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EVALUATING THE SEISMIC BEHAVIOR OF SUSPENDED HIGH-RISE STEEL BUILDINGS INCLUDING END SHEAR WALLS

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Abstract

Suspended structures are increasingly used in modern buildings due to architectural and structural considerations, such as creating open space on the ground floor without vertical members, except in the central core area. However, some disadvantages of suspended structures, such as changes in the length of vertical members, have led to the incorporation of end shear walls. By connecting the ends of shear walls on all floors, end shear walls alleviate stress at those ends. In this study, ETABS software was used to model three 21-story steel buildings. The first model, named SS1, was a suspended steel high-rise building without shear walls. The second model, named SS2, featured a suspended high-rise steel building with shear walls, but without end shear walls. Finally, the third model, named SS3, was a suspended high-rise steel building with both shear walls and end shear walls. The results revealed that the maximum story drift was reduced by 69.58% and 80.99% in SS2 and SS3, respectively, compared to SS1. Additionally, the maximum (top) horizontal displacement was reduced by 71.08% and 81.06% in SS2 and SS3, respectively, compared to SS1. The absolute maximum rotations for SS1 and SS2 were quite similar. Most importantly, the results showed that the absolute maximum rotation was reduced by 69.14% in the suspended high-rise steel building with both shear walls and end shear walls (SS3), compared to the suspended high-rise steel building without shear walls (SS1). Based on these findings, end shear walls significantly enhance the seismic behavior of suspended high-rise steel buildings.

Keywords: Seismic behavior; High-rise buildings; Steel structures; Suspended structures; End shear walls.

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1 INTRODUCTION

Suspended structures are frequently used in high-rise buildings to fulfill both architectural and structural requirements. Researchers have conducted various studies on suspended high-rise buildings.

Kheyroddin et al. [1] explored the influence of helipads on tall buildings and found that in a 30-story building with end shear walls and a helipad, the skewness and kurtosis coefficients were reduced by 18% and 70%, respectively. These results highlighted the effectiveness of end shear walls in tall reinforced concrete buildings with helipads.

Akhavan Salmassi and Kheyroddin [2] studied a 30-story structure with end shear walls and observed an 85% increase in the kurtosis coefficient and a 75% decrease in the skewness coefficient in the X direction. The end shear walls reduced residual drift by up to 22%, significantly impacting the building's lateral systems.

Akhavan Salmassi et al. [3] revealed that end shear walls in a 30-story building prevented increasing chaotic behavior in graphs like Chebyshev, Gaussian, and logistic mapping. The end shear walls played a crucial role in the building's lateral load systems.

Akhavan Salmassi et al. [4] found that normal Q-Q plots (quantile-quantile plots) displayed an approximate 20% reduction in the expected normal domain along the X and Y directions in 30-story buildings with end shear walls. The kurtosis coefficient decreased by 61% in the X direction and 92% in the Y direction. By reducing the dispersion of inter-story drift data, end shear walls enhanced confinement effects and improved seismic performance.

Belash and Svitlik [5] demonstrated that suspended structures can extend the natural oscillation period of buildings and decrease the seismic load on system elements.

Liu and Lu [6] indicated that, unlike a pendulum TMD, large suspended floor masses significantly contribute to reducing seismic response. Buildings designed as suspended systems are effective against strong earthquake motions combined with gravity.

Belash and Svitlik [7] explored effective earthquake-resistant construction by investigating the behavior of suspended structures under a wide frequency spectrum of seismic influences is essential.

Liu and Lu [8] showed that a suspended building with semi-rigid connections and appropriate suspended mass ratios can prevent local pounding failure and minimize seismic response.

Chulahwat [9] tested three structures (4-story, 2-bay; 7-story, 3-bay; and 10-story, 5-bay) using the Kanai-Tajimi spectrum for earthquake input and concluded that the suspended slab system can be quite an effective strategy for earthquake mitigation.

Chen et al. [10] analyzed the effect of suspended spans and compared them with traditional framed and symmetrical suspension structures. Larger suspended spans absorbed more seismic energy, resulting in a reduction in horizontal displacement and acceleration. The suspended part exhibited better seismic energy dissipation than normal framed structures, with two symmetrical parts outperforming a single asymmetrical part.

This study aims to investigate the effects of end shear walls on the seismic behavior of suspended high-rise steel buildings.

2 MODELING OF BUILDINGS

This study investigated the seismic behavior of suspended high-rise steel buildings by modeling and analyzing three 21-story frames, using the ETABS software [11] for spectrum analysis. The first model was a suspended high-rise steel building without shear walls. The second model was a suspended high-rise steel building with shear walls, but without end shear walls. Finally, the third model was a suspended high-rise steel building with both shear walls and end shear walls. The dead and live loads considered were 170 kg/m² and 200 kg/m², respectively. Additionally, a compressive strength of 0.15 MPa for concrete (f_c) and a yield strength of 400 N/mm^2 for steel (f_y) were used. The models comply with the ASCE7-16 code [12] and feature three-dimensional concrete moment frames with regular plans, four-meter or seven-meter spans, and four-meter heights, while maintaining the same site location (D type). Each story has an opening in the core area measuring 1.80×2.40 meters.

Figure 1 illustrates the three-dimensional view and plan of the suspended high-rise steel building without shear walls. This building has 21 story levels, two clusters, a reinforced concrete core, and trusses.

On the other hand, Figure 2 shows the three-dimensional view and plan of the suspended high-rise steel building with shear walls, but without end shear walls. This building includes 21 story levels, two clusters, a reinforced concrete core, trusses, and reinforced concrete shear walls.

Also, Figure 3 shows a three-dimensional view and plan of the suspended high-rise steel building with shear walls and end shear walls. This building includes 21 story levels, two clusters, a reinforced concrete core, trusses, reinforced concrete shear walls, and reinforced concrete end shear walls.

The plan dimensions and the total height of the three suspended steel high-rise buildings are assumed to be the same.

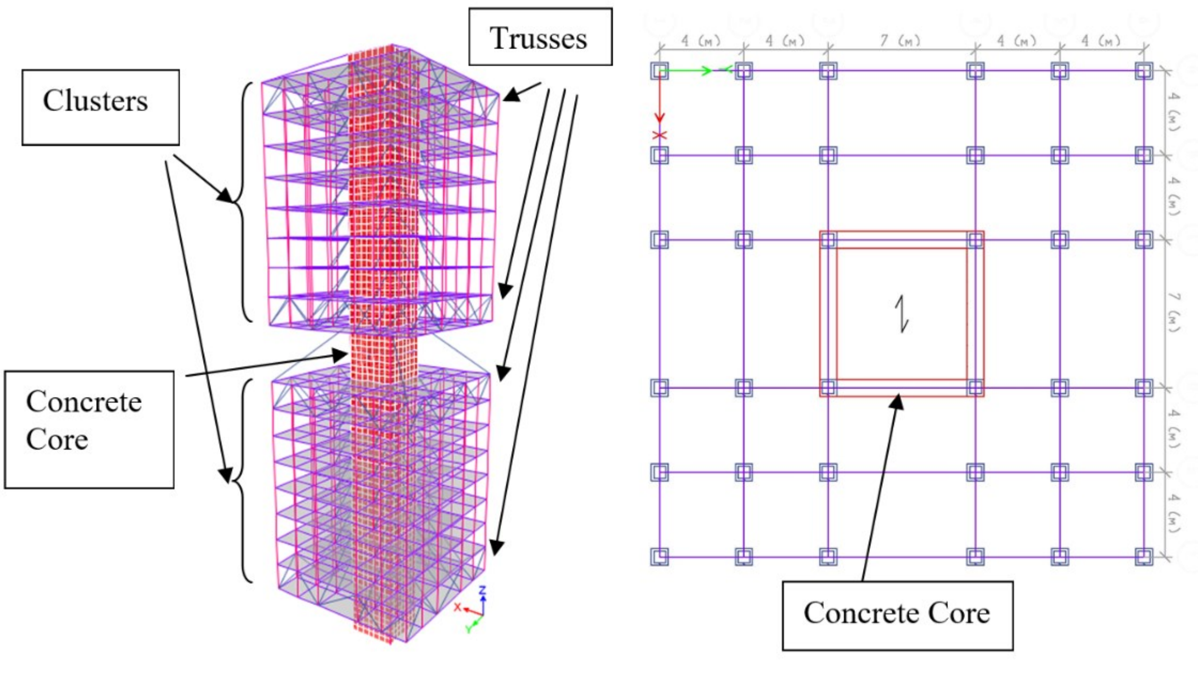

Figure 1: Three-dimensional view and plan of the suspended high-rise steel building without shear walls (SS1).

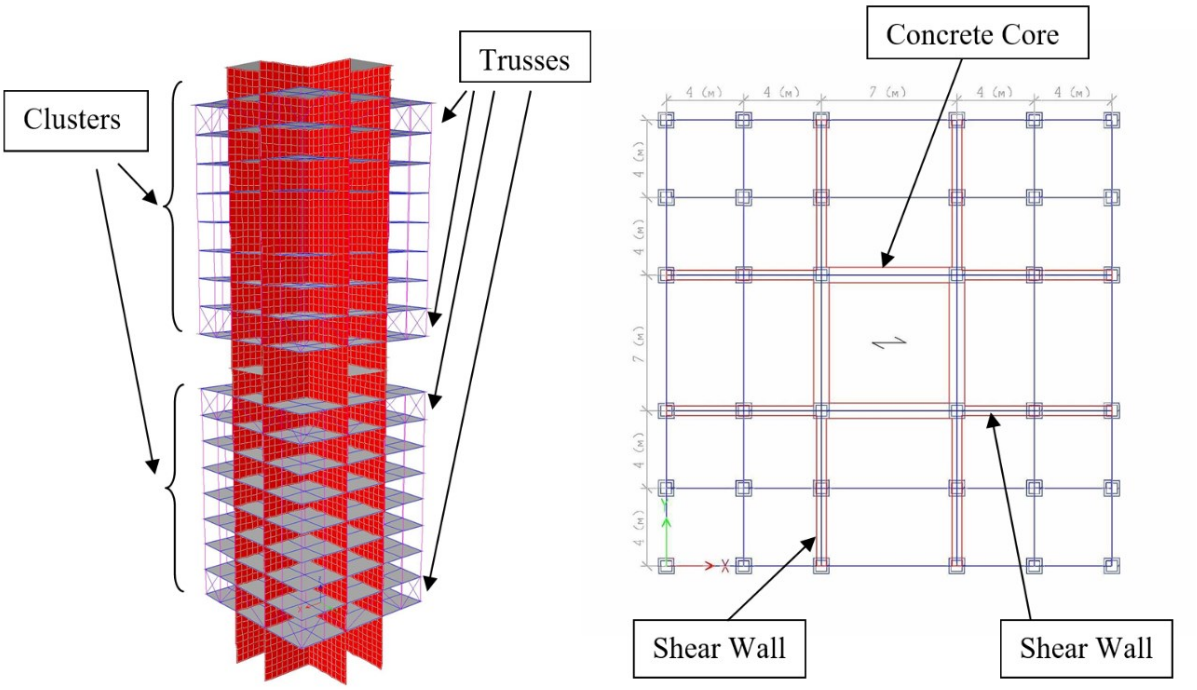

Figure 2: Three-dimensional view and plan of the suspended high-rise steel building with shear walls, but without end shear walls (SS2).

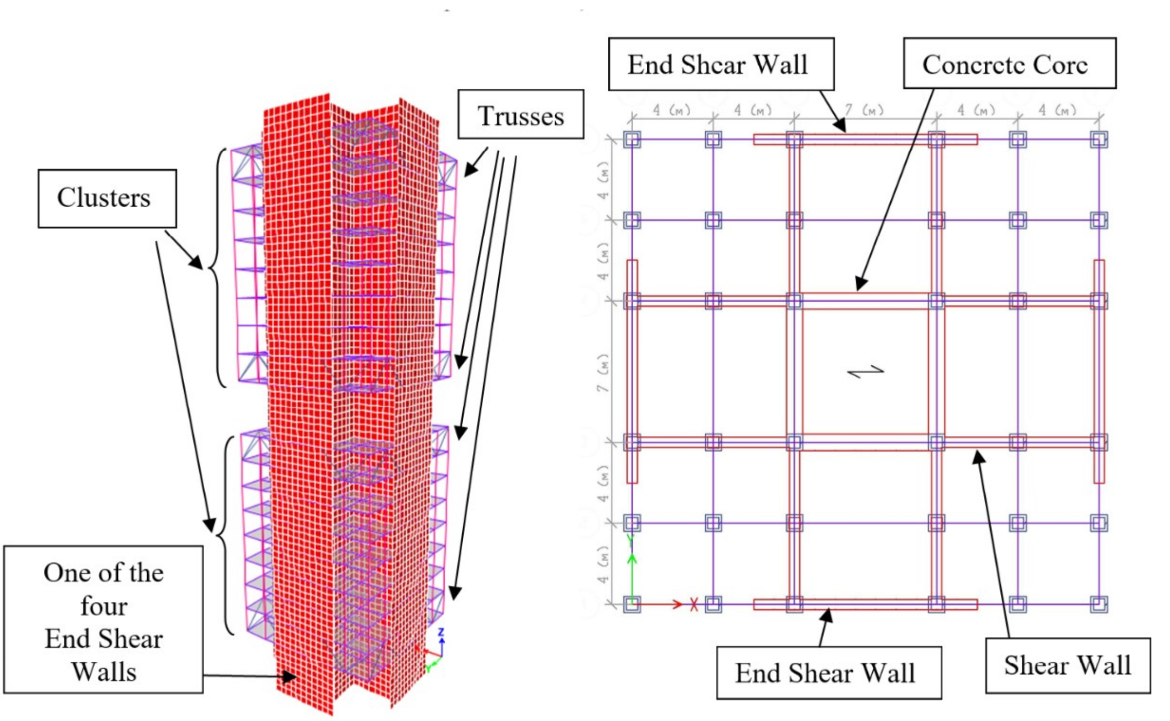

Figure 3: Three-dimensional view and plan of the suspended high-rise steel building with shear walls and end shear walls (SS3).

Table 1 presents the specifications of the element sections, providing the details of the steel sections for columns, beams, and trusses. It also includes the dimensions of the shear walls, end shear walls, concrete core, and concrete slabs.

Element	Type and Dimension
Columns	Tube 800×800 mm
Beams	IPE 600
Trusses	IPE 1200, IPE 800
Shear Walls	500 mm
End Shear Walls	500 mm
Concrete Core	800 mm
Concrete Slabs	150 mm

Table 1: Specifications of the sections.

Table 2 outlines the specifications of the suspended structure models, designated SS1 for the suspended structure without end shear walls, SS2 for the suspended structure with shear walls, and SS3 for the suspended structure with both shear walls and end shear walls.

Model	Explanation	No. of Stories	Total Height (m)	Plan dimensions (m×m)
SS1	Suspended structure without shear walls	21	84	23×23
SS2	Suspended structure with shear walls	21	84	23×23
SS3	Suspended structure with both shear walls and end shear walls	21	84	23×23

Table 2: Specifications of the building models.

3 RESULTS AND DISCUSSION

Figure 4 illustrates the drift ratio (%) at each story level of the SS1, SS2, and SS3 suspended 21-story steel buildings. In the SS3 building, the drift ratio significantly decreased due to the use of end shear walls. The maximum drift ratios were 0.2209% (at the 16th story level), 0.0672% (at the 15th story level), and 0.0420% (at the 15th story level) for SS1, SS2, and SS3 structures, respectively.

The results showed that the maximum story drift was reduced by 69.58% and 80.99% in the suspended high-rise steel building with shear walls (SS2), and the suspended high-rise steel building with both shear walls and end shear walls (SS3), respectively, compared to the suspended high-rise steel building without shear walls (SS1).

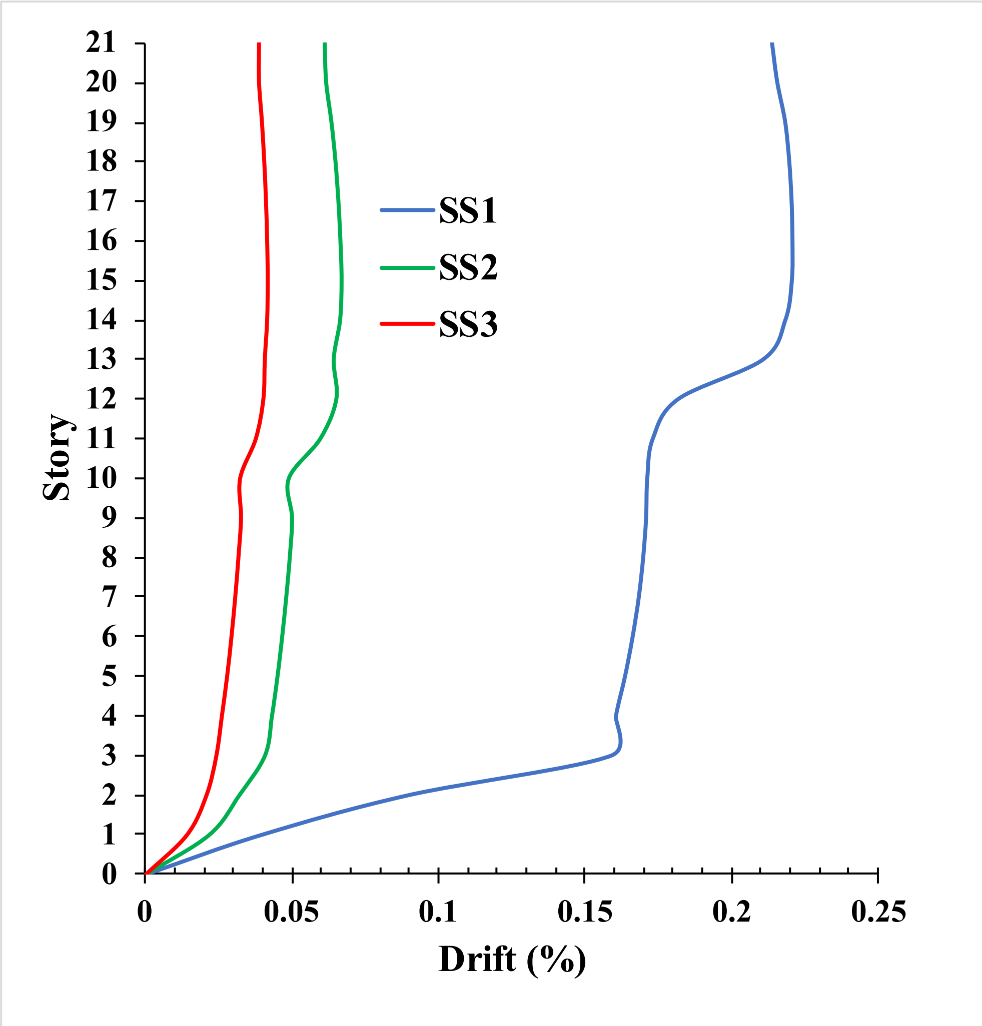

Figure 4: The drift ratios for SS1, SS2 and SS3 buildings.

The fundamental period is a critical parameter in suspended structures, particularly in high-rise buildings. Figure 5 shows the periods for the first 12 modes for the SS1, SS2 and SS3 buildings. As is well known, the period decreases as the mode number increases. The fundamental periods were 2.509 sec, 1.359 sec, and 1.095 sec in SS1, SS2, and SS3 buildings, respectively. This notable difference in the fundamental period is attributed to the effect of the end shear walls, especially in the first (fundamental) period.

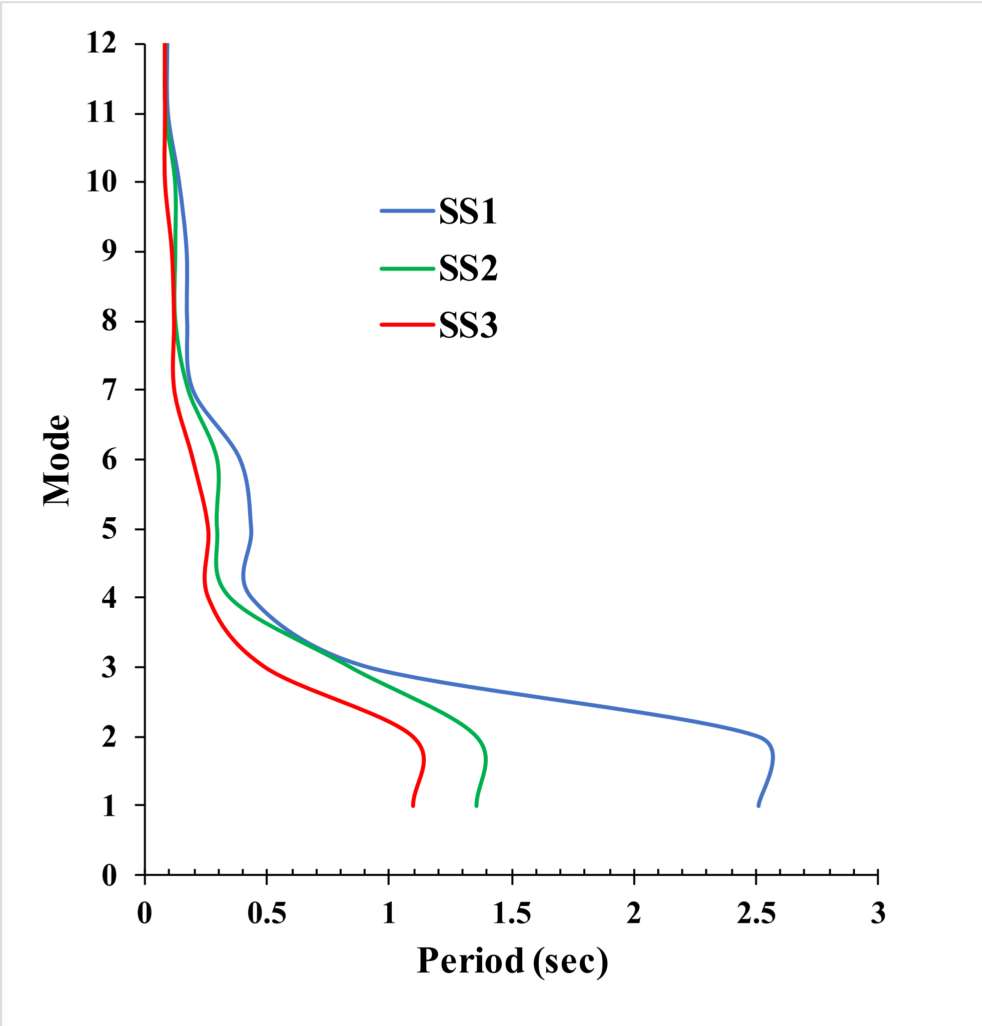

Figure 5: The periods for the first 12 modes of the SS1, SS2 and SS3 buildings.

Figure 6 shows the horizontal displacement of the SS1, SS2 and SS3 suspended 21-story high-rise steel buildings, which exhibit the expected increasing trend with height. The displacements in the SS1 building are much greater than those in the SS2 and SS3 buildings. The maximum (top) displacement values are 150.30 mm, 43.46 mm, and 28.46 mm for SS1, SS2, and SS3 structures, respectively. This indicates that the end shear walls further reduced the displacements in the SS3 suspended high-rise steel building.

The results showed that the maximum (top) horizontal displacement was reduced by 71.08% and 81.06% in the suspended high-rise steel building with shear walls (SS2), and the suspended high-rise steel building with both shear walls and end shear walls (SS3), respectively, compared to the suspended high-rise steel building without any shear walls (SS1).

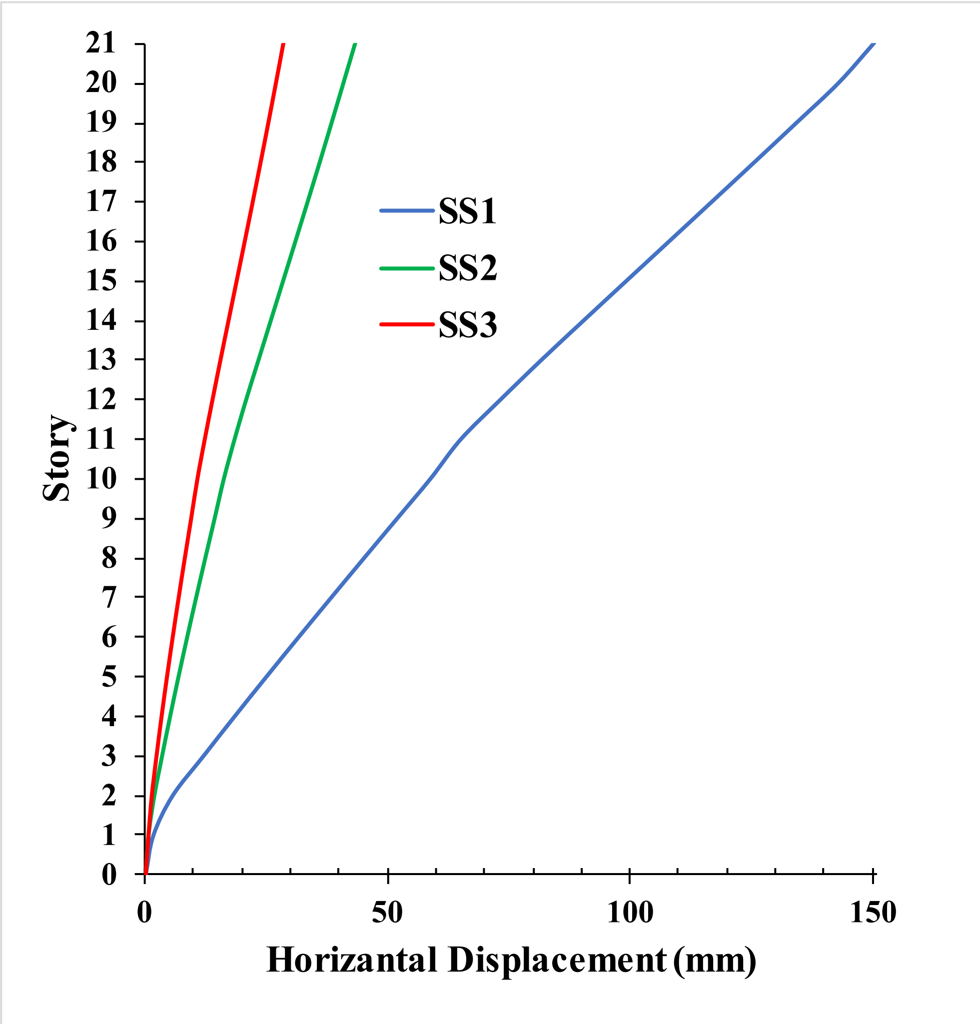

Figure 6: The horizontal displacement of SS1, SS2 and SS3 buildings.

The rotation in the vertical direction is an important factor in the seismic behavior of suspended tall buildings. Figure 7 shows the rotation in the vertical direction for the SS1, SS2, and SS3 suspended 21-story high-rise steel buildings. The rotation in the vertical direction increased with the story level. However, the slope of the graph for SS3 is much steeper than that for SS1 and SS2 structures. There are some fluctuations in the SS1 and SS2 graphs, whereas the graph for SS3 is nearly smooth. The results indicated that the absolute maximum rotations in the vertical direction are 0.000162 rad, 0.00017 rad, and 0.00005 rad for SS1, SS2, and SS3 structures, respectively. This indicates that the end shear walls significantly reduced the rotation in the vertical direction for the SS3 suspended high-rise steel building.

The results showed that the absolute maximum rotations for SS1 and SS2 buildings are quite similar. Specifically, the absolute maximum rotation increased by 4.94% in the suspended high-rise steel building with shear walls (SS2), compared to the suspended high-rise steel building without any shear walls (SS1).

Most importantly, the results showed that the absolute maximum rotation was reduced by 69.14% in the suspended high-rise steel building with both shear walls and end shear walls (SS3), compared to the suspended high-rise steel building without shear walls (SS1).

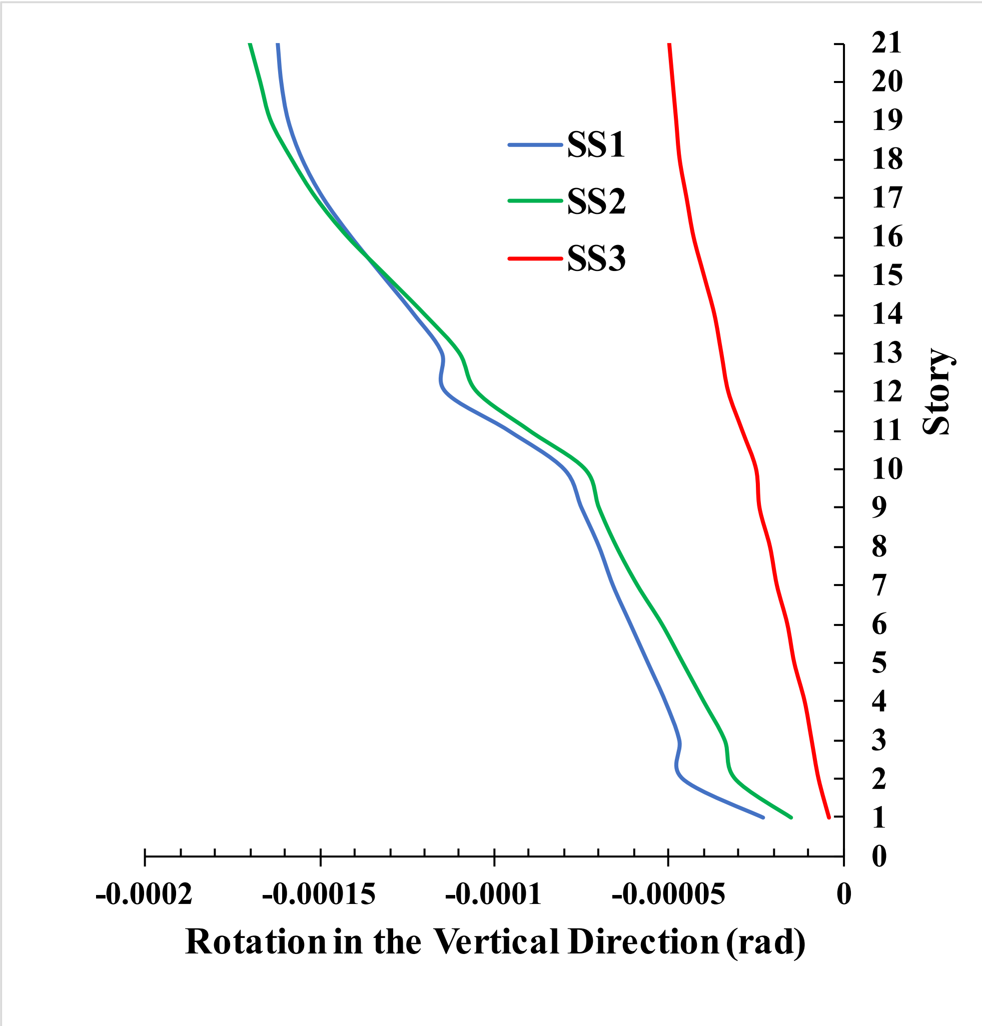

Figure 7: The rotation in the vertical direction for the SS1, SS2 and SS3 buildings.

4 CONCLUSIONS

This study utilized ETABS software to model and analyze three 21-story steel structures. The first model was a suspended high-rise steel building without shear walls (SS1), the second model was a suspended high-rise steel building with shear walls but without end shear walls (SS2), and the third model was a suspended high-rise steel building with both shear walls and end shear walls (SS3). Based on the analysis results, it was concluded that end shear walls provide several advantages:

- The maximum story drift decreased by 69.58% and 80.99% in SS2 and SS3, respectively, compared to SS1.
- The maximum (top) horizontal displacement was reduced by 71.08% and 81.06% in SS2 and SS3, respectively, compared to SS1.
- The absolute maximum rotations for SS1 and SS2 were quite similar.
- The absolute maximum rotation decreased by 69.14% in SS3, compared to SS1.

Overall, the findings suggest that end shear walls significantly enhance the seismic performance of suspended high-rise steel buildings.

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