Seismic Resistance Efficiency of RC Building Retrofitted with Fluid Viscous Dampers

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Abstract

Nowadays, retrofitting existing structures has become a critical aspect of seismic design, particularly because many reinforced concrete (RC) buildings were designed to withstand seismic forces but not in accordance with modern code provisions. Consequently, the existing RC buildings have required retrofitting interventions in order to withstand the effects of seismic action. Therefore, this study investigated the seismic retrofit of an existing RC building using fluid viscous damper (FVD). Moreover, this study investigates the seismic performance of retrofitted structure, focusing on the effectiveness of FVD in mitigating seismic effects. A four-story RC school building in Chiang Rai, Thailand, was selected as the target building, and its seismic performance was analyzed using nonlinear response history analysis (NLRHA). The structural responses before and after retrofitting were compared to evaluate the effectiveness of seismic retrofit with FVD. In this study, the retrofit design procedure and damper distribution were determined using the constant drift method (CD method) to achieve the targeted displacement of 0.5% rad. The results indicate that retrofitted RC structure with FVD significantly reduces the structural drifts to close the target story drift ratio of 0.5% rad., thereby enhancing seismic performance. These findings provide valuable insights into effective seismic retrofit strategies for enhancing the resilience of RC buildings.

Keywords**:** Seismic retrofit, RC buildings, Fluid viscous damper, Constant drift method, Nonlinear response history analysis

1. Introduction

An earthquake is a natural phenomenon caused by the sudden release of accumulated energy within the Earth's crust, resulting in ground shaking. The intensity of an earthquake can range from imperceptible levels to severe magnitudes that cause significant damage to human life and property [1].

Historically, major earthquakes have had devastating effects on many countries worldwide. One example is the earthquake and tsunami in the Indian Ocean on December 26, 2004, which had a magnitude of 9.1–9.3. The epicenter was near Sumatra, Indonesia, triggering massive tsunamis that struck coastlines of multiple countries, including Thailand, leading to substantial loss of life [2].

Although Thailand is not directly located on a major tectonic plate boundary, it has several active fault lines that remain capable of generating earthquakes [3-4]. One of the most significant earthquakes in Thailand occurred in Mae Lao, Chiang Rai, on May 5, 2014, with a magnitude of 6.1 [5]. The intense shaking caused extensive damage to numerous small buildings, including a RC school building that suffered severe structural failure [6]. Another notable earthquake occurred in Mae Rim, Chiang Mai, on December 13, 2006, with a magnitude of 5.1. This earthquake caused the walls of houses to crack [7].

These examples demonstrate that the severity of an earthquake is not limited to its epicenter but can extend its effects to surrounding areas. Therefore, the design and construction of infrastructure and buildings to withstand seismic activity are crucial in minimizing potential damage in the future.

Most earthquake damage is observed in older RC buildings, as these structures were constructed before the enactment of the Ministerial Regulations B.E. 2007, which define load-bearing capacity, resistance, and durability requirements for buildings and the supporting ground in order to withstand seismic vibrations [8-9]. These older buildings were typically designed without considering seismic loads, as earthquake-resistant design standards were either absent or not strictly enforced at the time of construction. Consequently, these buildings often exhibit structural deficiencies, including inadequate reinforcement detailing, insufficient lateral resistance, weak column-to-beam connections, and the lack of ductility. This means that such buildings are more likely to experience severe damage or complete collapse, posing significant risks to occupants and surrounding structures [10].

Given the substantial impact of earthquakes, retrofitting older RC buildings is imperative to enhance their structural integrity and their seismic resistance. Retrofitting RC buildings involve implementing design improvements to strengthen their resistance to seismic forces [11] and reduce the risk of structural failure [12] such as columns, beams, and walls, to improve their ability to withstand lateral forces. Traditional retrofitting methods have typically included enlarging the cross-section of lower columns and adding diagonal lateral bracing to improve resistance against lateral movement. These techniques include reinforced concrete jacketing, steel jacketing, and bracing [12]. However, many existing buildings were not originally designed to endure high lateral forces, making them vulnerable to future seismic events.

On the other hand, innovative seismic improvement techniques have been developed, incorporating energy dissipation devices (EDDs) to enhance the structural performance of RC buildings. Examples include buckling-restrained braces (BRBs), which yield in both tension and compression [13], friction damper (FD) that dissipate kinetic energy through friction [14], and fluid viscous damper (FVD), which convert kinetic energy into heat and release it into the air [15].

By implementing appropriate retrofitting measures, the risk of structural failure can be significantly reduced, thereby minimizing potential loss of life, injuries, and economic damage. Strengthening older buildings also ensures the continued functionality of essential structures such as schools, hospitals during and after an earthquake, contributing to community resilience and disaster preparedness. Therefore, upgrading existing RC buildings to comply with modern seismic standards is a critical step toward mitigating earthquake hazards and protecting both human life and property.

This study is an analysis of seismic resistance efficiency and preventive measures in RC buildings. The primary focus is to evaluate the effectiveness of retrofitting techniques in enhancing the structural performance of RC buildings subjected to seismic forces. In this analysis, existing data and a numerical model of a standard four-story RC building, originally designed in Chiang Rai, are utilized. The numerical model was developed in a previous study using the method of equivalent linearization and implemented with NLRHA to assess the structural response under seismic loading [11, 16-17].

Therefore, this study continues to use the same dataset and numerical model [11, 16-17] to evaluate the performance of retrofitted buildings. The validation process incorporates NLRHA simulations with three recorded ground motions from real earthquake events, ensuring that the analysis reflects realistic seismic conditions. By comparing the response of retrofitted and non-retrofitted structures, the study aims to determine the extent to which retrofitting can enhance the seismic resistance of RC buildings.

A particular focus of this research is to investigate the efficiency of FVDs in improving the seismic performance of RC buildings. FVDs function similarly to shock absorbers in a car, consisting of a closed cylinder filled with a viscous fluid, such as oil, with a piston rod connected to a piston head containing small holes. As the piston moves in and out of the cylinder, the fluid flows through these holes, creating friction that converts seismic energy into heat, thereby dissipating earthquake-induced forces. When integrated into a building's bracing system, typically by installing single diagonals, FVDs help control structural deformations, reduce inter-story drift ratios, and enhance overall stability. As the building sways during an earthquake, the piston moves within the cylinder, absorbing energy and reducing damage. Through this mechanism, retrofitted RC buildings are expected to exhibit improved energy absorption capacity, increased resilience, and minimized structural damage under seismic excitations [18].

2. Retrofit Design Method

2.1 *Simplification of RC building into a Single degree of freedom (SDOF) model*

Previous studies [19] have introduced the constant drift (CD) method, a retrofit design approach that eliminates iterative calculations by using the equivalent linearization technique [20]. This method simplifies RC buildings from a multi-degree-of-freedom (MDOF) system to a single-degree-of-freedom (SDOF) model, making seismic performance evaluations more efficient. By reducing computational complexity, the CD method provides a practical and reliable approach for designing retrofitting strategies while maintaining accuracy in predicting structural behavior under seismic loads.

The transformation process in the CD method involves determining key structural parameters, including the equivalent height (H_{eq}), equivalent mass (M_{eq}), and initial lateral stiffness (K_f) *of* the SDOF model ($SDOF_{RC}$), which are derived from the modal analysis of the existing structure in ETABS using parameters based on mass (m_i), displacement (u_i), height (H_i) of the ith floor, and the fundamental period (T_f) [11, 16, 21-23].

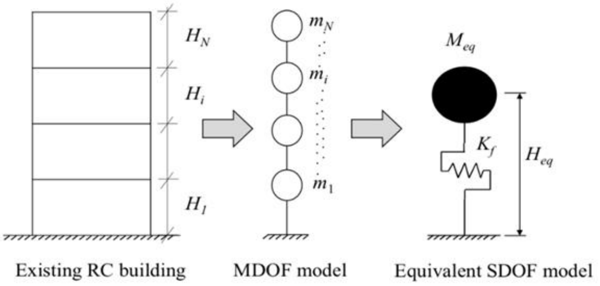


Fig. 1 Simplification of RC building into SDOF model. [11, 16, 21-23, 27]

Table 1 Design results of simplification of the RC building to SDOF. [11, 16, 21-23]

H_{eq} (m)	M_{eq} (tons)	$K_{f\,l}$ (kN/mm)	$K_{f,t}$ (kN/mm)
10	577	14.6	33.1

Table 2 Mass and lateral force distribution of the RC building. [11, 16, 21-23]

Bare RC Building (Before retrofit)

Story	m_i (tons)	Q_i (kN)
4	171	180.5
3	184	302.0
2	184	371.6
1	184	398.4

In this study, the CD method is applied to the seismic retrofit of RC buildings incorporating FVD. The seismic response of the SDOF model, which represents the target design story drift ratio (SDR), serves as the criterion for determining the necessity of retrofitting with dampers [16, 22].

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

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

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

2.2 Determine damper distribution

2.2.1 Loss stiffness of fluid viscous damper ($K''_{a,i}$) [12]

The required loss stiffness of the FVD at the i^{th} story ($K''_{a,i}$), which determines the necessary amount of damper for retrofitting the building as specified in Equations (4a) and (4b), is given by:

1) *The lateral force at the i^{th} story (Q_i)* is determined using either the Ai distribution from the Japanese seismic design code or the ASCE-SEI7 specifications.

2) Under lateral force distribution, *the maximum story drift (ϑ_{max})* at each story is assumed to *the target value (ϑ_{tar})*.

3) *The ductility of the RC frame (μ_{fi})* at ϑ_{max} is assumed to be the same for all stories, meaning the structure can undergo large deformations without significant strength loss.

$$K''_{a,i} = \frac{Q_i}{H_i}\frac{\sum_{i=1}^{N}\left(K_{f\,\mu,i}H_i^2\right)}{\sum_{i=1}^{N}\left(Q_i H_i\right)}\left(\eta_a + \frac{\mu_f}{\alpha_1\left(\mu_f - \mu_c\right)+\mu_c}\cdot r_{f1}\right) - \eta_a K_{f\,\mu,i}$$

for $\left(\mu_c < \mu_f \le 1\right)$ (4a)

$$K''_{a,i} = \frac{Q_i}{H_i}\frac{\sum_{i=1}^{N}\left(K_{f\,\mu,i}H_i^2\right)}{\sum_{i=1}^{N}\left(Q_i H_i\right)}\left(\eta_a + \frac{\mu_f}{\alpha_1\left(1 - \mu_c\right)+\mu_c}\cdot r_{f2}\right) - \eta_a K_{f\,\mu,i}$$

for $\left(1 < \mu_f\right)$ (4b)

2.3 Design example and Numerical model

2.3.1 Target building model

This study examines a standard four-story RC school building model based on the design specifications provided by the Office of the Basic Education Commission (OBEC) [24]. The selected building represents a typical school structure commonly found in Chiang Rai, northern Thailand.

The architectural and structural details of the building are illustrated in Figure 2 for clarify. Figure A presents the building's elevation, while Figure B details the RC column cross-section. Figure C illustrates the structural plan, and Figure D provides the RC beam cross-section [16, 21, 24].

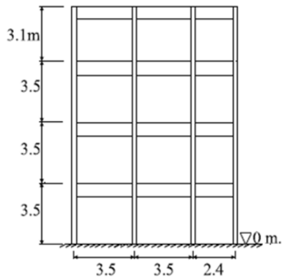


Fig. A Structural evaluation

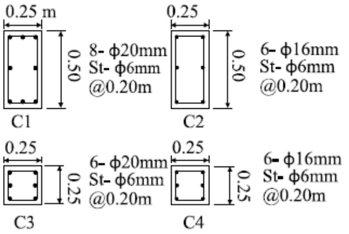


Fig. B Column cross section

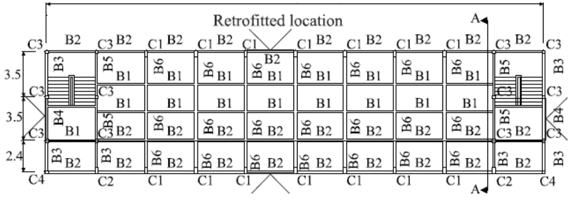


Fig. C Structural plan

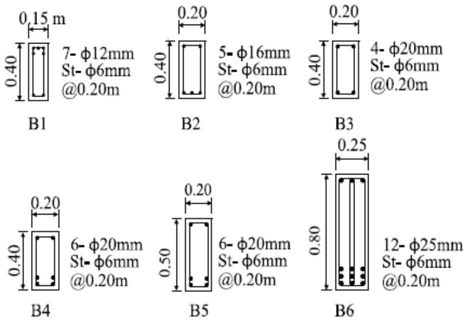


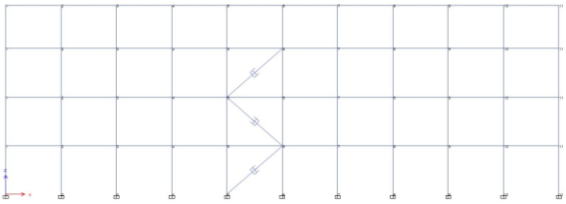
Fig. D Beam cross-section

Fig. 2 Details of the four-story RC school building in Thailand. [16, 21, 24]

2.3.2 Definition of three-dimensional model

Table 3 Retrofit design results using FVD by CD method. [16]

Story	Longitude direction		Transverse direction	
	Before retrofit	FVD	Before retrofit	FVD
	$K_{f,l}$ (kN/mm)	$K_{a,i}''$ (kN/mm)	$K_{f,l}$ (kN/mm)	$K_{a,i}''$ (kN/mm)
4th	39.6	-	74.8	-
3rd	32.2	31.5	70.2	12.2
2nd	32.1	60.3	74.5	39.6
1st	45.3	33.5	106.6	13.9



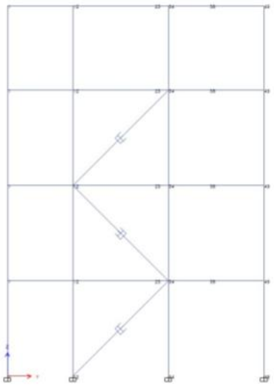


Fig. B 3D-RV3 transverse side

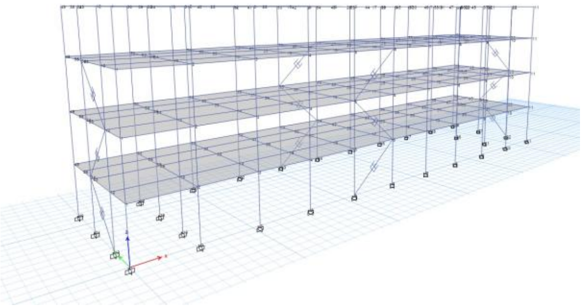


Fig. C 3D-RV3 model

Fig. 3 RV3 RC building model in ETABS.

3. Analysis Result

3.1 Nonlinear response history analyses (NLRHA)

This study evaluates building retrofit models using FVD through NLRHA. The model was analyzed with eleven scaled GM, considering only the initial horizontal component (longitudinal and transverse). Seismic efficiency was assessed the SDR_{max} under different ground motions, based on the mean and mean plus one standard deviation (SD) of the results [16, 21, 23].

3.1.1 Ground motions for NLRHA

The ground motions (GM) in this study were sourced from the PEER NGA West 2 database [25], considering local fault characteristics aligned with the design and maximum hazard scenarios. Scaling factors of 0.68–1.89 were applied to the selected records [18] for the design basic earthquake (DBE) suite, with an additional 1.5 scaling factor for the maximum considered earthquake (MCE) suite, following ASCE 7-16 recommendations [26].

Table 4 GM used for NLRHA. [21]

GM ID	Earthquake name	Year	Station name	Magnitude	Scaling factor
1	Superstition Hill-02	1987	Plaster City	6.5	1.69
2	Landers	1992	Desert Hot Springs	7.3	1.34
3	Darfield_ New Zealand	2010	DFHS	7	0.68

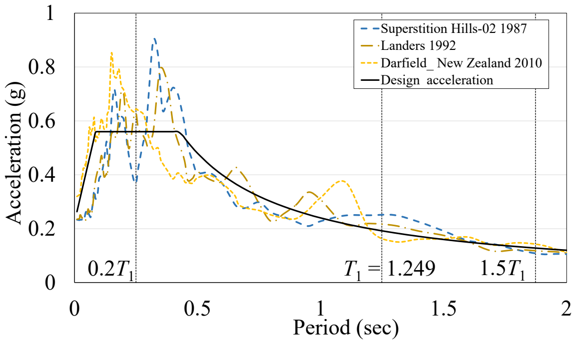


Fig. 4 The 5% damped response spectra of the scaled ground motions and the design acceleration spectrum.

3.1.2 Maximum story drift ratio (SDR_{max})

The SDR_{max} measures a building's maximum horizontal displacement during an earthquake, reflecting its structural response to dynamic loading. If SDR_{max} exceeds the target value (SDR_{tar}) of 0.5% rad. [16, 21-23], seismic retrofitting is required. According to the NLRHA study, in non-retrofitted buildings, the SDR_{max} at the first three stories significantly exceeds the SDR_{tar} of 0.5% rad. However, when the building was retrofitted using FVD, the retrofit was applied only to the first three stories, as the SDR_{max} at the fourth story did not exceed 0.5% rad. After the retrofit, the SDR_{max} at the first three stories remained within the SDR_{tar} threshold of 0.5% rad in both directions and exhibited a more uniform distribution.

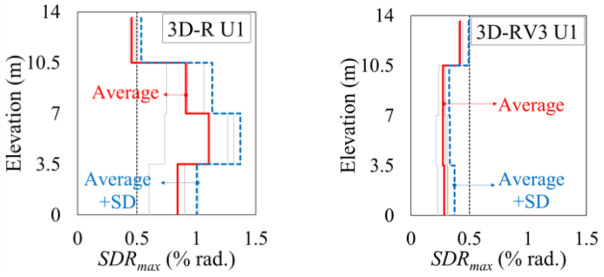


Fig. A 3D-non retrofit **Fig.** B 3D-FVD

Fig. 5 SDR$_{max}$ for longitudinal direction (U1)

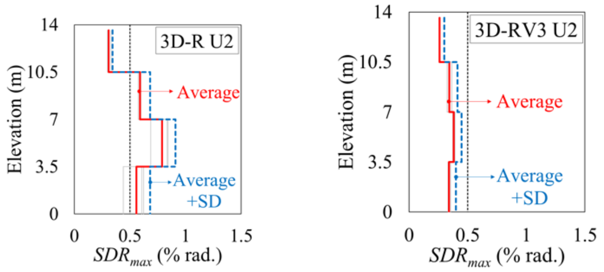


Fig. A 3D-non retrofit **Fig.** B 3D-FVD

Fig. 6 SDR$_{max}$ for transverse direction (U2)

4. Conclusion

This study focuses on the seismic retrofit design of a four-story reinforced concrete (RC) building using Fluid Viscous Dampers (FVDs) to enhance its earthquake resistance. By employing numerical model analysis, the study evaluates seismic performance of the retrofit. The findings derived from the NLRHA provide significant insights into the behavior of the retrofitted structure. Based on the analysis, the following conclusions can be drawn:

(1) The SDR$_{max}$ is a key parameter in assessing the structural response to seismic forces. The results indicate that, after implementing the FVD retrofit, the SDR$_{max}$ remains well within the target threshold of 0.5% rad in both directions and closely aligns with the specified target. This demonstrates that the retrofit strategy effectively controls the structural response.

(2) The results from the NLRHA indicate that the average SDR$_{max}$ graph exhibits a uniform distribution. This implies that the inter-story drifts are relatively consistent across floors. This uniformity is an essential factor in seismic performance, as it prevents excessive deformation, which could lead to localized failure or weak points in the structure.

(3) The NLRHA results confirm that retrofitting the building with FVD significantly enhances its seismic resistance. Before the retrofit, the SDR$_{max}$ for the first three stories exceeded the SDR$_{tar}$ of 0.5% rad. However, after implementing the FVD retrofit, the SDR$_{max}$ for these stories was reduced and remained within the 0.5% rad threshold in both directions.

(4) A comparison of the structural performance before and after the retrofit reveals that FVD effectively reduces structural deformation. This improvement enhances the building's seismic resistance and minimizes potential damage caused by seismic forces.

(5) The CD method plays a crucial role in optimizing the placement of FVDs, ensuring that the dampers are strategically positioned to achieve uniform drift control. The effective distribution of dampers enhances the overall stability of the building, improving its ability to withstand seismic forces while minimizing excessive deformation in any particular story. This approach contributes to a more balanced and efficient seismic response, ultimately increasing the building's resilience against earthquakes.

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