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Comparative Evaluation of Seismic Behavior of T-Shaped versus Rectangular Concrete Shear Walls in High-Rise Buildings

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A B S T R A C T

High-rise buildings exhibit complex seismic behavior due to their height and flexibility, requiring robust lateral load-resisting systems to ensure safety and serviceability. Among these, dual systems combining steel moment frames with reinforced concrete shear walls are widely adopted in tall building design. This study evaluates the seismic performance of a 30-story high-rise building located in a high seismic zone with a design base acceleration of A = 0.5, representing a conservative scenario for critical structures. Two shear wall configurations—rectangular and T-shaped were modeled and analyzed through both linear response spectrum and nonlinear time history analyses using six representative earthquake records. The results demonstrate that T-shaped shear walls provide superior lateral stiffness, reduced roof displacements, and lower inter-story drifts compared to rectangular walls under both elastic and inelastic conditions. This improved behavior is attributed to the higher moment of inertia of T-shaped walls, making them a more efficient and resilient choice for high-rise buildings in seismic-prone regions.

1. Introduction

As urban development trends increasingly favor vertical expansion, high-rise buildings have become a defining element of modern cityscapes. Due to their height and flexibility, these structures are especially vulnerable to lateral forces such as wind and seismic loads, which can significantly affect their dynamic response and overall stability [1, 2]. Therefore, the selection of an effective lateral load-resisting system is essential to ensure both structural safety and serviceability [3]. Among the available options, dual systems-combining moment-resisting frames with shear walls-offer a well-balanced solution by providing both ductility and stiffness [4, 5]. In particular, composite steel moment frames integrated with reinforced concrete shear walls are widely adopted in tall building design for their superior seismic resilience and structural efficiency. Given their increasing use, numerous studies have been conducted to evaluate the seismic performance of various shear wall configurations, particularly T-shaped walls, which are commonly used in high-rise construction [6, 7].

As part of efforts to evaluate the seismic performance of T-shaped shear walls, Thomsen IV and Wallace [8] conducted experimental and analytical studies, demonstrating that positive bending, which places the flange in compression, results in better ductility compared to negative bending, where the flange is in tension and ductility is reduced. Brueggen [9] tested two steel–concrete composite T-shaped shear wall models and found lower displacement capacity compared to rectangular or symmetrically flanged walls, emphasizing the need for careful design at the free web edge. Similarly, Pin-Le and Qing-ning [10] tested six scaled T-shaped walls under cyclic loading and found the web to be the weakest zone, failing due to concrete crushing and reinforcement yielding. Lu and Yang [6] also observed flexural failure at the free web boundary in slender steel-reinforced concrete T-shaped walls, highlighting the importance of proper confinement as axial load increases. Ji et al. [11] compared Chinese and American seismic codes and found GB 50011-2010 underestimates boundary element length at the non-flange end, risking premature failure; their proposed displacement-based method improved drift capacity without added reinforcement. Lan et al. [12] found that T-shaped

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composite walls performed best under 45° loading, with higher axial loads increasing strength but reducing ductility, and embedded steel enhancing performance, especially in flexure-dominant directions.

Following these findings, several recent studies have explored advanced configurations and loading conditions. Brueggen et al. [13] found that distributing longitudinal reinforcement across the flange, rather than concentrating it in boundary elements, reduced shear lag, crack widths, and damage in T-shaped RC walls under multidirectional cyclic loading. Wang et al. [14] further revealed that biaxial loading, especially with larger paths like the square, intensified damage and reduced strength and deformation capacity due to stress coupling and force redistribution at wall corners. In the context of precast systems, Shen et al. [15] developed a T-shaped wall with H-shaped shear keys and a design method to control yield force and displacement by adjusting key geometry, while Gu et al. [16] showed that T-shaped precast walls with U-shaped steel bar connections and higher axial loads matched or outperformed cast-in-place walls. Ji et al. [17] found that walls under high axial load (~0.19) achieved >2.0% drift with ACI 318-19 or displacement-based design, while GB 50011-2010 designs failed early; they also identified SFI-MVLEM-3D as the most accurate FE model for capturing shear-flexure interaction. Yang et al. [18] showed that rebar corrosion significantly reduces performance, especially under positive loading, and developed a validated FE model for evaluating aging walls in corrosive environments. Finally, Mo et al. [19] introduced a T-shaped steel–concrete composite wall with C-shaped steel frames, demonstrating excellent seismic performance, with lower shear span ratios, an optimal axial load ratio of 0.4, and greater steel thickness, all improving wall behavior.

This study investigates the seismic performance of a 30-story high-rise building located in a high seismic zone with a design base acceleration of A = 0.5, a conservative value exceeding the typical upper limit of A = 0.35 to account for proximity to active faults. The research focuses on a comparative analysis of two commonly used shear wall configurations, rectangular and T-shaped, to identify the optimal solution for enhancing seismic resilience and cost-effectiveness in tall buildings. The evaluation begins with linear response spectrum analysis to determine the most efficient wall arrangement based on roof displacements, followed by an assessment of story displacements and inter-story drifts. To capture inelastic behavior, nonlinear time history analyses were conducted using six representative earthquake records applied simultaneously in both orthogonal directions. The combined results of linear and nonlinear analyses reveal the relative seismic performance of each configuration, offering practical insights into the optimal shear wall design for high-rise structures in earthquake-prone regions.

2. Methodology

This section presents a summary of the modeling assumptions, building codes, analysis parameters, seismic load considerations, and software tools used for design and analysis. The structural design of the 30-story building was carried out using ETABS v15.2.2. For linear response spectrum analysis, ETABS v15.2.2 was employed, while SAP2000 v18 was used for nonlinear time history analysis.

2.1. Geometric specifications of the 30-story building

Fig. 1 shows the structural plan of the building, which consists of regular bays arranged in a grid of 5 bays in both the longitudinal and transverse directions, with each bay measuring 6 meters. The studied structure has 30 stories, with each story having a uniform height of 3.5 meters. The structural modeling has been conducted in three dimensions.

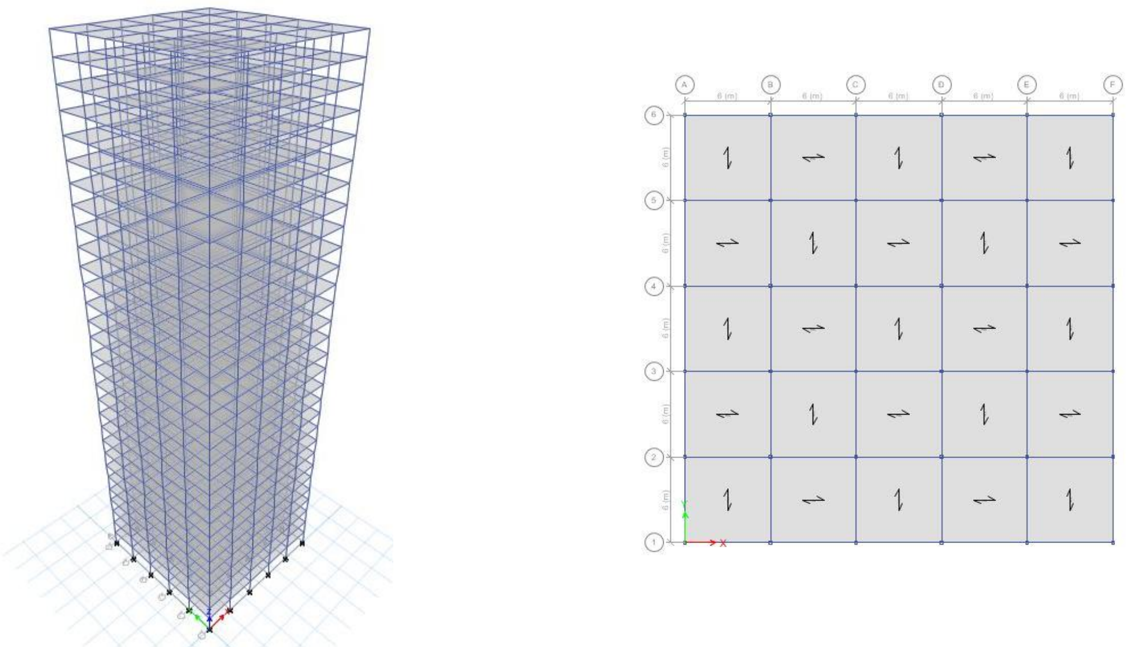


Fig. 1. 3D view and plan layout of the structural frame.

The lateral load-resisting system consists of a dual system: a special reinforced concrete shear wall system combined with a special moment-resisting steel frame system. For the 30-story building, the thickness of the shear walls is:

- 50 cm for floors 1–10
- 40 cm for floors 11–20
- 30 cm for floors 21–30

2.2. Loading

In the structural model, various types of gravity and wall loads were applied based on standard design considerations for residential buildings. These include dead loads such as the self-weight of structural components and floor finishes, as well as live loads representing occupancy. Wall loads were also assigned to account for the weight of perimeter walls on both typical floors and the roof. A summary of the applied loads is presented in Table 1.

Table 1. Applied dead, live, and wall loads.

Load Type	Magnitude	Unit
Dead load for floors	500	kg/m²
Partition load	100	kg/m²
Live load for floors	200	kg/m²
Wall load (dead)	600	kg/m²
Roof dead load	500	kg/m²
Roof live load	150	kg/m²
Roof wall load	300	kg/m²

2.3. Design codes and structural specifications

The structure is intended for residential use, and the potential for cracking in the shear walls has been explicitly considered in the design. The moment-resisting frame is designed to resist at least 25% of the earthquake-induced lateral forces, incorporating the consideration of P-Delta effects in the design process. Seismic analysis has been performed using the standard response spectrum defined in the Iranian Code 2800 [20], ensuring that the base shear demand exceeds the minimum allowable threshold. The building is assumed to be located in a seismic zone characterized by a design acceleration coefficient of A = 0.5. Additionally, the site soil conditions are classified as Type II. To extend the evaluation beyond the elastic range, nonlinear time history analysis was also performed to capture the inelastic seismic response of the structure under real ground motions applied in both principal directions.

The structural design, analysis, and validation are carried out per the following recognized standards:

1. Iranian Seismic Code – Standard 2800, 4th Edition [20];
2. Iranian National Building Code, Part 6 – Loadings (Edition 1392) [21];
3. ACI 318-14 for concrete shear wall design [22];
4. AISC 360-10 for steel frame design [23];
5. Time history nonlinear dynamic analysis;
6. Wall cracking effects and ductility capacity in time history analysis;
7. Time history records selected based on compatibility with site soil conditions and seismic design parameters.

The steel used for both beams and columns is of type ST37, with a yield strength of 2400 kg/cm² and an ultimate tensile strength of 3700 kg/cm². The concrete compressive strength used in the design of the shear walls is 25 MPa, and the reinforcing bars are of type AIII. The beams and columns have cross-sectional shapes of I and box, respectively.

2.4. Arrangement of shear walls

Figs. 2 and 3 illustrate various configurations of rectangular and T-shaped shear walls implemented in the building plan. To maintain uniformity and enable an objective comparison across these configurations, the total surface area of the shear walls was kept constant in all models. The rectangular and T-shaped shear walls were distributed across all floors of the structure and analyzed under identical structural and seismic conditions. Based on the analytical results, the most efficient arrangement for each wall type was identified and compared to determine the optimal shear wall layout.

3. Numerical results

This section presents the results of both linear and nonlinear time history analyses performed on a 30-story building located in a high seismic zone with a design base acceleration of A = 0.5. The study focuses on assessing both elastic and inelastic structural behavior under seismic loading conditions.

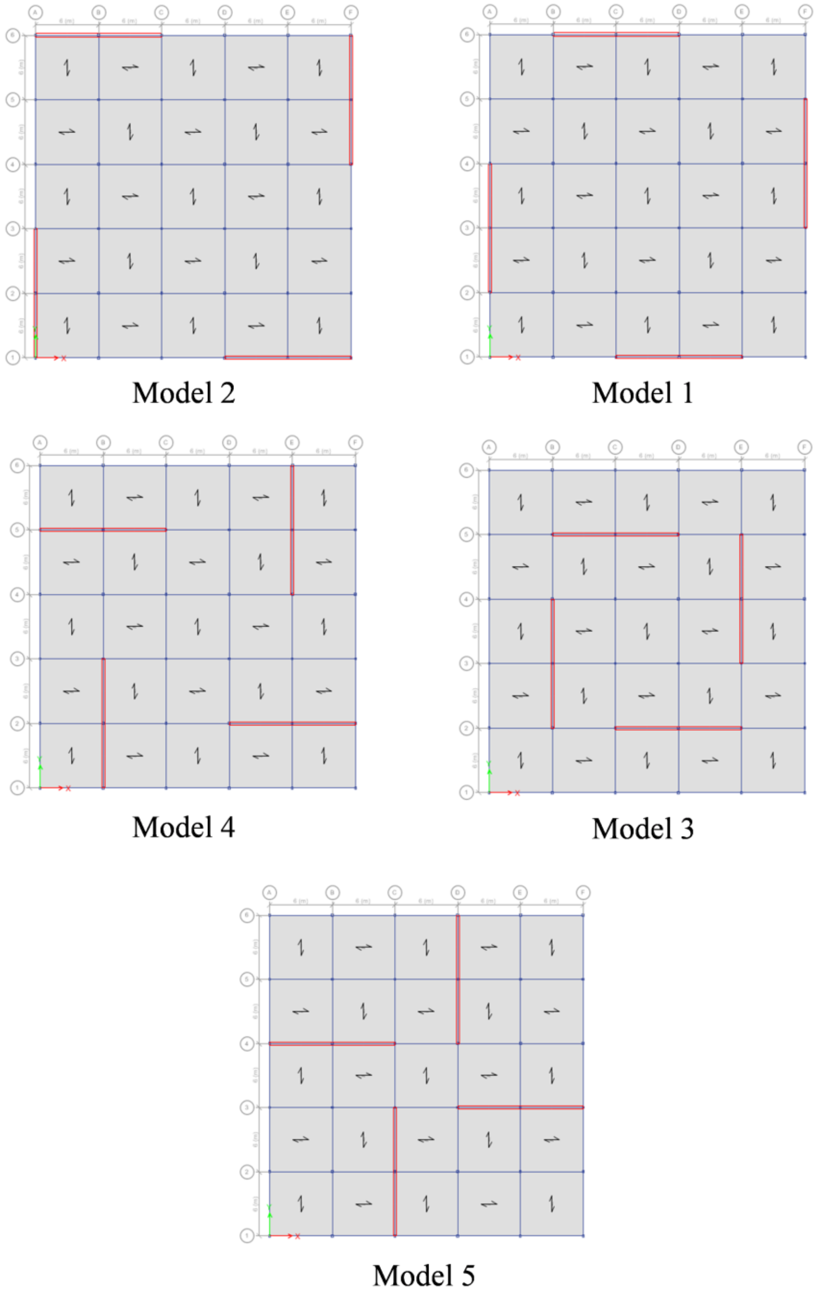


Fig. 2. Arrangements of rectangular shear walls in the building plan.

3.1. Linear behavior using response spectrum analysis

In this study, rectangular and T-shaped shear walls were first modeled in the plan of a 30-story high-rise building located in a region with seismic acceleration coefficient $A = 0.5$. The modeling was performed in three dimensions to closely approximate real behavior. Based on the roof displacement results, the optimal wall arrangement is determined. Figs. 4 and 5 illustrate the roof displacement result for various configurations of rectangular and T-shaped shear walls.

It is observed that Model 3 yields the best configuration for the rectangular shear wall, while Model 4 is the most effective for the T-shaped shear wall. The optimal placement of shear walls-both rectangular and T-shaped-occurs when the walls are located within interior frames. Placing shear walls in the outermost frames leads to stiffness concentration at the corners of the building, resulting in a flexible interior zone. Conversely, when the shear walls are positioned too close to the center of mass, the interior becomes excessively stiff while the exterior remains flexible. Therefore, the best structural performance is achieved when the shear wall is located at a distance between the innermost and outermost frames. Subsequently, the optimal configurations for rectangular and T-shaped shear walls are compared in terms of story displacement and inter-story drift. These optimal configurations, identified based on the roof displacement results shown in Figs. 4 and 5, are further analyzed in terms of story displacement and inter-story drift. Figs. 6a, 6b, 7a, and 7b present the corresponding results in both the X and Y directions, with all displacement values reported in centimeters.

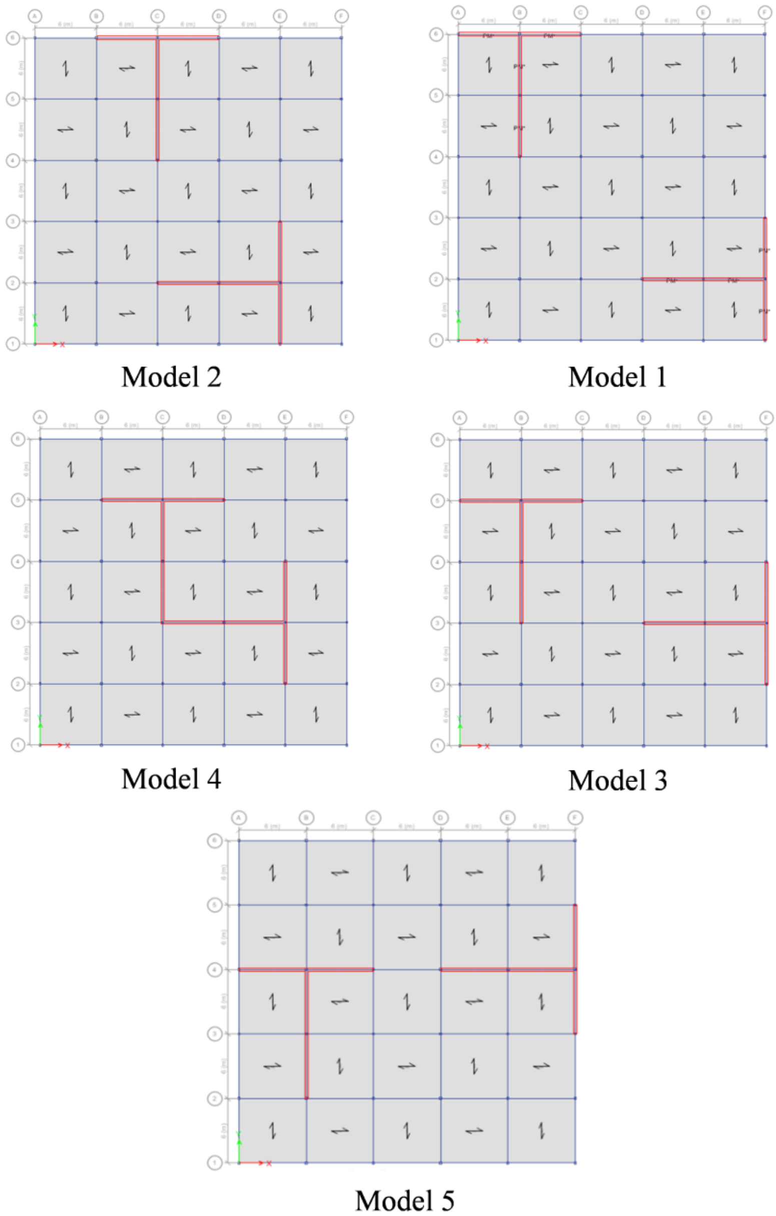


Fig. 3. Arrangements of T-shaped shear walls in the building plan.

Figs. 6 and 7 illustrate the comparison between the optimal rectangular and T-shaped shear wall configurations in terms of story displacement and inter-story drift. In these figures, the vertical axis represents the story levels, while the horizontal axis shows the displacement (in centimeters) and drift ratio, respectively. The red curve corresponds to the rectangular shear wall configuration, while the blue curve represents the T-shaped configuration. As shown in Fig. 6, the T-shaped walls result in lower lateral displacements in both the X and Y directions, particularly at the upper stories, indicating improved lateral stiffness and better control of overall building sway. Similarly, Fig. 7 shows that the T-shaped configuration produces lower inter-story drift ratios throughout the building height, which implies a more favorable deformation pattern under seismic loading. This improved behavior is attributed to the higher moment of inertia of T-shaped shear walls compared to rectangular ones, which leads to increased stiffness and consequently reduced displacements. These results demonstrate that the T-shaped shear wall configuration provides better seismic performance compared to the rectangular arrangement under the same conditions.

3.2. Nonlinear behavior analysis using earthquake time history records

To extend the evaluation beyond the linear response, nonlinear dynamic time history analysis was performed to investigate the seismic behavior of the structure under more realistic loading conditions. This analysis was carried out on the optimal configurations of rectangular and T-shaped shear walls identified in the previous section. Six representative earthquake ground motion records were used in this study, including Tabas, Bam, Kobe, Northridge, Imperial Valley, and Loma Prieta.

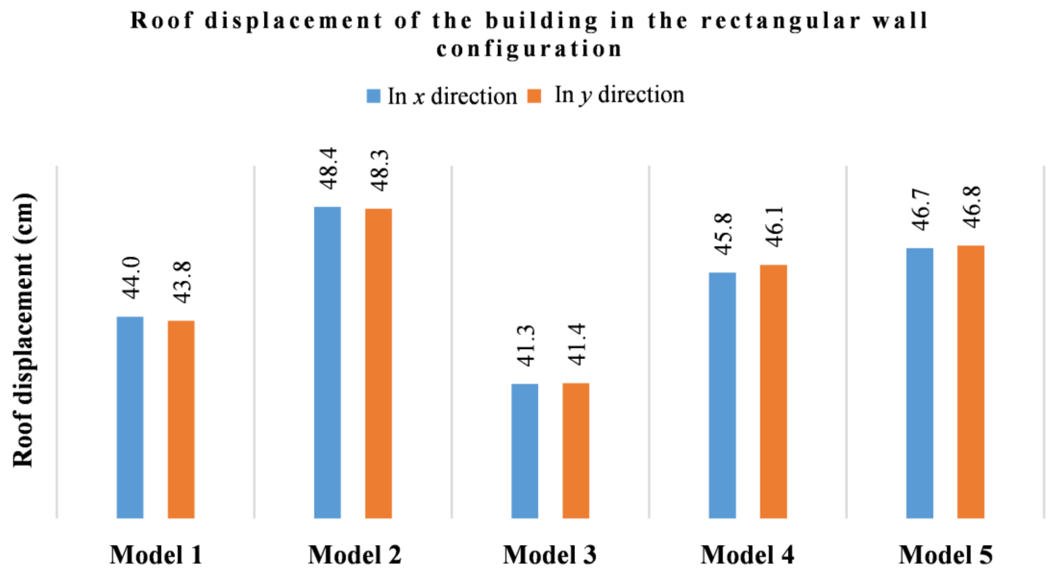


Fig. 4. Roof displacement for different configurations of rectangular shear walls.

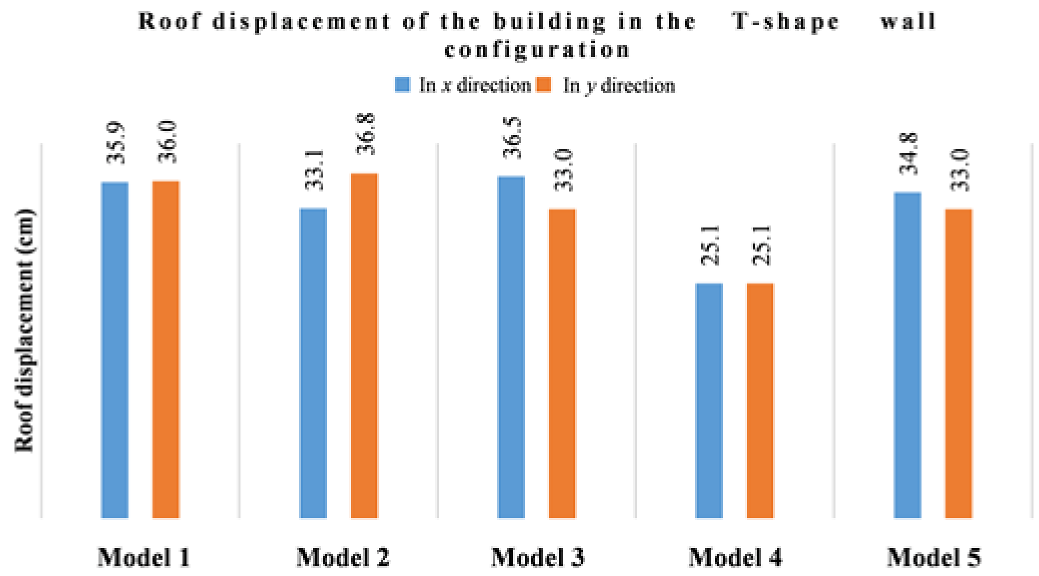
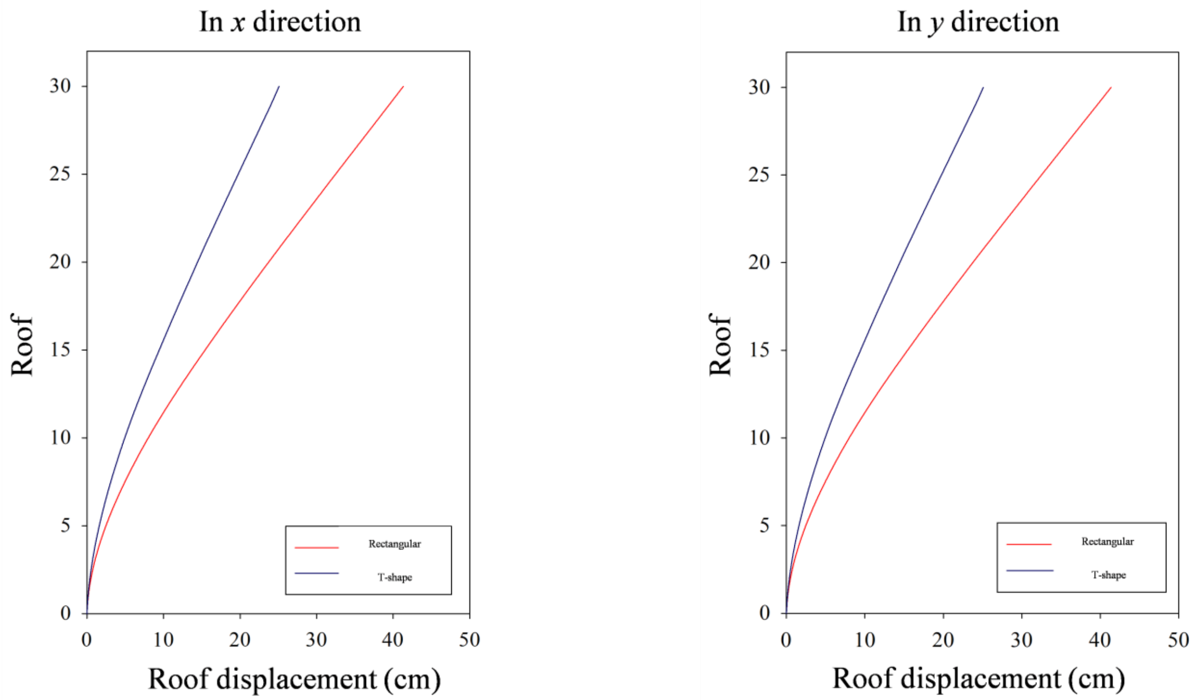


Fig. 5. Roof displacement for different configurations of T-shaped shear walls.

These records were applied simultaneously in both X and Y directions to capture the true multi-directional effects of seismic loading and assess the nonlinear response of each wall configuration. All ground motions were obtained from the Pacific Earthquake Engineering Research Center (PEER) Ground Motion Database, hosted by the University of California, Berkeley [24]. The detailed characteristics of these records are provided in Table 2.

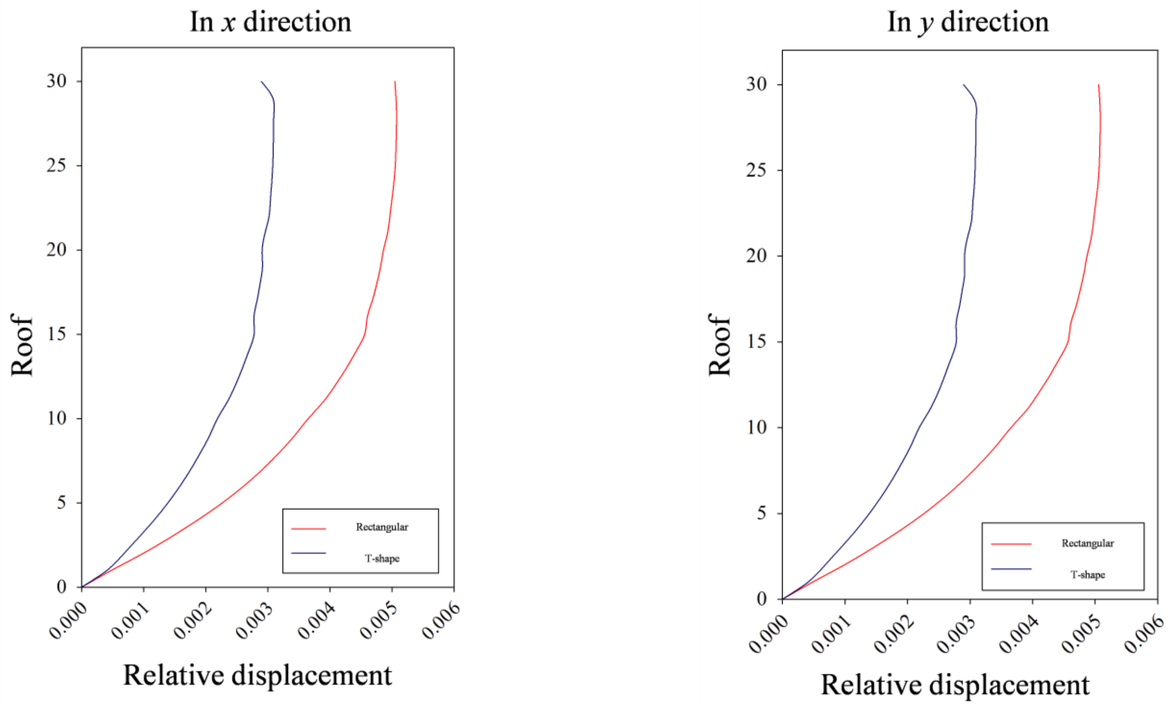
In the nonlinear dynamic analysis, the shear walls were modeled using nonlinear shell elements to accurately capture their inelastic behavior. Beams and columns were assigned plastic hinges of the "auto" type per the guidelines provided by FEMA 356. The analysis was conducted in three dimensions, with the selected earthquake ground motion records applied simultaneously in both the X and Y directions to account for multi-directional seismic effects. To ensure consistency, the average response spectrum of the six records was used, and a uniform scale factor was applied to all ground motions. The results of the nonlinear time history analysis, including the structural response to each of the six individual records and their averaged response, are illustrated in Figs. 8 and 9 for both X and Y directions.

As illustrated in Figs. 8 and 9, the rectangular shear wall configuration (shown in blue) consistently exhibits higher roof displacements compared to the T-shaped configuration (shown in orange) in both the X and Y directions. This trend is evident across all individual records and their average, indicating that the T-shaped walls offer greater lateral stiffness and more effective control of seismic deformation.



(a) X direction **(b) Y direction**

Fig. 6. Story displacement for the optimal rectangular and T-shaped wall configurations.



(a) X direction **(b) Y direction**

Fig. 7. Inter-story drift for the optimal rectangular and T-shaped wall configurations.

The superior performance of the T-shaped configuration is attributed to its higher moment of inertia, which results in reduced displacements under lateral loads. These findings are consistent with the results of the linear analysis and confirm the T-shaped shear wall's enhanced seismic performance under both linear and nonlinear dynamic conditions. In addition to the roof displacement results under individual and average ground motions, a more detailed assessment of lateral deformation along the height of the structure is presented in Fig. 10.

As observed in Fig. 10, the T-shaped shear wall configuration (blue curve) consistently exhibits lower story displacements compared to the rectangular configuration (red curve) throughout the height of the building. This indicates that the T-shaped walls provide better lateral stiffness and improved seismic control under average earthquake loading conditions.

Table 2. Ground motion records used in nonlinear time history analysis.

Earthquake Name	*R* (km)	PGA_T	PGA_L	*M*	Station Name	Year	RSN
Northridge	5.43	1.00g	0.54g	6.69	Jensen Filter	1994	983
Bam	1.70	0.58g	0.77g	6.60	Bam	2003	4040
Tabas	2.05	0.80g	0.77g	7.35	Tabas	1978	143
Imperial Valley	2.66	0.79g	0.57g	6.53	Bonds Corner	1979	160
Loma Prieta	17.47	0.66g	0.39g	6.93	Waho	1989	811
Kobe	1.46	0.67g	0.61g	6.90	Takatori	1995	1120

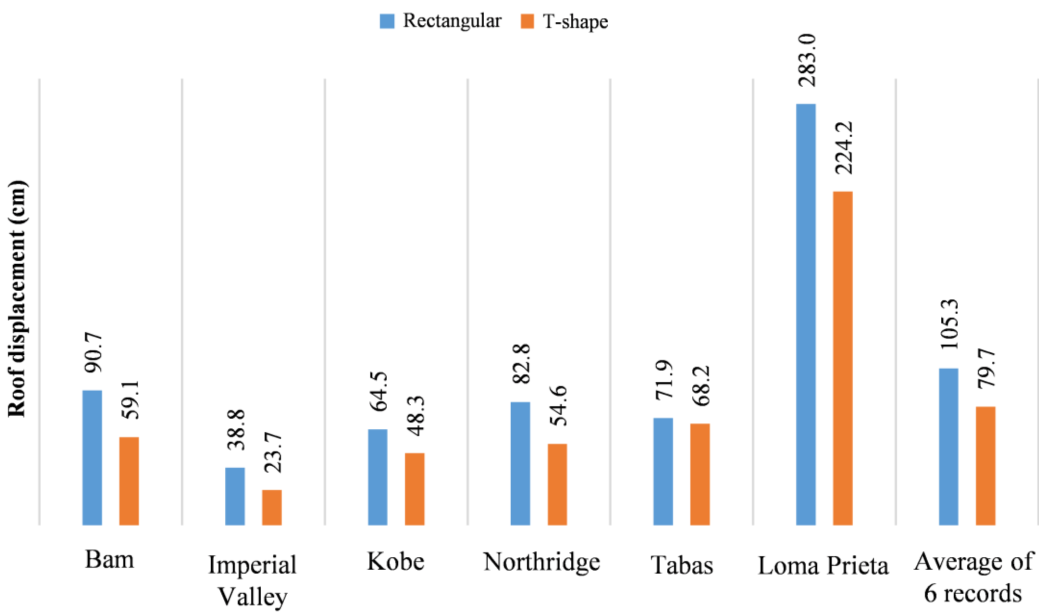


Fig. 8. Roof displacement in the X direction for the optimal rectangular and T-shaped shear wall configurations under each earthquake record.

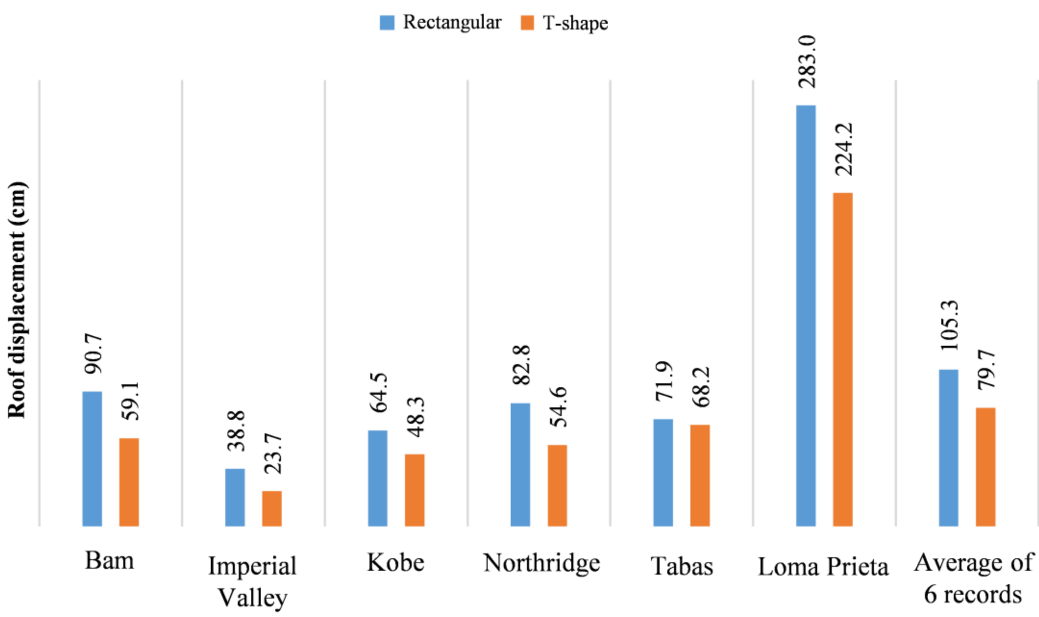
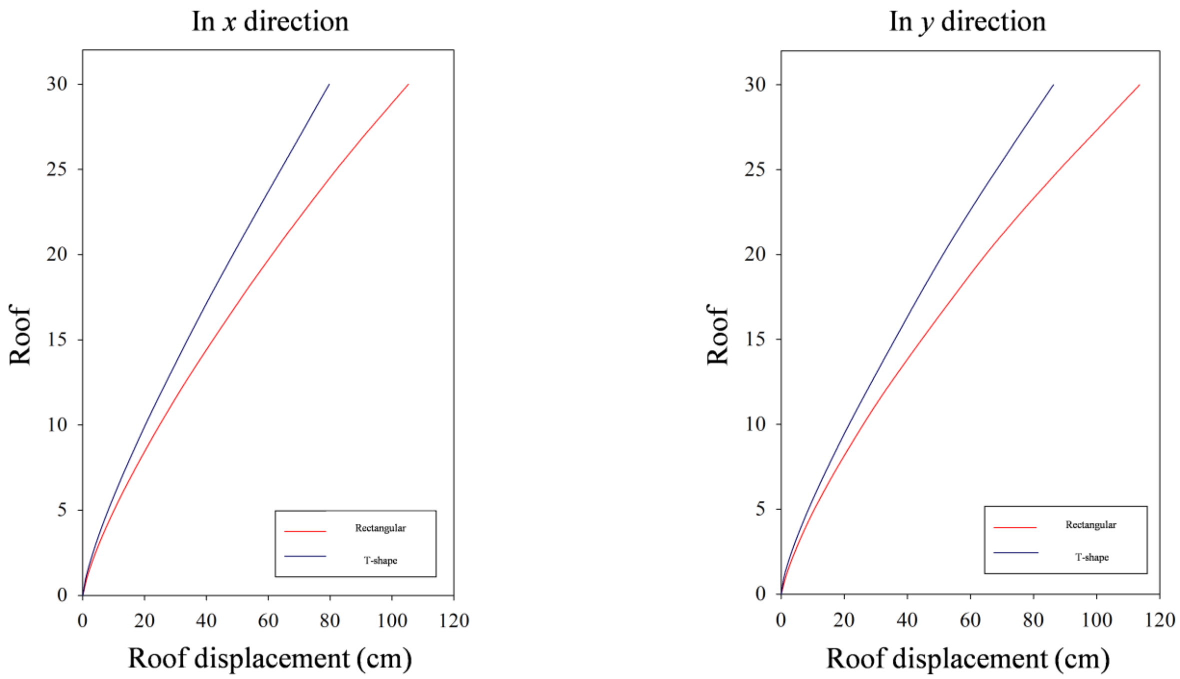


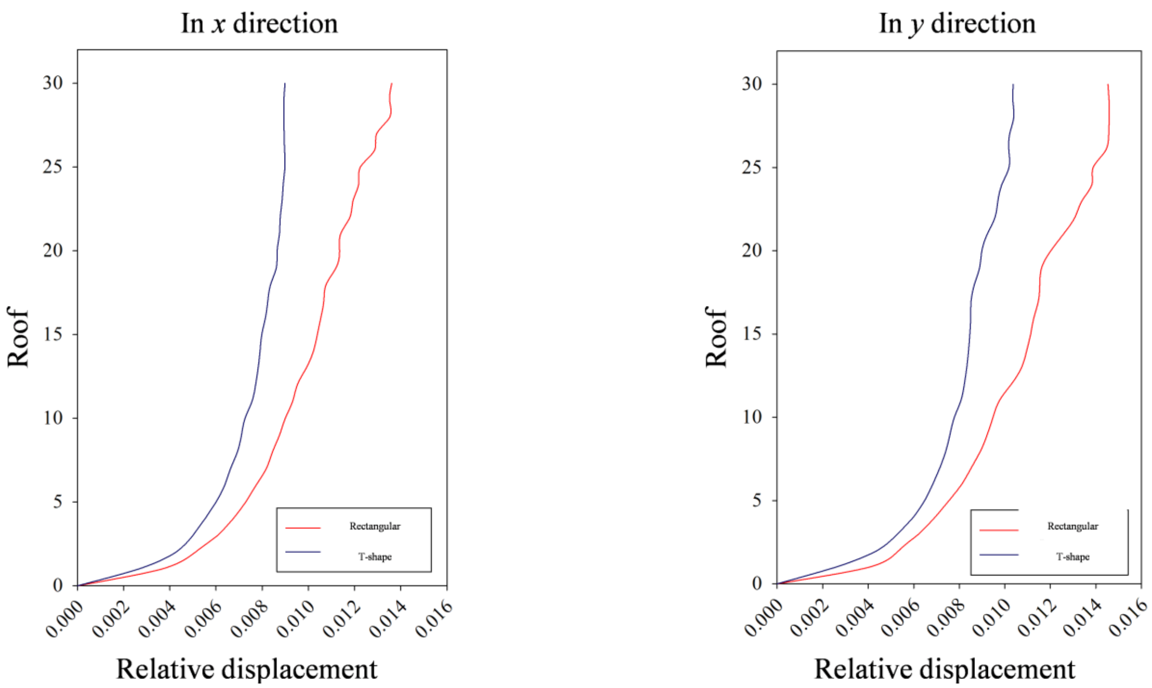
Fig. 9. Roof displacement in the Y direction for the optimal rectangular and T-shaped shear wall configurations under each earthquake record.

These findings reinforce the earlier results obtained from individual ground motions and confirm the superior performance of the T-shaped configuration in limiting lateral deformations under dynamic excitation. Finally, the average inter-story drift for the six earthquake records is shown in Fig. 11.



(a) X direction **(b) Y direction**

Fig. 10. Story displacement in the nonlinear analysis for the optimal rectangular and T-shaped shear wall configurations.



(a) X direction **(b) Y direction**

Fig. 11. Inter-story drift distribution for the optimal rectangular and T-shaped shear wall configurations obtained from nonlinear time history analysis.

Fig. 11 illustrates the average inter-story drift distribution obtained from the nonlinear time history analysis for the optimal rectangular and T-shaped shear wall configurations in both the X and Y directions. The vertical axis represents the story levels, while the horizontal axis indicates the relative inter-story drift ratio. As shown in both graphs, the T-shaped configuration (blue curve) results in lower inter-story drift values throughout the height of the building compared to the rectangular configuration (red curve). This indicates that the T-shaped walls provide better control over story deformation, leading to improved seismic performance and reduced damage potential in structural and non-structural components. These results are consistent with previous displacement analyses and further confirm the superior behavior of the T-shaped shear wall configuration under nonlinear dynamic loading.

4. Conclusions

As observed, the optimal placement of both rectangular and T-shaped shear walls occurs when the walls are located within the intermediate (central) frames of the structure. This configuration resulted in the minimum displacement in both the X and Y directions. When shear walls are placed in the outermost frames, stiffness tends to concentrate at the building corners, leading to a more flexible interior. Conversely, placing shear walls too close to the center of mass increases the stiffness of the interior zones while leaving the exterior zones relatively flexible. Therefore, the most balanced and efficient structural behavior is achieved when the shear walls are positioned at a distance between the innermost and outermost frames. The structure with T-shaped shear walls exhibits superior performance compared to the one with rectangular shear walls, both in terms of roof displacement and inter-story drift. This improvement is attributed to the fact that the stiffness of a shear wall is directly related to its moment of inertia in plan, and the T-shaped wall possesses a higher moment of inertia than the rectangular wall in this case. In the following section, the optimal configurations of rectangular and T-shaped shear walls, identified earlier, were subjected to nonlinear time history analysis for comparison of their inelastic behavior. As observed, in both the X and Y directions, and across all six individual ground motion records as well as their average response, the structure with T-shaped shear walls consistently demonstrates superior performance under nonlinear conditions. In conclusion, for a seismic zone with a design base acceleration of $A = 0.5$, the structure with T-shaped shear walls demonstrated superior performance compared to the one with rectangular shear walls, both in terms of linear and nonlinear.

Statements & Declarations

Author contributions

Mehran Rahimi: Conceptualization, Investigation, Formal analysis, Resources, Writing - Original Draft, Writing - Review & Editing.

Khosrow Bargi: Conceptualization, Formal analysis, Resources, Supervision, Project administration, Writing - Review & Editing.

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Data availability

The data presented in this study will be available on interested request from the corresponding author.

Declarations

The authors declare no conflict of interes.

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