Response Control on Seismic Retrofit of Low-Rise RC Frame Using Viscous Damper

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Abstract. In recent years, seismic design and detailing requirements for buildings have considerably improved worldwide. For example, in Thailand, a new seismic design code was published in 2021, but many existing buildings do not satisfy the new code and require retrofit. The seismic retrofit is required to improve the seismic performance of the existing building. However, the response control method to control the target story drift ratio of the retrofitted RC buildings using the viscous damper is lack introduction. This study proposes a response control retrofit strategy using viscous dampers, designed using an equivalent linearization approach. A constant stiffness method is introduced to efficiently distribute the dampers along with the building height. The stiffness of the damper is equally distributed for all stories. A design example is introduced of a low-rise reinforced concrete school building in Thailand, which was damaged in the 2014 Mae Lao earthquake. Nonlinear response history analysis is used to validate the introduced method. The results indicate that the average peak story drifts ratios can be controlled within the target story drift ratio of 0.67% rad.

Keywords: Response control · Seismic retrofit · Low-rise RC building · Viscous dampers

1 Introduction

Thailand has historically been considered to have a low seismic hazard, and the most current existing buildings were designed to resist only gravity load. However, the seismic resistance was not considered in the designs.

In recent years, the earthquake has damaged several buildings around the world. Therefore, in 2009, the Department of Public Works and Town & Country Planning of Thailand published a seismic design specification for new buildings [1], followed by a specification for seismic retrofit [2]. Shortly after the May 15, 2014 Mae Lao earthquake struck, causing extensive damage to older buildings that were constructed before the seismic specifications were implemented. Much of the damage was observed in reinforced concrete (RC) structures, as reported in [3, 4] including some school buildings. Figure 1a shows a typical 2-story RC school building in Thailand, which was constructed in many places in the country. The buildings are non-ductile RC moment frames with vertical

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irregularities due to infill masonry walls. The 2-story building, as shown in Fig. 1b, received significant structural damage during the Mae Lao earthquake, as indicated by the severe damage to the beam-column joint at the top of the ground story columns. According to the severe damage from the Mae Lao in 2014, the Ministry of Interior of Thailand published a new seismic design code, which is a regulation in 2021 [5]. This affects that all buildings in the seismic region in Thailand are required to improve their seismic performance by strengthening or retrofitting.

A conventional retrofit solution for seismically deficient reinforce concrete (RC) frames is to install a stiff shear wall [6, 7], which limits drift and ensures that the mainframe remains elastic but imposes large floor accelerations. This implies extensive nonstructural damage, as building contents and nonstructural components are unlikely to be detailed for seismic resistance in Thailand. An alternative retrofit solution is to employ energy dissipation devices to control both drift and accelerations while protecting the existing structure.

Energy dissipation devices have been reported to be an effective seismic retrofit solution for RC frame buildings and have been applied in practice. A retrofit design method for RC frame structures, where the buckling-restrained braces (BRBs), are installed in parallel with a supplementary elastic steel frame was introduced in [8, 9]. In addition, a retrofit RC building was proposed in the study [10]. The results from the study [8–12] indicated that energy-dissipating devices can improve efficiently the seismic performance of the retrofitted RC buildings. The challenge in Thailand is that the seismic hazard is relatively small, with response control retrofits requiring smaller dampers installed at fewer stories than in a typical Japanese application. While still a potentially effective retrofit solution, the low demands introduce unique challenges in determining an efficient number, size and distribution of dampers, as the optimal damper type, distribution and design approach may be different from those countries. Although the study [9] proposed installing viscous dampers into the target building, the controlled response on seismic retrofit RC building method with a viscous damper is rarely proposed.

This study introduces a response control method to retrofit the RC buildings, which is named a constant stiffness method. The method is used to design and retrofit the example 2-story building as shown in Fig. 1. The seismic performance of the existing RC building and the retrofitted RC building is investigated and compared. The design is verified through nonlinear response history analysis.

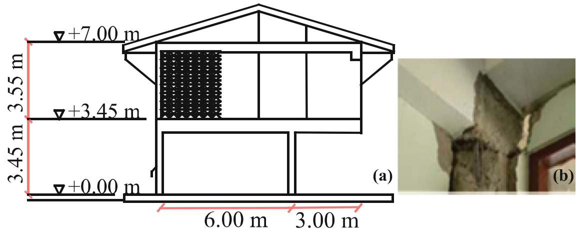

Fig. 1. School building: (a) Elevation of 2-story, (b) Observed damage.

2 Constant Stiffness Method

The inelastic story force-displacement response of the bare RC frame is first obtained through pushover analysis. While the example building as shown in Fig. 1 was subjected to large drift and strength degradation due to column bending failure in Mae Lao 2014 earthquake, only the response up to the target story drift is needed for this analysis, which is set as $\theta_{tar} = 1/150$ (0.67% rad) to validate the proposed design method.

A tri-linear degrading Takeda model is adopted to represent the existing RC frame [13] and is calibrated to match the area under the pushover curve at each story i^{th} story. The post-yield response is assumed perfectly plastic ($\alpha_2 = 0$), the yield story drift θ_{fy} is limited to 1/100–1/300 rad, and the crack (δ_{fci}) to yield (δ_{fyi}) displacement ratio is initially set as $\mu_c = 0.1$ [13], but permitted up to $\mu_c = 0.2$. The yield shear force Q_{fyi} and displacement δ_{fyi} are then estimated, and the cracking shear force Q_{fci} and displacement δ_{fci} are adjusted to produce the same shear force ratio $N = Q_{fyi}/Q_{fci}$ and cracked stiffness ratio $\alpha_1 = [(Q_{fyi} - Q_{fci})/(\delta_{fyi} - \delta_{fci})]/K_{fi}$ at all stories, where the initial story stiffness $K_{f0i} = Q_{fci}/\delta_{fci}$. This treatment reduces the multi-story frame to a simplified representation, with the same pre-yield stiffness ratio α_1, crack-to-yield drift ratio μ_c, ductility $\mu_f = \delta_{tar}/\delta_{fyi}$, and secant stiffness $K_{f\mu} = pK_{f0}$ at each story. The multi-degree of freedom (MDOF) model is then reduced to an equivalent single-degree-of-freedom (SDOF) system using the equivalent height (H_{eq}), mass (M_{eq}), and stiffness (K_f) [8]. The cyclic hysteretic response of the SDOF system is shown in Fig. 2 for the cracked and yielding stages.

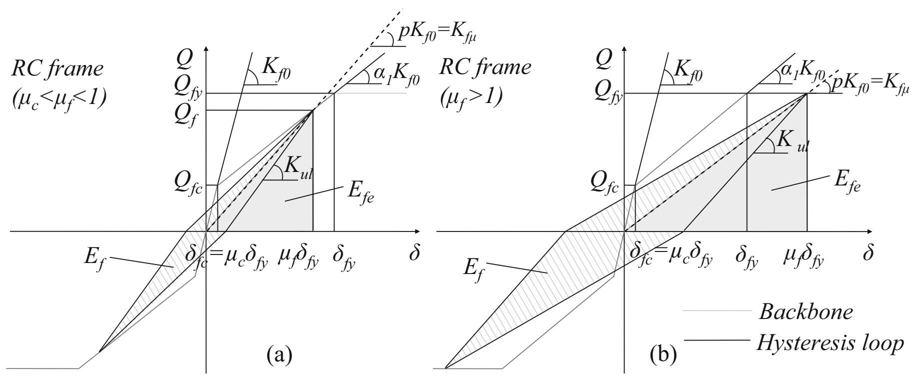

Fig. 2. Hysteresis loops for RC frame: (a) Cracked ($\mu_c\mu_f > 1$, $\mu_f < 1$) and (b) Yielding ($\mu_f > 1$).

The hysteretic energy dissipated by the RC frame (E_f) depends on the unloading stiffness (K_{ul}), with the unloading stiffness degradation parameter λ assumed as 0.4 [13]. The equivalent hysteretic damping for a constant cyclic displacement ($h'_{f\mu} = h'_{f0} + E_f/4\pi E_{fe}$) is then determined from the hysteretic energy E_f, strain energy E_{fe} and intrinsic damping h_{f0} is assumed to be 0.03 for RC structures.

As displacement ductility in each cycle varies when subjected to earthquake excitation, the study [14] introduced the average damping concept (Eq. 1) is employed.

$$h_{f\mu} = h_{f0} + \frac{1}{\mu_{tar}} \int_{1}^{\mu_{tar}} \left(h'_{f\mu} - h_{f0} \right) d\mu \quad (1)$$

However, for simplicity, the average equivalent damping ($h_{f\mu}$) (Eq. 2) may be estimated from the equivalent damping of the maximum cycle ($h'_{f\mu}$) and a calibrated damping reduction factor ($R_{f\mu}$). The average $h_{f\mu}$ and peak $h'_{f\mu}$ equivalent damping are shown in Fig. 3a and the corresponding reduction factors $R_{f\mu}$ is shown in Fig. 3b.

$$h_{f\mu} = h_{f0} + R_{f\mu}\left(h'_{f\mu} - h_{f0} \right) \quad (2)$$

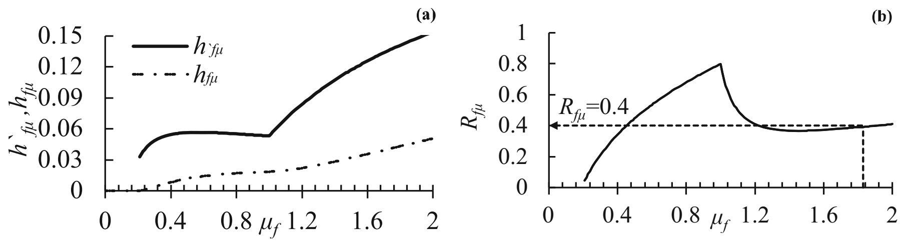

Fig. 3. Equivalent damping reduction factor: (a) Equivalent damping and (b) $R_{f\mu}$.

The spectral displacement S_d ($T_{f\mu}$,$h_{f\mu}$) of the bare RC frame is estimated from the design elastic displacement response spectrum at the secant period ($T_{f\mu}$), reduced from the 5% damped spectrum using equivalent damping ($h_{f\mu}$) and reduction factor proposed which was introduced as $a = 25$ in the study [15]. The secant period is given by Eq. 3 and uses the secant stiffness ($K_{f\mu}$) of the bare RC frame at the target drift. The roof drift of the bare RC frame ($\theta_{f\mu}$) is estimated from Eq. 4 and dampers are required if $\theta_{f\mu}$ exceeds the target story drift θ_{tar}.

$$T_{f\mu} = 2\pi\sqrt{\frac{M_{eq}}{K_{f\mu}}} \quad (3)$$

$$\theta_{f\mu} = \frac{S_d(T_{f\mu},\ h_{f\mu})}{H_{eq}} \quad (4)$$

The viscous (VS) dampers are velocity-dependent devices, which are effective in controlling drifts and enhancing the system energy dissipation. The VS are typically installed in series with an elastic brace element, with the assembly acting in parallel to the RC and supplemental steel frames, as indicated by Fig. 4(a). The component force-displacement relationships are shown in Fig. 4(b), where E_{dVS} is the equivalent damping of the viscous damper, K_a'' the loss stiffness Eq. 8, C_d the damping coefficient, K_b the brace stiffness, ω the circular frequency, $E_{\sum e}$ the equivalent potential energy of a total system, K_a' the storage stiffness Eq. 5, and η_a the brace-damper subassembly's loss factor Eq. 7.

$$K_a' = \frac{C_d^2 K_b \omega^2}{K_b^2 + C_d^2 \omega^2} \tag{5}$$

$$\frac{K_a''}{K_f} = \frac{p\left(\frac{\theta_{f\mu}}{\theta_{tar}}\right)^2 D_h^2 - p}{\gamma_s + \frac{1}{\eta_a}} \tag{6}$$

$$\eta_a = \frac{K_a''}{K_a'} = \frac{K_b}{C_d \omega} \tag{7}$$

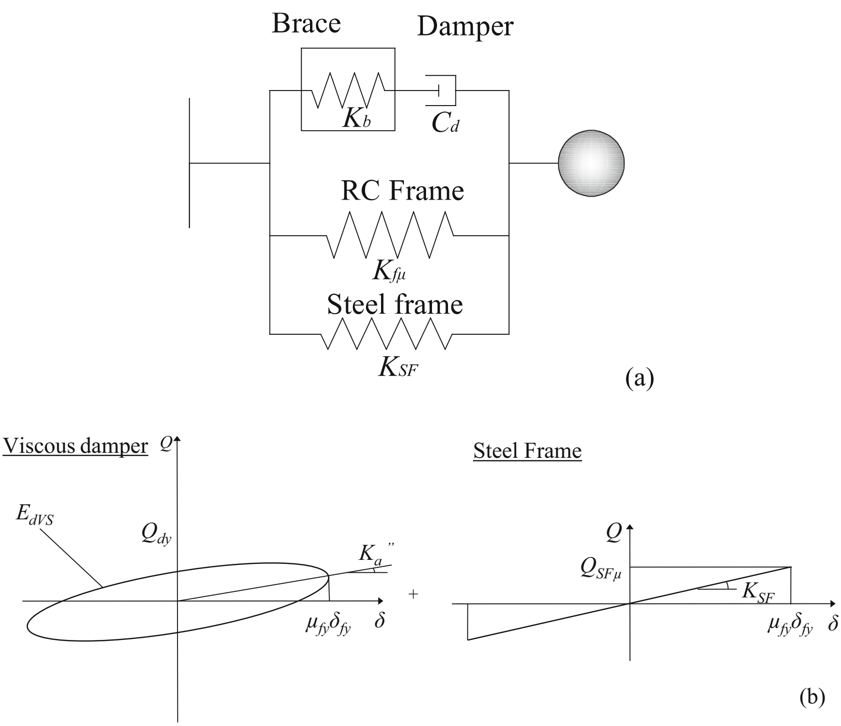

Fig. 4. (a) Viscous damper with the brace, RC frame and elastic steel frame model. (b) Viscous damper and elastic steel frame force-displacement model.

$$K_a'' = \frac{C_d K_b^2 \omega}{K_b^2 + C_d^2 \omega^2} \tag{8}$$

The required loss stiffness ratio $(r_{dVS}) = K_a''/K_f$ of the brace-damper subassembly is referred to as the added component and is given by for the RC frame cracking and yielding stages as shown in Eqs. 9(a) and 9(b), respectively.

$$r_{dVS} = \frac{K_a''}{K_f} = \frac{p\left(\left(\frac{\theta_{f\mu}}{\theta_\Sigma}\right)^2 - 1\right)\left(1 + 25\left(h_{f0} + \frac{1}{\pi} \cdot \frac{\mu_c(1-p)}{p\mu_f + \mu_c} \cdot R_{f\mu}\right)\right)}{\left(1 + 25h_{f0}\right)(\gamma_s + 1/\eta_a) + (0.5x25R_{eqVS})} (\mu_c\mu_f > 1, \mu_f < 1) \tag{9a}$$

$$r_{dVS} = \frac{K_a''}{K_f} = \frac{p\left(\left(\frac{\theta_{f\mu}}{\theta_\Sigma}\right)^2 - 1\right)\left(1 + 25\left(h_{f0} + \frac{1}{\pi} \cdot \frac{p\mu_f + \mu_c - p\left(\mu_f\right)^\lambda (1+\mu_c)}{p\mu_f + \mu_c} \cdot R_{f\mu}\right)\right)}{\left(1 + 25h_{f0}\right)(\gamma_s + 1/\eta_a) + (0.5x25R_{eqVS})} (\mu_f > 1) \tag{9b}$$

Though the supplemental damping provided by the viscous dampers is velocity, rather than displacement dependent, the hysteretic damping of the RC frame still contributes to equivalent damping of the system, which consequently varies cycle by cycle. The reduction factor R_{eqVS} relating the average (h_{eq}) and peak cycle (h'_{eq}) equivalent damping is shown in Fig. 5.

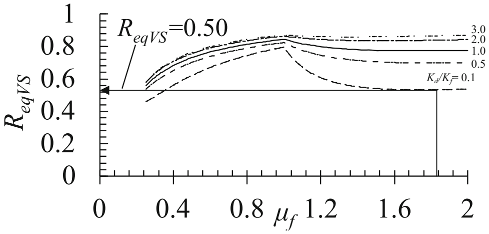

Fig. 5. Damping reduction factor for the system with VS dampers (R_{eqVS}).

3 Design Example and Validation

3.1 Design Example

This section applies the constant drift method procedure to the 2-story RC school buildings depicted in Fig. 1, which requires seismic retrofit. Thailand Seismic Design Code [5]. The newest seismic Thai code has been written based on ASCE 7-05 [16], and the design level spectral response acceleration parameters for these structures are $S_{DS} = 0.56$(g) and $S_{D1} = 0.24$(g) (site class D, Phan, Chiang Rai), approximately half of the seismic demands in Japan.

The story masses of the 2-story building are 266 and 172 tons at the first and roof stories, respectively, and the fundamental period of the bare RC frame is 0.59 s in both the longitudinal and transverse directions. Pushover curves and calibrated tri-linear Takeda models for the 2-story building are shown in Fig. 6 for the first story and second story, respectively. Figure 6a and 6b illustrate the story shear to story displacement of the 1st story for longitudinal and transverse directions, respectively. Figure 6c and 6d show the story shear to story displacement of the 2nd story for longitudinal and transverse directions, respectively. Structural properties of the bare $SDOF_{RC}$ structures are summarized in Table 1. The ratios of the area under the pushover curves and tri-linear model ($A_{pushover}/A_{tri}$) are close to 1.0 at each story, indicating a good fit. Table 2 shows damper distributions for 2-story building model.

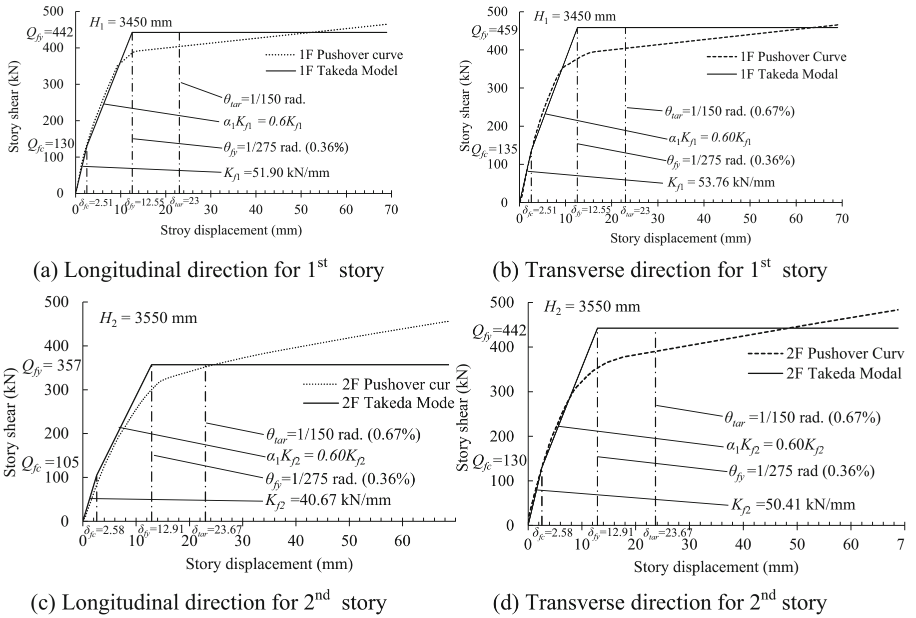

Fig. 6. Pushover curve and tri-linear model of the 2-story building (a) Longitudinal direction for the first story, (b) Transverse direction for the first story, (c) Longitudinal direction for the second story, (d) Transverse direction for the second story.

Table 1. Characteristic of bare RC frame

Direction	μ_f	K_{f0} kN/mm	H_{eq} mm	M_{eq} ton	μ_c	α_1	$T_{f\mu}$ sec	$K_{f\mu}$ kN/mm
$R_{f\mu} = 0.6$ and $\theta_{tar} = 1/150$ rad								
Longitudinal	1.83	46.6	4510	412	0.20	0.60	0.97	17.3
Transverse	1.83	49.4	4469	415	0.20	0.60	0.95	18.3

Table 2. Damper distributions for 2-story building model

Direction	Story	K''_a/K_f	K_{fi} kN/mm	K''_{ai} kN	K_b kN/mm	h_{eq}	C_d kN · s/mm	n_i
Longitudinal	2	0.11	40.7	4.4	68.2	0.104	0.36	2
	1		51.9	5.7	68.7		0.46	2
Transverse	2	0.09	50.4	4.5	68.2	0.097	0.36	1
	1		53.8	4.8	68.7		0.39	1

3.2 Validation of Effectiveness of Constant Stiffness Method

To validate the retrofit designs, nonlinear response history analyses were performed, targeting the design acceleration response spectrum described earlier ($S_{DS} = 0.56$(g) and $S_{D1} = 0.24$(g)). Two suites of ground motions were used, reflecting common practice in Japan and the US, which the Thai code is based upon. First, a suite of four earthquake ground motions were spectrally matched, consisting of El Centro NS (1940), JMA Kobe NS (1995), TAFT EW (1925), and Hachinohe NS (1968). The duration of four observed waves was 30 s for each wave and compared to the design spectrum in Fig. 7(a). Additionally, a suite of 11 scaled single component records were selected from the PEER NGA2 ground motion database 2 (Fig. 7(b)). Scaling was conducted over a target period range of $0.2T_{1,min}$ and $1.5T_{1,max}$ following ASCE 7-16 [17], where $T_{1,min}$ and $T_{1,max}$ are the minimum and maximum fundamental periods from the two models, resulting in a target period range of 0.1 to 2 s. Records were limited to strike-slip events with magnitudes of $6 \le M_w \le 7.5$ within 20 km and on soil class D ($180 \le V_{s,30} \le 360$ m/s), consistent with the dominant seismic hazard in the Chiang Rai province and local site conditions. Scale factors varied from 0.5 to 2.0, and the average spectrum matches or exceeds the target spectrum over the range of interest. While the average acceleration response spectra are similar for both suites, the average displacement spectra exceed the design spectra by a relatively large margin for the scaled suite at periods greater than 1 s, as shown in Fig. 7 while the displacement spectra are shown in Fig. 7(c).

The peak story drift ratios of the existing RC frame and the retrofitted models using viscous dampers are shown in Fig. 8 for the 2-story building. Only the longitudinal direction is shown here as the response is similar in the two orthogonal directions. Drift is concentrated at the first story, exceeding the target story drift angle and matching the observed damage experienced during the Mae Lao earthquake.

Figure 8(a) and Fig. 8(b) show the peak story drift ratios of the existing RC frame and the retrofitted with viscous dampers, respectively. Using the spectrally matched suite, adding dampers in proportion to the RC frame stiffness using the constant stiffness method improves the seismic performance of the retrofitted building. The second story drift under all ground motions is 0.2% for the design using the constant stiffness method (Fig. 8(b)) but increases to 0.67% to 0.78% at the first story.

The scaled ground motions produce a similar average drift distribution for the 2-story building (Fig. 8) but exhibit greater record-to-record variability.

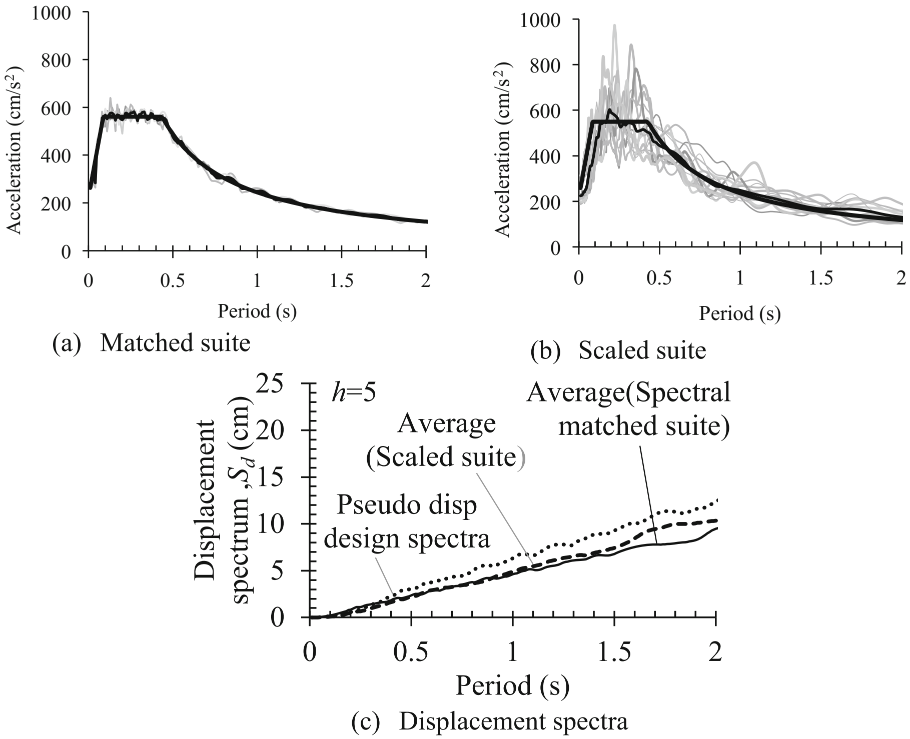

Fig. 7. 5% damped response spectra: (a) Matched suite, (b) Scaled suite and (c) Displacement spectra.

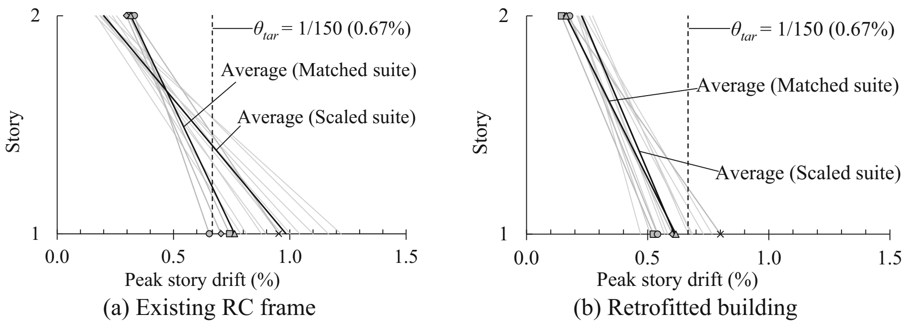

Fig. 8. Peak story drifts of the 2-story building in longitudinal direction: (a) Bare RC frame, (b) Retrofitted building.

4 Conclusions

A response control retrofit based on equivalent linearization, which is called a constant stiffness method, was introduced to assign an efficient damper distribution. The peak story drift ratios of the introduced method were compared to the existing RC frame on the example RC building. The results indicated that assigning viscous damper in proportion to the bare RC frame stiffness using the constant stiffness method improved the seismic performance of the retrofitted building. In addition, the average peak story drift ratios from both matched and scaled suites can be controlled within the target story drift ratio of 0.67% rad. Further study should apply and investigate the performance of the proposed retrofit method to taller RC buildings.

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