,EPD} = 4K_d(\mu_d - 1)(\delta_{dy})^2 \quad ; (1 < \mu_d) \quad (6)$$

$$h_{eq} = h_{f0} + R \left( \frac{E_f + E_d}{4\pi E_{fe}} \right) \quad (7)$$

$$D_h = \sqrt{\frac{1 + ah_{f\mu}}{1 + ah_{eq}}} \quad (8)$$

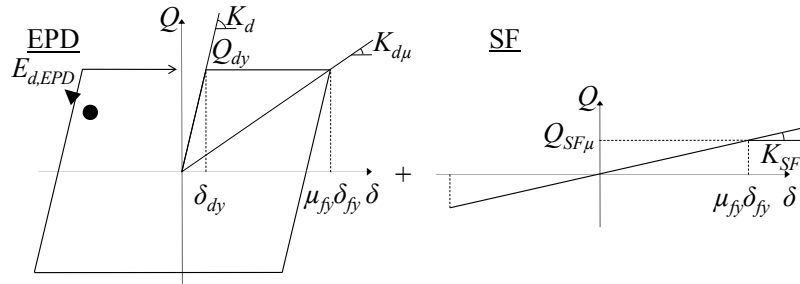


Fig. 4 –Hysteresis of EPD and SF

$$\frac{K_d}{K_f} = \frac{p \left( \frac{\theta_{f\mu}}{\theta_{tar}} \right)^2 D_h^2 - p}{\gamma_s + \frac{1}{\mu_d}} \quad (9)$$

The  $K_{di}$ , as shown in Eq. (10), can be obtained with the following assumptions.

- The lateral force distribution along the building height for the  $i^{\text{th}}$  story ( $Q_i$ ) can be calculated based on either  $A_i$  distribution described in the Japanese seismic design [16] or the ASCE-SEI7 specifications [17].
- Under the lateral force distribution, a maximum story drift ( $\theta_{\max}$ ) at each story is equal to the  $\theta_{tar}$ .
- The story damper ( $\mu_{di}$ ) and RC frame ( $\mu_{fi}$ ) ductilities at the  $\theta_{\max}$  are the same in all stories, as well as the steel frame-to-damper stiffness ratio ( $\gamma_{si}$ ) are the same in all stories.

$$K_{di} = \frac{Q_i}{H_i} \frac{\sum_{i=1}^N (K_{f\mu} H_i^2)}{\sum_{i=1}^N (Q_i H_i)} \left( \frac{1}{\gamma_s + \frac{1}{\mu_d}} + \frac{\mu_f}{\alpha_1(\mu_f - \mu_c) + \mu_c} \cdot \frac{K_d}{K_f} \right) - \frac{K_{f\mu i}}{\gamma_s + \frac{1}{\mu_d}} \quad ; (\mu_c < \mu_f \leq 1)$$

$$K_{di} = \frac{Q_i}{H_i} \frac{\sum_{i=1}^N (K_{f\mu} H_i^2)}{\sum_{i=1}^N (Q_i H_i)} \left( \frac{1}{\gamma_s + \frac{1}{\mu_d}} + \frac{\mu_f}{\alpha_1(1 - \mu_c) + \mu_c} \cdot \frac{K_d}{K_f} \right) - \frac{K_{f\mu i}}{\gamma_s + \frac{1}{\mu_d}} \quad ; (1 < \mu_f)$$

### 2.2.1. Fluid viscous damper

The concept of the proposed method is extended to FVD, which is a velocity-dependent device. Although the FVD does not have any inherent stiffness, this study assumes the viscous dampers are used serially attached to the elastic brace, which exhibits stiffness. Fig. 5(a) and Fig. 5(b) show the retrofitted model and retrofit configuration of the RC frame using FVD with SF. The viscous damper and additional SF force-deformation relationship are shown in Fig. 5(c). In this study, the viscous damper hysteretic response is considered as an equivalent SDOF system parallel to the SDOF<sub>RC</sub> and the SF. The hysteretic energy of the FVD ( $E_{d,FVD}$ ) is given in Eq. (11), where  $K''_a$  is loss stiffness. The storage stiffness of the viscous damper ( $K'_a$ ) can be calculated by Eq. (12), where  $K_b$  is the elastic brace stiffness,  $C_d$  is the damping coefficient of FVD, and  $\omega$  is circular frequency. The ratio of the  $K''_a$  to  $K_f$  is introduced in Eq. (13), where  $\eta_a$  is the loss factor of the brace-damper subassembly in Eq. (14). The  $K''_a$  can be obtained by Eq. (15).

$$E_{d,FVD} = \pi K''_a (\mu_f \delta_{fy})^2 \quad (11)$$

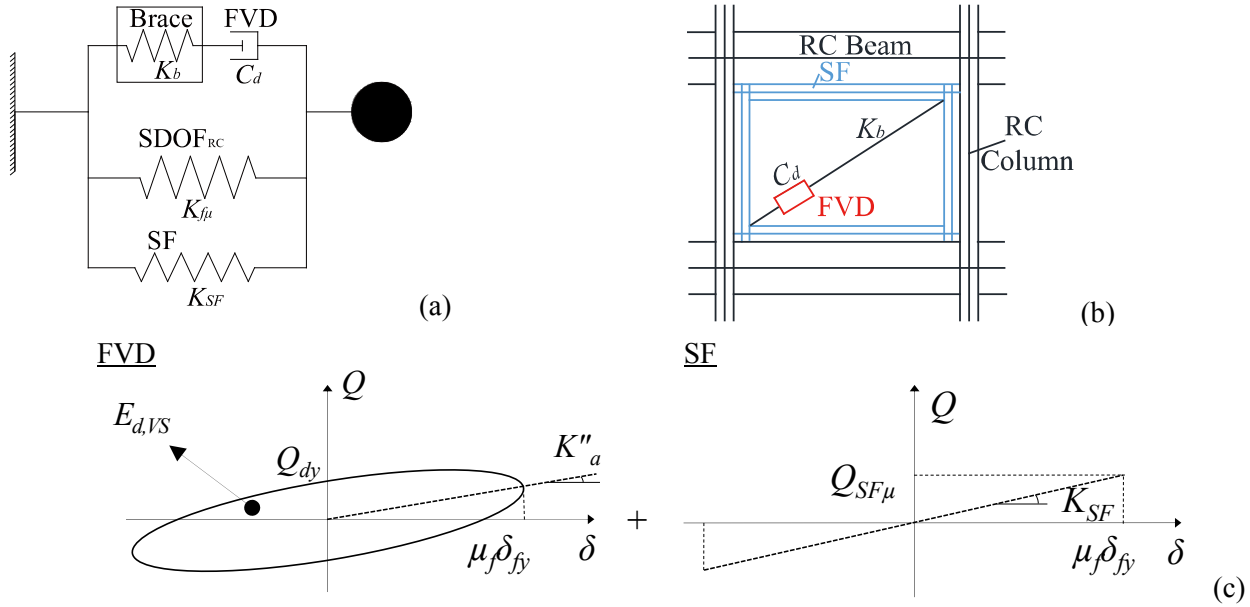


Fig. 5 –FVD (a) Retrofitted model, (b) Retrofit configuration, and (c) Hysteresis of FVD with a brace and SF

$$K'_a = \frac{C_d^2 K_b \omega^2}{K_b^2 + C_d^2 \omega^2} \quad (12)$$

$$\frac{K''_a}{K_f} = \frac{p \left( \frac{\theta_{f\mu}}{\theta_{tar}} \right)^2 D_h^2 - p}{\gamma_s + \frac{1}{\eta_a}} \quad (13)$$

$$\eta_a = \frac{K''_a}{K'_a} = \frac{K_b}{C_d \omega} \quad (14)$$

$$K''_a = \frac{C_d K_b^2 \omega}{K_b^2 + C_d^2 \omega^2} \quad (15)$$

The required loss stiffness of FVD ( $K''_{ai}$ ) given in Eq. (16) can obtain with the following same assumptions as in the EPD case, where the  $\eta_a$  is assumed to be 1 for this study, and it is substituted in Eq. (15). Therefore, the required damping coefficient of FVD in the  $i^{\text{th}}$  story ( $C_{di}$ ) can be obtained by Eq. (17).

$$K''_{ai} = \frac{Q_i}{H_i} \frac{\sum_{i=1}^N (K_{f\mu i} H_i^2)}{\sum_{i=1}^N (Q_i H_i)} \left( \frac{1}{\gamma_s + 1} + \frac{\mu_f}{\alpha_1 (\mu_f - \mu_c) + \mu_c} \cdot \frac{K''_a}{K_f} \right) - \frac{K_{f\mu i}}{\gamma_s + 1} \quad ; (\mu_c < \mu_f \leq 1)$$

$$K''_{ai} = \frac{Q_i}{H_i} \frac{\sum_{i=1}^N (K_{f\mu i} H_i^2)}{\sum_{i=1}^N (Q_i H_i)} \left( \frac{1}{\gamma_s + 1} + \frac{\mu_f}{\alpha_1 (1 - \mu_c) + \mu_c} \cdot \frac{K''_a}{K_f} \right) - \frac{K_{f\mu i}}{\gamma_s + 1} \quad ; (1 < \mu_f)$$

$$C_{di} = \frac{2K''_{ai}}{\omega} \quad (17)$$



### 3. Target building and seismic region

A typical four-story RC school building is chosen as an example building in this study. The example RC building is located in Chiang Rai province, which is the northernmost province of Thailand. Fig. 6a and Fig. 6b show the elevation and structural plan of the four-story RC school building, respectively. Fig. 6c and Fig. 6d shows the cross-sectional member details of the RC beams and columns, respectively. The compressive strength of the concrete is 24 MPa, and the yield stress of the rebar is 300 MPa. The masses are 184 tons in the 1<sup>st</sup> to 3<sup>rd</sup> stories and 171 tons in the 4<sup>th</sup> story. The concrete slab is typically 100 mm thick in each story. Based on the modal analysis, the first to the third mode periods are 1.249 sec (translation in the longitudinal direction), 0.871 sec (torsional deformation), and 0.830 sec (translation in the transverse direction), respectively.

Fig. 7a and Fig. 7b present the design acceleration and displacement spectra, respectively, corresponding to a damping ratio of 5% in Thailand (Chiang Rai province) [18], where  $S_{DS}$  is the design spectral acceleration when the period is 0.2 sec and  $S_{D1}$  is the design spectral acceleration when the period is 1.0 sec. The target story drift ratio ( $\theta_{tar}$ ) is limited to 1/200 rad. (0.5% rad.).

The four-story RC school building is simplified to the SDOF<sub>RC</sub> model with the  $H_{eq}$  equals to 10 m (73.5% of building height), and the  $M_{eq}$  equals 577 tons (80% of the total mass). The lateral stiffness of the SDOF<sub>RC</sub> model in the longitudinal ( $K_{f,l}$ ) and transverse ( $K_{f,t}$ ) directions are 14.6 and 33.1 kN/mm, respectively. Based on the design displacement spectrum (Fig. 7b), the spectral displacements of the SDOF<sub>RC</sub> model are 76 and 48 mm in the longitudinal ( $\delta_{d,l}$ ) and transverse ( $\delta_{d,t}$ ) directions, respectively. The maximum story drift ratio ( $SDR_{max}$ ) of the building in the longitudinal and transverse directions before retrofit is 0.76% ( $=\delta_{d,l}/H_{eq}$ ) and 0.48% rad. ( $\delta_{d,t}/H_{eq}$ ), respectively. Therefore, the retrofit is required only for the longitudinal direction. Fig. 6a also indicates retrofit location.

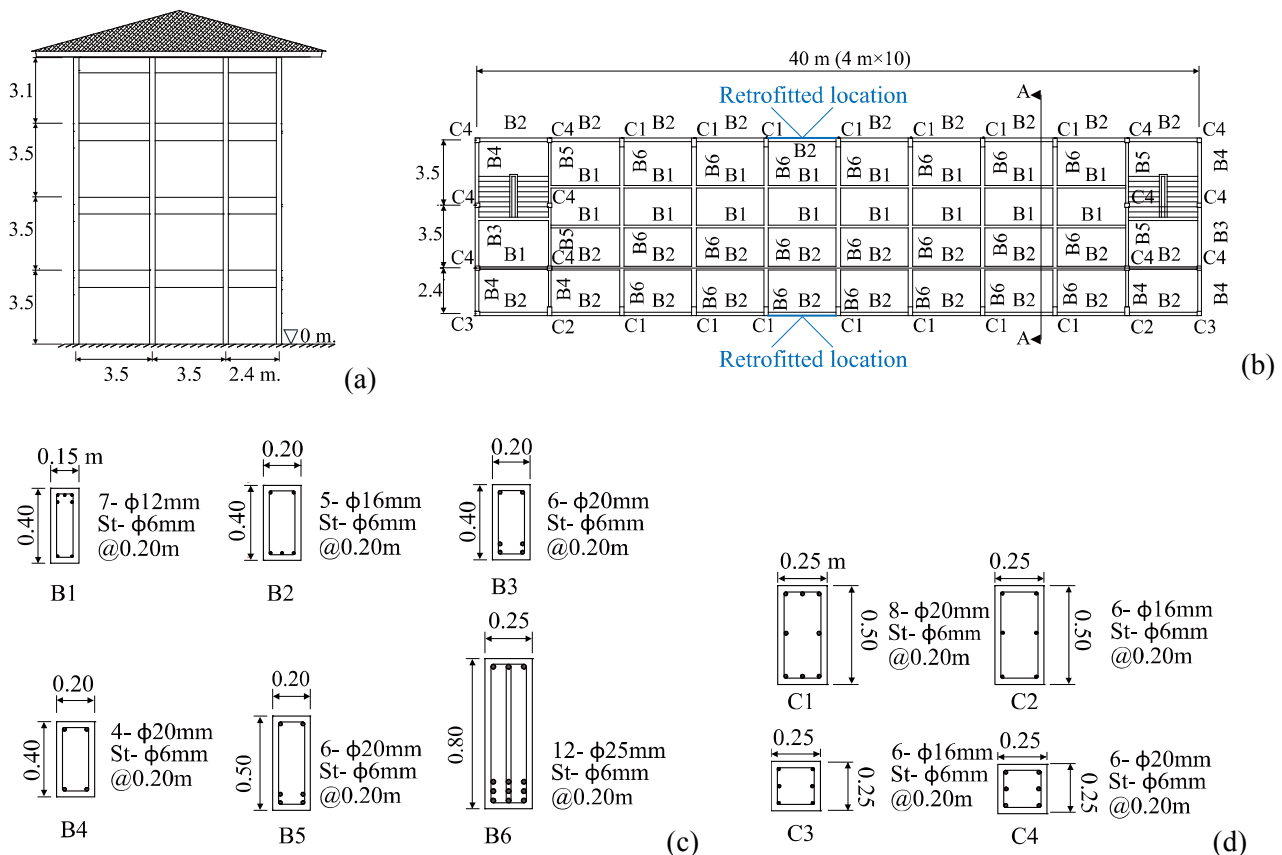


Fig. 6 –Details of the four-story RC school building (a) Section A-A, (b) Structural plan, (c) Cross-sectional details of the RC beams, and (d) Cross-sectional details of the RC columns

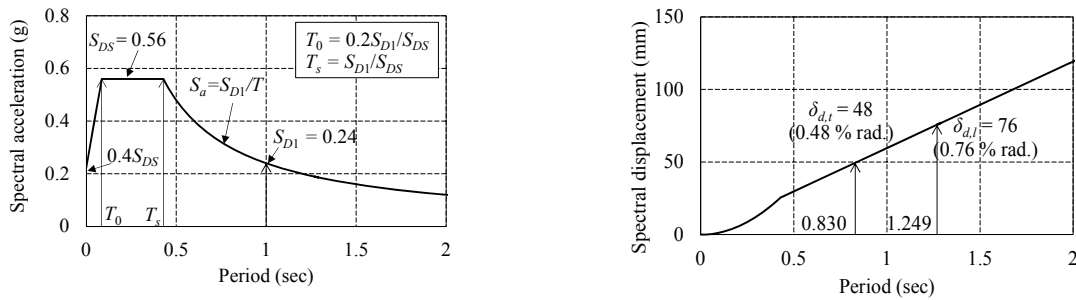


Fig. 7 –Design spectra of Chiang Rai province in Thailand (a) Acceleration and (b) Displacement.

#### 4. Validation of the proposed retrofit design method

The proposed retrofit design method is examined on the target four-story RC school building. NLRHA is performed in order to validate the proposed retrofit method. Retrofit design examples of the four-story RC buildings using either EPD or FVD with SF is presented in this section. The details of ground motions, analysis models, and the analysis results are shown in the following.

##### 4.1. Retrofit design example

Table 1 shows the retrofit design result of the example four-story RC school buildings using EPD with SF. The elastic stiffness of RC building in the  $i^{\text{th}}$  story ( $K_{fi}$ ) is obtained by performing pushover analysis. The EPD to frame stiffness ratio ( $K_d/K_f$ ) of 0.90 is calculated using Eq. (9). The required stiffness of EPD in the  $i^{\text{th}}$  story ( $K_{di}$ ) is obtained by Eq. (10). Based on the proposed retrofit design method using EPD, the required EPD stiffness in the 4<sup>th</sup> ( $K_{d4}$ ) is less than 0 under the design  $SDR_{tar}$  of 0.5%. Therefore, there is no need to install the EPD in the 4<sup>th</sup> story. This will be confirmed by the NLRHA results in the following sections.

Table 1. EPD distribution

Story	$K_{fi}$ (kN/mm)	$K_d/K_f$	$h_{eq}$	$K_{di}$ (kN)
4	39.6	0.90	0.064	-
3	32.2			34.8
2	32.1			65.4
1	45.3			43.7

Table 2 presents the retrofit design result of the example four-story RC school buildings using FVD with SF. The ratio of  $K''_d/K_f$  is obtained by Eq. (13), the  $K''_{ai}$  is calculated by Eq. (16), and the  $C_{di}$  is obtained by Eq. (17). Based on the proposed retrofit design method using FVD, the required loss stiffness of FVD in the 4<sup>th</sup> story ( $K''_{a4}$ ) is less than 0, which is the same as the retrofitted RC building by using EPD under the design  $SDR_{tar}$  of 0.5%. Therefore, there is no need to install a FVD in the 4<sup>th</sup> story.

Table 2. FVD distribution

Story	$K''_d/K_f$	$h_{eq}$	$\omega$ (rad/s)	$K''_a$ (kN/mm)	$C_{di}$ (kN·sec/mm)
4	0.20	0.051	5.03	-	-
3				6.62	2.63
2				14.56	5.79
1				6.33	2.52

##### 4.2. Analytical model

A three-dimensional (3-D) model was constructed using ETABS [19]. The model of the building without any retrofit (3D-R) is used as a benchmark model. Fig. 8 shows the 3-D model with retrofit using the EPD (3D-EPD). The model retrofitted with the FVD (3D-FVD) is constructed the same as the 3D-EPD apart from the



FVD is substituted instead of the EPD. It should be noted that the RC columns, RC beams, and slabs of all three models are the same. Based on Fig 7(b), the retrofit is required only for the longitudinal direction; therefore, the seismic response only in the longitudinal direction will be discussed in the following sections. The period of the 3-D model in the longitudinal direction of the 3D-FVD model is constant at 1.249 sec when compare the 3D-R model. The period decreases to 0.870 sec in the EPD model after the EPD has been installed.

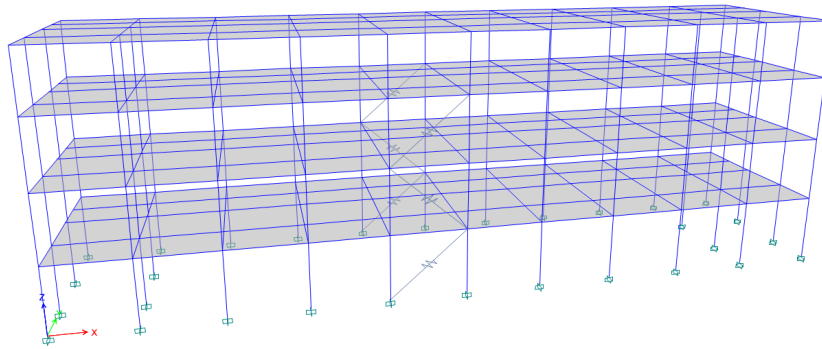


Fig. 8 –3-D view of the analytical model

### 4.3. Ground motions for NLRHA

A suite of scaled single component records is selected from the PEER NGA2 ground motion database 2 [20]. The detail of each ground motion is shown in Table 3, and the scaled spectra are shown in Fig. 9. The scaling is conducted over a target period range of  $0.2T_1$  and  $1.5T_1$ , where  $T_1$  is the fundamental period of the non-retrofitted building. The scaling follows the requirements described in [17].

Table 3 Ground motions used for NLRHA

Ground ID (GM)	Earthquake Name	Year	Station Name	Magnitude	Scaling factor
1	Imperial Valley-06	1979	El Centro Array #13	6.5	1.89
2	Kobe Japan	1995	Sakai	6.9	1.32
3	El Mayor-Cucapah	2010	Holtville Post	7.2	1.20

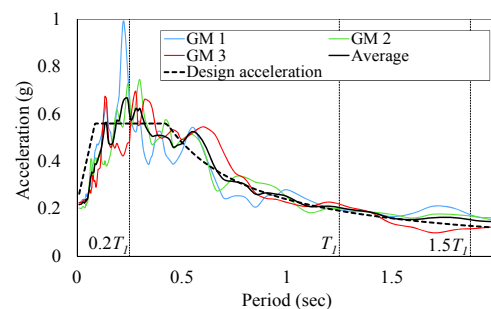


Fig. 9 – 5% damped response spectra of the scaled ground motions and the design acceleration spectrum.

### 4.4. NLRHA result

The NLRHA is performed on the 3D-R, 3D-EPD, and 3D-FVD models using three scaled ground motions to investigate the seismic response and validate the proposed retrofit method. The results of each ground and average from the NLRHA are shown in the following.



#### 4.4.1. Maximum story drift ratio

The maximum story drift ratio ( $SDR_{max}$ ) responses of each ground motion for the 3D-R, 3D-EPD, and 3D-FVD models are shown in Figs 10(a), 10(b), and 10(c), respectively. Fig 10(a) shows the  $SDR_{max}$  of the RC building without retrofit (3D-R) model. The  $SDR_{max}$  in 1<sup>st</sup> to 3<sup>rd</sup> stories, as obtained from NLRHA with all ground motions, exceed the  $SDR_{tar}$  of 0.5% rad. These results agree with the proposed retrofit method that no damper is required in the 4<sup>th</sup> story, as shown in Table 1, for the case of installing EPD and Table 2 for the case of installing FVD. Fig 10(b) and Fig 10(c) present the  $SDR_{max}$  of the 3D-EPD and 3D-FVD, respectively. The analysis results of all ground motions indicate that the proposed retrofit method using either EPD or FVD with SF can efficiently limit the  $SDR_{max}$  in every story within  $SDR_{tar}$  of 0.5% rad. The  $SDR_{max}$  is uniform after retrofit using both types of dampers with SF. The  $SDR_{max}$  of all stories except the 4<sup>th</sup> story is in line with the  $SDR_{tar}$  of 0.5% rad. It implies that the proposed retrofit method using either EPD or FVD with SF can result in  $SDR_{max}$  close to the  $SDR_{tar}$ .

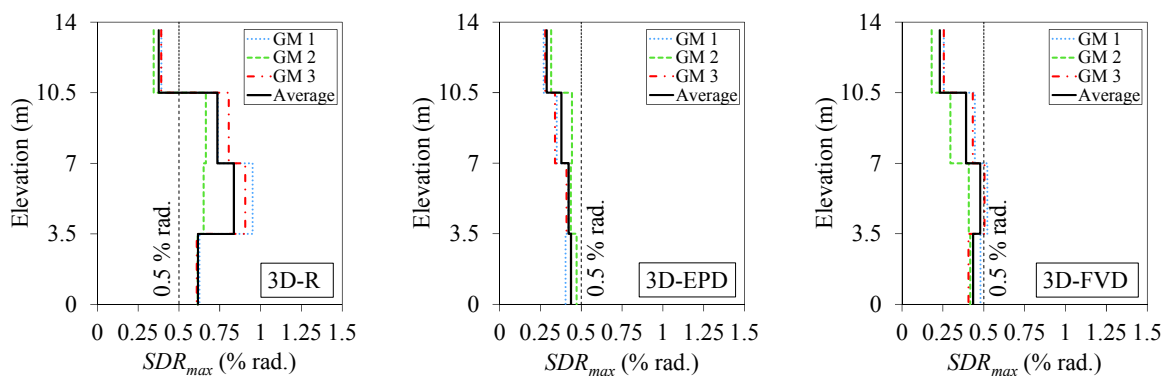


Fig. 10 –Maximum story drift ratio

#### 4.4.2. Residual story drift ratio

The residual drift ratio ( $SDR_{re}$ ) responses of each ground motion for the 3D-R, 3D-EPD, and 3D-FVD models are shown in Figs 11(a), 11(b), and 11(c), respectively. Figs 11(a) shows  $SDR_{re}$  of the RC building without retrofit. The analysis result of the bare RC building indicates that the  $SDR_{re}$  exceeds 0.1% for the 1<sup>st</sup>, 2<sup>nd</sup>, and 3<sup>rd</sup> stories, and the distribution of  $SDR_{re}$  along the building height is not uniform. Figs 11(b) and 11(c) present the  $SDR_{re}$  of 3D-EPD and 3D-FVD models, respectively. The results of all ground motions for both 3D-EPD and 3D-FVD models indicate that the  $SDR_{re}$  is reduced significantly, and the  $SDR_{re}$  is much smaller than 0.1% after retrofitted RC building using either EPD or FVD with SF. It implies that both structural and non-structural damage can be mitigated for the retrofitted buildings.

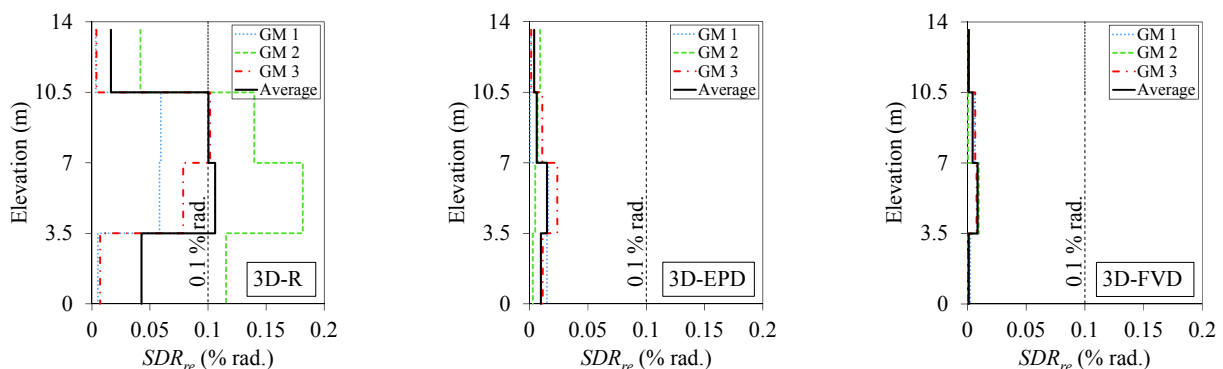


Fig. 11 –Residual story drift ratio



#### 4.4.3. Maximum acceleration

Figs 12 shows the maximum acceleration ( $A_{max}$ ) responses of the 3D-R, 3D-EPD, and 3D-FVD models as obtained from the NLRHA. The trend of the  $A_{max}$  is decreased for the retrofitted buildings by both EPD and FVD. Based on the NLRHA analysis, the  $A_{max}$  of the retrofitted RC building with FVD significantly reduces by around 29 % to 44 % when compared to the bare RC building without retrofit. For the retrofitted with EPD, the  $A_{max}$  decreases by about 10% when compared to the bare RC building without retrofit. The reduction in the  $A_{max}$  value of the retrofitted with dampers is expected because the  $SDR_{max}$  can be efficiently limited by using dampers, and the energy-dissipated by the dampers can increase the total damping of the retrofitted buildings.

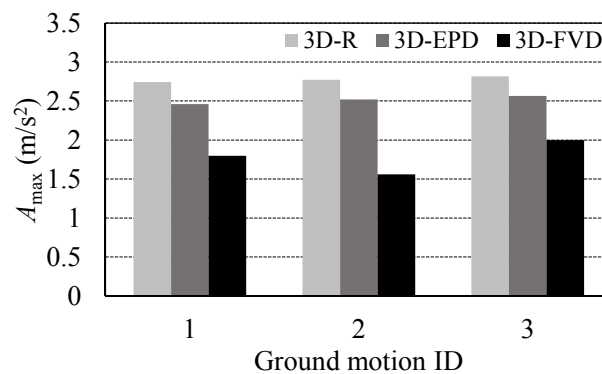


Fig. 12 –Maximum roof acceleration

## 5. Conclusions

The seismic retrofit method of RC building using either EPD or FVD implementing SF based on equivalent linearization without an iterative procedure to achieve the design  $SDR_{tar}$  is introduced. The proposed method is validated by NLRHA on the four-story RC school building. The response of the existing bare RC building was compared to retrofitted RC buildings using dampers with SF. The conclusions of this study can be drawn as follows:

- 1) The installation of either EPD or FVD to the bare RC building can improve the seismic performance of the RC building. The  $SDR_{max}$  of the retrofitted building can be reduced significantly.
- 2) Based on the example retrofit design, the  $SDR_{max}$  in the 1<sup>st</sup> to the 3<sup>rd</sup> stories as obtained from NLRHA with all ground motions exceed the  $SDR_{tar}$ . However, the  $SDR_{max}$  in the 4<sup>th</sup> was within the  $SDR_{tar}$ . This agrees with the proposed retrofit evaluation that no retrofitted damper is required in the 4<sup>th</sup> story.
- 3) The NLRHA analysis result suggests that the proposed retrofit method can result in the  $SDR_{max}$  close to the design  $SDR_{tar}$ . The  $SDR_{max}$  values were controlled within the  $SDR_{tar}$  in all stories when both types of dampers retrofitted the RC building.
- 4) The  $SDR_{re}$  of the retrofitted RC building using either EPD or FVD implementing SF can be controlled within 0.1%, which implied that both structural and non-structural damage could be mitigated in the retrofitted buildings.
- 5). Based on the example retrofit design, the trend of  $A_{max}$  was decreased after the building was retrofitted. The reduction in the  $A_{max}$  value can be expected because the  $SDR_{max}$  can be efficiently limited by using both types of the damper, and the energy-dissipated by the dampers can increase the total damping of the retrofitted buildings. The  $A_{max}$  is significantly reduced by 29% to 44% for the building retrofitted with FVD, and the reduction of  $A_{max}$  is reduced by 10% for retrofitted RC building with EPD.



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