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Analytical Study on the Dynamic Behavior of RC High-Rise Buildings with Staggered Openings in Shear Walls

Rushikesh P. Deshmukh[1,*], R.S. Londhe[2]

Abstract

This research investigates the seismic performance of a 15-story reinforced concrete building with varying shear wall configurations, focusing on the effects of vertical and staggered openings. The study compares three models: one with solid shear walls, one with vertical openings, and one with staggered openings. Using ETABS V21 software and performing the analysis in Seismic Zone IV under the Response Spectrum Method (IS 1893:2016), the results show that solid shear walls offer the best seismic performance, with minimal displacement, drift, and shear. The models with openings exhibited higher displacements and reduced stiffness, with staggered openings performing slightly better than solid shear wall (without opening). This research highlights the importance of optimized shear wall designs to enhance the seismic resilience of multistory buildings. The results of the analysis indicate that the model with solid shear walls demonstrates superior seismic performance, exhibiting the lowest values of displacement, drift, and base shear. This confirms the effectiveness of uninterrupted shear walls in enhancing the overall stability and stiffness of multistory buildings during seismic events. In contrast, the models incorporating openings – both vertical and staggered – showed increased displacements and reduced stiffness, highlighting the detrimental effects of discontinuities in the shear wall system. Interestingly, among the two types of openings, the model with staggered openings performed marginally better than the one with vertical openings, suggesting that the distribution and arrangement of openings can influence the seismic response. This research underscores the critical importance of optimizing shear wall design, particularly when openings are unavoidable due to architectural or service requirements. By carefully considering the size, location, and pattern of openings, engineers can mitigate adverse effects and enhance the seismic resilience of multistory RC buildings. The findings provide valuable insights for structural designers aiming to balance functional needs with safety and performance in earthquake-prone regions.

Keywords: Seismic performance, reinforced concrete (RC) building, shear wall openings, vertical openings, staggered openings, response spectrum analysis ETABS, story displacement, story drift, story shear, story stiffness, IS 1893:2016, seismic zone IV structural analysis, earthquake resistance

***Author for Correspondence**
Rushikesh P. Deshmukh
E-mail: rushikeshdeshmukh@rocketmail.com

[1]Student, Department of Applied Mechanics, Government College of Engineering Aurangabad, Chhatrapati Sambhajinagar, Maharashtra, India
[2]Professor, Department of Applied Mechanics, Government College of Engineering Aurangabad, Chhatrapati Sambhajinagar, Maharashtra, India

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INTRODUCTION

Reinforced concrete (RC) shear walls are essential in high-rise buildings for resisting seismic forces due to their high stiffness and strength. While openings in these walls can affect displacement and lateral resistance, proper design and placement help maintain structural stability and minimize earthquake damage.

Shear Walls with Staggered Openings

Shear walls with staggered openings offer design flexibility but create structural challenges due to uneven load transfer and stress concentrations, which can reduce lateral stiffness and increase seismic vulnerability. Earthquakes pose serious risks to life and infrastructure, causing damage to buildings, triggering landslides, fires, floods, and tsunamis, especially in vulnerable regions.

LITERATURE REVIEW

A concise review of literature addressing the impact of vertical and staggered openings on shear wall efficiency is presented.

A seismic analysis of a 7-story building using ETABS, comparing shear walls without openings, with vertical openings, and with staggered openings. Their results showed that the arrangement of openings significantly influences structural parameters like displacement and base shear. Staggered openings demonstrated improved lateral resistance compared to vertical openings [1].

The effectiveness of adding haunches to octagonal openings in coupled shear walls to enhance structural strength. Using analytical methods and nonlinear finite element analysis, they found that octagonal openings significantly improved load capacity with only a minor increase in structural weight compared to rectangular openings [2].

A case study to analyze the impact of shear wall openings in irregular RC structures subjected to seismic and blast loads. The study focused on a high-rise building with shear walls to assess lateral loads, story drifts, and torsional effects. The results indicated that properly placed shear walls offer better resistance to lateral forces in irregular structures [3].

The tests on six scaled RC walls with various openings to study how size and arrangement affect seismic performance, focusing on cracks, failure modes, and energy absorption. Yanez et al. found that adding flanges to walls increased strength but reduced deformation capacity, changing failure from ductile to brittle and causing issues like concrete crushing and rebar fracture [4].

The seismic performance of shear walls with different staggered opening shapes in a 10-story building using ETABS and response spectrum analysis. The results showed that staggered square and rectangular openings performed better in terms of displacement, drift, shear, and stiffness compared to uniform openings [5].

The behavior of hybrid walls with centered and staggered openings using nonlinear finite element analyses with the ATENA software. The study compared the structural performance of hybrid walls with openings to solid walls, focusing on key parameters, such as maximum load, deformation capacity, and stiffness degradation. The results, based on previous tests on 1:3 scale steel–concrete composite elements, highlighted the nonlinear behavior of these walls with openings [6].

The performance of RC shear walls with staggered openings under lateral loading. The study focused on walls with vertically arranged openings and different opening angles. Using the ABAQUS program, the failure analysis of these walls was conducted, and the results were compared with experimental data. Due to test setup limitations, the models were scaled to 1:4, and the failure modes of a 4-story wall with varying opening angles were analysed [7].

The size and placement of openings affect the stiffness and seismic response of a 15-story RC building with shear walls. Using STAAD software, they analyzed 32 models with different inline and staggered openings under various seismic zones and soil conditions. Results showed staggered openings provided more uniform stress distribution, and the optimal opening size varied with seismic and soil factors [8].

The behavior of RC shear walls with and without openings using nonlinear finite element methods. The study found that walls with central openings had lower displacement, while openings near boundaries reduced performance under seismic loads. It emphasized avoiding boundary openings to improve seismic resilience [9].

The impact of opening shape and size on the lateral deformations of a multi-storeyed structure. They examined triangular, square, and circular openings, with 20% and 25% openings, in shear walls of a ten-story building under seismic load using SAP2000. The study compared the maximum lateral deformations at the top story for different configurations [10].

AIM AND OBJECTIVES

The specific objectives of the research are:

- To study irregularities in structural analysis and analysis of 15 stores structure as per IS code 1893 (2016).
- To determine the effect of staggered openings in RC shear wall regular building under seismic loads.
- To compare and get a better efficient lateral stiffness system of the solid shear wall and staggered openings in RC shear wall building.

Analytical Study

To address this concern, the present study investigates the impact of different shear wall opening configurations specifically solid (without openings) and staggered openings on the seismic performance of a multistory building, size of opening given in Table 1. Using ETABS software, three identical building models were analyzed with varying shear wall openings using the Response Spectrum Method. Key performance indicators, such as lateral displacement, base shear, story drift, and stiffness, were compared to determine the most effective configuration for better structural performance in seismic conditions. The goal is to guide design decisions for safer and more efficient high-rise buildings [11–13].

As per IS Code 1893 (Part 1) 2016, seismic parameters are outlined in Table 2, and a damping factor of 5% is used to define the response spectrum function. The performance of shear wall structural systems with different opening configurations is evaluated by comparing results in terms of story displacement, story drift, story shear, and time period, all analyzed using the Response Spectrum Method [14, 15].

Table 1. Building description.

S.N.	Building Data	Parameters
1	Type of Building	Commercial Building.
2	Building Frame Type	SMRF with Shear wall.
3	Plan Dimension	30 m X 14 m.
4	Number of Stories	G+14.
5	Height of Building	52.5 m.
6	Floor Height	3.5 m.
7	Support Condition	Fixed.
8	Grade of Concrete	M30.
9	Grade of Steel	HYSD Reinforcement of Fe500.
10	Column Size	900 mm X 600 mm.
11	Beam Size	700 mm X 400 mm.
12	Length of Shear wall in Plan	6 m.
13	Thickness of Shear wall	300 mm.
14	Opening Size in Shear wall	2 m x 2.5 m.
15	Thickness of Slab	150 mm.
16	Thickness of Wall	230 mm.

Table 2. Loding condition and parameters.

S.N.	Loads	Specification	Value	References
1	Dead Load	Self-Weight Factor	1.0 kN/m^2	IS 875 (Part-1) 1987
		Outer Wall Load	15 kN/m	
		Internal Wall Load	10 kN/m	
		Parapet Wall Load	5 kN/m	
		Floor Finish + Ceiling Plaster	1.5 kN/m^2	
2	Live Load	Live Load	4 kN/m^2	IS 875 (Part-2)
		Roof Live	2 kN/m^2	
3	Earthquake Load	Seismic Zone	Zone IV	IS 1893 (Part-1) 2016
		Zone Factor (Z)	0.24	
		Soil Type	Medium	
		Damping Ratio	5%	
		Response Reduction Factor (R)	5	
		Importance Factor (I)	1.5	

When analyzing irregular structures with plan or vertical irregularities, the response spectrum method is crucial for accurately estimating seismic forces and deformations. This method offers a code-compliant and realistic approach, ensuring dynamic earthquake effects are properly addressed for safer, more resilient designs.

PLAN AND 3D VIEW OF MODEL

This study models a multistory RC building with a 30 m by 14 m rectangular footprint and 3.5m floor height to evaluate the effects of various shear wall openings. The structural layout, including beams, columns, and shear walls, is developed in ETABS-V21, with Figures 1–4 showing detailed plan, elevation, and 3D views for seismic performance analysis.'

- *Model I:* SMRF structure without opening in shear wall.
- *Model II:* SMRF structure with staggered opening shear wall.

RESULT AND DISCUSSIONS

To compare seismic performance, key parameters – story displacement, drift, and base shear were evaluated across models with varying shear wall configurations.

Story Displacement in X Direction

The solid wall model had the lowest displacement, indicating greater stiffness. Displacement increased with height in all models, with the staggered opening model showing just a 0.14% rise at the top. This confirms that well-designed openings have little effect on seismic performance, emphasizing the need for careful opening placement to maintain structural integrity (Table 3 and Figure 5).

Story Displacement in Y Direction

Story displacement in the Y direction increases with height across all models as presented in Table 4. The solid wall model shows the lowest displacement (37.756 mm), indicating higher stiffness.

The staggered opening model shows a slight increase in displacement compared to the solid shear wall, indicating a minor reduction in lateral stiffness. However, the difference is minimal and does not significantly affect seismic performance, demonstrating that well-designed staggered openings can be safely used without compromising structural integrity.

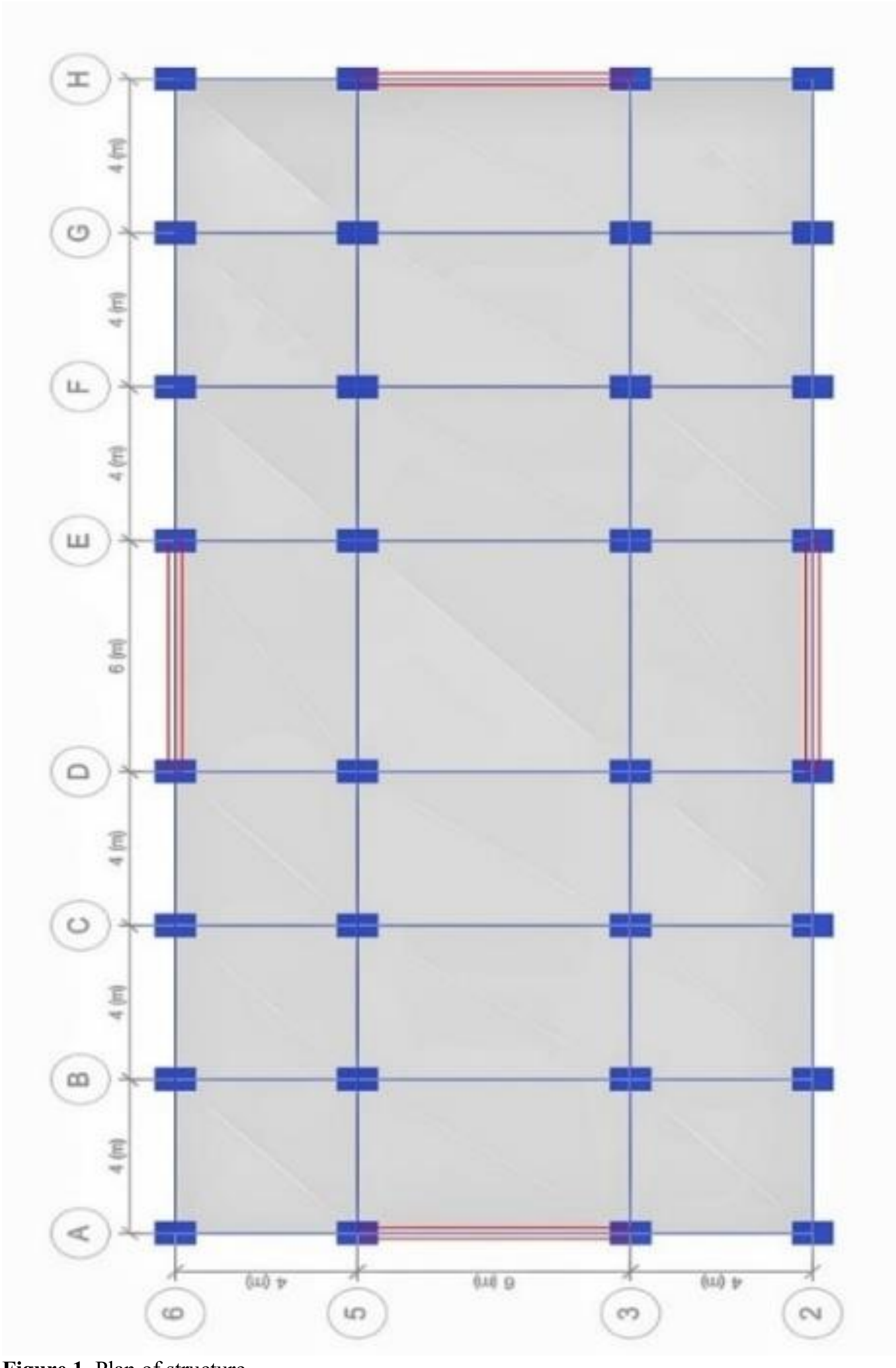

Figure 1. Plan of structure.

Figure 2. Model I – SMRF structure without opening in shear wall.

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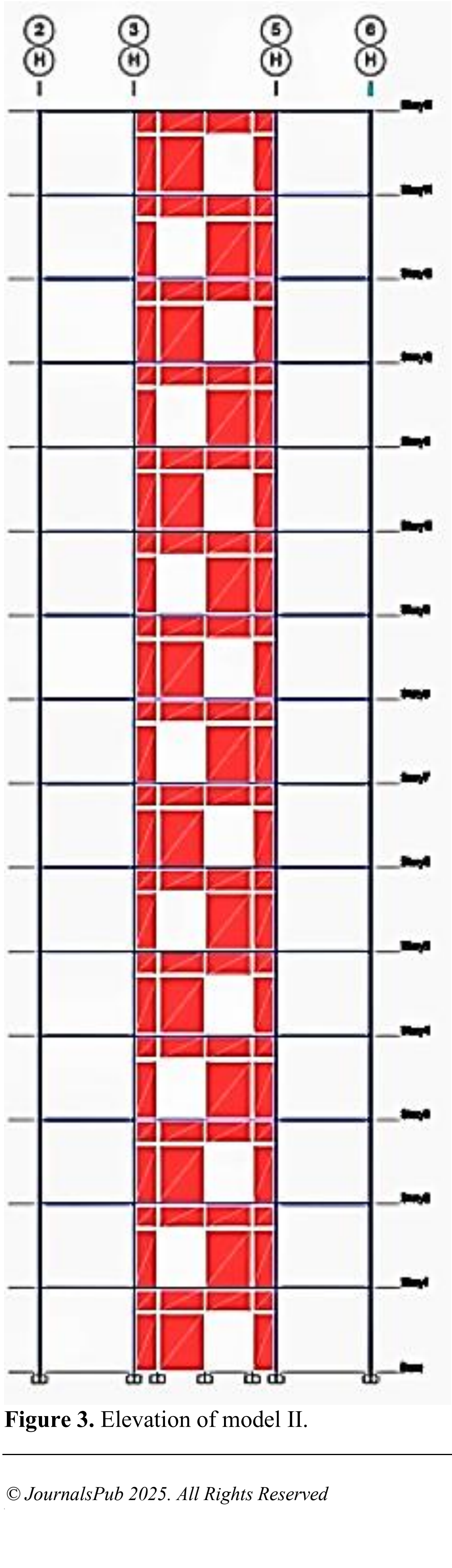

Figure 3. Elevation of model II.

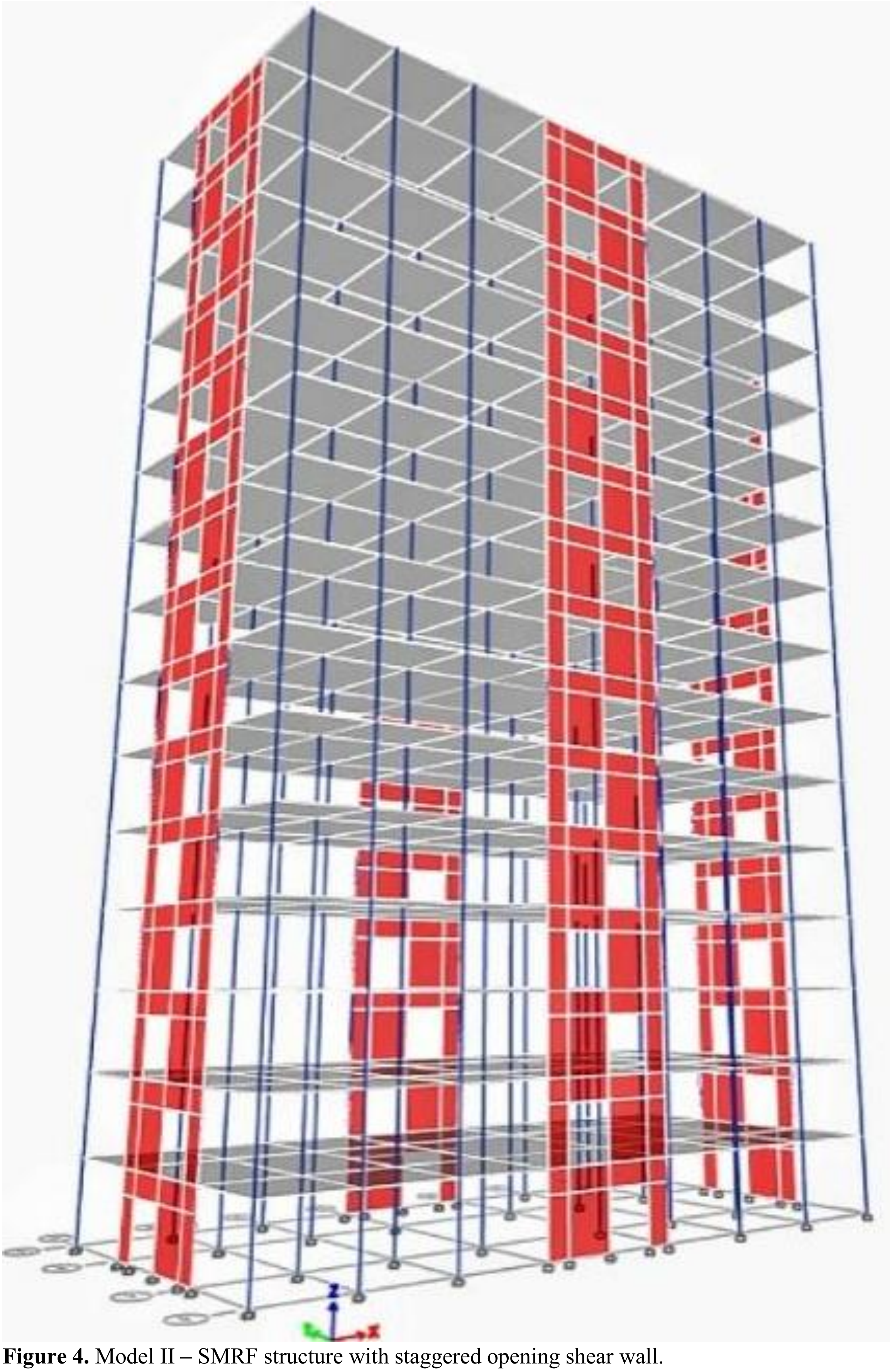

Figure 4. Model II – SMRF structure with staggered opening shear wall.

Table 3. Comparison of story displacement in X direction (mm).

S.N.	No. of Story	Story Height (m)	Without Opening	Staggered Opening
1	Story 15	52.5	34.498	34.546
2	Story 14	49	32.571	32.759
3	Story 13	45.5	30.452	30.754
4	Story 12	42	28.191	28.583
5	Story 11	38.5	25.771	26.238
6	Story 10	35	23.193	23.718
7	Story 9	31.5	20.478	21.047
8	Story 8	28	17.66	18.257
9	Story 7	24.5	14.788	15.396
10	Story 6	21	11.92	12.519
11	Story 5	17.5	9.13	9.701
12	Story 4	14	6.507	7.022
13	Story 3	10.5	4.152	4.583
14	Story 2	7	2.187	2.5
15	Story 1	3.5	0.73	0.884

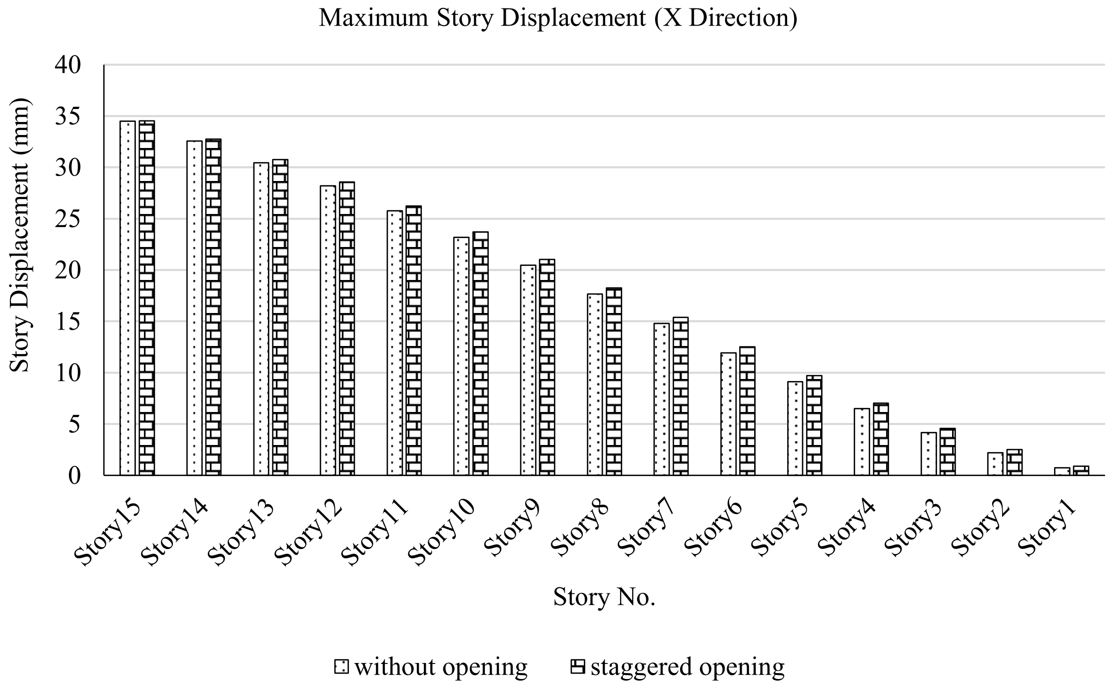

Figure 5. Story displacement in X direction.

Story Drift in X Direction

Story drift peaks near mid-height in both models, with the solid wall model exhibiting the least drift, indicating higher stiffness. While the staggered opening model shows higher drift values, it remains within the permissible limits specified in IS 1893:2016, confirming that staggered openings can be safely used in shear walls when properly designed (Figures 6 and 7 and Table 5).

Story Drift in Y Direction

Story drift in the Y-direction increases up to the mid-height and decreases toward the top, reflecting typical seismic behavior, as presented in Tables 6–8.

Table 4. Comparison of story displacement in Y direction (mm).

S.N.	No. of Story	Story Height (m)	Without Opening	Staggered Opening
1	Story 15	52.5	37.756	37.882
2	Story 14	49	35.391	35.627
3	Story 13	45.5	32.895	33.228
4	Story 12	42	30.221	30.639
5	Story 11	38.5	27.415	27.898
6	Story 10	35	24.49	25.02
7	Story 9	31.5	21.466	22.026
8	Story 8	28	18.38	18.956
9	Story 7	24.5	15.281	15.857
10	Story 6	21	12.232	12.791
11	Story 5	17.5	9.307	9.828
12	Story 4	14	6.593	7.054
13	Story 3	10.5	4.187	4.559
14	Story 2	7	2.187	2.437
15	Story 1	3.5	0.694	0.819

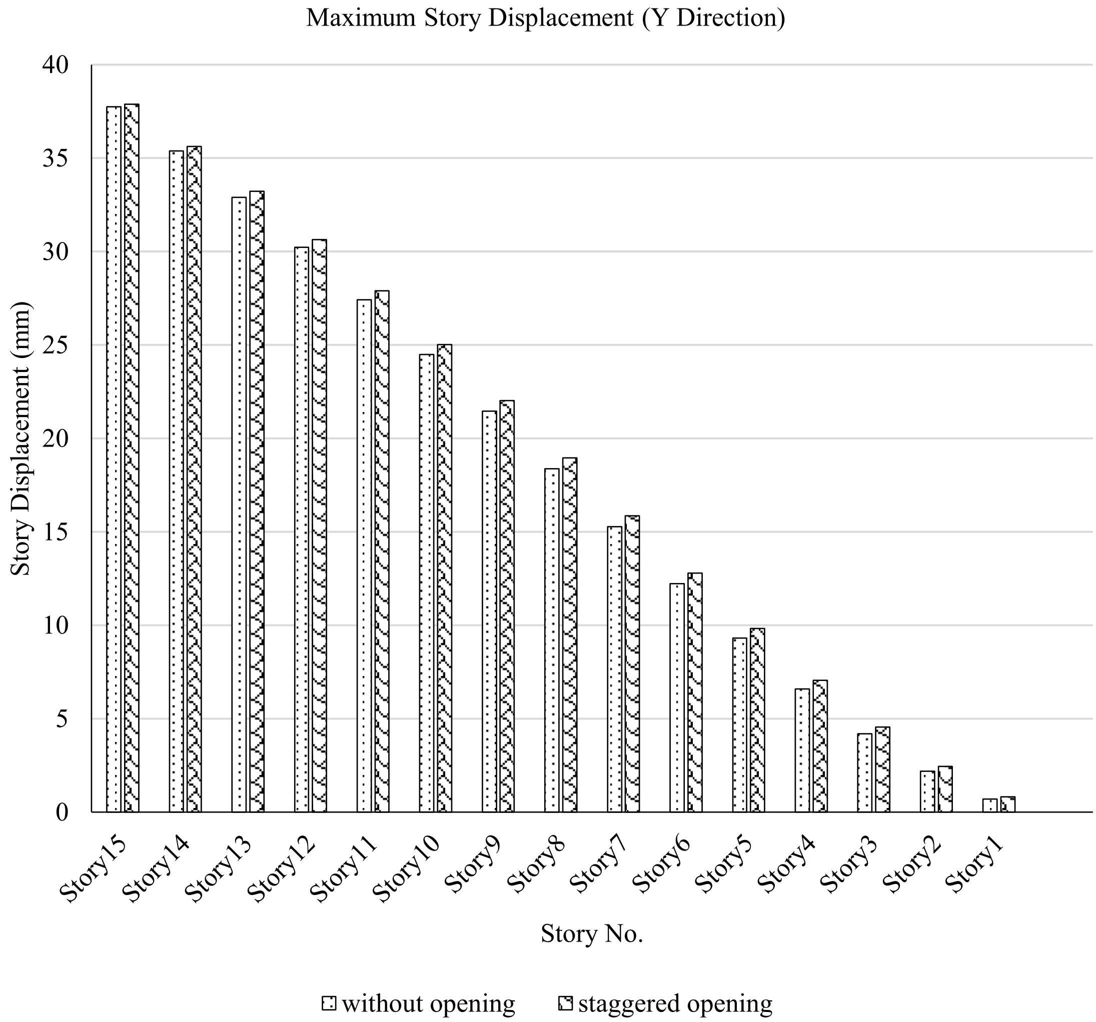

Figure 6. Story displacement in Y direction.

Table 5. Comparison of story drift in X direction (mm).

S.N.	No. of Story	Story Height (m)	Without Opening	Staggered Opening
1	Story 15	52.5	0.000568	0.000525
2	Story 14	49	0.000611	0.000579
3	Story 13	45.5	0.000652	0.000628
4	Story 12	42	0.000698	0.00068
5	Story 11	38.5	0.000742	0.000731
6	Story 10	35	0.000781	0.000775
7	Story 9	31.5	0.000809	0.000809
8	Story 8	28	0.000824	0.00083
9	Story 7	24.5	0.000822	0.000834
10	Story 6	21	0.000799	0.000818
11	Story 5	17.5	0.000751	0.000779
12	Story 4	14	0.000674	0.000711
13	Story 3	10.5	0.000563	0.000609
14	Story 2	7	0.000417	0.00047
15	Story 1	3.5	0.000209	0.000253

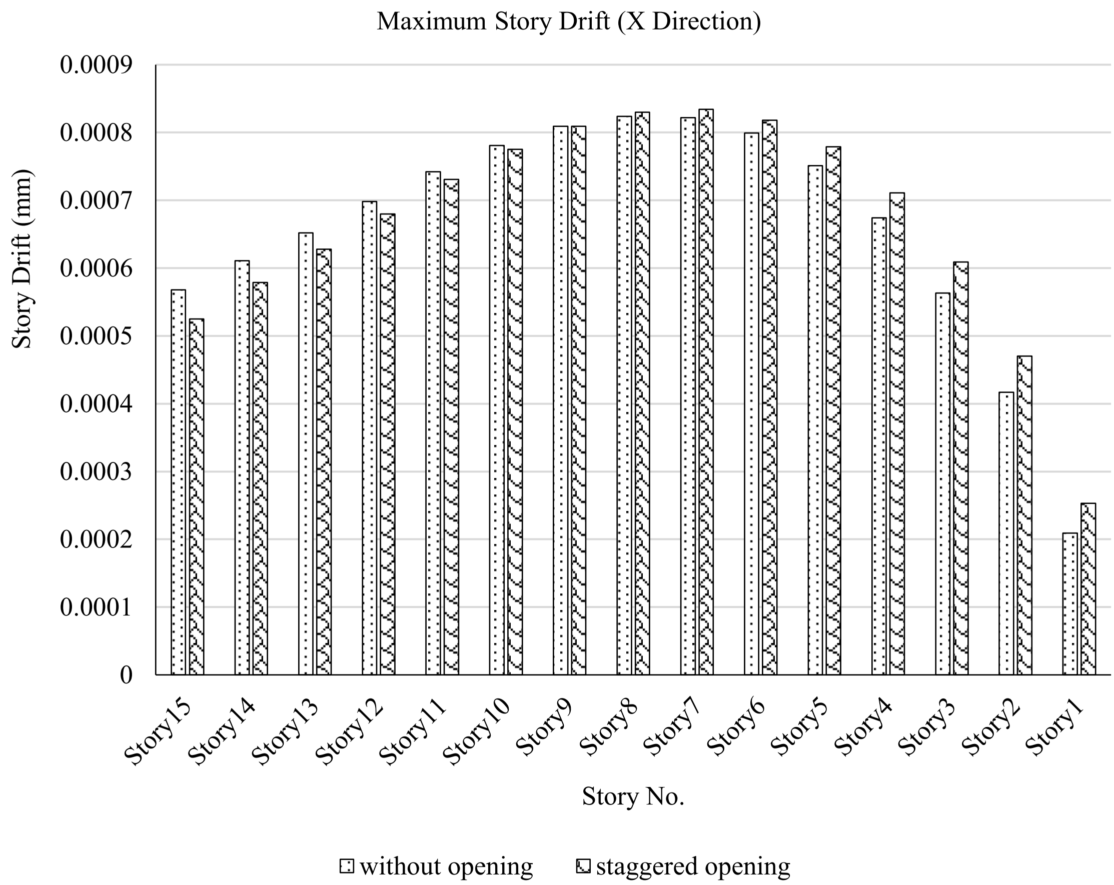

Figure 7. Story drift in X direction.

At some levels, such as Story 10, the staggered model, performs nearly as well or slightly better than the vertical model, suggesting that staggered openings can offer a more balanced seismic response (Figure 8).

Tabel 6. Comparison of story drift in Y direction (mm).

S.N.	No. of Story	Story Height (m)	Without Opening	Staggered Opening
1	Story 15	52.5	0.000694	0.000656
2	Story 14	49	0.000728	0.0007
3	Story 13	45.5	0.00077	0.000747
4	Story 12	42	0.000808	0.000791
5	Story 11	38.5	0.000842	0.000833
6	Story 10	35	0.000869	0.000867
7	Story 9	31.5	0.000886	0.00089
8	Story 8	28	0.000889	0.000899
9	Story 7	24.5	0.000874	0.00089
10	Story 6	21	0.000839	0.000861
11	Story 5	17.5	0.000779	0.000808
12	Story 4	14	0.000691	0.000728
13	Story 3	10.5	0.000572	0.000615
14	Story 2	7	0.000427	0.00047
15	Story 1	3.5	0.000198	0.000234

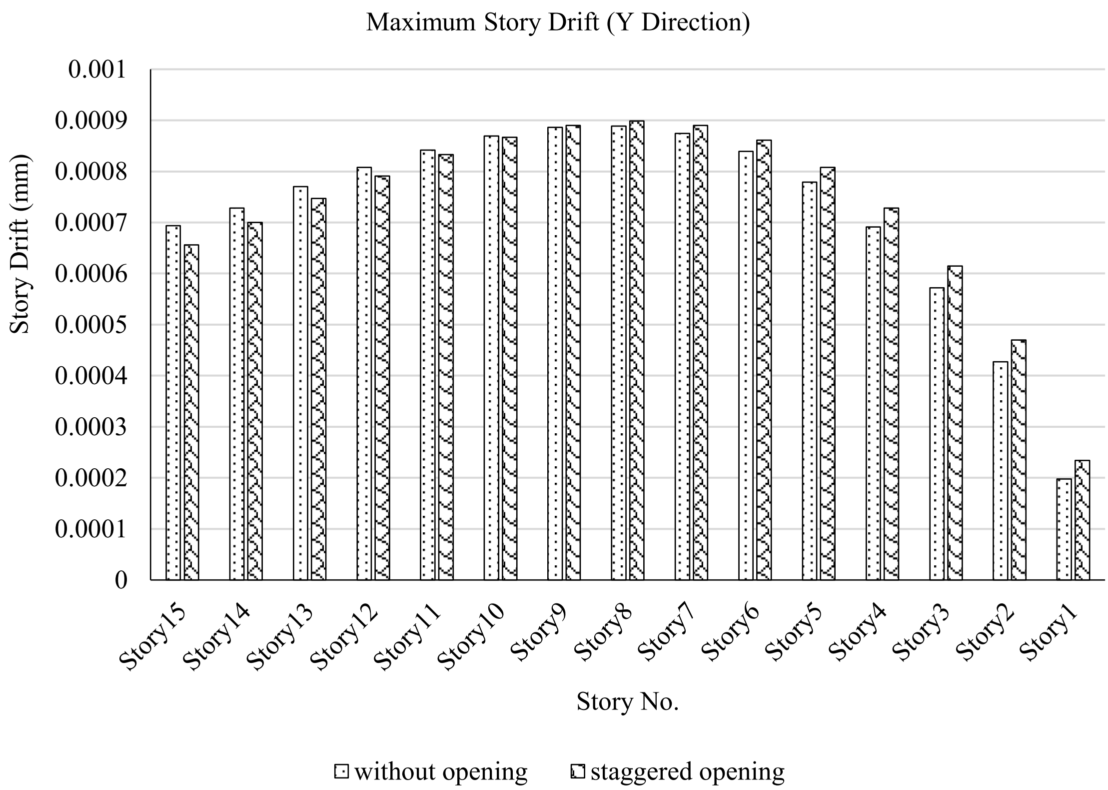

Figure 8. Story drift in Y direction.

Story Shear in X Direction

Story shear increases with height, with the solid wall model showing the highest values, indicating superior seismic resistance. Staggered openings consistently perform better than vertical ones, offering slightly improved shear resistance and more balanced stress distribution. While solid walls remain most effective, staggered openings provide a practical compromise between structural strength and architectural flexibility.

Table 7. Comparison of story shear in X direction.

S.N.	No. of Story	Story Height (m)	Without Opening	Staggered Opening
1	Story 15	52.5	413.3132	387.1463
2	Story 14	49	1053.957	991.9656
3	Story 13	45.5	1612.611	1524.406
4	Story 12	42	2106.438	1996.96
5	Story 11	38.5	2549.22	2421.395
6	Story 10	35	2945.939	2802.593
7	Story 9	31.5	3297.52	3141.579
8	Story 8	28	3605.887	3439.921
9	Story 7	24.5	3873.029	3699.334
10	Story 6	21	4098.612	3919.58
11	Story 5	17.5	4281.671	4099.679
12	Story 4	14	4423.344	4240.351
13	Story 3	10.5	4525.496	4343.02
14	Story 2	7	4588.219	4407.333
15	Story 1	3.5	4612.722	4433.016

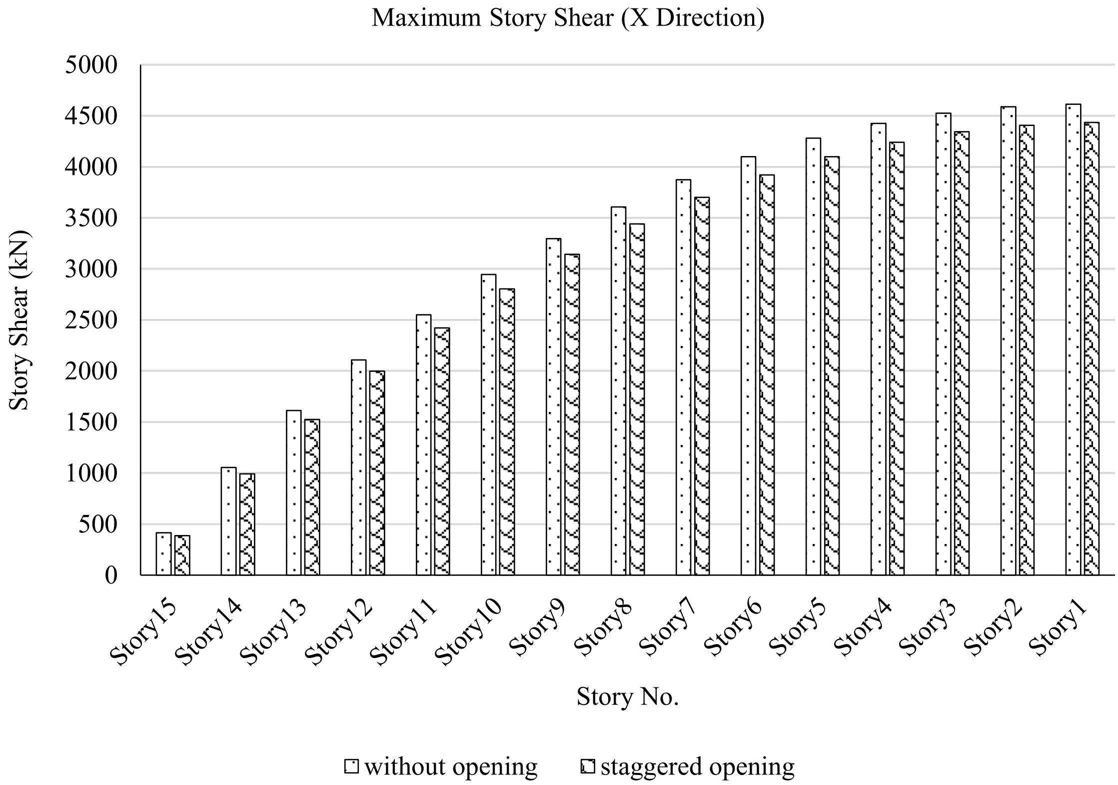

Figure 9. Story shear in X direction.

Story Shear in Y Direction

Story shear in the Y-direction increases downward, with the solid wall model consistently showing the highest values, indicating greater lateral strength. Both vertical and staggered opening models show slight reductions in shear, with the staggered configuration performing marginally better. This trend highlights the effectiveness of staggered openings in maintaining structural performance (Figures 9 and 10).

Table 8. Comparison of story shear in Y direction.

S.N.	No. of Story	Story Height (m)	Without Opening	Staggered Opening
1	Story 15	52.5	397.5338	376.2034
2	Story 14	49	1013.479	960.283
3	Story 13	45.5	1548.177	1471.261
4	Story 12	42	2016.372	1920.984
5	Story 11	38.5	2431.151	2320.345
6	Story 10	35	2799.115	2675.131
7	Story 9	31.5	3124.415	2989.414
8	Story 8	28	3409.355	3265.521
9	Story 7	24.5	3654.945	3504.337
10	Story 6	21	3862.465	3706.993
11	Story 5	17.5	4032.147	3873.71
12	Story 4	14	4163.526	4003.878
13	Story 3	10.5	4258.063	4098.469
14	Story 2	7	4316.684	4157.759
15	Story 1	3.5	4339.009	4180.532

The staggered opening model shows slightly reduced lateral resistance compared to the solid shear wall but provides improved stress distribution and adequate seismic performance. While effective, it remains less robust than the solid wall, which is more suitable for high seismic zones due to its superior strength and stiffness.

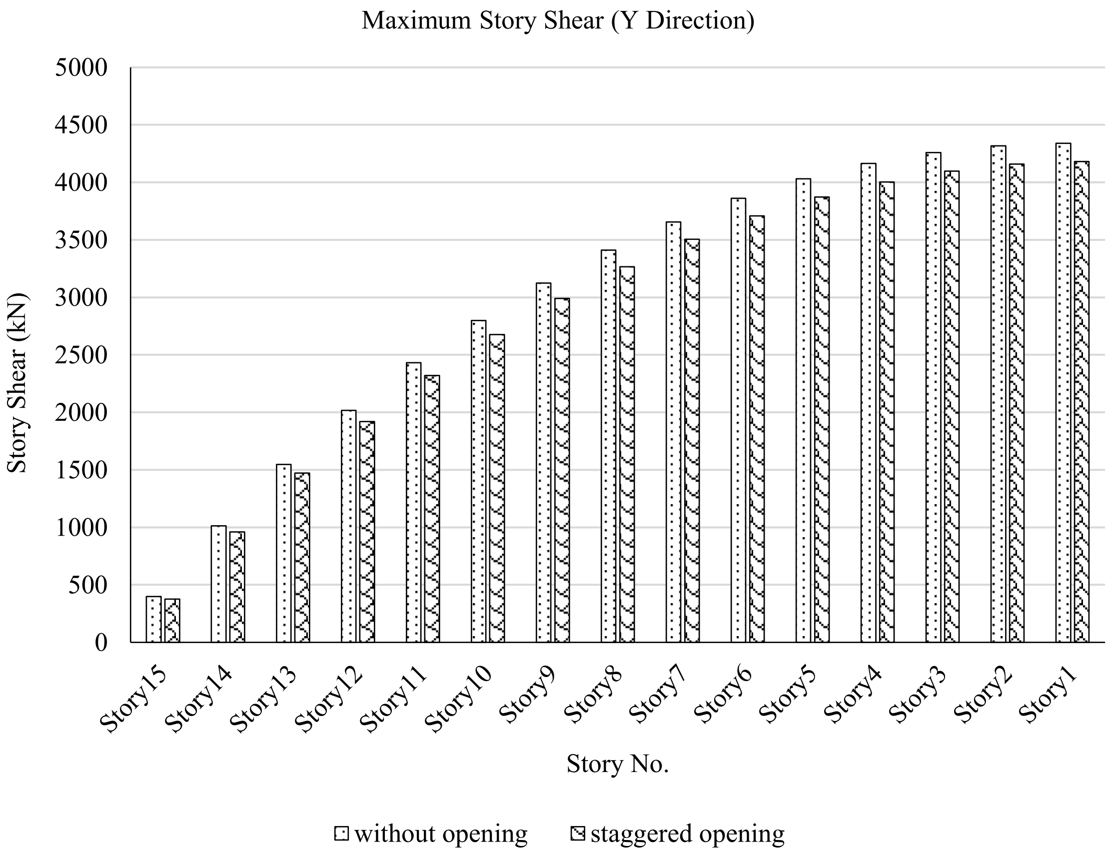

Figure 10. Story shear in Y direction.

CONCLUSIONS

The seismic performance of Model I (solid walls) and Model II (staggered openings) was evaluated using the response spectrum method as per IS 1893:2016, revealing differences in displacement, drift, shear, and stiffness.

- *Model I:* with solid shear walls, consistently outperformed the other configurations, showing the highest resistance to lateral forces across all parameters.
- *Model II:* with staggered openings showed slightly higher displacement and lower stiffness than Model I, but the impact on overall performance was minimal.
- *Model I:* (solid shear walls) demonstrated the best seismic resistance, with minimal displacement, drift, and maximum stiffness and shear capacity.
- *Model II*: (with staggered openings) offered a balanced compromise between structural integrity and design flexibility compared to Model I (without openings).
- *Model II:* (with staggered openings) showed a slight reduction in seismic resistance compared to the solid shear wall in Model I, emphasizing the importance of strategic placement of openings in shear wall design.

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