

Article

Two-Stage Optimal Design Method for Asymmetric Base-Isolated Structures Subject to Pulse-Type Earthquakes

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Abstract: Asymmetric base-isolated structures subjected to severe torsion may suffer further aggravation of their torsional and translational responses under pulse-type earthquakes. To counteract these detrimental impacts, this study introduces a two-stage optimal design method. The first stage involved the application of the NSGA-II algorithm for determining an optimal isolator arrangement—namely, position and category—with the objective of reducing both the maximum interstory rotation of the superstructure and the isolation layer. In the second stage, the inclusion of viscous dampers served to minimize the excessive translational response triggered by pulse-type earthquakes. The influence of these dampers' positions on the structural response was carefully evaluated. The final application of this optimal design method was demonstrated on an asymmetric base-isolated structure. The results indicated a significant reduction in the translational and torsional responses of the asymmetric base-isolated structure when the two-stage optimal design method was utilized, compared to those of structures designed using traditional conceptual methods. It was found that by installing viscous dampers in the isolation layer along both the x and the y directions—specifically, underneath the mass center of the superstructure (CMS)—the effectiveness of the torsional resistance from the first stage could be effectively maintained.

Keywords: asymmetric base-isolated structures; pulse-type earthquakes; NSGA-II algorithm; two-stage optimal design method; isolator arrangement; viscous dampers; structural response



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1. Introduction

The growing popularity of the seismic isolation technology is primarily attributed to its ability to isolate the majority of the energy from earthquakes by extending buildings' natural period [1–3]. However, recent research suggests that the efficacy of isolators diminishes under long-period pulse-type earthquakes [4–7]. Increased deformation is a common outcome for base-isolated structures exposed to pulse-type earthquakes [8–10]. Furthermore, the challenge is amplified for asymmetric base-isolated structures that may experience severe torsion due to the eccentricity of the isolation system (e_b) (i.e., the distance between the CMS and the stiffness center of the isolation system (CSI)) [11–13]. Such structures may suffer an exacerbated adverse impact from pulse-type earthquakes [14]. Thus, this work proposes an optimization design method aiming to effectively mitigate the detrimental impacts of pulse-type earthquakes on asymmetric base-isolated structures.

Several studies have already proposed approaches that lessen the significant torsion of asymmetric base-isolated structures and decrease the excessive translational response caused by pulse-type earthquakes. The torsion of asymmetric base-isolated structures is predominantly influenced by structural parameters such as e_b , the ratio of torsional to lateral frequency, and the effective period of base-isolated structures [15–19]. One of the most efficient approaches that lessen the torsional response involves altering the arrangement of

isolators in the isolation system [20,21], enabling the adjustment of structural parameters to favor the torsional resistance. Additionally, it was found that adding viscous dampers to the isolation systems can successfully lessen the excessive structural response of base-isolated structures induced by pulse-type earthquakes. For instance, Kelly [22] used a two-degree-of-freedom linear model to simulate a base-isolated structure, demonstrating that damper installation in the isolation layer can lessen the isolation layer displacement while elevating the interstory drift. Politopolous [23] found that as the viscous damping ratio increases, the acceleration and shear of isolated structures decrease, using a model similar to Kelly's. He and Agrawal [24] argued that viscous damping is most effective when the pulse period closely aligns with the system period, as shown through base-isolated building structural analysis. Additionally, Mazza and Vulcano [25] conducted a dynamic response analysis of a five-story isolated frame structure with viscous dampers under pulse-type earthquakes to assess the effect of additional damping of the isolation layer. Their findings suggest that viscous dampers can effectively manage the displacement of isolators.

However, when an asymmetric base-isolated structure with severe torsional response is adversely affected by pulse-type earthquakes, it becomes imperative to explore whether these two aforementioned measures retain their effectiveness in reducing the structural response and how to synergize these measures to optimize their advantages. Consequently, this work suggests a two-stage optimal design method to leverage both measures. This optimization approach considers the impacts of both structural parameters and pulse-type characteristics on the structural response to more effectively mitigate the translational and torsional responses of asymmetric base-isolated structures under pulse-type earthquakes.

The first stage of the optimization design method aims to adjust the isolator arrangement to minimize the torsional response as much as possible. The traditional conceptual design of torsional resistance for asymmetric base-isolated structures usually employs a trial-and-error method to modify the isolator arrangement in order to lessen the structural torsional response. However, this method can be labor-intensive and inefficient. Moreover, the final isolator arrangement scheme obtained may not always be effective, even if it can somewhat reduce the torsional response. To enhance the efficiency of the torsional resistance, this paper introduces a multi-objective optimization algorithm in the first stage. Some scholars have conducted research on multi-objective optimal design methods [26,27]. It is worth noting that metaheuristic algorithms are increasingly popular for solving multi-objective optimization problems. For example, Ali et al. [28,29] achieved the optimal isolation period and isolation damping ratio of isolated structures through the multi-objective water cycle (MOWCA), crow search (CSA), and whale optimization (WOA) algorithms and the grey wolf optimizer (GWO). Kaveh and Zakianan [30] obtained minimal structural weight and cost through an improved grey wolf optimizer (IGWO) algorithm in truss systems. However, the decision variables of these metaheuristic algorithms are structural parameters with continuous values. When referring to a set of isolated points comprising parameters for different isolator categories in the first stage of the optimization design method, metaheuristic algorithms have certain limitations. Except for the metaheuristic algorithms, the fast non-dominated sorting genetic algorithm (NSGA-II), which offers advantages such as quick operation, excellent solution set convergence, high optimization accuracy, and guaranteed population diversity, is superior to general genetic algorithms [31–35]. Further, the decision variables of the NSGA-II algorithm are suitable for both continuous values and discrete values. Owing to these benefits, the NSGA-II method can rapidly generate a balanced set of Pareto optimal solutions, enabling decision-makers to select an optimal isolator arrangement scheme that maximizes the torsional response reduction while keeping the superstructure in an elastic state. The effectiveness and advantages of the NSGA-II algorithm have also been thoroughly demonstrated in research, with significant work by Song et al. [36], Xu et al. [37], Li et al. [38], and Zhong et al. [39]. Therefore, this paper applied the NSGA-II algorithm to achieve the optimal isolator arrangement.

The second stage of the optimization design method aims to install viscous dampers in the isolation system to decrease the excessive translational displacement induced by pulse-type earthquakes. The traditional conceptual design for enhancing the torsional resistance, which was described in JGJ297-2013 [40] and DBJ53/T-125-2021 [41], suggests that installing viscous dampers around a structure's perimeter can increase its torsional stiffness due to the dampers' additional stiffness. However, for asymmetric base-isolated structures that have undergone the first stage of torsional resistance, the isolation layer already possesses adequate torsional stiffness, and e_b is nearly zero. In this scenario, even though the installation of viscous dampers in the outer layer of isolation could provide more torsional stiffness for the optimized structure, the additional stiffness from the viscous dampers would shift the CSI significantly away from the CMS, severely compromising the structural torsional resistance. To prevent this negative impact, it is crucial to identify the most suitable position for the viscous dampers, enabling a reduction in the excessive translational displacement caused by pulse-type earthquakes while also preserving the efficiency achieved in the first stage.

This study first elaborates on the principle of the two-stage optimal design method before applying it to a five-story L-shaped planar asymmetric base-isolated structure exposed to pulse-type earthquakes. To assess the benefits of this optimal design method, the structural response of the optimized asymmetric isolated structure is compared to that of an asymmetric base-isolated structure designed using traditional conceptual methods. Moreover, we examine the effect of the viscous dampers' position on the structural response. The results suggest that in order to maintain the efficiency of the torsional resistance achieved in the first stage, it is advisable to install the viscous dampers in the isolation layer along the x and y directions, directly below the CMS, in the second stage. Further, the asymmetric base-isolated structure designed using this optimal method was shown to better mitigate the translational and torsional responses when subjected to pulse-type earthquakes compared to structures designed using traditional methods.

2. Specific Implementation of the Two-Stage Optimal Design Method

This section outlines the detailed implementation of the proposed two-stage optimal design method. The first stage seeks to eliminate the torsional response by optimizing the isolator arrangement using the NSGA-II algorithm [32–35]. Subsequently, the second stage aims to decrease the excessive translational displacement of this optimized structure, caused by pulse-type earthquakes, by installing viscous dampers in the isolation layer.

2.1. First Stage of the Optimization Design Method

2.1.1. Problem Formulation for the Optimization of Isolation Systems

The optimization objective of the first stage is to identify an optimal isolator arrangement, including positions and categories, as described in Equations (1) and (2), that simultaneously minimizes the maximum interstory rotation of the superstructure ($\theta_{s,max}$), the maximum rotation of the isolation layer ($\theta_{b,max}$), and the maximum interstory displacement of the superstructure ($u_{s,max}$) (see Equation (3)) without exceeding the displacement limit of the isolators (d_{max}) (see Equation (4)). The optimization problem for the first stage can be stated as follows:

$$\text{find} \quad \mathbf{X} = [x_1, x_2, \dots, x_N] \quad (1)$$

$$x_i \in R^d \quad (2)$$

$$\text{minimize} \quad f(\mathbf{X}) = [u_{s,max}, \theta_{s,max}, \theta_{b,max}] \quad (3)$$

$$\text{subject to} \quad d_0 \leq d_{max} \quad (4)$$

where $\mathbf{X}$ is the isolator arrangement scheme encompassing positions and categories; $x_i (i = 1, 2, \dots, N)$ represents the isolator category installed in the isolation layer in position i ; N indicates the total number of isolators; R^d stands for the selection range of the

isolator categories, including lead rubber bearings (LRBs) and laminated rubber bearings (LNRs); and d_0 denotes the maximum calculated displacement of the isolator.

2.1.2. Specific Implementation for the Optimization of the Isolation System

The three optimization objectives in Equation (3) have differing optimization weights. Both the rotation of the isolation layer and the interstory rotation of the superstructure should be reduced as much as possible, while the interstory translational displacement of the superstructure only needs to be reduced within its elastic limits. Achieving these specific objectives is difficult using general genetic algorithms. However, owing to the advantages of the NSGA-II algorithm [32–35], it is possible to quickly generate a set of well-balanced Pareto optimal solutions, enabling decision-makers to choose an optimal isolator arrangement scheme that fulfills this specific demand effectively. Therefore, the NSGA-II algorithm was applied to obtain a set of well-balanced Pareto optimal solutions in the first stage of the optimization design. From these selected solutions, the one that concurrently minimized both $\theta_{b,max}$ and $\theta_{s,max}$ while maintaining $u_{s,max}$ in its elastic limits was ultimately selected.

Figure 1 presents a detailed illustration of the first stage of the optimization design method. During this optimization stage, several factors must be considered:

1. To determine the range of the isolator categories, R^d , the isolator's diameter should be estimated, adhering to the vertical compressive stress limit requirements of the isolator under gravity load.
2. To maintain high-quality individuals within the population, the objective functions of those individuals whose isolator displacements do not meet the constraint $d_0 \leq d_{max}$ should be assigned high values during the non-dominated sorting process.
3. To improve the optimization efficiency, large-diameter LRBs should be used as peripheral isolators to enhance base-isolated structures' torsional resistance, as defined in Equation (1).
4. The structural analysis of asymmetric base-isolated structures and the first-stage NSGA-II algorithm are executed using ETABS v21.1.0 [42] and MATLAB [43], respectively. ETABS API v21.1.0 allows for the integration of a structural analysis in ETABS with the NSGA-II algorithm in MATLAB, courtesy of its function library. Consequently, these software tools can effectively implement the first stage of the optimal design of asymmetric base-isolated structures using the NSGA-II algorithm to enhance the torsional resistance.
5. The principle of adjusting the isolator arrangement to minimize the torsional response is predicated on the understanding that altering the isolator placement allows for the adjustment of structural parameters that determine the structural properties of torsional resistance for asymmetric base-isolated structures. This adjustment can notably enhance the torsional resistance. As the time history analysis method is time-consuming and these structural properties remain unaffected by different analysis methods and ground motion spectrum characteristics, this paper adopted the response spectrum analysis method for the first optimization stage to derive the optimal isolator arrangement.

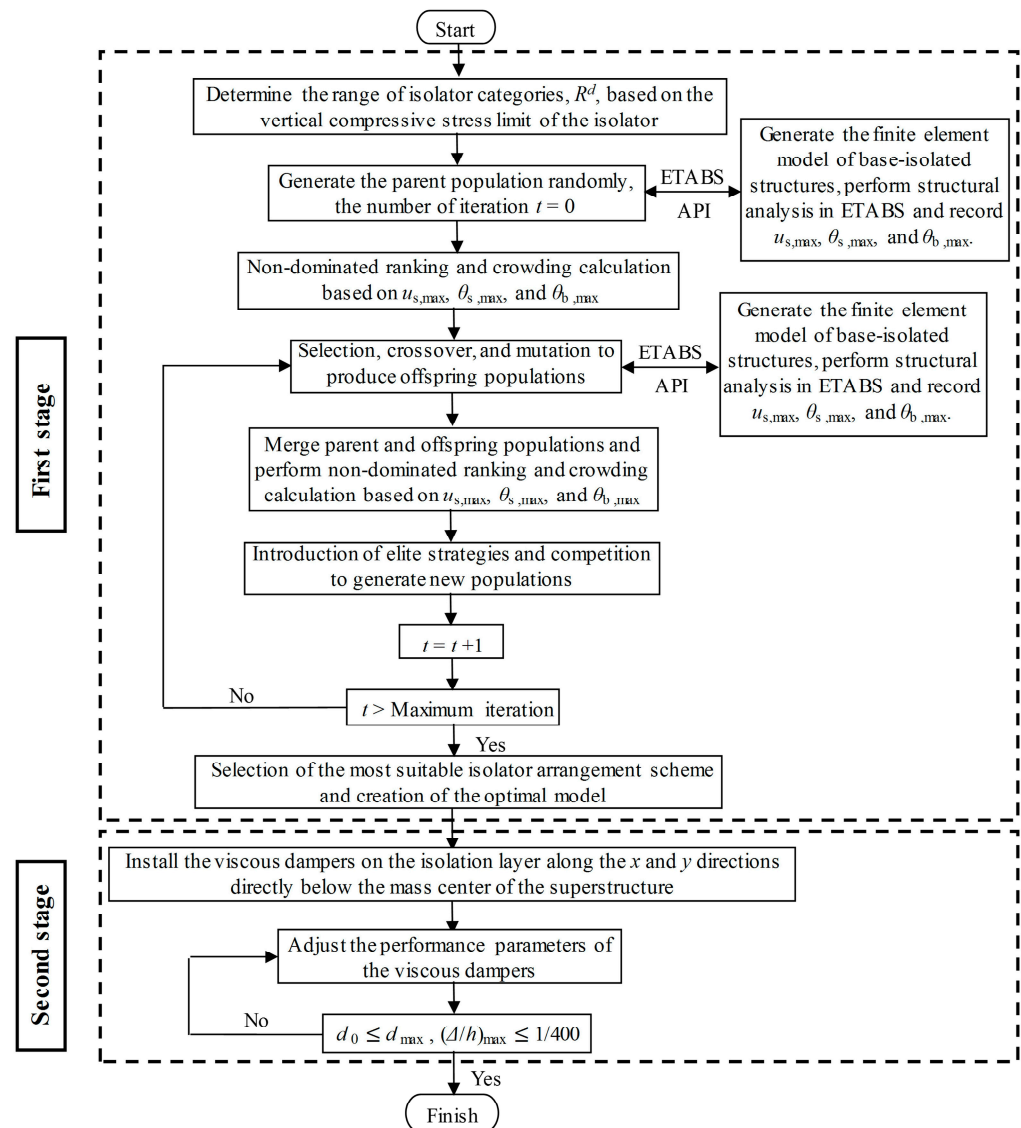


Figure 1. Flow chart of the two-stage optimal design method.

2.2. Second Stage of the Optimization Design Method

Following the first stage of optimization, the asymmetric base-isolated structure's structural parameters are all favorable for the torsional resistance. For instance, the torsional stiffness is ample, and the isolation system's eccentricity is nearly zero. At this point, the optimized structure's torsion could be contained within a limited range, even under pulse-type earthquakes. The second stage aims to reduce the excessive translational displacement caused by pulse-type earthquakes by strategically placing viscous dampers in the isolation layer. It is worth noting that viscous dampers and the parts that link them may build up fatigue as a result of repeated pulse-type earthquakes. Thus, it is important to monitor how well they function after prolonged usage. In order to preserve their performance, viscous dampers need to have their damping fluids and other components replaced on a regular basis. Figure 1 depicts the detailed process of the second stage of the optimization. During this optimization stage, several considerations should be made:

1. Energy dissipators in structures designed for energy dissipation and vibration reduction provide additional dynamic stiffness to the structure, as stipulated in the standards JGJ297-2013 [40] and DBJ 53/T-125-2021 [41]. Hence, the added stiffness given by energy dissipators to the structural response should be considered while

installing viscous dampers in the isolation layer. Following the first stage of optimization, the isolation layer possesses sufficient torsional stiffness, and e_b is nearly zero. At this point, installing viscous dampers in the outer isolation layer can cause the CSI to move significantly away from the CMS due to the dampers' additional stiffness, which would be detrimental to the structure's torsional resistance. Therefore, to preserve the first stage's torsional resistance efficiency, it may be advisable to install the viscous dampers in the isolation layer along the x and y directions, directly beneath the CMS. This method can ensure ample torsional stiffness and maintain e_b close to zero.

2. The time history analysis method is employed to evaluate the potential negative impacts of the pulse-type ground motion's pulse features on the base-isolated structures' translational displacement.
3. The performance parameters of the viscous dampers are iteratively adjusted until the maximum isolator displacement ($x_{b,max}$) and the maximum interstory drift ratio $(\Delta/h)_{max}$ meet the specified limits. $(\Delta/h)_{max}$ is the drift (Δ) divided by the story height (h). According to the drift ratio threshold defined in the GB/T51408-2021 code [44], the status of the superstructure is elastic when the $(\Delta/h)_{max}$ is less than 1/400. A limited number of dampers and their predetermined locations allow designers to modify only the performance parameters of the viscous dampers to reduce the base-isolated structures' translational response. The second stage, compared to the first stage of the optimization design for improving the torsional resistance, is straightforward to execute and does not require optimization algorithms.

3. Description of the Scheme Study

To assess the two-stage optimal design method's effectiveness, a typical five-story L-plan asymmetric base-isolated structure containing a reinforced concrete frame superstructure was selected. The structure was subjected to a seismic fortification intensity of eight, with a basic design acceleration of 0.2 g, a class II site category, and a group II seismic design according to the GB50011-2010 code [45]. The structure's original isolator arrangement was designed using traditional conceptual design methods. One of the most crucial torsional design principles is that large-diameter LRBs should be used as peripheral isolators to enhance base-isolated structures' torsional resistance [21]. Figures 2 and 3 illustrate the original object's finite element model and isolator arrangement, respectively, while Table 1 presents the isolators' property parameters.

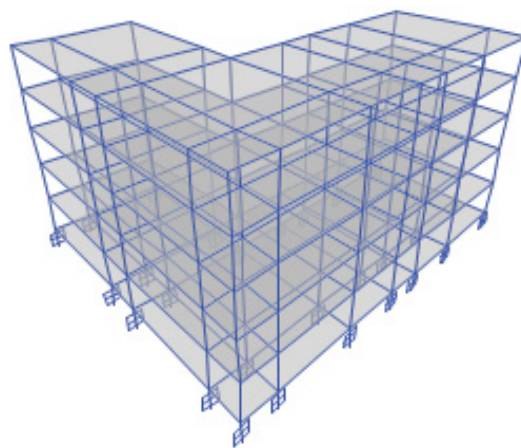


Figure 2. The finite element model of the original asymmetric base-isolated structure.

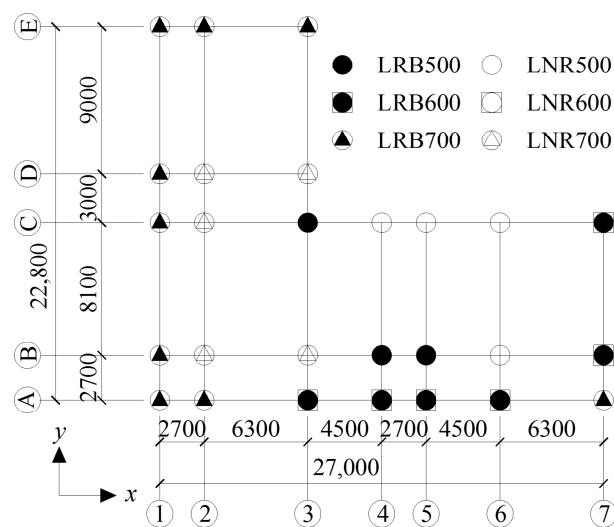


Figure 3. The arrangement of the isolation layer of the original asymmetric base-isolated structure without viscous dampers (unit: mm).

Table 1. The property parameters of isolators.

No	Name	Type	K (kN·m ⁻¹)	$\gamma = 100\%$ (kN·m ⁻¹)	$\gamma = 250\%$ (kN·m ⁻¹)	K_v (kN·m ⁻¹)	Q_d (kN)	Ratio	d_{max} (mm)
1	LRB500	LRB	6411	1374	950	1,721,000	62.8	0.1	275
2	LRB600	LRB	7918	1697	1174	2,321,000	90.4	0.1	330
3	LRB700	LRB	8741	1873	1296	2,784,000	123.1	0.1	385
4	LNR500	LNR	798	798	798	1,592,000	0	0	275
5	LNR600	LNR	987	987	987	2,186,000	0	0	330
6	LNR700	LNR	1090	1090	1090	2,632,000	0	0	385

Note: K symbolizes the pre-yield stiffness of the isolator; γ indicates the effective stiffness of the isolator at a shear strain equal to 100% and 250%; K_v represents the vertical stiffness of the isolator; Q_d denotes the yield force of the isolator; and *Ratio* is the ratio of the post-yield stiffness to the pre-yield stiffness of the isolator.

Viscous dampers can notably decrease the excessive translational displacement resulting from pulse-type earthquakes. Compared to the two-stage optimal design method suggested herein, the original object’s viscous dampers were installed in the isolation layer using traditional conceptual design methods, as illustrated in Figure 4.

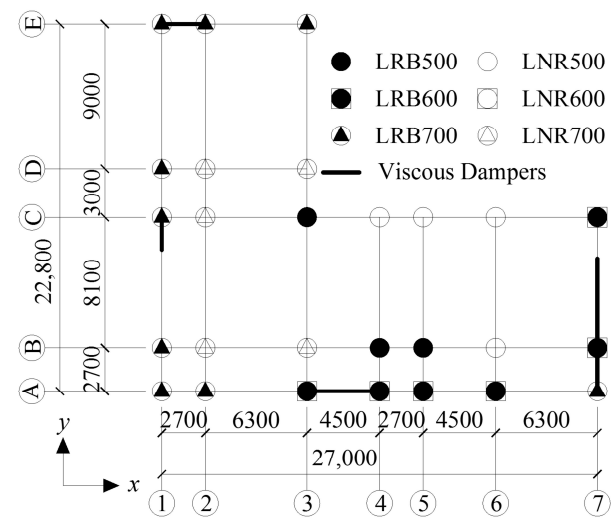


Figure 4. The arrangement of the isolation layer of the original asymmetric base-isolated structure with viscous dampers (unit: mm).

4. Selecting the Earthquakes

This section details the earthquakes used for the comparison of the structural responses to both non-pulse-type and pulse-type earthquakes.

4.1. Non-Pulse-Type Earthquakes

Seven non-pulse-type earthquakes were chosen depending on the site condition of the selected structure. The specifics about the characteristics and selection principles of the earthquakes were suggested by Reference [46]. Figure 5 displays the response spectra of these seven non-pulse-type earthquakes and the average spectrum that aligns with the target spectrum of the standard GB/T51408-2021 [44].

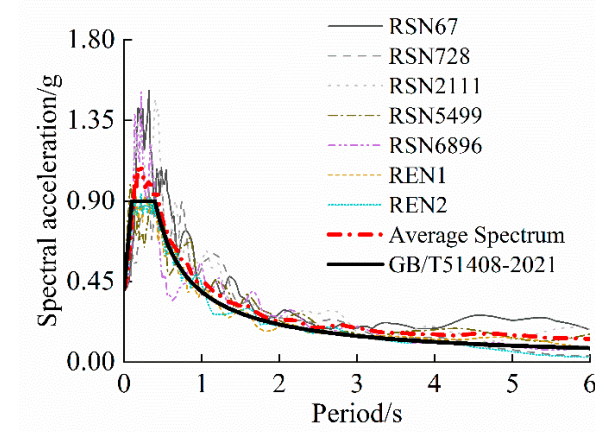


Figure 5. The response spectra of the selected non-pulse-type earthquakes [44].

4.2. Pulse-Type Earthquakes

The near-field coefficient, as per standard GB50011-2010 [45] and in accordance with code UBC97 [47], was utilized to augment the design response spectrum of near-fault earthquakes. The theory dictates that the near-field coefficient should be 1.5 within a 5 km radius of the fault and more than 1.25 within a 5–10 km radius. This strategy accounts for the effects of pulse-type earthquakes by amplifying non-pulse-type earthquakes' acceleration.

To better align with the standard GB50011-2010 [45], the design response spectrum—as per the standard GB/T51408-2021 [44] for a seismic fortification intensity of eight and a class II site category—was first multiplied by the near-field coefficient values of 1.5 and 1.25. This accounted for pulse-type earthquakes' amplification. The resulting amplified design response spectra were then compared with the average response spectrum of 29 near-field pulse-type earthquakes for a class II site category in the Pacific Earthquake Engineering Research Center (PEER) [48] Ground Motion Database.

It was found that the design response spectrum with a near-field coefficient of 1.5 for long periods (greater than the characteristic period T_g) better fitted the average response spectrum of these 29 near-field pulse-type earthquakes for this site condition. To further improve the match with the average response spectrum, T_g of the design response spectrum for pulse-type earthquakes was set to 0.8 s. The detailed process can be found in Reference [49]. This design response spectrum of pulse-type earthquakes was then applied herein, as depicted in Figure 6.

For the structural analysis, seven pulse-type earthquakes with long pulse periods (T_p) were selected from the PEER Ground Motion Database. These motions were chosen as their response spectra perfectly aligned with the pulse-type design response spectrum during primary vibration periods. When the building's seismic fortification intensity was eight under rare earthquakes, the peak ground acceleration of the seven selected earthquakes had to be adjusted to 0.4 g, according to the GB50011-2010 [45]. Figure 6 presents the response spectra of the selected pulse-type earthquakes. Table 2 presents the characteristics of the selected pulse-type earthquakes. These pulse-type earthquakes were input in the x and y

directions. The structural response was evaluated based on the average value computed from the seven chosen pulse-type earthquakes.

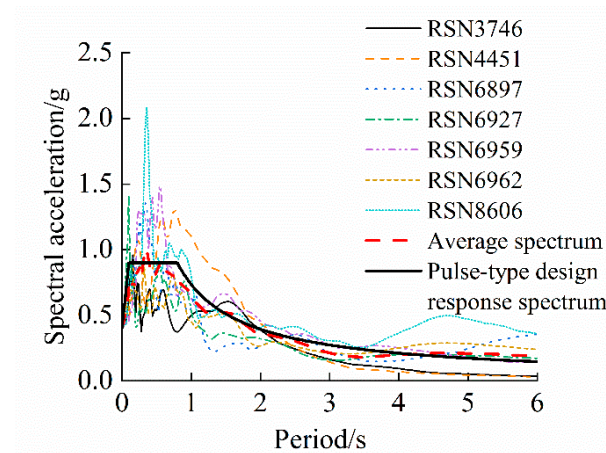


Figure 6. The response spectra of the selected pulse-type earthquakes.

Table 2. The characteristics of the selected pulse-type earthquakes.

Earthquake ID	Event	Station	M_w	T_p (s)	V_{S30} (m/s)	S_{90} (s)
RSN3746	Cape Mendocino	Centerville Beach_ Naval Fac	7.01	1.97	459.04	10.6
RSN4451	Montenegro_ Yugoslavia	Bar-Skupstina Opstine	7.10	1.44	462.23	21.3
RSN6897	Darfield_ New Zealand	DSLCL	7.00	7.83	295.74	19.6
RSN6927	Darfield_ New Zealand	LINC	7.00	7.37	263.20	12.7
RSN6959	Darfield_ New Zealand	Christchurch Resthaven	7.00	12.02	141.00	30.5
RSN6962	Darfield_ New Zealand	ROLC	7.00	7.14	295.74	11.4
RSN8606	El Mayor-Cucapah_ Mexico	Westside Elementary School	7.20	7.08	242.00	25.3

5. First Stage of the Optimization Design of the Selected Scheme

In this section, we employed the first stage of the optimization design method to optimize the isolator arrangement of the original asymmetric base-isolated structure, as detailed in Section 3. The effectiveness of this stage was then assessed by contrasting the structural responses of the optimal and original asymmetric base-isolated structures.

5.1. Optimization Process and Results of the First Stage

Following the optimization process of the first stage described in Section 2.1, the isolator range was initially determined to be LRB500, LNR500, LRB600, LNR600, LRB700, and LNR700. This was based on the gravity load at the base of each column and the isolators' ultimate vertical compressive stress, which was set to 12 MPa for the chosen scheme in the standard GB/T51408-2021 [44]. The characteristics of these isolators are detailed in Table 1.

In this study, the parameters of the NSGA-II algorithm were first designed with a focus on establishing a balance between computational precision and time efficiency, as suggested by Deb [32,35]. Throughout the iterative process, these parameters were adjusted in response to emerging solution trends. Finally, the population size was set to 50, with a crossover probability of 0.8, a mutation probability of 0.05, and an iteration number of 100. The values of the three optimization objectives remained stable when the number of iterations exceeded 85, indicating the convergence of the set of solutions. Thus, 100 iterations were sufficient for the NSGA-II algorithm to demonstrate effective convergence characteristics for this optimization problem's first stage.

After establishing the range of isolators and parameters for multi-objective optimization, the iteration for the first stage was successfully executed, as depicted in Figure 1.

A set of Pareto optimal solutions was swiftly obtained, which achieved a good balance among the three optimization objectives, as displayed in Figure 7. Following the optimization objectives of the first stage, the solutions exhibiting minimal maximum interstory displacement of the superstructure were first chosen. From these selected solutions, the one that concurrently minimized both $\theta_{s,max}$ and $\theta_{b,max}$ was ultimately selected as the optimal isolator arrangement scheme (Figure 8).

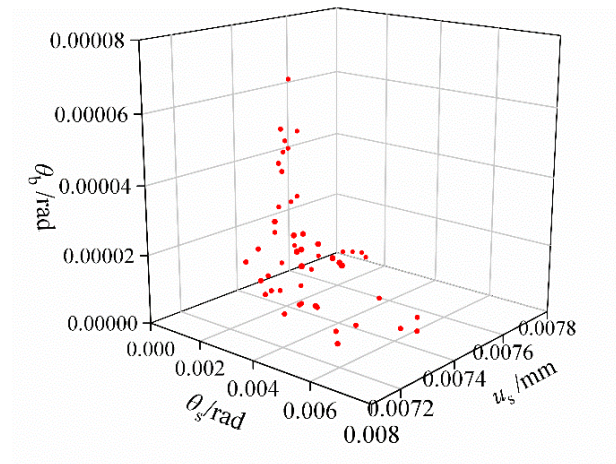


Figure 7. Optimal points of the Pareto optimal solutions.

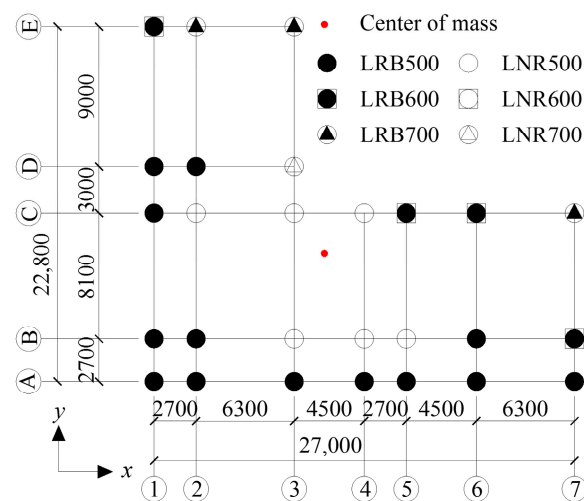


Figure 8. The optimal isolator arrangement scheme of the asymmetric base-isolated structure (unit: mm).

5.2. Discussion of the Results of the First Stage

The efficiency of the first stage was evaluated by comparing the structural responses of schemes 1 and 2. The effects of pulse-type earthquakes on the structural response of asymmetric base-isolated structures were evaluated by comparing the structural responses of schemes 2 and 3. Detailed descriptions of these three schemes are tabulated in Table 3. The isolator arrangement of scheme 1 is presented in Figure 3, while those of schemes 2 and 3 are shown in Figure 8. The primary structural responses are represented by $(\Delta/h)_{max}$, $(\Delta/h)_{max}$ of the superstructure $(\Delta/h)_{max,1}$, the maximum displacement of the isolation layer $(x_{b,max})$, the maximum interstory rotation (θ_{max}) , and the maximum displacement ratio $(\Delta_{max}/\Delta_{ave})_{max}$.

Table 3. The description of the different schemes in this paper.

Scheme	Type of Earthquakes	Design Methods of the Isolation Layer	
		First Stage	Second Stage
1	Non-pulse-type	Traditional conceptual design	-
2	Non-pulse-type	Optimization design	-
3	Pulse-type	Optimization design	-
4	Pulse-type	Optimization design	Optimization design
5	Pulse-type	Traditional conceptual design	Traditional conceptual design
6 and 7	Pulse-type	Optimization design	Traditional conceptual design

Table 4 presents the CMS, the CSI, and e_b of schemes 1–3. It is clear that e_b for the optimal asymmetric base-isolated structure was significantly less than for the original asymmetric base-isolated structure and very close to zero. This indicates that the first stage of the optimization design method effectively minimized e_b for the asymmetric base-isolated structure.

Table 4. The CMS and CSI of the structures.

Structures	Coordinates of CMS (m)		Coordinates of CSI (m)		e_b (m)	
	X	Y	X	Y	X	Y
Original asymmetric base-isolated structure (Scheme 1)	10.9346	8.2445	10.4576	7.7271	0.4770	0.5174
Optimal asymmetric base-isolated structure (Scheme 2 and Scheme 3)	10.9346	8.2445	11.0181	8.2865	0.0835	0.0420

Note: $e_b = |\text{Mass center} - \text{stiffness center}|$.

Figure 9 displays $(\Delta/h)_{\max}$ for all the superstructure stories in schemes 1–3. Notably, $(\Delta/h)_{\max}$ for scheme 3 was substantially larger than for schemes 1 and 2. $(\Delta/h)_{\max}$ for schemes 1–3 peaked on the first story, with these maximum values summarized in Table 5 as $(\Delta/h)_{\max,1}$. Both Figure 9 and Table 5 reveal that the values of $(\Delta/h)_{\max}$ for schemes 1 and 2 were less than the elastic limit of 1/400, while $(\Delta/h)_{\max,1}$ for scheme 3 was 1/369 in the x direction and 1/319 in the y direction. Table 5 also reports the values of $x_{b,\max}$. $x_{b,\max}$ for scheme 3 was significantly larger than for schemes 1 and 2, leading to $x_{b,\max}$ for scheme 3 exceeding the isolator's displacement limit ($d_{\max}$). These results highlight that pulse-type earthquakes substantially increased the translational displacements in both the superstructure and the isolation layer of the selected scheme, causing both the interstory drift ratio and the isolators' displacement to exceed their respective limits.

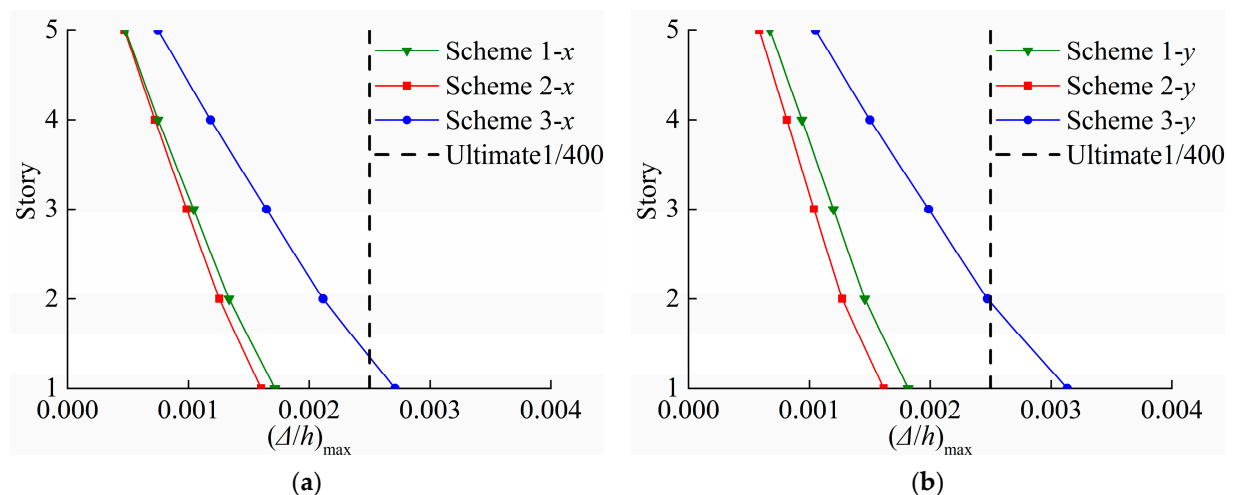
**Figure 9.** The values of $(\Delta/h)_{\max}$ for schemes 1–3 in the (a) x direction and (b) y direction.

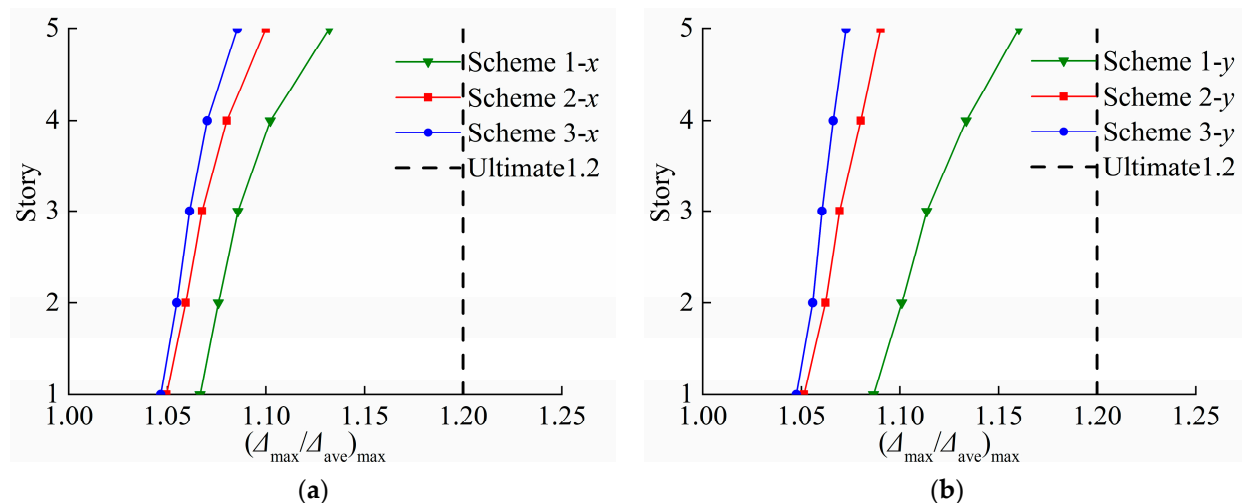
Table 5. The values of $(\Delta/h)_{\max,1}$ and $x_{b,\max}$ for schemes 1–3.

Scheme	$(\Delta/h)_{\max,1}$		$x_{b,\max}$ (mm)
	x	y	
1	1/582	1/550	222.96
2	1/624	1/619	191.91
3	1/369	1/319	317.14

Table 6 and Figure 10 display the torsional response of schemes 1–3, which includes $\theta_{\max}$ and $(\Delta_{\max}/\Delta_{\text{ave}})_{\max}$. $(\Delta_{\max}/\Delta_{\text{ave}})_{\max}$ is the ratio between the maximum or interstory translation and the average value of the floor's vertical elements' translation. The code GB/T51408-2021 [44] defines particular displacement ratio thresholds linked to different levels of structural torsion-related injury to reinforced concrete elements. The structural elements have the potential to suffer significant torsional damage if the value of $(\Delta_{\max}/\Delta_{\text{ave}})_{\max}$ surpasses 1.2, indicating a severe torsional effect. If the value of $(\Delta_{\max}/\Delta_{\text{ave}})_{\max}$ is between 1 and 1.2, the damage to elements caused by structural torsion is slight. Nevertheless, if the value of $(\Delta_{\max}/\Delta_{\text{ave}})_{\max}$ is close to 1.0, the structural torsion effect is minimal, and the elements almost suffer no damage caused by structural torsion.

Table 6. The values of $\theta_{\max}$ for schemes 1–3.

Story	$\theta_{\max}$ (rad)		
	Scheme 1	Scheme 2	Scheme 3
5	-3.14×10^{-6}	-8.57×10^{-7}	4.14×10^{-6}
4	-5.14×10^{-6}	-3.43×10^{-6}	4.86×10^{-6}
3	-7.43×10^{-6}	-5.43×10^{-6}	5.00×10^{-6}
2	-9.71×10^{-6}	-7.43×10^{-6}	3.86×10^{-6}
1	-1.27×10^{-5}	-8.14×10^{-6}	4.29×10^{-7}
0	4.90×10^{-4}	3.02×10^{-4}	3.05×10^{-4}

**Figure 10.** The values of $(\Delta_{\max}/\Delta_{\text{ave}})_{\max}$ for schemes 1–3 in the (a) x direction and (b) y direction.

Upon completion of the first stage of optimization, both $\theta_{\max}$ and $(\Delta_{\max}/\Delta_{\text{ave}})_{\max}$ for scheme 2 were noticeably lower than for scheme 1. This reduction signified the first stage's effectiveness in enhancing the structure's torsional resistance. While $\theta_{\max}$ for scheme 3 was slightly higher than for scheme 2 due to pulse-type earthquakes, $(\Delta_{\max}/\Delta_{\text{ave}})_{\max}$ for schemes 2 and 3 was near 1.0.

In conclusion, the first stage of the optimization considerably reduced the torsional response of the optimal asymmetric base-isolated structure. Moreover, pulse-type earth-

quakes had a little impact on the torsion of this structure, given that all structural parameters were optimized for torsional resistance. However, the translational displacements in the superstructure and the isolation layer of the optimal asymmetric base-isolated structure increased dramatically under pulse-type earthquakes, thereby exceeding the maximum limits for interstory drift ratio and isolator displacement. This finding suggests the need for further design enhancements to improve the lateral resistance under pulse-type earthquakes.

6. Second Stage of the Optimization Design of the Selected Scheme

This section discusses the second stage of the optimization design. The optimal asymmetric base-isolated structure was fitted with viscous dampers to mitigate the excessive translational response induced by pulse-type earthquakes, using the optimization method proposed in Section 2.2. The optimal structure's primary responses were then compared with those of a structure designed using traditional methods. Lastly, the influence of the viscous dampers' positions on the structural response was evaluated.

6.1. Optimization Process and Results of the Second Stage

The Maxwell model [50], a simplified mechanical model for viscous dampers, was employed in this study. Figure 11 depicts the model's diagram, while Equation (5) describes the damping force of a viscous damper

$$F = CV^\alpha + KD \quad (5)$$

where C is the damping coefficient of the viscous damper; V indicates the relative speed of the two opposite ends of the viscous damper; $\alpha \in [0.2, 0.4]$ represents the damping exponent of the viscous damper and its range, as specified by the internal construction of the viscous damper; K denotes the stiffness of the viscous damper; and D is the relative displacement of the two opposite ends of the viscous damper.

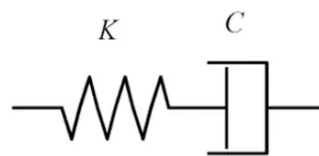


Figure 11. The diagram of the simplified mechanical model for viscous dampers.

In order to maintain the isolation system's eccentricity close to zero, the viscous dampers were initially applied to the isolation layer, directly beneath the CMS, along the x and y directions. Subsequently, the structural response was evaluated using the average value derived from the seven pulse-type earthquakes specified in Section 4.2. The length and the parameters of the viscous dampers were continually adjusted according to the structural response. This adjustment ensured that $x_{b,max}$ and $(\Delta/h)_{max}$ remained within the specification limits. The final damping coefficient for the viscous dampers was set at $C = 700 \text{ kN}\cdot\text{s}/\text{m}$, with a damping exponent $\alpha = 0.3$. The dampers, featuring ball hinges at the bottom, were installed at an oblique angle. As a construction precaution, it was necessary to place secondary beams under the floor slab at the damper positions. A stirrup reinforcement was employed to ensure an adequate bearing capacity at the joint where the dampers intersected the beams. Consequently, the two-stage optimal design method resulted in the optimal asymmetric base-isolated structure with viscous dampers, referred to as scheme 4 in Table 3. Figure 12 details the isolation layer arrangement in scheme 4.

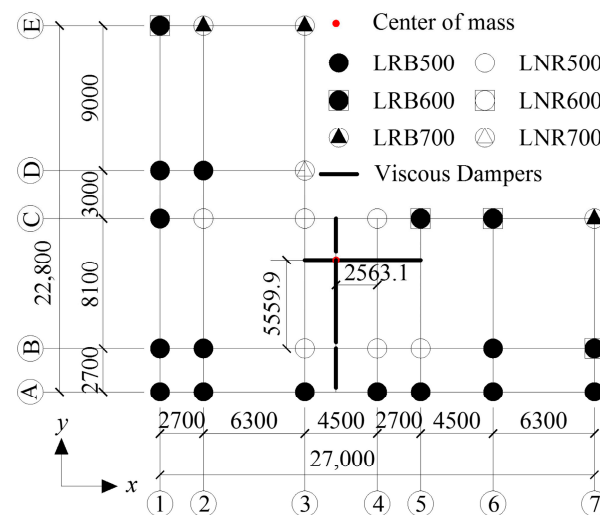


Figure 12. The isolation layer arrangement scheme of the optimal asymmetric base-isolated structure with viscous dampers (unit: mm).

6.2. Discussion of the Results of the Second Stage

This section first compares the primary structural responses of schemes 3 and 4 to assess the impact of the viscous dampers in alleviating the excessive translational displacements caused by pulse-type earthquakes. Following that, the primary structural response of the optimal scheme 4 is compared with that of scheme 5 (as seen in Table 3), which employed traditional design methods for arranging isolators and viscous dampers. Figure 4 illustrates the arrangement of the isolators and viscous dampers in scheme 5.

In order to preserve the torsional resistance efficiency achieved in the first stage, the dampers were applied to the isolation layer directly beneath the CMS, along the x and y directions. This installation contradicts the traditional damper arrangement principle, which recommends dispersing viscous dampers around the isolation layer's perimeter. Consequently, schemes 6 and 7 were designed with dampers distributed around the isolation layer's perimeter, and the response of scheme 4 was compared with those of schemes 6 and 7. To enhance the analysis of the damper position effects on the structural response, the structural arrangements of schemes 6 and 7 mirrored that of scheme 4, except for damper positioning. Figure 13 illustrates the arrangement of the isolators and viscous dampers in schemes 6 and 7.

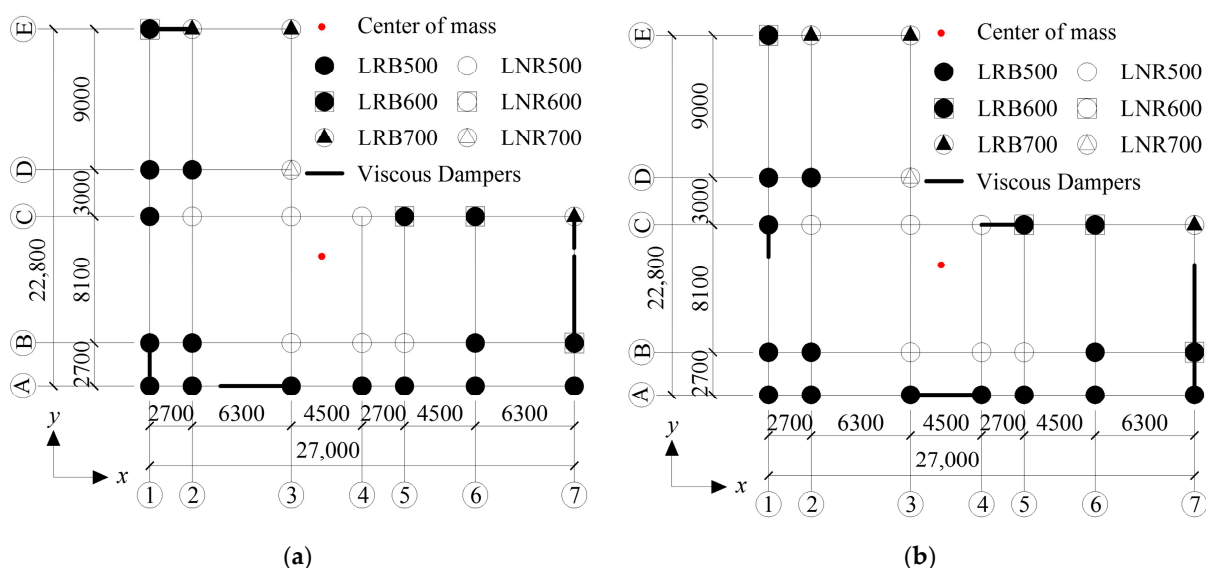


Figure 13. The arrangement of isolators and viscous dampers in schemes (a) 6 and (b) 7. (unit: mm).

Figure 14 presents $(\Delta/h)_{\max}$ for schemes 3–7 in both the x and y directions. Each scheme's maximum value occurred on the first story, and these values are summarized as $(\Delta/h)_{\max,1}$ in Table 7. Table 7 also displays $x_{b,\max}$ for schemes 3–7. Figure 14 shows that $(\Delta/h)_{\max}$ for scheme 4 was less than that for scheme 3. Moreover, it is evident that $(\Delta/h)_{\max,1}$ and $x_{b,\max}$ for scheme 4 were significantly reduced, staying within acceptable limits, due to the addition of the viscous dampers. This stands in contrast to what observed for scheme 3, as in that case, both exceeded their respective limits. These results suggest that viscous dampers can notably decrease both $(\Delta/h)_{\max}$ and $x_{b,\max}$ in a base-isolated structure under the influence of pulse-type earthquakes.

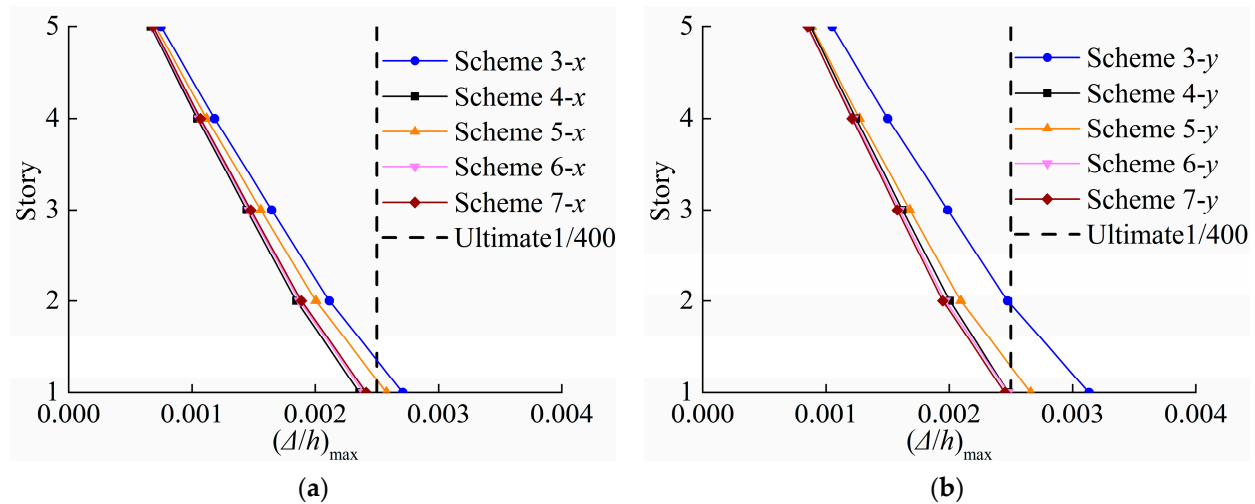


Figure 14. The values of $(\Delta/h)_{\max}$ for schemes 3–7 in the (a) x direction and (b) y direction.

Table 7. The values of $(\Delta/h)_{\max,1}$ and $x_{b,\max}$ for schemes 3–7.

Scheme	$(\Delta/h)_{\max,1}$		$x_{b,\max}$ (mm)
	x	y	
3	1/369	1/319	317.14
4	1/424	1/403	233.71
5	1/388	1/376	215.46
6	1/418	1/404	274.16
7	1/415	1/408	277.66

Furthermore, for scheme 5, designed using traditional conceptual design methods, there was a 9.29% increase in $(\Delta/h)_{\max,1}$ over scheme 4, and the elastic threshold of 1/400 in terms of $(\Delta/h)_{\max,1}$ was exceeded, even though $x_{b,\max}$ remained within its limits. This revealed that the two-stage optimal design method outperformed the traditional conceptual design methods, particularly in reducing the superstructure's maximum interstory drift.

Additionally, it is clear that $(\Delta/h)_{\max}$ and $(\Delta/h)_{\max,1}$ for schemes 4, 6, and 7 share similar values and did not exceed their respective limits, as seen from Figure 14 and Table 7. This suggests that the viscous dampers' position had a little adverse impact on the structure's interstory drift in the second stage. However, schemes 6 and 7 showed a 17.31% increase in $x_{b,\max}$ over scheme 4. The reason for the increase might be that the traditional arrangement method resulted in a larger $\theta_{\max}$ of the isolation layer in schemes 6 and 7, which increased the corner isolator displacements with respect to that observed for scheme 4. The following provides a comparative analysis of the torsional response of several schemes under various design methods in order to validate this issue.

Table 8 and Figure 15 show the $\theta_{\max}$ and $(\Delta_{\max}/\Delta_{\text{ave}})_{\max}$ values for schemes 3–7. Notably, $\theta_{\max}$ for scheme 4 was significantly less than for scheme 5, as seen in Table 8. Specifically, $\theta_{\max}$ of the isolation layer in scheme 4 was merely 14.16% of that in scheme

5, and $\theta_{\max}$ of the superstructure in scheme 4 was reduced to a maximum of 51.28% of that in scheme 5. Moreover, for scheme 5, $(\Delta_{\max}/\Delta_{\text{ave}})_{\max}$ greatly exceeded the limit of 1.2, whereas for scheme 4, it was notably lower. This revealed that the two-stage optimal design method outperformed traditional conceptual design methods, particularly in reducing the interstory rotation and the displacement ratio.

Table 8. The maximum interstory rotation ($\theta_{\max}$) for schemes 3–7.

Story	$\theta_{\max}$ (rad)				
	Scheme 3	Scheme 4	Scheme 5	Scheme 6	Scheme 7
5	4.14×10^{-6}	-6.00×10^{-6}	1.13×10^{-5}	1.10×10^{-5}	1.19×10^{-5}
4	4.86×10^{-6}	-8.00×10^{-6}	1.56×10^{-5}	1.50×10^{-5}	1.56×10^{-5}
3	5.00×10^{-6}	-1.20×10^{-5}	1.94×10^{-5}	1.90×10^{-5}	1.94×10^{-5}
2	3.86×10^{-6}	-1.90×10^{-5}	2.36×10^{-5}	2.30×10^{-5}	2.31×10^{-5}
1	4.29×10^{-7}	-2.10×10^{-5}	2.84×10^{-5}	2.60×10^{-5}	2.81×10^{-5}
0	3.05×10^{-4}	4.44×10^{-4}	3.07×10^{-3}	3.63×10^{-3}	6.62×10^{-3}

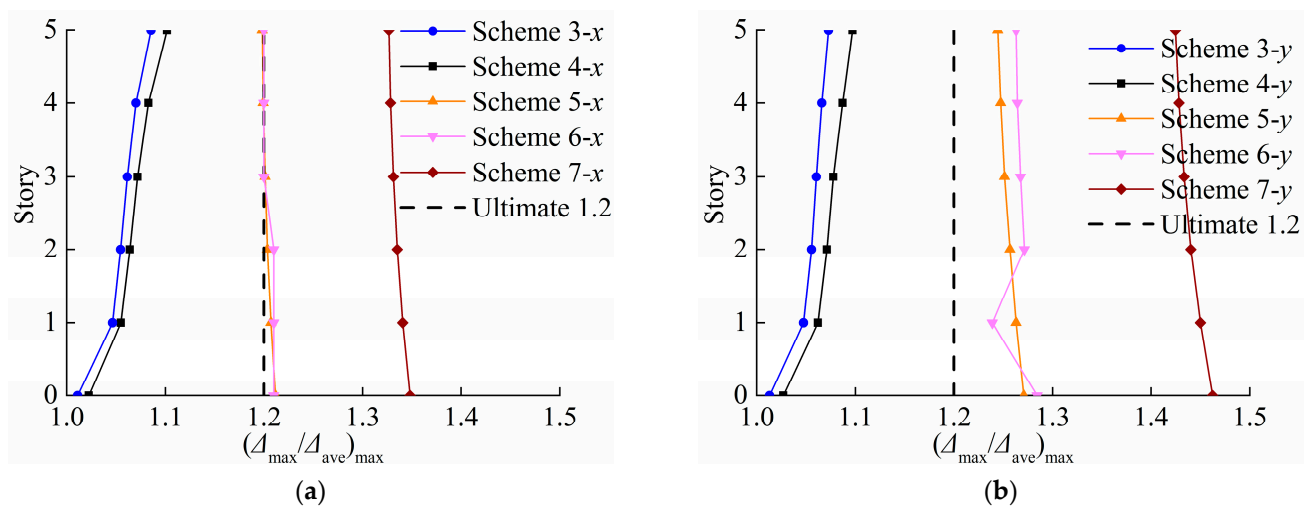


Figure 15. The maximum displacement ratio for schemes 3–7 in the (a) x direction and (b) y direction.

Furthermore, Table 8 reveals that $\theta_{\max}$ for schemes 6 and 7 was significantly higher than for scheme 4. Particularly in the isolation layer, $\theta_{\max}$ for scheme 4 was approximately 10% of that for schemes 6 and 7. As depicted in Figure 15, $(\Delta_{\max}/\Delta_{\text{ave}})_{\max}$ for schemes 6 and 7 was significantly greater than for scheme 4. Moreover, for schemes 6 and 7, $(\Delta_{\max}/\Delta_{\text{ave}})_{\max}$ exceeded the limit of 1.2, suggesting a negative impact on the structure due to torsion. These results indicate that the optimal design method of the viscous damper arrangement can better improve the torsional resistance efficiency than traditional conceptual design methods.

These findings suggest that compared to traditional design methods for asymmetric base-isolated structures, the two-stage optimal design method significantly reduces the torsional response under pulse-type earthquakes, while also ensuring a strong lateral resistance. Especially, the interstory drift ratio and the displacement ratio of the optimized asymmetric base-isolated structure were significantly reduced to acceptable limits. Additionally, during the second stage of optimization, the damper positions had a little impact on the structure's interstory drift. However, installing viscous dampers around the perimeter of the isolation layer negatively enlarged the rotation of the isolation layer, which increased the corner isolator displacements. This adverse effect was primarily due to the added stiffness of the dampers when they were distributed around the isolation layer's perimeter. After the first stage of optimization, the CSI and the CMS essentially coincided. The added damper stiffness increased the distance between the CSI and the CMS, thus

exacerbating the torsional response. Consequently, it is recommended to install the viscous dampers directly under the CMS, along the x and y directions of the isolation layer, during the second stage of the optimization design.

7. Conclusions

In this study, we presented a two-stage optimal design method for asymmetric base-isolated structures subjected to pulse-type earthquakes. The advantages of this proposed method were demonstrated through an examination of a typical five-story L-plan asymmetric base-isolated structure. Furthermore, we analyzed the most appropriate positioning of viscous dampers during the second stage of the design. The key conclusions from our study are:

1. During the first stage of the design, the NSGA-II algorithm provides a more efficient and quicker means of finding an optimal isolator arrangement compared to other algorithms. This optimized arrangement minimizes the rotation of the isolation layer and the interstory rotation of the superstructure, thereby reducing the negative effects caused by the torsional response to negligible levels.
2. Our findings revealed that distributing viscous dampers across the perimeter of the isolation layer during the second stage of optimization can negatively impact the torsional response. To maintain the effectiveness of the torsional resistance achieved in the first stage and significantly decrease the overrun of the translational response of asymmetric base-isolated structures caused by pulse-type earthquakes, it is advisable to install the viscous dampers in the isolation layer along the x and y directions, directly below the CMS in the second stage.
3. Compared to traditional conceptual design methods for isolators and viscous dampers, the two-stage optimal design method proposed herein can more effectively enhance the lateral resistance and torsional resistance of asymmetric base-isolated structures. As per the case study presented, both the maximum interstory drift ratio and the maximum displacement of the isolators in the optimal asymmetric base-isolated structure under pulse-type earthquakes were reduced within their limits, as compared to those in the structure designed using traditional conceptual design methods. Furthermore, the maximum rotation of the isolation layer and the maximum interstory rotation of the superstructure of the optimal asymmetric base-isolated structure were merely 14.16% and 51.28% of those of the structure designed using traditional conceptual design methods, respectively. Moreover, the maximum displacement ratio of the optimal asymmetric base-isolated structure was reduced within its limit following the two-stage optimal design, indicating that the adverse effect caused by torsional responses can be effectively disregarded.
4. In addition to damper positioning, future research could also target the optimization of damper parameters to achieve better lateral and torsional resistance. When site condition limitations are eliminated from the analysis of the structural response, the number of pulse-type earthquakes available for investigation grows considerably. At this point, it is crucial to investigate the impact of the characteristics of pulse-type earthquakes on the structural response. For example, Sharma et al. [51] found that a high directivity ratio of the pulse-type earthquakes has a significant effect on the structural response. Thus, future research should explore a new optimal design method that not only provides better lateral and torsional resistance to asymmetric base-isolated structures under pulse-type earthquakes that are suitable for the site condition of the selected structure, but also allows these structures to perform well under pulse-type earthquakes with different characteristics.

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