

Article

Study on Vibration Reduction Effect of the Building Structure Equipped with Intermediate Column–Lever Viscous Damper

Qiang Zhou ^{1,2,*}, Wen Pan ^{1,2,*} and Xiang Lan ³ 

¹ Faculty of Civil Engineering and Mechanics, Kunming University of Science and Technology, Kunming 650500, China

² Yunnan Seismic Engineering Technology Research Center, Kunming 650500, China

³ College of Architecture and Civil Engineering, Kunming University, Kunming 650214, China; lx523947015@kmu.edu.cn

* Correspondence: qzhou19920120@163.com (Q.Z.); 13312039@kust.edu.cn (W.P.)

Abstract: Generally speaking, the traditional lever amplification damping system is installed between adjacent columns in a building, which occupies a significant amount of space in the building. In contrast to amplification devices in different forms, the damper displacement of the intermediate column damper system is smaller, and the vibration reduction efficiency is lower. In light of these drawbacks, this study proposes a new amplification device for energy dissipation and vibration reduction, which is based on an intermediate column–lever mechanism with a viscous damper (CLVD). Initially, a specific simplified mechanical model of CLVD is derived. Subsequently, an equivalent Kelvin mechanical model of CLVD is derived to intuitively reflect CLVD's damping and stiffness effect. The damping ratio added by CLVDs to the structure is calculated according to that model; the additional damping ratio and additional stiffness are utilized to calculate the displacement ratio R_d and shear force ratio R_v of the structure with CLVDs to the structure without CLVDs. R_d and R_v are introduced to evaluate the vibration reduction effect of the structure with CLVDs, and the effects of various parameters (such as intermediate column position, beam's bending line stiffness, lever amplification factor, damping coefficient, and earthquake intensity) on R_d and R_v are analyzed. The results indicate that when the ratio of the distance from the intermediate column to the edge column to the span of the beam is 0.5, CLVD owns the optimal vibration reduction effect. Increasing the beam's bending line stiffness is beneficial for CLVD to control structural displacement and shear force; when the leverage amplification factor is too large, the CLVD provides the structure with stiffness as the main factor, followed by damping. Additionally, when the ratio of the displacement amplification factor to the geometric amplification factor satisfies $f_d/\gamma = 1/2^{1-0.5\alpha}$, the CLVD has the optimal displacement control effect on the structure. After that, measures are provided to optimize the CLVD in different situations in order to effectively control the inter-story displacement and the story shear force of the structure. Consequently, a nine-story frame is taken as an example to elaborate the application of CLVDs in the design for energy dissipation and vibration reduction. The results reveal that the CLVD scheme adopting the proposed optimization method can effectively enhance the displacement amplification ability of CLVDs, resulting in an additional damping ratio of up to 12%. At the same time, the inter-story displacement was reduced by almost 40% under fortification earthquakes. Through the research in this study, designers can obtain a new choice in structural vibration reduction design.



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Keywords: energy dissipation structure; intermediate column–lever viscous damper; simplified mechanical model of CLVD; displacement amplification factor; vibration reduction effect

1. Introduction

The passive control technology [1–4] for energy dissipation and vibration reduction is designed to control the structural seismic response by installing dampers in the structure to

consume the seismic input energy. Compared to the active control system and semi-active control system [5,6], the passive control system has the advantage of not requiring external energy, low overall cost, and simple maintenance in the later stage. These dampers can be divided into displacement-related dampers [7,8] and velocity-related dampers according to different energy dissipation principles. Currently, installing velocity-dependent viscous dampers [9,10] in structures has become a typical example of energy dissipation and vibration reduction technology. Under frequent or fortification earthquakes, when the structural deformation is small or the connecting components of dampers deform significantly, the insufficient deformation of dampers makes it difficult to effectively control the seismic response of the structure [11–14]. Therefore, it is essential to propose an efficient viscous damping energy dissipation system to significantly control the seismic response of structures.

In recent years, numerous researchers have proposed various amplification dampers to effectively control the seismic response of structures. Yang [15] proposed the displacement-amplified mild steel bar joint damper using a lever and analyzed the performance of each component of the damper using ABAQUS finite element software. The analysis results indicated that the energy consumption of dampers is almost three-times that of ordinary dampers. Naeem [7] proposed a rotational friction damper with restoring force characteristics. The research results indicated that the use of torsion springs in rotational friction dampers is more effective in improving the seismic performance of structures than traditional dampers. Ribakov et al. [16–18] studied different forms of the inclined brace lever damping system and proposed an optimal design program to realize the design of the lever damping system, demonstrating that this system possessed a good control effect on the inter-story displacement of the structure through numerical simulation. Combining a lever amplification device with a viscous damping wall, He et al. [19,20] conducted model and vibration table experiments, revealing that this new amplification viscous damping wall had a significant energy dissipation ability. The research of Fournier et al. [21,22] indicated that the flexibility of the support would significantly reduce the effect of the viscous damper. Thus, to ensure significant stiffness in the lever amplification device, the traditional lever amplification devices in various forms require a considerable cross-sectional size due to the longer axial length of the support or lever arm. Meanwhile, the traditional lever amplification device within the entire frame is likely to affect the building's functionality at its location. Learning from the crank and connecting rod technology in the mechanical field, Constantinou et al. [23,24] proposed toggle-brace dampers in different forms and conducted theoretical analyses and vibration table tests. The results revealed that the toggle-brace damping device can multiplicatively magnify the inter-story displacement to make the damper fully dissipate energy. Sigaher et al. [25] proposed a scissor-type damping system and analyzed the impact of different scissor-type arrangements on the damper energy dissipation and structural seismic response. Hwang et al. [26] proposed a toggle-brace device that directly connected the dampers to beam column nodes, and established a program for the relationship among displacement amplification factors, toggle geometry, and maximum inter-story displacement limits. Huang et al. [27] analyzed the impact of the toggle's geometry and brace stiffness on the displacement amplification of the damper and demonstrated that the toggle-brace stiffness has a significant influence on the structure's displacement response. Jiang et al. [28] applied a toggle damper to a cable bridge system. In order to improve the issue of traditional toggle devices occupying too much space in the building, Polat et al. [29] proposed an open damping amplification device. Lan et al. [30] suggested a local toggle-brace damper device and designed the local toggle amplifier using the geometric optimization method. Xu [31] proposed a new calculation method for the displacement amplification effect of the toggle-brace damper and suggested installing the toggle-brace damper in a frame with lower floor height and large span. Zhou [32] studied the displacement amplification effect and energy dissipation effect of the toggle-style negative stiffness dampers. The research results indicated that compared to the traditional toggle-brace damper, toggle-style negative stiffness dampers add a negative

stiffness device, which further increases the displacement of the dampers. The premise for achieving high displacement amplification capability in the above-mentioned toggle-brace damper is to have high installation accuracy, which increases the difficulty for practical application.

The traditional intermediate column damper [33,34] links viscous dampers or viscous damping walls to the upper and lower intermediate columns, and then arranges them within the frame span. Due to the advantages of having a low impact on the building function and its convenient construction, this system is widely used in engineering. A number of researchers have adopted different methods of studying the optimization of dampers to achieve optimal control of the seismic response. Lan [35] conducted shaking table experiments on intermediate column damper systems. The results indicated that when the intermediate column is located in the middle of the span, the displacement of the viscous damper is relatively large, and the inter-story displacement of the structure can be effectively controlled. Sonmez et al. [36] adopted the artificial bee colony algorithm to determine the optimal placement of dampers in the structure; Bishop et al. [37,38] adopted the genetic algorithm; and Lan et al. [39] employed the response surface method. However, the increase in damper displacement caused by optimization is significantly smaller than the amplification effect caused by the amplification device. In addition, the amplification effect reduces the demand for the number of dampers, resulting in a decrease in cost. Therefore, when comparing different forms of amplification devices, it is particularly important to significantly increase the deformation in the intermediate column damper.

In order to make the lever damping system have the characteristics of a large displacement method effect, convenient construction, and small impact on building space, this study proposes a new intermediate column-lever viscous damping system (CLVD). Firstly, the displacement amplification mechanism of the CLVD is developed. Subsequently, the simplified mechanical model of the CLVD is derived. In order to visually display the damping and stiffness effects of CLVD, an equivalent Kelvin mechanical model of CLVD is provided. On the basis of the Kelvin mechanical model, theoretical expressions for displacement ratio R_d and shear force ratio R_v are established, and these two indicators are utilized to comprehensively evaluate the vibration reduction effect of the structure with a CLVD. After that, the effects of the intermediate column's position, the beam's bending line stiffness, the lever amplification factor, the damping coefficient, the damping index, and the earthquake intensity on the additional CLVD structure's total damping ratio ζ , the stiffness ratio k_d'/k_f , R_d , and R_v are analyzed. On this basis, specific measures for optimizing additional CLVD structure's damping effects under different situations are also provided to guide the damping design. Consequently, a nine-story frame structure is taken as an example to illustrate the application of CLVDs in vibration reduction structures. Through the research in this paper, designers can obtain a new choice in structural vibration reduction design.

2. Composition and Mechanical Model of CLVD

2.1. Composition and Characteristics of CLVD

The intermediate column-lever viscous damper (CLVD) consists of an intermediate column, a lever amplification device, and a viscous damper (VD). In Figure 1, a comparison is provided between the traditional intermediate column viscous damper and the intermediate column-lever viscous damper. The CLVD can be flexibly arranged within the span of beams according to the limitations of the building space. During the construction process of the building, the intermediate column can be integrated with the beam for pouring, and the lever amplification device and viscous damper can be installed after the structural construction is completed.

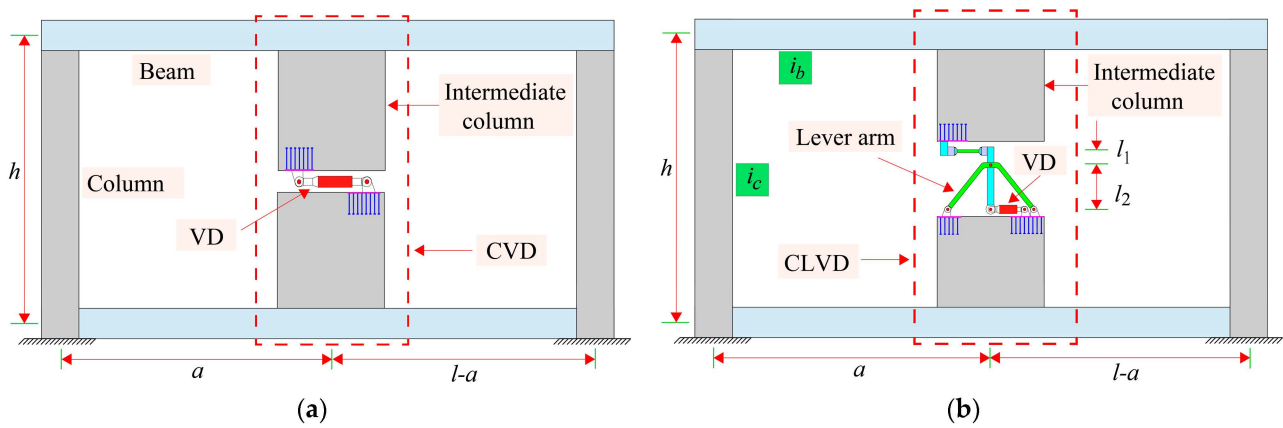


Figure 1. Traditional intermediate column viscous damper (CVD) and intermediate column-lever viscous damper (CLVD): (a) CVD; (b) CLVD.

For the CLVD, the viscous damper (VD) is connected to the lower intermediate column and a lever. The lever amplification device is connected to the upper intermediate column and the lower intermediate column, and both the upper intermediate column and lower intermediate column are connected to the beam. When the structure undergoes horizontal deformation, the deformation of the beam causes the upper intermediate column to rotate. The horizontal movement and rotation of the upper intermediate column cause the significant deformation of the VD through the rotation of the lever arm. Therefore, the displacement amplification effect of the viscous damper in the CLVD damping system originates from the deformation of the beam and the rotation of the lever arm. The deformations in the CVD and CLVD are shown in Figure 2.

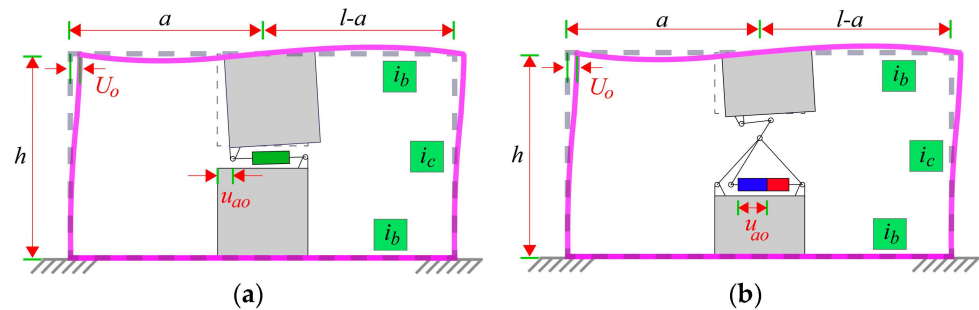


Figure 2. Schematic diagram of structural deformation and damper deformation: (a) CVD; (b) CLVD.

2.2. Simplified Mechanical Model of CLVD

To derive the mechanical model of CLVD, the following provisions are made for the CLVD damping system and are revealed in either Figure 1b or Figure 2b. The span length where the CLVD is located is l ; the floor height is h ; the distance from the intermediate column to the left column is a ; l_1 and l_2 are the lengths of the upper and lower ends of the lever arm; i_b is the bending line stiffness of the beam; and i_c is the bending line stiffness of the column. The damping force of VD is $F = c \operatorname{sgn}(\dot{u}_d) |\dot{u}_d|^\alpha$, where c and α represent the VD's damping coefficient and damping index, respectively; $\dot{u}_d$ is the velocity of the damper; ρ represents the line stiffness ratio of the beam to column; β represents the position of the intermediate column; and χ represents the leverage amplification factor, as shown in Equation (1):

$$\rho = i_b / i_c, \beta = a / l, \chi = l_2 / l_1 \quad (1)$$

Under earthquake action, the maximum inter-story displacement of the structure is U_o , and the maximum displacement of the VD is u_{d0} . When U_o remains constant and the damping coefficient $c = 0$, the maximum displacement of the VD is u_{a0} . This study refers to the ratio of u_{a0} to U_o as the geometric amplification factor γ , which represents the geometric

amplification property of the CLVD. In concept, this amplification property is consistent with the damper's displacement amplification factor $\cos \theta$ (θ is the angle between the slant brace and the horizontal direction) in the classic slant brace connection. Through analysis, γ can be calculated as follows:

$$\gamma = u_{ao}/U_o = \chi - 3\chi \left[6(\beta^2 - \beta) + 1 \right] / [2(3\rho + 2)] \quad (2)$$

Figure 3 depicts the changes in γ with respect to ρ and β . $\beta_A = 1/2 - 1/\sqrt{12}$ and $\beta_B = 1/2 + 1/\sqrt{12}$. Whether it is the CVD or CLVD, with the increase in β , the geometric amplification factor γ first increases and then decreases and reaches its maximum value when $\beta = 0.5$. When $\beta_A < \beta < \beta_B$, γ decreases as ρ increases. Meanwhile, due to the amplification effect of the leverage, the geometric amplification factor t of the CLVD is much greater than that of CVD.

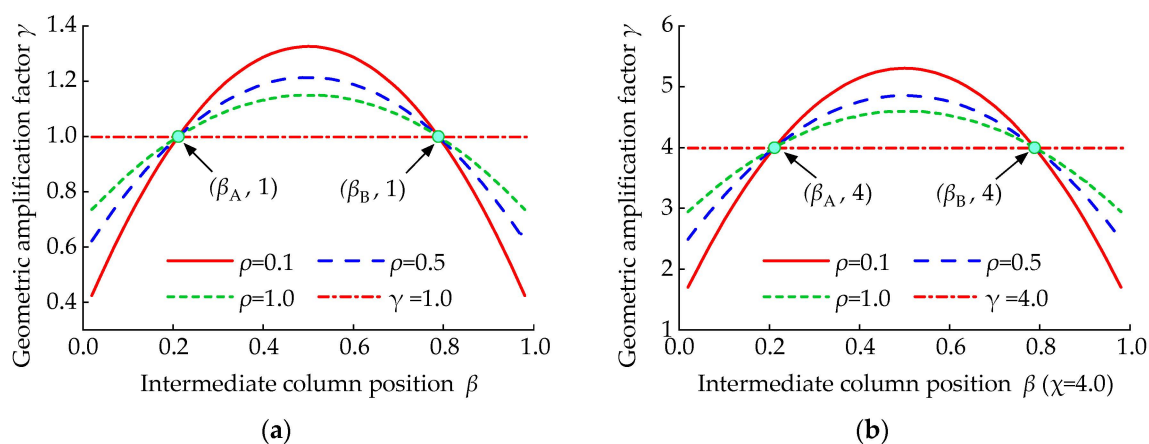


Figure 3. Geometric amplification factor γ : (a) CVD; (b) CLVD ($\chi = 4.0$).

The simplified mechanical model of the CLVD is shown in Figure 4a. In this figure, the leverage amplification factor in the mechanical model is γ . k is the equivalent stiffness for connecting the intermediate column and the lever in series. The equivalent stiffness is composed of the following three types of the equivalent stiffness in series: the equivalent stiffness of the upper intermediate column k_{mc-up} , the equivalent stiffness of the lower intermediate column k_{mc-low} , and the lever's equivalent stiffness k_{le} . Schematic diagrams of these three equivalent stiffness types are displayed in Figure 4b–d. The equivalent stiffness k is calculated using Equation (3):

$$k = \frac{k_{le}k_{mc-up}}{2k_{le} + k_{mc-up}} \quad (3)$$

$$k_{le} = \frac{1}{\frac{(l_1 + l_2)^2 \chi^2}{3i_{le}(\chi + 1)^2} + \frac{(\chi + 1)^2 l_b}{2EA_b \cos^2 \theta}} \quad (4)$$

$$k_{mc-up} = \frac{1}{\frac{\chi^2 [\beta f_1 + (1 - \beta) f_2] h^2}{2f_3 i_b} + \frac{\chi^2 (12i_{mc} + i_{vmc} h^2)}{12i_{mc} i_{vmc}}} \quad (5)$$

In Equation (5), $f_1 = (1 + \frac{\beta}{\rho})[\beta(2 - 3\beta) - 2(1 + \frac{1}{\rho})(1 - \beta)(3\beta - 1)]$, $f_2 = (1 + \frac{1-\beta}{\rho})[(1 - \beta)(3\beta - 1) - 2\beta(1 + \frac{1}{\rho})(2 - 3\beta)]$, $f_3 = 2 - 8(1 + \frac{1}{\rho})^2$.

In Equation (3), k_{le} is calculated using Equation (4) and k_{mc-up} is calculated using Equation (5). In Equation (4), l_b is the length of the support; θ is the horizontal angle of the support; A_b is the cross-sectional area of the support; i_{mc} and i_{vmc} are the bending line

stiffness and shear line stiffness of the intermediate column, respectively; and l_{le} is the bending line stiffness of the lever arm. In Equation (5), due to the assumption that the height of the upper intermediate column is 1/2 of the floor height, it can be considered safe to assume that k_{mc-low} is approximately equal to k_{mc-up} .

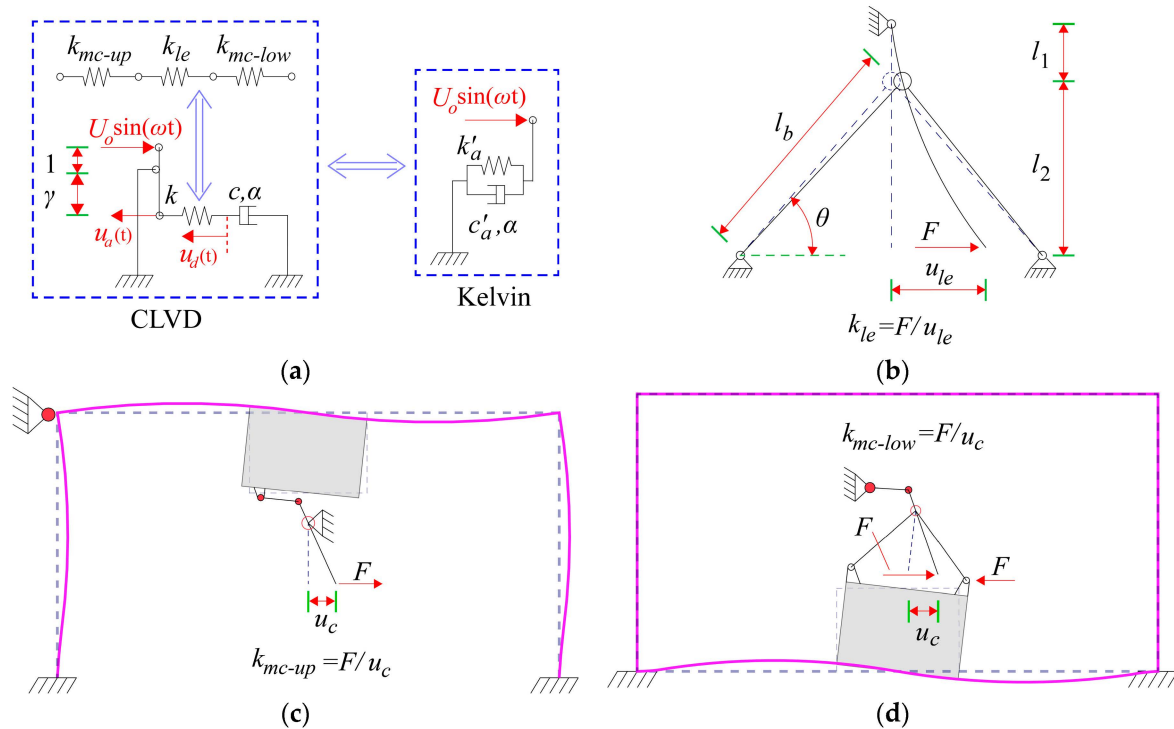


Figure 4. Schematic diagram of the CLVD's mechanical model and equivalent stiffness: (a) simplified mechanical model and Kelvin model; (b) k_{le} ; (c) k_{mc-up} ; (d) k_{mc-low} .

According to Equations (2) and (3), the position of the intermediate column will simultaneously affect the geometric amplification factor γ and the intermediate column–lever equivalent stiffness k . Therefore, the CLVDs located at different positions within the span will provide different vibration reduction effects to the structure.

2.3. Kelvin Model of CLVD

The vibration reduction effect of the energy dissipation structure originates from the stiffness and damping effects that are added by the relevant damping system. The Kelvin mechanical model directly adds stiffness and damping to the structure. In order to facilitate the analysis of the vibration reduction effect of the CLVD damping structures, it is necessary to transform the simplified mechanical model of the CLVD into a Kelvin mechanical model. In the Kelvin model, the damping coefficient is c'_a , the damping index is α , and the spring stiffness is k'_a , as shown in Figure 4a.

When the VD is linear, the mechanical model of the CLVD can be transformed into the Kelvin model. Here, the transformation of the mechanical model is achieved through application of the following three conditions: equal deformation, equal force, and equal energy dissipation. The constitutive relationship of VD is that $F(t) = c\dot{u}_d(t)$, where $u_d(t)$ and $\dot{u}_d(t)$ are the deformation and velocity of VD, respectively. Assuming that the CLVD mechanical model is subjected to stable sinusoidal excitation, the system can then be studied in a steady state without involving dynamic analysis. We assume that the sinusoidal deformation generated by CLVDs is $U_0 \sin(\omega t)$. Since the mechanical model of the CLVD and the Kelvin model have equal deformation and force, the $u_d(t)$, $\dot{u}_d(t)$, and $F(t)$ of the VD are as follows:

$$\begin{cases} u_d(t) = \gamma U_0 \sin(\omega t) - [k'_a U_0 \sin(\omega t) + c'_a \omega U_0 \cos(\omega t)] / (\gamma k) \\ \dot{u}_d(t) = \gamma \omega U_0 \cos(\omega t) - [k'_a \omega U_0 \cos(\omega t) - c'_a \omega^2 U_0 \sin(\omega t)] / (\gamma k) \\ F(t) = c \dot{u}_d(t) = [k'_a U_0 \sin(\omega t) + c'_a \omega U_0 \cos(\omega t)] / \gamma \end{cases} \quad (6)$$

In this study, the ratio of VD's maximum displacement u_{do} to the inter-story maximum displacement U_0 is identified as CLVD's displacement amplification factor f_d , representing the CLVD's displacement amplification ability. The Laplace transform is conducted in Equation (6) to solve k'_a and c'_a . The fact that the energy dissipation of the CLVD mechanical model and Kelvin model is equal is utilized to solve f_d , as follows:

$$f_d = u_{do} / U_0 = \gamma / \left[1 + (c\omega/k)^2 \right]^{0.5} \quad (7)$$

$$\begin{cases} k'_a = (\gamma^2 - f_d^2)k \\ c'_a = f_d^2 c \end{cases} \quad (8)$$

Equations (7) and (8) are linear for the VD. When the VD is nonlinear, its constitutive relationship is $F = c \operatorname{sgn}[\dot{u}_d(t)] |\dot{u}_d(t)|^\alpha$. When the damping index $\alpha = 0$, $f_d = \gamma / [1 + c/(u_{do}k)]$, $k'_a = \gamma^2(1 - f_d/\gamma)k$, and $c'_a = f_d c$. When $0 < \alpha \leq 1$, f_d , k'_a and c'_a are as follows:

$$f_d = \gamma / \left\{ 1 + [c\omega^\alpha / (u_{do}^{1-\alpha}k)]^{1+\alpha} \right\}^{1-0.5\alpha}, \quad 0 \leq \alpha \leq 1 \quad (9)$$

$$\begin{cases} k'_a = \gamma^2 [1 - (f_d/\gamma)^{\frac{1}{1-0.5\alpha}}]k, & 0 \leq \alpha \leq 1 \\ c'_a = f_d^{1+\alpha} c, & 0 \leq \alpha \leq 1 \end{cases} \quad (10)$$

3. Parameter Analysis of CLVD's Vibration Reduction Effect and Optimization

3.1. Evaluation Indicators of CLVD's Vibration Reduction Effect

The principle of setting a damper to reduce the seismic response of a structure is based on the effect achieved by increasing the damping due to both the energy dissipation of the damper and the stiffness effect of decreasing the period of the structure due to the additional stiffness. The damping effect enables the structure's displacement and shear force to decrease simultaneously, and the stiffness effect makes the displacement decrease and the shear force increase. According to the discussion in Sections 2.2 and 2.3, the single-layer structure with a CLVD is illustrated in Figure 1b, the simplified mechanical model is shown in Figure 5a, and the equivalent Kelvin mechanical model is revealed in Figure 5b. According to the Chinese Code [40], the total damping of the damping structure can be obtained as follows:

$$\zeta = \zeta_0 + \lambda c'_a \omega^\alpha U_0^{\alpha-1} / [2\pi(1 + k'_a/k_f)k_f] \quad (11)$$

where ζ_0 is the inherent damping ratio of the structure; ω can be approximated as the natural vibration period of the structure; k_f is the lateral stiffness of the structure; and k'_a/k_f represents the additional stiffness characteristics of CLVD. λ is a function of the damping index, whose value is referenced in the Chinese Code [40].

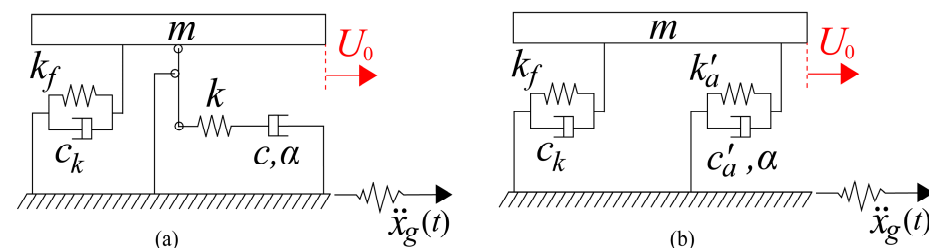


Figure 5. Mechanical model of the single-story structure with CLVD: (a) simplified mechanical model; (b) equivalent Kelvin model.

The displacement ratio R_d is the ratio of the damping structure's displacement U_0 to the non-damping structure's displacement U_0' . The shear force ratio R_v is the ratio of the damping structure's shear force V_0 to the non-damping structure's shear force V_0' . For most frame structures with additional viscous damping systems, the natural vibration period of the structure is in the medium and long period of the quasi-velocity response spectrum with a constant value. The authors of reference [41] identified that for the structure of the additional energy dissipation devices with medium and long periods, the damping effect of the energy dissipation device can be represented with $[(1 + 25\zeta_0)/(1 + 25\zeta)]^{0.5}$, and the stiffness effect can be represented with $[1/(1 + k'_a/k_f)]^{0.5}$. Therefore, R_d and R_v are as follows:

$$R_d = U_0/U_0' = [(1 + 25\zeta_0)/(1 + 25\zeta) \times 1/(1 + k'_a/k_f)]^{0.5} \quad (12)$$

$$R_v = V_0/V_0' = [(1 + 25\zeta_0)/(1 + 25\zeta) \times (1 + k'_a/k_f)]^{0.5} \quad (13)$$

When the damping index $\alpha < 1$, the calculation cannot directly use Equation (9) due to the unknown displacement u_{do} of the damper. Since the non-damping structure's inter-story displacement is known, the following iterative method can be applied for calculation:

- (1) It is assumed that the displacement of the damper u_{do} is equal to the inter-story displacement U_0' of the non-damping structure.
- (2) u_{do} is substituted into Equation (9) for calculation f_d , and k'_a , c'_a , ζ , R_d , and R_v are calculated through Equations (10)–(13), respectively.
- (3) The error $\varepsilon = u_{do}/(f_d R_d U_0') - 1$ is calculated. When $\varepsilon > 1\%$, u_{do} is made to be equal to $f_d R_d U_0'$. Steps 2 and 3 are repeated. When $\varepsilon < 1\%$, the iteration ends, and the final calculation values R_d and R_v are obtained.

3.2. Parameter Analysis

There are many factors that influence R_d and R_v , including the position of the intermediate column β , the beam's bending line stiffness i_b , the leverage amplification factor χ , the damping coefficient c , and the damping index α . In this section, the impacts of the above various factors on R_d and R_v are successively discussed.

For the convenience of discussion, the following assumptions are made regarding the single-story structure in Figure 1b. The structural floor height is $h = 4000$ mm; the span length is $l = 8100$ mm; the beam section is 400 mm $\times$ 800 mm; the column section is 600 mm $\times$ 600 mm; the intermediate column section is 1600 mm $\times$ 250 mm; and the concrete material grade is C35. The box section corresponding to the lever arm is 300 mm $\times$ 140 mm $\times$ 20 mm $\times$ 20 mm, the section of the inclined strut box is 200 mm $\times$ 200 mm $\times$ 25 mm $\times$ 25 mm, and the material grade is Q235. The lever length is 1000 mm, and the lever amplification factor is $\chi = 4$. The intermediate column position is $\beta = 0.5$. The parameter of the viscous damper is $c = 5$ kN/(mm/s)^{0.5}. The structural modal frequency is that $\omega = 8.1$ rad/s; the lateral stiffness is that $k_f = 120$ kN/mm; and the structural inherent damping ratio is $\zeta_0 = 0.05$. Under fortification earthquakes (PGA = 2 m/s²), the non-damping structure's displacement is $U_0' = h/200$.

3.2.1. Impact of the Position of Intermediate Column

This section explores the impact of changing the intermediate column position β on R_d and R_v . Figure 6 reveals the curves of changes in k'_a/k_f , ζ , R_d , and R_v with the intermediate column position β . As shown in Figure 6, when the intermediate column is in the middle of the span, the stiffness k'_a and total damping ratio ζ provided by the CLVD to the structure reach their maximum values, while R_d and R_v reach their minimum values. Therefore, in order to ensure the control effect of the CLVD on structural displacement and shear force, the CLVD should be located at the mid-span as long as the building function is available.

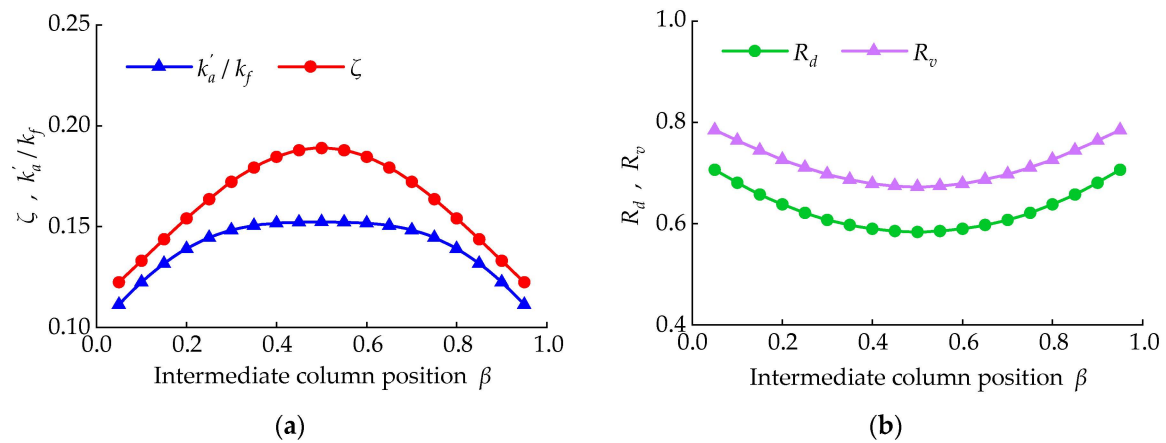


Figure 6. Changes in k'_a/k_f , ζ , R_d , and R_v with β : (a) changes in ζ and k'_a/k_f with β ; (b) changes in R_d and R_v with β .

3.2.2. Impact of Beam's Bending Line Stiffness

This section explores the impact of changing the beam's bending line stiffness i_b on R_d and R_v . In Figure 7, i_{b1} represents the beam's bending line stiffness with a cross-section of 400 mm $\times$ 800 mm. When the intermediate column is located in different positions, the impact of the change in i_b on k'_a/k_f and ζ is different. As illustrated in Figure 7a, when the intermediate column is located at the end of the span, the stiffness k'_a provided by the CLVD to the structure increases with the increase in i_b .

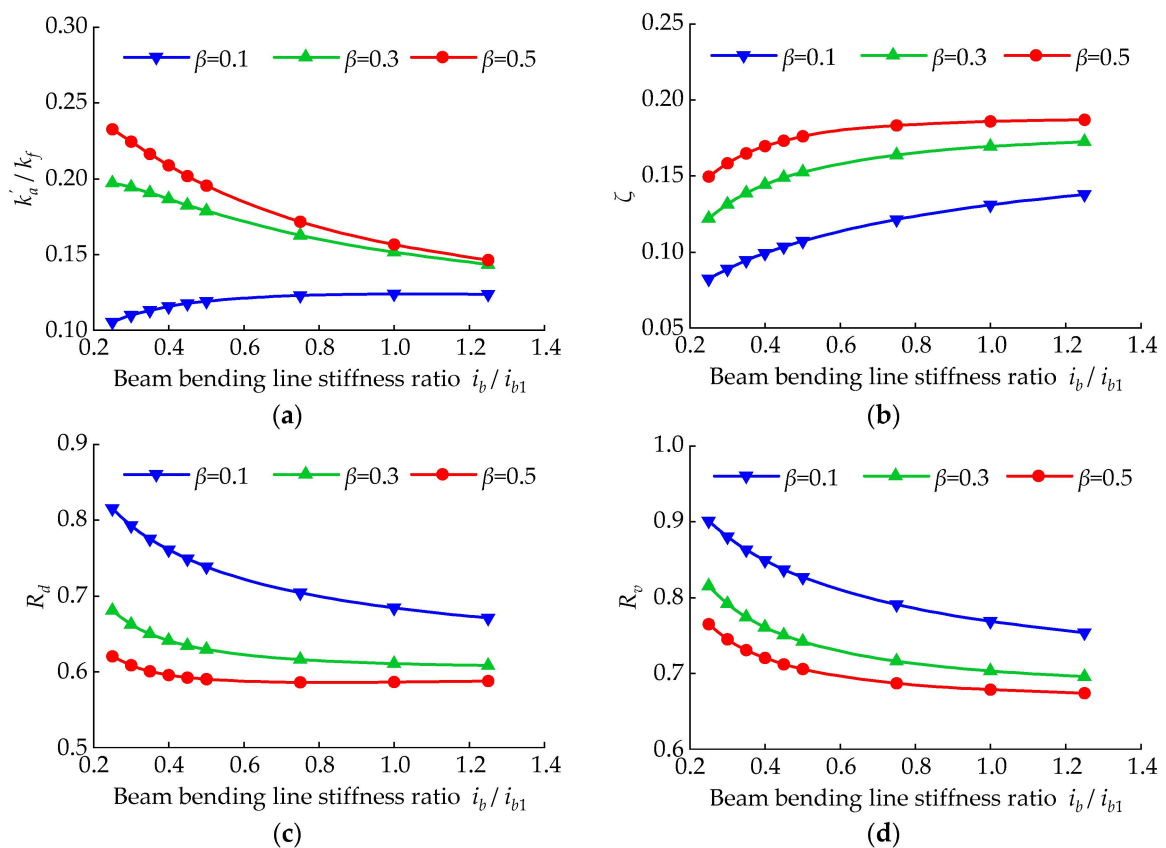


Figure 7. Changes in k'_a/k_f , ζ , R_d , and R_v with i_b/i_{b1} : (a) changes in k'_a/k_f with i_b/i_{b1} ; (b) changes in ζ with i_b/i_{b1} ; (c) changes in R_d with i_b/i_{b1} ; (d) changes in R_v with i_b/i_{b1} .

When the intermediate column is located in the middle of the span, the stiffness k'_a provided by the CLVD to the structure decreases as i_b increases. In Figure 7b, the total

damping ratio ζ is shown increasing with the increase in i_b . From Figure 7c,d, it can be seen that no matter where the intermediate column lies within the span, R_d and R_v decrease with the increase in i_b . In contrast to the CLVD located in the middle of the span, the CLVD located at the end of the span requires a larger beam section to control the structure's displacement and shear force.

3.2.3. Impact of the Leverage Amplification Factor

This section explores the impact of changing the leverage amplification factor χ on R_d and R_v . In Figure 8a, it can be seen that with the increase in the leverage amplification factor χ , k'_a/k_f increases, and ζ first increases and then decreases. Therefore, an optimal leverage amplification factor χ exists that maximizes the total damping ratio ζ of the structure. In Figure 8b, with the increase in χ , R_d and R_v are shown to first decrease and then increase. When the leverage amplification factor is too large, the CLVD provides the structure with stiffness as the main factor, followed by damping. This enables the CLVD to have an improved displacement control effect on the structure, while it has a worse control effect on the shear force.

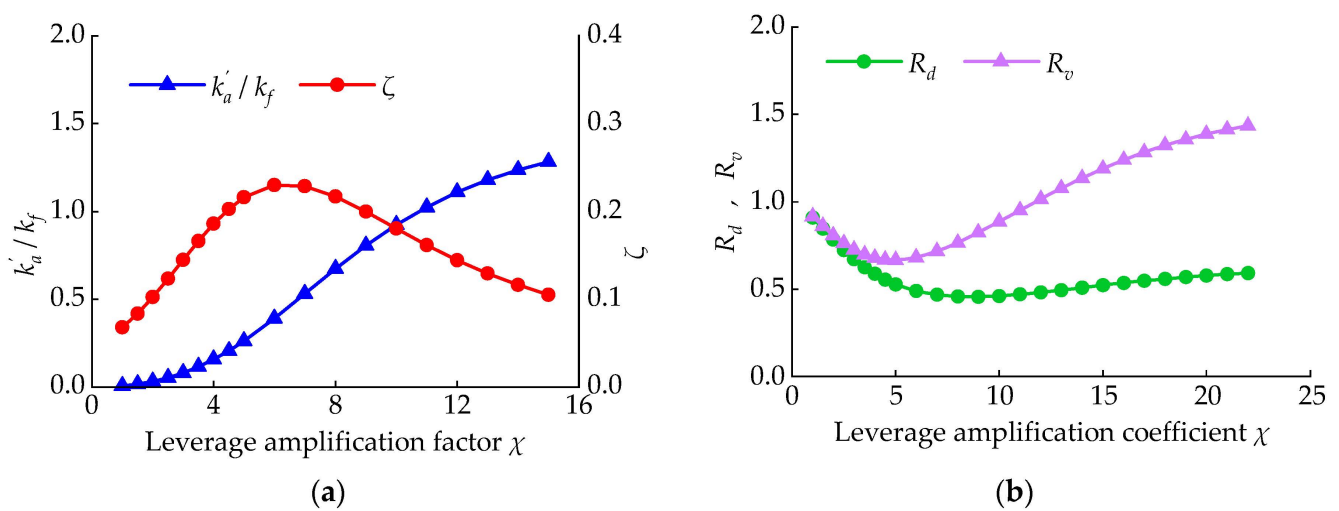


Figure 8. Changes in k'_a/k_f , ζ , R_d , and R_v with χ : (a) changes in ζ and k'_a/k_f with χ ; (b) changes in R_d and R_v with χ .

3.2.4. Impact of the Damping Coefficient and Damping Index

This section explores the impact of changing the damping coefficient c and damping index α on the R_d and R_v . In Figure 9a,c, it can be seen that as c or α increases, k'_a/k_f gradually increases, and ζ first increases and then decreases. From Figure 9b,d, it can be seen that as c or α increase, R_d and R_v first decrease and then increase. Therefore, an optimal combination exists of c and α to achieve optimal control of the structural displacement. In Figure 9e, R_{dP} represents the peak points of each curve, and R_{dP}^S represents R_d of each curve when $(\gamma/f_d)^{1/(1-0.5\alpha)} = 2$. In Figure 9e, it can be seen that the CLVD has the optimal effect on structural displacement control when c and α make $(\gamma/f_d)^{1/(1-0.5\alpha)} = 2$.

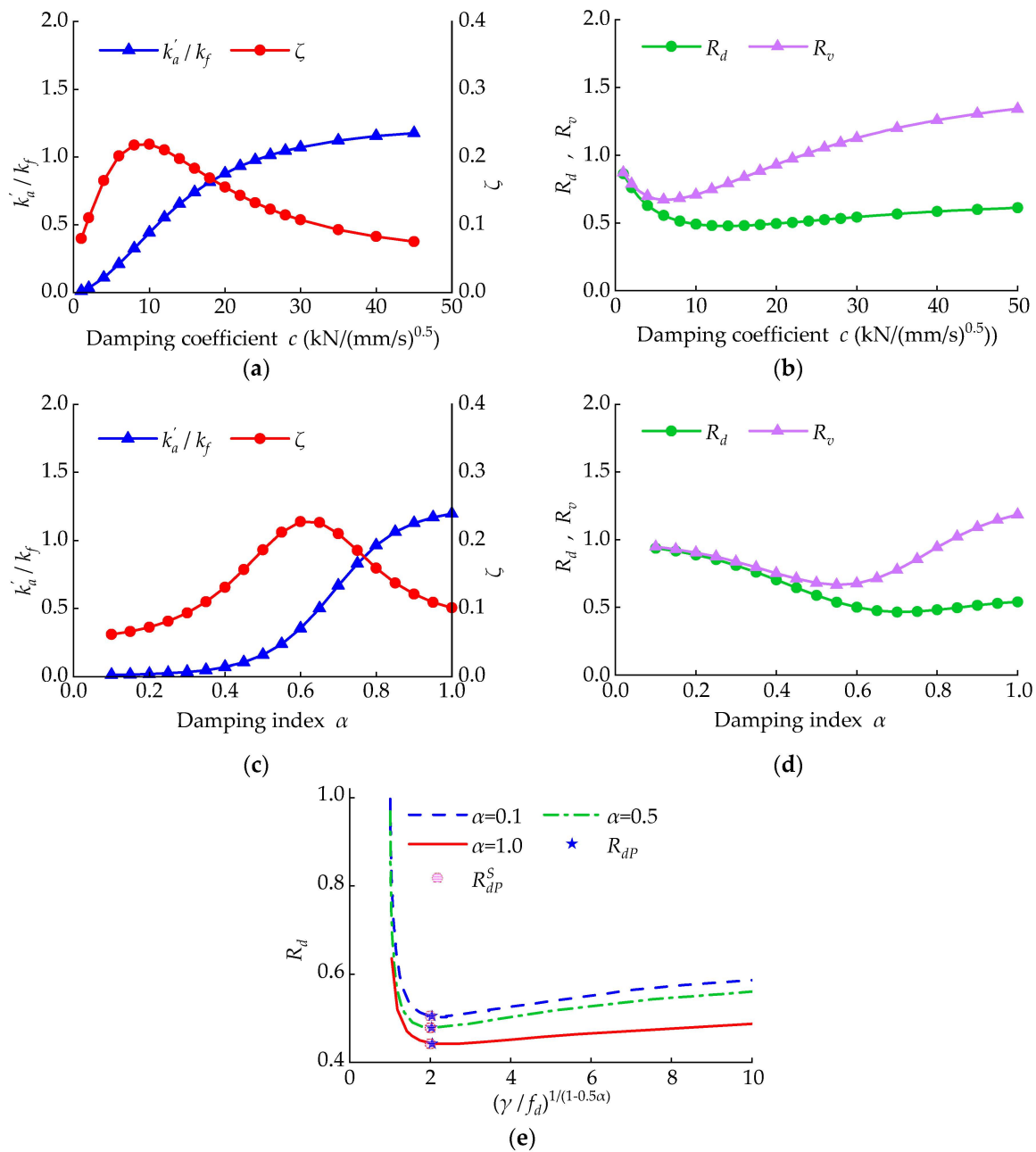


Figure 9. Changes in k'_a/k_f , ζ , R_d , and R_v with c and α : (a) changes in k'_a/k_f and ζ with c ; (b) changes in R_d and R_v with c ; (c) changes in k'_a/k_f and ζ with α ; (d) changes in R_d and R_v with α ; (e) changes in R_d with $(\gamma/f_d)^{1/(1-0.5\alpha)}$.

3.2.5. Impact of Earthquake Intensity

This section analyzes the impact of changing the earthquake intensity on R_d and R_v . When the VD is nonlinear, the displacement amplification factor f_d of the CLVD is related to the displacement of the damper. Therefore, under different earthquake intensities, R_d and R_v are different. In Figure 10a,b, it can be seen that as the earthquake intensity increases, k'_a/k_f gradually decreases, while ζ first increases and then decreases. In the initial stages of the increasing earthquake intensity, the CLVD mainly provides stiffness to the structure. This provides the CLVD with a better displacement control effect on the structure and a poorer control effect on the shear force. When the earthquake intensity is high, the CLVD mainly provides damping to the structure.

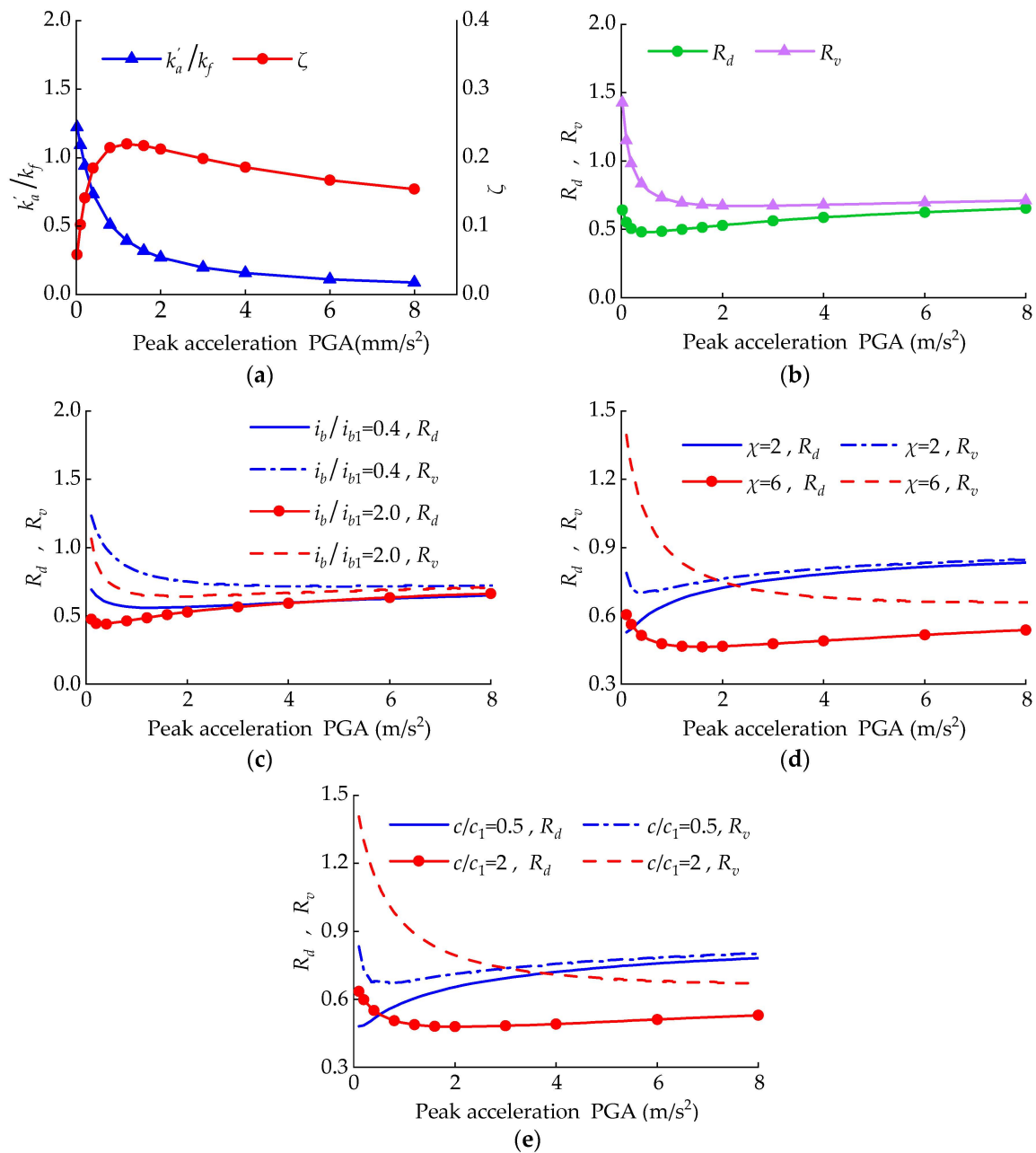


Figure 10. Changes in k'_a/k_f , ζ , R_d , and R_v with PGA: (a) changes in k'_a/k_f and ζ with the PGA; (b) changes in R_d and R_v with the PGA; (c) changes in R_d and R_v with the PGA and i_b ; (d) changes in R_d and R_v with the PGA and χ ; (e) changes in R_d and R_v with PGA and c .

In Figure 10c, i_{b1} represents the bending line stiffness of a beam with a cross-section of 400 mm $\times$ 800 mm. In Figure 10c, it is revealed that when the earthquake intensity is low, increasing i_b can significantly reduce both R_d and R_v . However, when the earthquake intensity is high, increasing i_b has a worse effect on decreasing R_d and R_v .

In Figure 10d, when the earthquake intensity is high, it is illustrated that increasing the leverage amplification factor χ has a significant reducing effect on R_d and R_v . However, when the earthquake intensity is low, increasing χ has an insignificant effect on reducing R_d . Meanwhile, R_v will be significantly increased.

In Figure 10e, $c_1 = 5(\text{kN}/(\text{mm}/\text{s})^{0.5})$. In Figure 10e, when the earthquake intensity is large, it is shown that an increase in the damping coefficient c can significantly reduce R_d . However, when the earthquake intensity is low, increasing the damping coefficient c will result in an increase in R_d and R_v .

In order to ensure that the CLVD demonstrates significant control effects on the structure's displacement and shear force under different-intensity earthquakes, in Figure 10c–e, three methods are illustrated for achieving this goal. The first method is to simultaneously increase the leverage amplification factor χ and the beam's bending line stiffness i_b ; the second one is to simultaneously increase the damping coefficient c and the beam's bending line stiffness i_b ; and the third one is to increase the leverage amplification factor χ while reducing the damping coefficient c .

In summary, under the allowable conditions of construction engineering, the position of the intermediate column should be $\beta = 0.5$, and the beam connected to the intermediate column should have high stiffness. Meanwhile, an excessive leverage amplification factor should be avoided, and the recommended value is between 2 and 5, and $f_d/\gamma < 1/2^{1-0.5\alpha}$ should also be avoided. When the displacement and shear control effect of CLVD on the structure is poor, the suggestions proposed in Section 3.2.5 should be selected for improvement. When CLVD is applied to real-world buildings, the universal ball node shown in Figure 1 should be applied to reduce the adverse effect of CLVD's out-of-plane deformation on the CLVD displacement amplification ability. Due to the large force transmitted by the lever amplification device to the intermediate column, it is necessary to strengthen the node connecting the lever amplification device and the intermediate column.

3.3. Optimization Strategy for CLVD

The design of the energy dissipation and vibration reduction structures generally adopts an elastic section design when encountering frequent earthquakes (or fortification earthquakes) and an elastic–plastic deformation verification calculation when encountering rare earthquakes. In the process of the vibration reduction design, continuous trial and error are required for optimizing the relevant damping system. The discussion in Section 3.2 dealt with the effective reduction in the displacement and shear force of the structure with a CLVD; consequently, this section provides optimization strategies for the CLVD in different situations to guide the seismic design of buildings, as illustrated in the following scenarios:

- (1) As long as permitted by the building space, efforts should be made to position the CLVD at the mid-span.
- (2) If both R_d and R_v are very large in frequent earthquakes (or fortification earthquakes), the optimization measures should be as follows: try to increase the damping coefficient c while increasing the beam section, or try to increase the lever amplification factor χ while increasing the beam section.
- (3) If R_d is relatively small while R_v is relatively large under frequent earthquakes (or fortification earthquakes), and both R_d and R_v are relatively small under rare earthquakes, the optimization measures are as follows: try to increase the beam section, or reduce the damping coefficient c , or reduce the leverage amplification factor χ .
- (4) If R_d is relatively small while R_v is relatively large under frequent earthquakes (or fortification earthquakes), and R_d is relatively large under rare earthquakes, the optimization measures are as follows: try to increase the beam section while increasing the quantity of CLVDs.
- (5) If both R_d and R_v are relatively small under frequent earthquakes (or fortification earthquakes), and R_d is relatively large under rare earthquakes, the optimization measures are as follows: try to increase the damping coefficient c , or increase the leverage amplification factor χ , or increase the quantity of CLVDs.

The above-mentioned optimization scenarios are applicable to both single and different-intensity earthquakes. In the optimization process of the CLVD, it may be necessary to repeatedly utilize the improvement measures of the above five different scenarios. For instance, after adopting the improvement measures in Scenario 2, the CLVD is likely to shift from Scenario 2 to Scenario 5. At this point, it is necessary to continue adopting the improvement measures of Scenario 5 until the expected goals of displacement reduction and shear force reduction are satisfied.

4. Finite Element Analysis of Engineering Example

4.1. Project Overview

This section takes a nine-story building as the research object and elaborates on the application of CLVD dampers in energy dissipation and vibration reduction structures. This concrete frame has a fortification intensity of 8 degrees (0.2 g), a building height of 36 m, a self-weight of 9784 tons, and a site characteristic period of 0.45 s. The fundamental periods of the structure are 1.61 s (E-W), 1.53 s (N-S), and 1.38 s (rotation). The structural inherent damping ratio is 5.0%. The column section of the first floor is 700 mm × 700 mm; the second floor is 600 mm × 600 mm; from the third floor to the fourth floor is 550 mm × 550 mm; and from the fifth floor to the ninth floor is 500 mm × 500 mm. The main beam section is 300 mm × 600 mm, and the secondary beam section is 200 mm × 400 mm. The beams and columns from the first floor to the fourth floor are made of concrete material with a grade of C40, while the beams and columns on the fifth floor to the ninth floor are made of concrete material with a grade of C35. The expected goals for the vibration reduction design are as follows: an additional damping ratio of 10% and a limit of 1/300 of the inter-story displacement angle of the structure under fortification earthquakes (with a peak earthquake acceleration of 0.2 g); the limit of the inter-story displacement angle of the structure under rare earthquakes (with a peak earthquake acceleration of 0.4 g) is 1/150.

4.2. Scheme Design

This section adopts the optimization strategy set out in Section 3.3 to conduct multiple trial calculations on the CLVD, consequently obtaining Scheme 1. Firstly, We set the number of CLVDs based on the total area of the building. According to the engineering experience, when the ratio of the total building area to the number of viscous dampers is between 100 and 200, it is relatively reasonable. This study takes 56 sets of CLVDs, including 28 sets in the north–south direction. Subsequently, according to the inter-story deformation of the structure without the CLVDs under fortification earthquakes, we choose to arrange CLVDs from the second floor to the eighth floor. According to engineering experience, the parameters of the intermediate column section, beam section, lever, and damper for CLVD are preliminarily selected. We select the position of the intermediate column $\beta = 0.2$ and obtain Scheme 3 through preliminary calculation. As Scheme 3 does not meet the set goals and belongs to Scenario 3 proposed in Section 3.3, increasing the beam section will result in Scheme 2. Since Scheme 2 also cannot meet the set goals and belongs to Scenario 1 proposed in Section 3.3, we further optimize it to make the position of the intermediate column $\beta = 0.5$ and obtain Scheme 1. After calculation, Scheme 1 meets the set goal.

The intermediate column of Scheme 1 is located in the middle of the span, namely, $\beta = 0.5$. The cross-section of the intermediate column is 1700 mm × 350 mm. The lever arm and support are made of Q235 steel. The box section corresponding to the lever arm is 300 mm × 140 mm × 20 mm × 20 mm, and the box section corresponding to the support is 200 mm × 200 mm × 25 mm × 25 mm. The horizontal angle of the support is 48°, and the total length of the lever arm is 1000 mm. The lever amplification factor is $\chi = 4$. The parameters of the viscous dampers from the second floor to the fifth floor are $c = 10 \text{ kN}/(\text{mm}/\text{s})^{0.5}$; the parameters of the viscous dampers from the sixth floor to the eighth floor are $c = 6 \text{ kN}/(\text{mm}/\text{s})^{0.5}$. The position of the intermediate column in Scheme 2 is $\beta = 0.2$, and the beam section connected to the intermediate column in Scheme 3 is 300 mm × 600 mm. The parameters of CLVD for Scheme 1, Scheme 2, and Scheme 3 are shown in Table 1. The arrangements of the CLVDs in the structure are illustrated in Figure 11.

Table 1. Parameters of CLVD.

Scheme	Story	β	Beam Section (mm × mm)	Column Section (mm × mm)	χ	c (kN · (s/mm) ^{0.5})
Scheme 1	6–8	0.5	400 × 800	1700 × 350	4	6
	2–5	0.5	400 × 800	1700 × 350	4	10
Scheme 2	6–8	0.2	400 × 800	1700 × 350	4	6
	2–5	0.2	400 × 800	1700 × 350	4	10
Scheme 3	6–8	0.2	300 × 600	1700 × 350	4	6
	2–5	0.2	300 × 600	1700 × 350	4	10

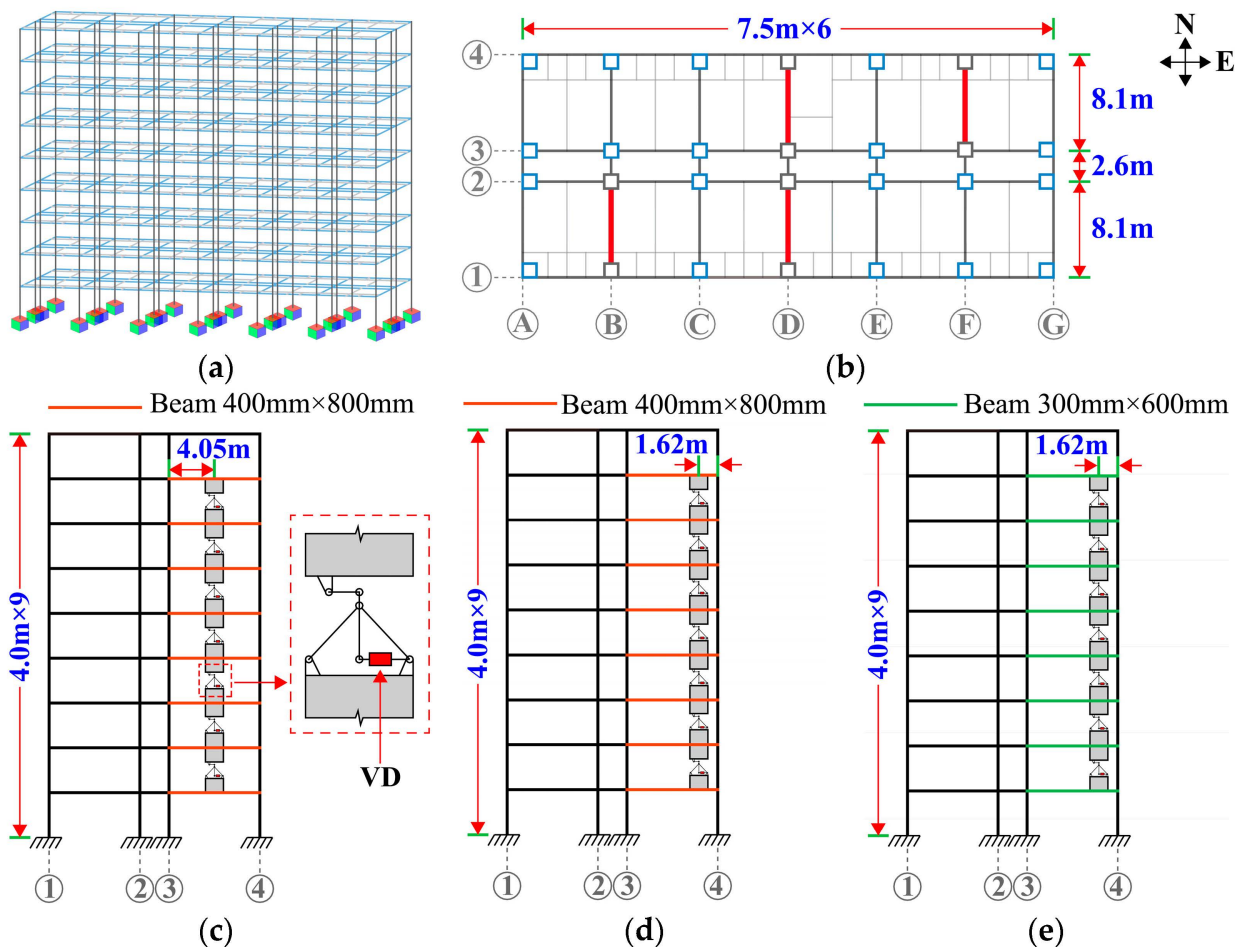


Figure 11. Three-dimensional schematic diagram of the structure and layout of dampers in different schemes: (a) a 3D schematic diagram of the structure; (b) the layout of CLVD; (c) Scheme 1 (F-axis); (d) Scheme 2 (F-axis); (e) Scheme 3 (F-axis).

The elastic section design of the additional CLVD structure is based on the response spectrum design under fortification earthquakes according to the Chinese Code [42]. In the response spectrum design, the effect of CLVDs on the structure is replaced by the equivalent damping ratio and the equivalent stiffness of Scheme 1. The seismic elastic dynamic analysis is conducted utilizing SAP2000 software (version 23.3.0), while the elastic–plastic dynamic analysis for rare earthquakes is conducted utilizing Perform-3d software (version 7.0). In the elastic–plastic analysis, fiber section models are adopted for beam and column components, and the steel reinforcement adopts a double-line model; the unconstrained concrete adopts a three-line model; and the constrained concrete adopts the Mander model. The viscous damper adopts a fluid damper element. In the parameter analysis of the vibration reduction efficient of the CLVD in Section 3.2, it is assumed that the structure

without a CLVD maintains elasticity. Therefore, the structure without an additional CLVD is forced to maintain elasticity. Subsequently, the dynamic calculations of rare earthquakes are performed. This can avoid the plastic deformation of the structure without a CLVD, which increases the complexity of the vibration reduction effect analysis. According to the Chinese Code [42], five natural waves and two artificial waves are selected. A comparison between the normalized spectrum of the selected seismic wave and the normalized standard response spectrum is shown in Figure 12. All analysis results in this section are taken as the average of seven seismic wave calculation results. Due to space limitations, this section only elaborates on the application of CLVD damping systems in the north–south direction of structures.

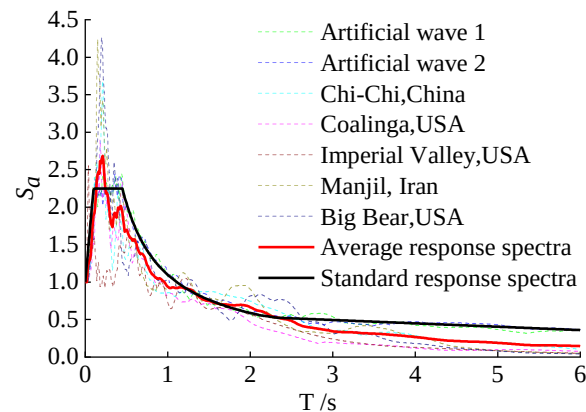


Figure 12. Normalized time-history response spectra and standard response spectra.

4.3. Vibration Reduction Effect

Table 2 summarizes the damping ratios, which are added to structures under different damper schemes. The calculation of the additional damping ratio is based on the traditional specification method in [40]. $\zeta_d = W_c / (4\pi W_s)$. ζ_d is the additional damping ratio, W_c is the total energy dissipation of the damper, and W_s is the total potential energy of the structure. According to Table 2, under fortification earthquakes, the additional damping ratios from Scheme 1 to Scheme 3 are 12.1%, 7.1%, and 4.4%, respectively. Scheme 1 also meets the expected additional damping ratio of 10%.

Table 2. Additional damping ratios for three schemes under fortification earthquakes.

Earthquake Wave	Scheme 1	Scheme 2	Scheme 3
Artificial wave 1	11.2%	6.8%	3.9%
Artificial wave 2	12.2%	6.9%	4.3%
Chi-Chi	12.6%	7.3%	4.9%
Coalinga	12.8%	7.1%	4.1%
Imperial Valley	12.6%	7.9%	4.8%
Manjil	11.6%	6.6%	4.3%
Big Bear	11.9%	7.1%	4.2%
Average of multiple waves	12.1%	7.1%	4.4%

Figure 13 reveals the CLVD's displacement amplification factor f_d under different schemes. On comparing the three schemes, we observe that under fortification earthquakes and rare earthquakes, Scheme 1 is the best, while Scheme 2 and Scheme 3 are relatively poor. On comparing Scheme 1 and Scheme 2, we discover that the CLVD mid-span layout is better than the edge-span layout. On comparing Scheme 2 and Scheme 3, we demonstrate that increasing the beam's bending line stiffness can significantly improve the displacement of the damper.

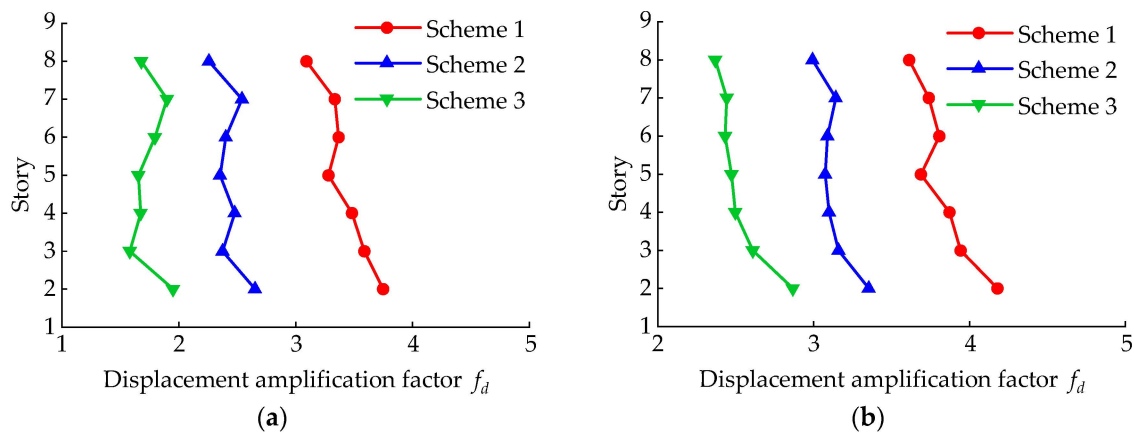


Figure 13. Displacement amplification factors f_d under fortification earthquakes and rare earthquakes: (a) f_d under fortification earthquakes; (b) f_d under rare earthquakes.

Figure 14a illustrates the hysteresis curves of the damper at position F-(3-4) on the fifth floor under the Big Bear wave in different schemes. In Figure 14a, due to the good displacement amplification ability of the CLVD in Scheme 1, it is illustrated that the hysteresis curve of its damper is also increased in size. In Figure 14b, under rare earthquakes, the CLVD energy dissipation of Scheme 1 is significantly greater than the inherent damping energy dissipation of the structure, which suppresses the plastic deformation of the structure.

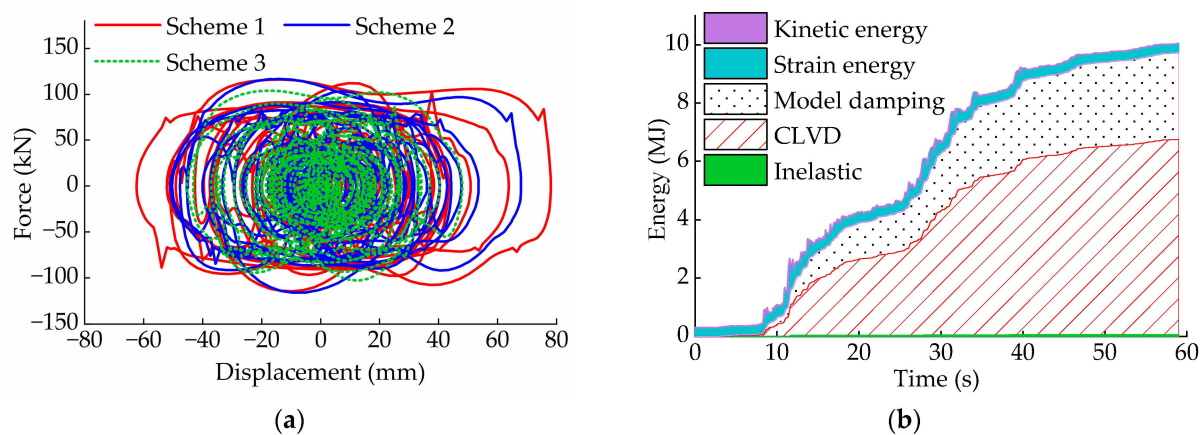


Figure 14. VD hysteresis curve and energy dissipation under rare earthquake and the Big Bear wave: (a) damper hysteresis curve at position 5-F-(3-4); (b) energy dissipation in Scheme 1.

The control effects of the CLVD damping system for the inter-story displacement and floor shear force from Schemes 1 to Scheme 3 are illustrated in Figures 15 and 16. According to Figure 15, Scheme 1 has a maximum inter-story displacement angle of less than $1/300$ under fortification earthquakes and less than $1/150$ under rare earthquakes. For all the floors except for the first floor, the inter-story displacement of Scheme 1 has been reduced by almost 40% under fortification earthquakes and by almost 30% under rare earthquakes. In comparison with Scheme 1, Scheme 2 and Scheme 3 have worse effects. The story shear forces of Scheme 1 are reduced to a certain extent, while the reduction is smaller than the reduction in inter-story displacement. This is because the CLVD adds both damping and stiffness to the structure. For Scheme 2 and Scheme 3, the reduction in the story shear forces is greater than the reduction in inter-story drift. This is because the structures with CLVDs in Schemes 2 and Schemes 3 undergo significant plastic deformation during rare earthquakes, while the structure without CLVDs is forced to maintain its elasticity.

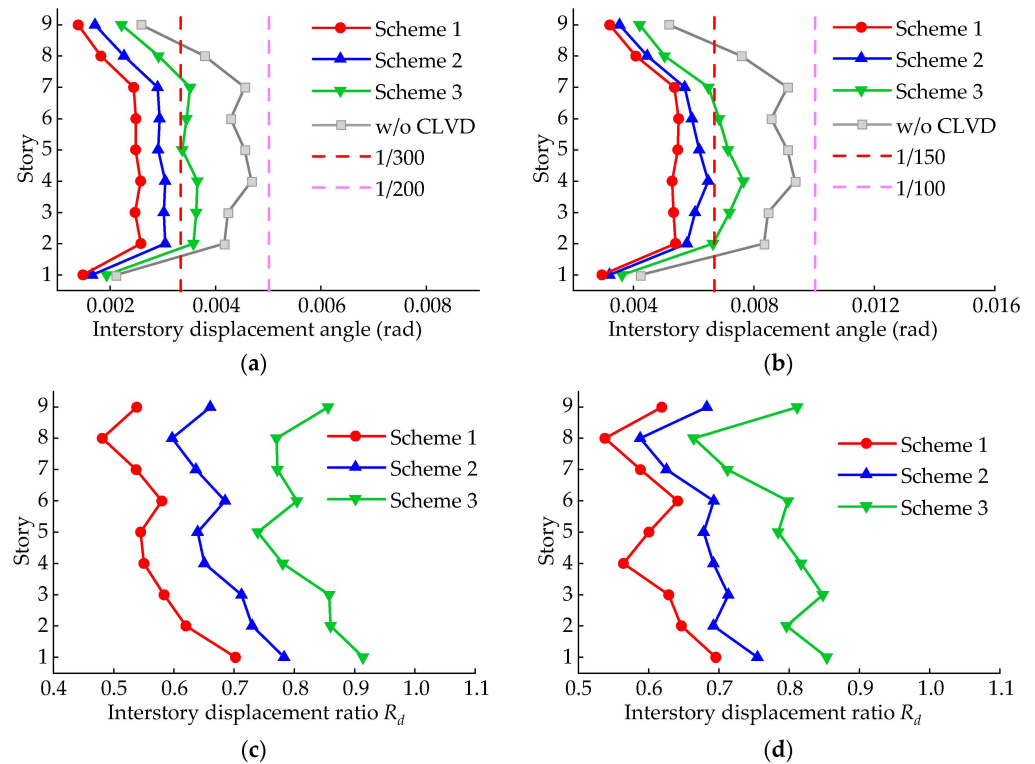


Figure 15. Inter-story displacement angle and R_d under fortification earthquakes and rare earthquakes: (a) inter-story displacement angle under fortification earthquakes; (b) inter-story displacement angle under rare earthquakes; (c) R_d under fortification earthquakes; (d) R_d under rare earthquakes.

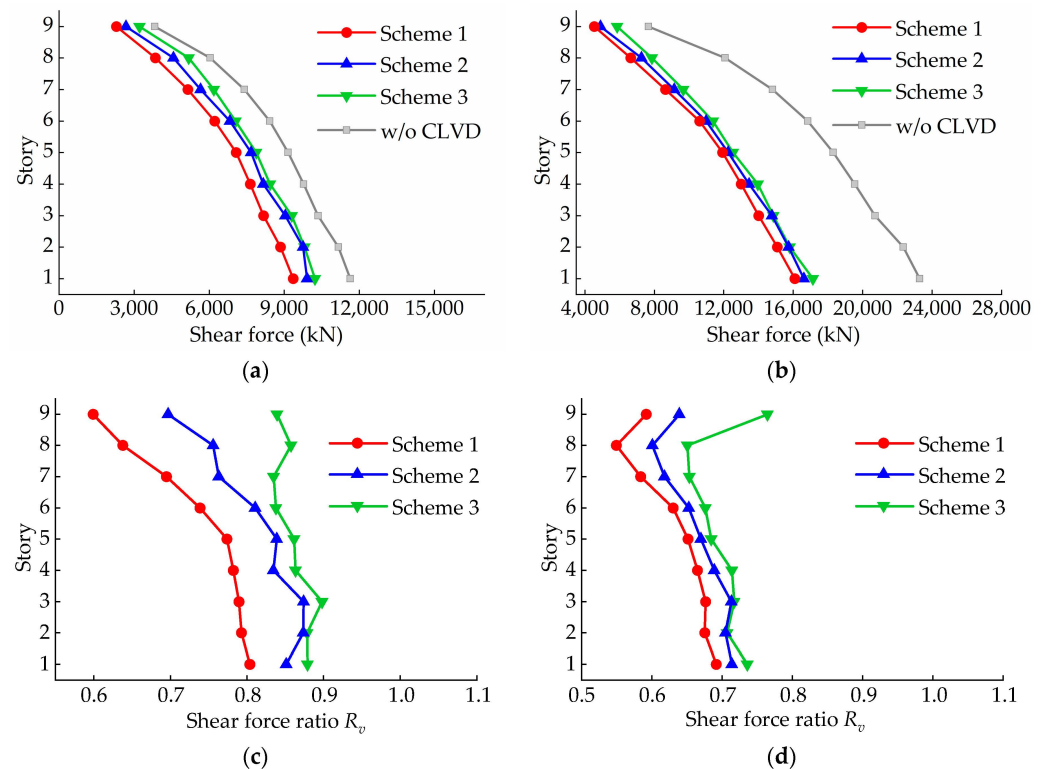


Figure 16. Story shear force and R_v under fortification earthquakes and rare earthquakes: (a) story shear force under fortification earthquakes; (b) story shear force under rare earthquakes; (c) R_v under fortification earthquakes; (d) R_v under rare earthquakes.

The research on the vibration reduction efficiency of CLVD in this study mainly considers the frame structure. For frame shear wall structures and shear wall structures, the proportion of inter-story bending deformation to the total inter-story deformation is relatively large. Therefore, the control effect of CLVD on inter-story displacement and shear force of such structures will deteriorate, which is not covered in this paper. CLVD has a high demand for the stiffness of beams, and applying negative stiffness devices to CLVD can further increase the deformation of dampers and reduce the stiffness demand of beams. We will further explore the displacement amplification effect and vibration reduction efficiency of CLVD dampers containing negative stiffness devices in the future.

5. Conclusions

CLVDs are a combination of an intermediate column, lever, and viscous damper, which are mainly designed to overcome the drawbacks of the low-energy-consumption effect of the intermediate column damper and the high cost and significant occupation of building space of the lever damper. Specifically, in this study, the displacement ratio R_d and the shear force ratio R_v of the structure with CLVDs to the structure without CLVDs are proposed as a means of comprehensively evaluating the vibration reduction effect of the structure with CLVDs; the effects of the position of the intermediate column, the beam's bending line stiffness, the lever amplification factor, the damping coefficient, and the earthquake intensity on the additional CLVD structure's total damping ratio ζ , the stiffness ratio k'_a/k_f , R_d , and R_v were studied; countermeasures to improve the damping effect of the structure with CLVDs under different conditions were provided. The main conclusions are as follows:

- (1) In contrast to the intermediate column located at both ends of the span, when the ratio of the distance from the intermediate column to the edge column to the span of the beam is 0.5, the stiffness k'_a and total damping ratio ζ provided by CLVDs to the structure reach the maximum value, and the CLVD owns the optimal vibration reduction effect.
- (2) When the intermediate column is located at the end of the span, k'_a/k_f increases with the increase in the beam's bending line stiffness i_b . When the intermediate column is located in the middle of the span, k'_a/k_f decreases as i_b increases. Regardless of the position of the intermediate column, ζ increases as i_b increases. Meanwhile, increasing the beam's bending line stiffness is beneficial for CLVD to control structural displacement and shear force.
- (3) There exists an optimal lever amplification factor χ , viscous damping coefficient c , and exponent α to achieve the optimal values of R_d and R_v . When the leverage amplification factor is too large, the CLVD provides the structure with stiffness as the main factor, followed by damping. When the ratio of the displacement amplification factor to the geometric amplification factor satisfies $f_d/\gamma = 1/2^{1-0.5\alpha}$, the CLVD possesses the optimal effect for controlling structural displacement.
- (4) In order to ensure that the CLVD has positive control effects on the structure's displacement and shear force under different intensity earthquakes, there are three approaches for achieving this goal. The first approach is to simultaneously increase the leverage amplification factor χ and the beam's bending stiffness i_b ; the second one is to simultaneously increase the damping coefficient c and the beam's bending line stiffness i_b ; and the third one is to increase the leverage amplification factor χ while reducing the damping coefficient c .
- (5) In the design of energy dissipation and vibration reduction, it is recommended to adopt the CLVD optimization strategy proposed in Section 3.3 to guide the design analysis. The CLVD with optimized parameters possesses a good control effect on the structure's inter-story displacement and story shear force. Scheme 1 using optimization methods has an additional damping ratio of up to 12% under fortification earthquakes. At the same time, the inter-story displacement was reduced by almost

40% under fortification earthquakes, and the inter-story displacement was reduced by almost 30% under rare earthquakes.

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References

1. Symans, M.D.; Charney, F.A.; Whittaker, A.S.; Constantinou, M.C. Energy dissipation systems for seismic applications: Current practice and recent developments. *J. Struct. Eng.* **2008**, *134*, 3–21. [\[CrossRef\]](#)
2. Gioiella, L.; Tubaldi, E.; Gara, F.; Dezi, L.; Dall'Asta, A. Modal properties and seismic behaviour of buildings equipped with external dissipative pinned rocking braced frames. *Eng. Struct.* **2018**, *172*, 807–819. [\[CrossRef\]](#)
3. Mcnamara, R.J.; Taylor, D.P. Fluid viscous dampers for high-rise buildings. *Struct. Des. Tall Spec. Build.* **2003**, *12*, 145–154. [\[CrossRef\]](#)
4. Pavia, A.; Scozzese, F.; Petrucci, E.; Zona, A. Seismic upgrading of a historical masonry bell tower through an internal dissipative steel structure. *Buildings* **2021**, *11*, 24. [\[CrossRef\]](#)
5. Ou, J.P.; Li, H. Design approaches for active, semi-active and passive control systems based on analysis of characteristics of active control force. *Earthq. Eng. Eng. Vib.* **2009**, *8*, 493–506. [\[CrossRef\]](#)
6. Bhowmik, K.; Debnath, N. Semi-active Vibration Control of Soft-Storey Building with Magnetorheological Damper under Seismic Excitation. *J. Vib. Eng. Technol.* **2024**, *12*, 6943–6961. [\[CrossRef\]](#)
7. Naeem, A.; Kim, J. Seismic retrofit of structures using rotational friction dampers with restoring force. *Adv. Struct. Eng.* **2020**, *23*, 16. [\[CrossRef\]](#)
8. Rayegani, A.; Soureshjani, O.K.; Alaee, S.A.M.; Mualla, I.H.; Nemati, F. Seismic Performance of Buildings Equipped with Four-Joint Rotational Friction Dampers in Mainshock–Aftershock Sequences. *J. Struct. Eng.* **2024**, *150*, 04023235. [\[CrossRef\]](#)
9. Dong, B.; Sause, R.; Ricles, J.M. Seismic Response and Damage of Reduced-Strength Steel MRF Structures with Nonlinear Viscous Dampers. *J. Struct. Eng.* **2018**, *144*, 04018221. [\[CrossRef\]](#)
10. Kang, J.D.; Tagawa, H. Seismic performance of steel structures with seesaw energy dissipation system using fluid viscous dampers. *Eng. Struct.* **2013**, *56*, 431–442. [\[CrossRef\]](#)
11. Pollini, N.; Lavan, O.; Amir, O. Minimum-cost optimization of nonlinear fluid viscous dampers and their supporting members for seismic retrofitting. *Earthq. Eng. Struct. Dyn.* **2017**, *46*, 1941–1961. [\[CrossRef\]](#)
12. Chen, Y.T.; Chai, Y.H. Effects of brace stiffness on performance of structures with supplemental Maxwell model-based brace-damper systems. *Earthq. Eng. Struct. Dyn.* **2011**, *40*, 75–92. [\[CrossRef\]](#)
13. Londono, J.M.; Neild, S.A.; Wagg, D.J. A noniterative design procedure for supplemental brace-damper systems in single-degree-of-freedom systems. *Earthq. Eng. Struct. Dyn.* **2013**, *42*, 2361–2367. [\[CrossRef\]](#)
14. Li, S.Y.; Chen, Y.T.; Chai, Y.H. Effects of Brace Stiffness and Nonlinearity of Viscous Dampers on Seismic Performance of Structures. *Int. J. Struct. Stab. Dyn.* **2021**, *21*, 2150188. [\[CrossRef\]](#)
15. Yang, L.Y.; Ye, M.; Huang, Y.H.; Dong, J.K. Study on Mechanical Properties of Displacement-Amplified Mild Steel Bar Joint Damper. *Iran. J. Sci. Technol. Trans. Civ. Eng.* **2023**, *7*, 01268. [\[CrossRef\]](#)
16. Ribakov, Y.; Gluck, J.; Gluck, N. Practical design of MDOF structures with supplemental viscous dampers using mechanical levers. In Proceedings of the 8th ASCE Specialty Conference on Probabilistic Mechanics and Structural Reliability, Notre Dame, IN, USA, 24–26 July 2000.
17. Ribakov, Y.; Reinhorn, A.M. Design of Amplified Structural Damping Using Optimal Considerations. *J. Struct. Eng.* **2003**, *129*, 1422–1427. [\[CrossRef\]](#)
18. Aly, S.A.; Zasso, A.; Resta, F. Proposed Configurations for the Use of Smart Dampers with Bracings in Tall Buildings. *Smart Mater. Res.* **2012**, *2012*, 251543. [\[CrossRef\]](#)
19. He, W.; Xu, H.; Xu, Z.; Liu, W. Experimental investigation and earthquake response analysis of a multilayer viscous damping wall with amplified deformation. *Eng. Struct.* **2022**, *251*, 113427. [\[CrossRef\]](#)
20. Shang, F.; Liu, W.G.; Zhang, Q.; Xu, H.; Guo, Y. Shaking table test and seismic behaviour evaluation of viscous damping wall with amplification mechanism. *Eng. Struct.* **2023**, *284*, 115974. [\[CrossRef\]](#)

21. Fournier, J.A.; Cheng, S.H. Impact of damper stiffness and damper support stiffness on the efficiency of a linear viscous damper in controlling stay cable vibrations. *J. Bridge Eng.* **2014**, *19*, 04013022. [\[CrossRef\]](#)
22. Losanno, D.; Londono, J.M.; Zinno, S.; Serino, G. Effective damping and frequencies of viscous damper braced structures considering the supports flexibility. *Comput. Struct.* **2017**, *207*, 121–131. [\[CrossRef\]](#)
23. Constantinou, M.C.; Tsopelas, P.; Hammel, W.; Sigaher, A.N. New configurations of fluid viscous dampers for improved performance. In *Proceedings of the Passive Structural Control Symposium*; Tokyo Institute of Technology: Yokohama, Japan, 2000.
24. Constantinou, M.C.; Tsopelas, P.; Hammel, W.; Sigaher, A.N. Toggle-brace-damper seismic energy dissipation systems. *J. Struct. Eng.* **2001**, *127*, 105–112. [\[CrossRef\]](#)
25. Sigaher, A.N.; Constantinou, M.C. Scissor-jack-damper energy dissipation system. *Earthq. Spectra.* **2003**, *19*, 133–158. [\[CrossRef\]](#)
26. Hwang, J.S.; Huang, Y.N.; Hung, Y.H. Analytical and experimental study of toggle-brace-damper systems. *J. Struct. Eng.* **2005**, *131*, 1035–1043. [\[CrossRef\]](#)
27. Huang, H.C. Efficiency of the motion amplification device with viscous dampers and its application in high-rise buildings. *Earthq. Eng. Eng. Vib.* **2009**, *8*, 521–536. [\[CrossRef\]](#)
28. Jiang, H.J.; Wu, S.Y.; He, L.S. Theoretical analysis and optimization of toggle-brace damper for cable tray system. *J. Constr. Steel Res.* **2021**, *187*, 106936. [\[CrossRef\]](#)
29. Polat, E.; Constantinou, M.C. Open-space damping system description, theory, and verification. *J. Struct. Eng.* **2017**, *143*, 04016201. [\[CrossRef\]](#)
30. Lan, B.J.; He, H.X.; Wu, S.; Cheng, S.T.; Chen, Y.F. Multi-performance objectives optimum design method and vibration control application of generalized toggle-brace-damper system. *Earthq. Eng. Struct. Dyn.* **2022**, *51*, 1410–1435. [\[CrossRef\]](#)
31. Xu, J.W.; Ma, P.F.; Hu, Y.K.; Yao, J.T. Discussion on Calculation Method of Magnification Factor of Toggle-Brace-Viscous Damper. *Buildings* **2024**, *13*, 2006. [\[CrossRef\]](#)
32. Zhou, Q.; Pan, W.; Lan, X. Analysis of Amplification Effect and Optimal Control of the Toggle-Style Negative Stiffness Viscous Damper. *Buildings* **2024**, *14*, 1625. [\[CrossRef\]](#)
33. Lan, X.; Pan, W.; Kuang, H.W. Correction additional damping of an energy-dissipation structure based on a story drifts utilization ratio method. *J. Vib. Shock.* **2017**, *36*, 64–71. (In Chinese)
34. Çerçevik, A.E.; Aşar, Ö.; Dilsiz, A. Optimal placement of viscous wall dampers in RC moment resisting frames using metaheuristic search methods. *Eng. Struct.* **2021**, *249*, 113108. [\[CrossRef\]](#)
35. Lan, X.; Zhang, L.F.; Sun, B.F.; Pan, W. Study on the Damping Efficiency of a Structure with Additional Viscous Dampers Based on the Shaking Table Test. *Buildings* **2024**, *14*, 1506. [\[CrossRef\]](#)
36. Sonmez, M.; Aydin, E.; Karabork, T. Using an artificial bee colony algorithm for the optimal placement of viscous dampers in planar building frames. *Struct. Multidiscip. Optim.* **2013**, *48*, 395–409. [\[CrossRef\]](#)
37. Bishop, J.A.; Striz, A.G. On using genetic algorithms for optimum damper placement in space trusses. *Struct. Multidiscip. Optim.* **2004**, *28*, 2–3. [\[CrossRef\]](#)
38. Sarcheshmehpour, M.; Estekanchi, H.E.; Ghannad, M.A. Optimum placement of supplementary viscous dampers for seismic rehabilitation of steel frames considering soil-structure interaction. *Struct. Des. Tall Spec. Build.* **2020**, *29*, e1682. [\[CrossRef\]](#)
39. Lan, X.; Wei, G.L.; Zhang, X.X. Study on the Influence and Optimization Design of Viscous Damper Parameters on the Damping Efficiency of Frame Shear Wall Structure. *Buildings* **2024**, *14*, 497. [\[CrossRef\]](#)
40. *JGJ 297–2013*; Chinese Standard, Technical Specification for Seismic Energy Dissipation of Buildings. Chinese Architecture and Building Press: Beijing, China, 2013.
41. Kasal, K.; Ito, H.; Watanabe, A. Peak response prediction rule for a SDOF elasto-plastic system based on equivalent linearization technique. *J. Struct. Constr. Eng.* **2003**, *571*, 53–62. (in Japanese).
42. *GB 50011–2016*; Chinese Standard, Code for Seismic Design of Buildings. Chinese Architecture and Building Press: Beijing, China, 2016.

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