

Seismic Performance Evaluation of Step-Back Buildings on Various Sloping Ground Conditions

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Abstract—This study investigates the seismic performance of step-back buildings constructed on varying slopes, reflecting the rising challenge of urbanization in hilly terrains. Using nonlinear time-history analysis in ETABS 2021, models for 10, 15, and 20-storey buildings were analyzed for slope angles ranging from 5 to 20 degrees. Key seismic parameters—base shear, roof displacement, and storey drift—were compared to identify structural vulnerabilities and optimal design strategies. Results indicate that increasing slope angle amplifies seismic vulnerability, stress concentration, and differential movement, pointing to the need for specialized design guidelines and retrofitting strategies for sloped ground buildings. Findings contribute to urban resilience and earthquake risk mitigation.

Keywords: Seismic performance; step-back buildings; sloping ground; base shear; roof displacement; storey drift; structural irregularity; ETABS; RC frames.

INTRODUCTION

Rapid urbanization and land scarcity have increased the construction of high-rise buildings on sloping grounds, particularly in seismically active regions. These step-back configurations, preferred for functional and aesthetic reasons, exhibit unique vulnerabilities during earthquakes due to irregular mass, stiffness distribution, and various geometric factors. Previous seismic events have revealed that irregular structures, especially those on slopes, suffer disproportionately more damage compared to regular structures on flat terrain.

LITERATURE REVIEW

Ram Krishna Shreshtha et. al., (2024) represented a comprehensive study on seismic performance of a step

back building resting on a sloping ground. The static linear analysis method is carried out by using SAP-2000 to achieve the study's objective. Total 8 models were selected and they are plain surface building, plain surface and set back building, step back building, step back and set back building, double step back and set back building, double step back building, step by step back building, step by step back and set back building. These models are investigated through pushover analysis by comparing the base shear, storey displacement and storey drift. According to the results the step by step back and set back building model exhibits a higher shear force in its pushover analysis when compared to other 6 models. The storey displacements of step by step back building were found less than other 7 models hence he concluded that step by step back and set back buildings were the most vulnerable among all the other building configurations.

Amit chougale et. al., (2023) conducted a seismic analysis of building on sloping ground including soil structure interaction. Research was done on a G+4 RCC building whose dimensions were (9mx9m) which is resting on a sloping ground with angles from 0° to 45° and analysed them by equivalent static force method and response spectrum method. E-TABS 2016 was the software used in this research work. Total 8 models were modelled and research was carried out. The G+4 building was modelled based on its sloping angles 0°, 15°, 30° and 45°. The building lies in seismic zone-V. This performance of the building was compared by base shear, column bending moments and displacement. According to the results the models with 0°, 15°, 30° has low base shear and model with 45° has high base shear so it means the base shear depends on the slope of the ground whereas the maximum

displacements was decreasing with increase of slope angle. Whereas the max displacements was decreasing with increase of slope angles. When it comes to bending moments of column the columns on higher level had more moment than on the lower level.

Harsh Patel et. al.,(2022) found in this study that use of shear wall and bracing is found to be effective in improving the seismic performance of building. In this study seismic coefficient approach in E-TABS V16 to explain the behaviour of step back, step back set back and set back buildings with three to five stories with $0^\circ, 5^\circ, 10^\circ, 15^\circ, 20^\circ, 25^\circ$ and 27° the seismic susceptibility associated with their dynamic response qualities is investigated by comparing the base shear, top storey displacements, torsion and underpinning. In this study it was found that step back building were most seismic vulnerable on sloping grounds than set back and step back set back buildings where as in step back, setback step back the shorter columns were worst affected due to seismic loads. Top storey displacements, torsion in setback structure is lesser than other two configurations. The underpinning demand of set back building is satisfactory where as in step back, step back and set back it is not satisfactory. Hence step back building is not suitable in hilly areas as compared to step back set back and set back building configurations.

Numesh Sahu (2021) studied the dynamic analysis of slopped building. In his study he concentrated on 2D frame of G+8 building on plane and sloping ground with angles 45° and 65° . The analysis was done by using response spectrum method in E-TABS by comparing storey shear force storey deflection, torsion moment and base shear. In this study 3 different building configuration are considered they are step back, step back set back and set back structures rest on various sloping and also plain ground. According to the results the storey shear decreases from bottom to top. The base shear was found to be decreasing from lower angle to higher angle. Out of all 3 building configurations the step back buildings were proved to be more vulnerable than the setback step back and set back building. In step back set back building the torsion moment was less when compared to the remaining configurations. The buildings resting on sloping ground have less base shear than the building resting on plain ground. As the ground angle increases the top storey decreases hence it is recommended to go for step back set back building instead of step back,

set back buildings.

METHODOLOGY

A parametric numerical study was performed using ETABS 2021. Building models with 10, 15, and 20 storeys, each with varying slope angles ($5^\circ, 10^\circ, 15^\circ$, and 20°), were analyzed. Nonlinear time-history analysis was adopted to capture dynamic response characteristics under simulated earthquake loading. Structural parameters analyzed included base shear, roof displacement, storey drift, and stiffness.

Nonlinear time history analysis (NLTHA) is a type of seismic analysis that simulates the dynamic response of a structure to earthquake ground motion, taking into account the nonlinear behavior of the structure.

Nonlinear Time History Analysis (NLTHA) is the most detailed and complex dynamic analysis method for assessing the response of structures subjected to seismic loads, particularly when inelastic behavior is expected.

OBJECTIVES OF THE STUDY

The project work aims the following objectives:

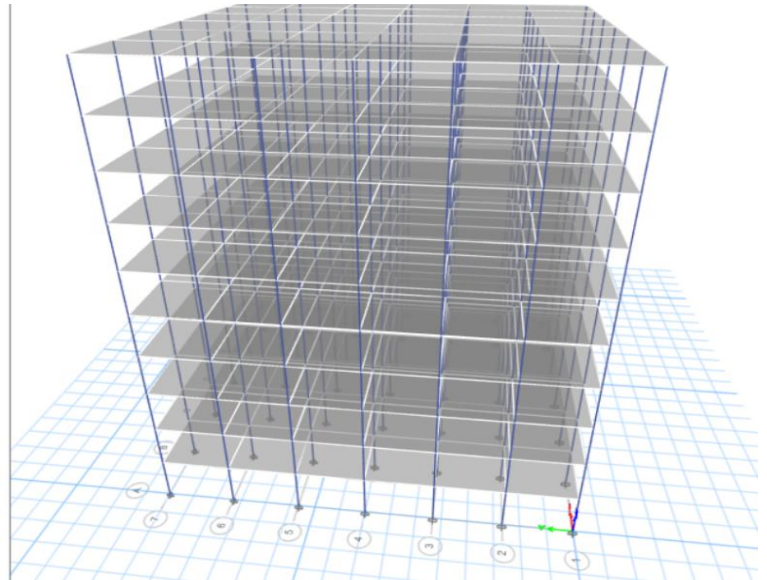
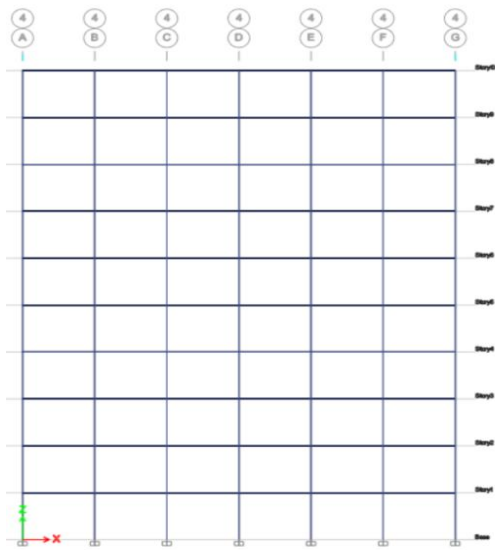
- ❖ To study the effect of earthquake on building with sloping ground ($0^\circ, 5^\circ, 10^\circ, 15^\circ, 20^\circ$) In terms of base shear, roof displacements, time period.
- ❖ To study the effect of setback building and step back-setback building in terms of base shear, roof displacements, time period etc.
- ❖ To identify weak zones in the structure and to understand shear stress distribution in the structures considered in the study.

Model details

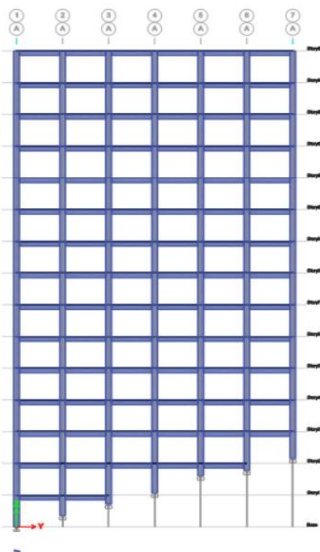
Details	Description
No of storey	G+10,G+15,G+20
Zone	V
Grade of concrete	M40
Grade of steel	Fe550
Type of frame	Special moment resistance Frame
Response Reduction Factor	5
Column size	500x500 for G+10,600x600 for G+15,700x700 for G+20
Beam size	300x450 for G+10,300x600 for G+15,450x600 for G+20
No of bays in X direction	6
No of bays in Y	6

direction	
Spacing of bays	4 metres
Live load	3kN/m ²
Floor load	1 kN/m ²
Thickness of wall	200mm

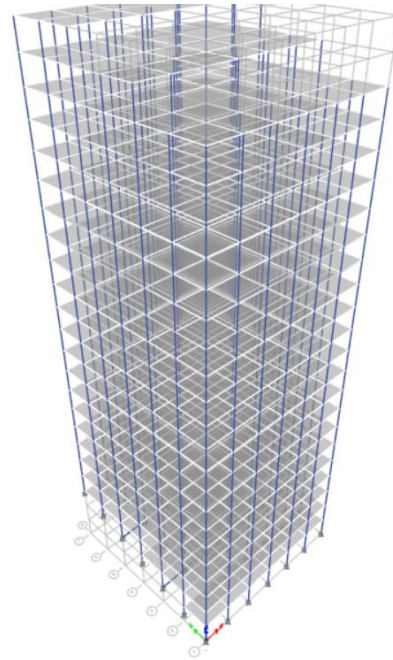
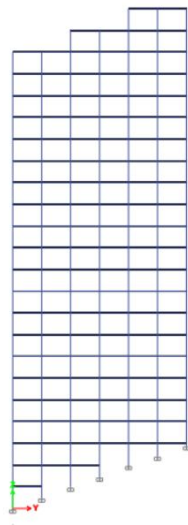
Shear wall	200mm-250mm
Grade of concrete in shear wall	M50
Grade of steel in shear wall	Fe550



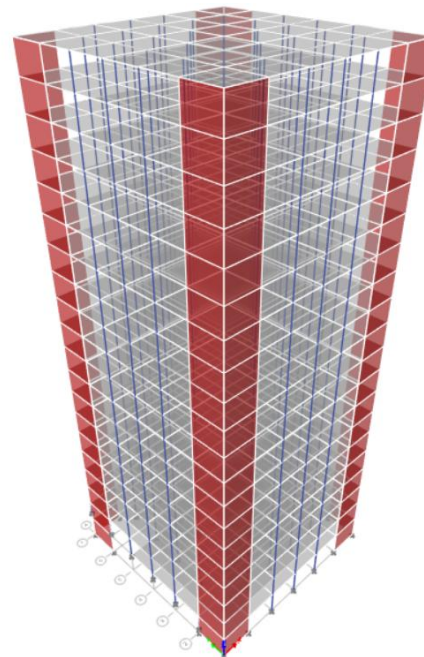
M10SP0°:10 storey model with stepback and 0° slope



M15SP15° 15 storey model with stepback and 15° slope



M20SPSB20° 20 storey model with stepback setback and 20° slope



M15SP10°15 storey model with stepback and 10° slope with shear wall

RESULTS AND DISCUSSIONS

This study involves 60 models which were modelled in E-TABS 21 by varying slopes of the ground along with stepback and setback. These models were subjected to gravity, lateral loads were designed then nonlinear time history analysis was performed to

analyze the performance of structure. Step-back and setback configurations with retrofitted elements such as shear walls, steel bracing, and reinforced columns offer significant improvements in seismic performance. Results suggest that setback or step-back setback designs—rather than pure step-back—should be favored. Site-specific design guidelines, detailed

dynamic analysis, and preventive retrofitting are essential to mitigate earthquake risks in hilly regions.

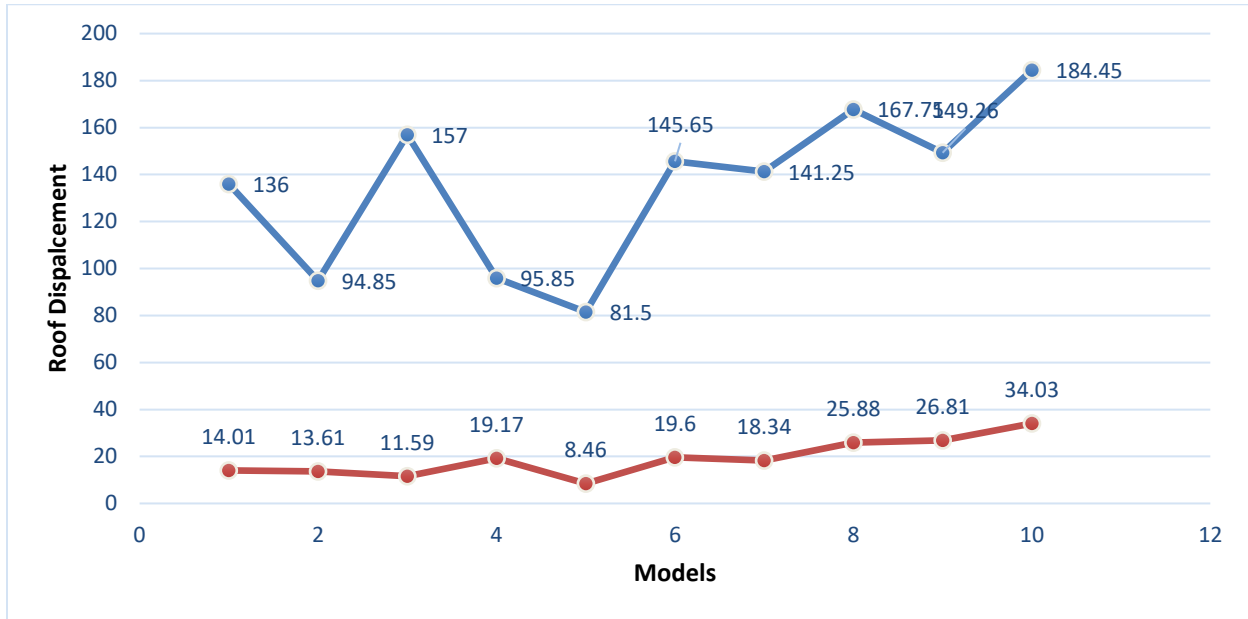


Fig 1 Roof Displacement for models with G+10

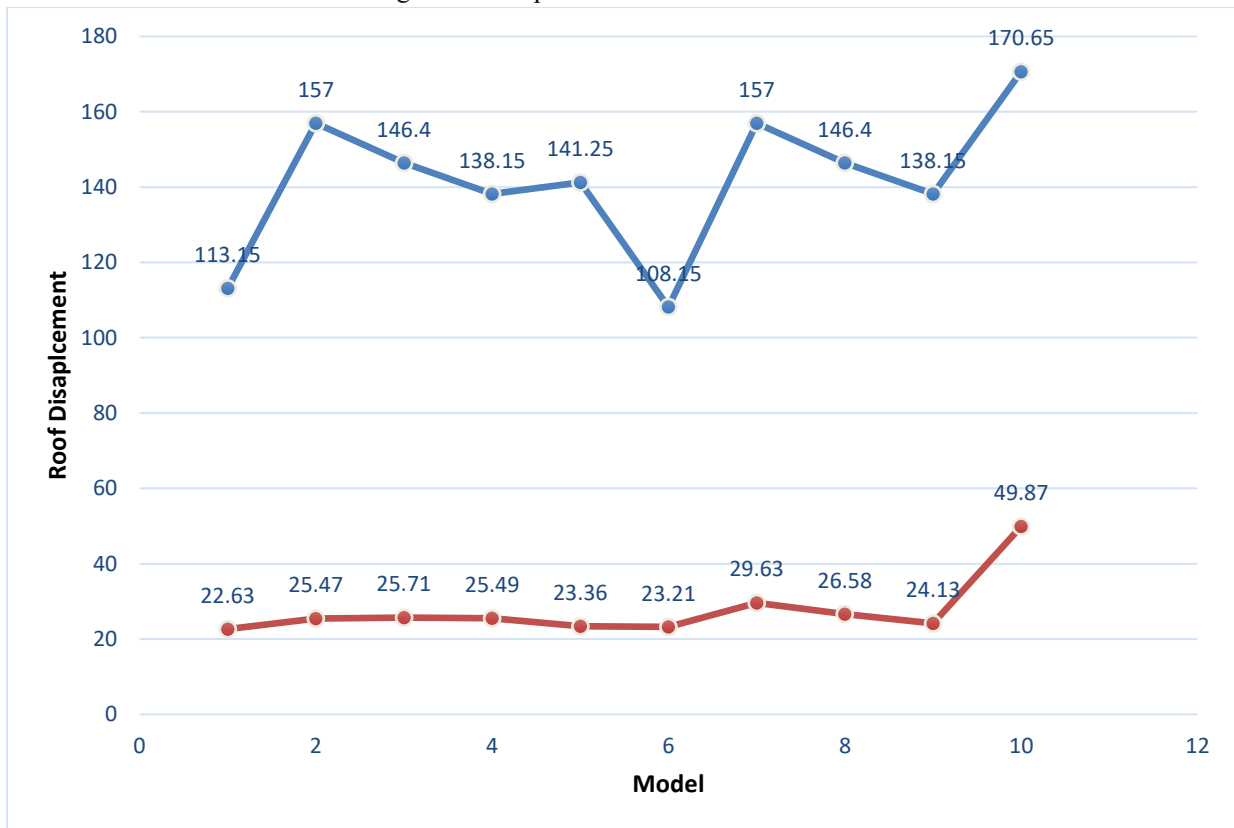


Fig 2 Roof displacement for models with G+15

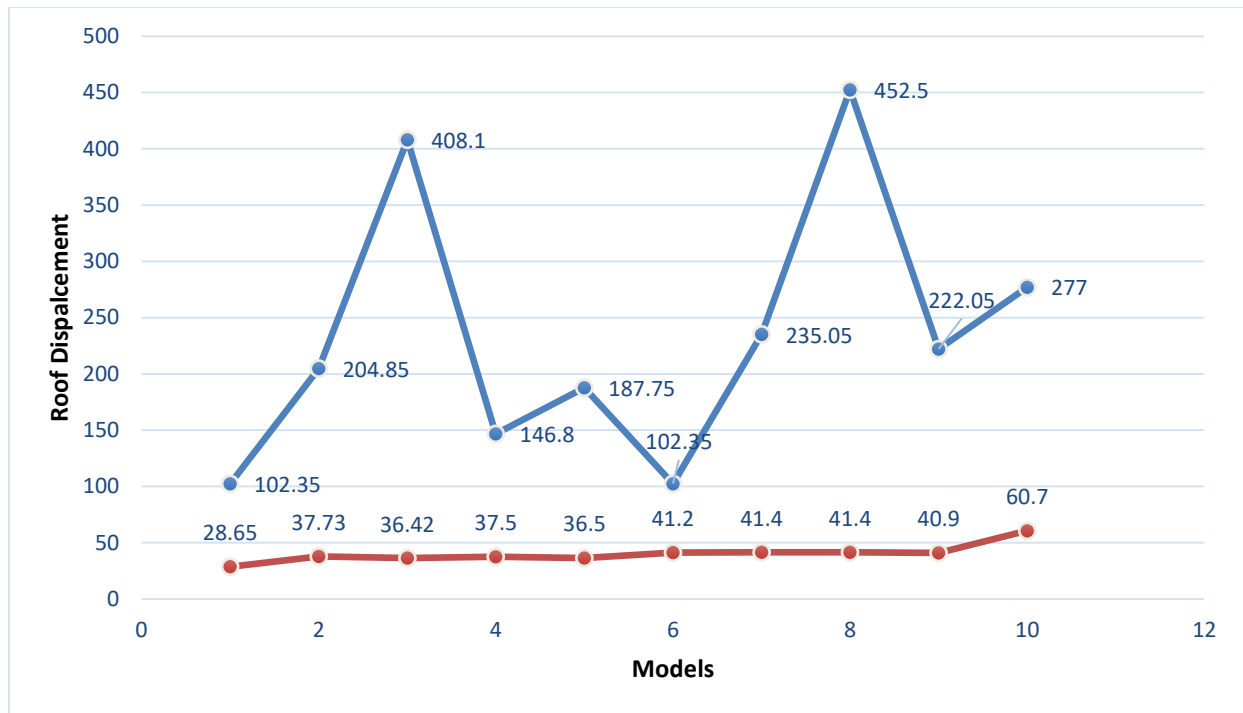


Fig 3 Roof Displacements for models with G+20



Fig 4- Base shear for models with G+10

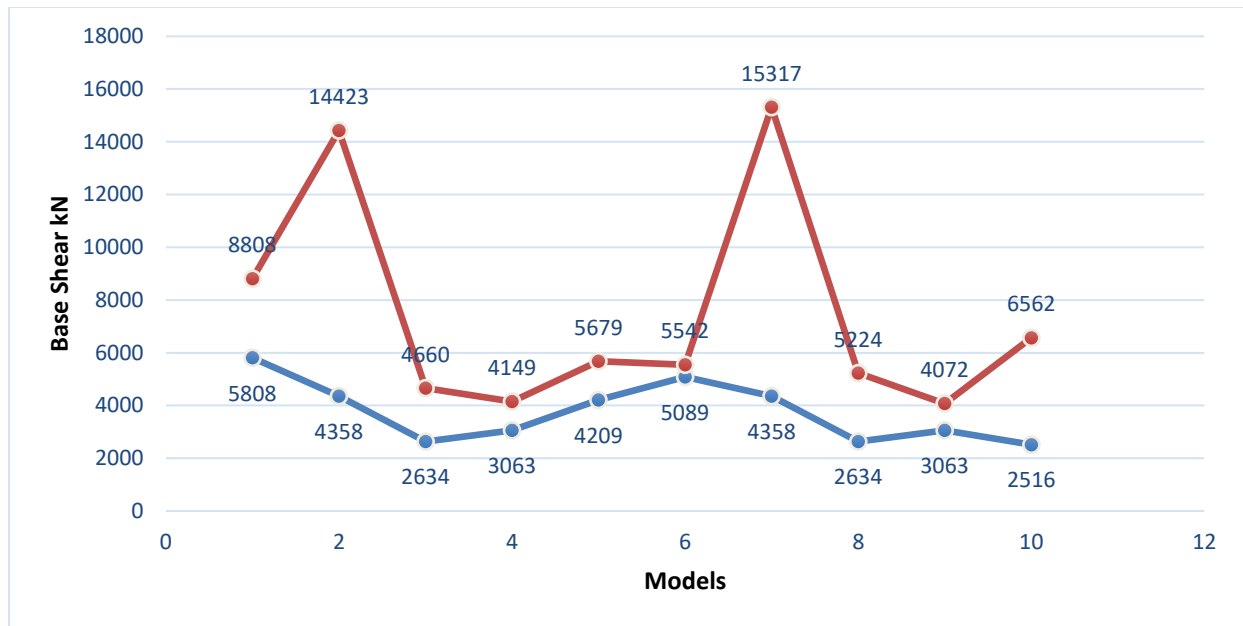


Fig 5- Base shear for models with G+15

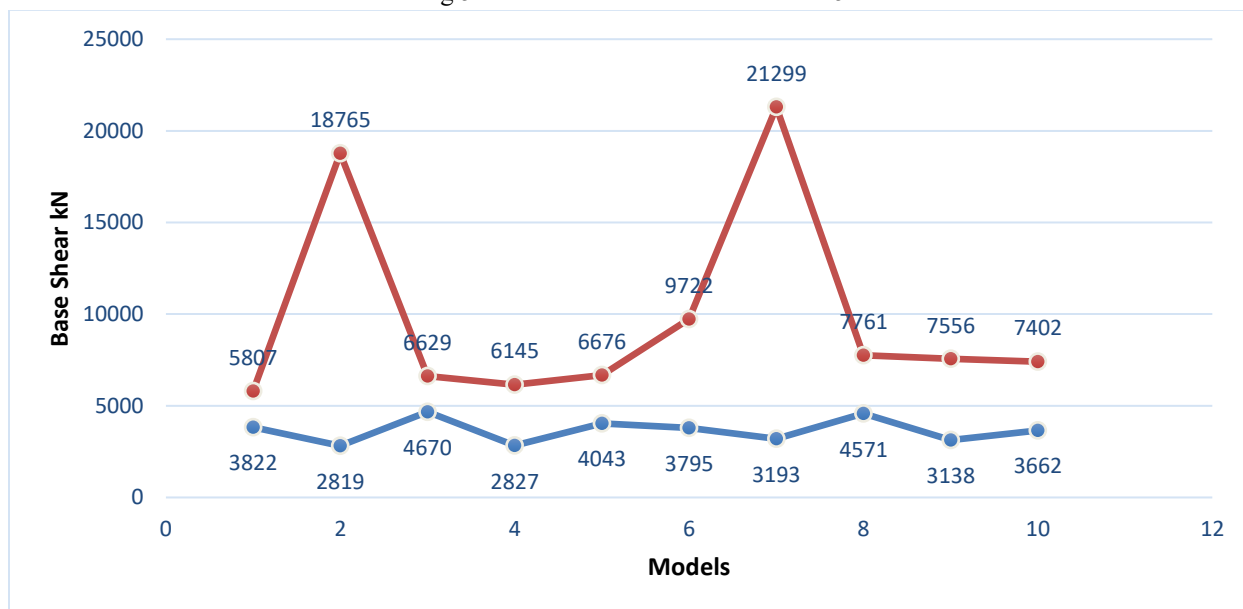


Fig 6- Base shear for models with G+20

5.3 Time Period

SI No.	Models	TIME PERIOD(Sec)
1	M10SP0°	0.844
2	M10SP5°	0.8
3	M10SP10°	1.87
4	M10SP15°	0.69
5	M10SP20°	0.63
6	M10SPSB0°	0.95
7	M10SPSB5°	0.9
8	M10SPSB10°	1.93
9	M10SPSB15°	0.77
10	M10SPSB20°	0.71
11	M10SP0° SW	0.51
12	M10SP5° SW	0.48

13	M10SP10° SW	0.45
14	M10SP15° SW	0.69
15	M10SP20° SW	0.38
16	M10SPSB0° SW	0.6
17	M10SPSB5° SW	0.57
18	M10SPSB10° SW	0.47
19	M10SPSB15° SW	0.48
20	M10SPSB20° SW	0.48
21	M15SP0°	1.04
22	M15SP5°	1.25
23	M15SP10°	2.42
24	M15SP15°	1.14
25	M15SP20°	1.08
26	M15SPSB0°	0.97

27	M15SPSB5°	1.25
28	M15SPSB10°	2.42
29	M15SPSB15°	1.41
30	M15SPSB20°	1.22
31	M15SP0°SW	1.04
32	M15SP5°SW	0.86
33	M15SP10°SW	0.83
34	M15SP15°SW	0.79
35	M15SP20°SW	0.75
36	M15SPSB0°SW	0.7
37	M15SPSB5°SW	0.97
38	M15SPSB10°SW	0.9
39	M15SPSB15°SW	0.86
40	M15SPSB20°SW	0.93
41	M20SP0°	1.39
42	M20SP5°	1.71
43	M20SP10°	2.93
44	M20SP15°	1.6
45	M20SP20°	1.53
46	M20SPSB0°	1.12
47	M20SPSB5°	1.82
48	M20SPSB10°	3.05
49	M20SPSB15°	1.8
50	M20SPSB20°	1.73
51	M20SP0°SW	1.09
52	M20SP5°SW	1.28
53	M20SP10°SW	1.25
54	M20SP15°SW	1.24
55	M20SP20°SW	1.24
56	M20SPSB0°SW	1.23
57	M20SPSB5°SW	1.38
58	M20SPSB10°SW	1.38
59	M20SPSB15°SW	1.35
60	M20SPSB20°SW	1.33

5.4 Stiffness

Sl No.	Models	STIFFNESS(kN/m)
1	M10SP0°	1492745
2	M10SP5°	1023711
3	M10SP10°	830728
4	M10SP15°	894881
5	M10SP20°	2077104
6	M10SPSB0°	1490747
7	M10SPSB5°	1024868
8	M10SPSB10°	843859
9	M10SPSB15°	890216
10	M10SPSB20°	2034299
11	M10SP0° SW	9201481
12	M10SP5° SW	9942840
13	M10SP10° SW	11992939
14	M10SP15° SW	13564857
15	M10SP20° SW	5966768
16	M10SPSB0° SW	8901517
17	M10SPSB5° SW	9942840
18	M10SPSB10° SW	12286453
19	M10SPSB15° SW	3822199
20	M10SPSB20° SW	5140196
21	M15SP0°	1971201
22	M15SP5°	1014513
23	M15SP10°	820937
24	M15SP15°	879564
25	M15SP20°	1054554
26	M15SPSB0°	1972202
27	M15SPSB5°	1014513
28	M15SPSB10°	820937
29	M15SPSB15°	879564
30	M15SPSB20°	1399541

31	M15SP0°SW	9971201
32	M15SP5°SW	8957741
33	M15SP10°SW	11242014
34	M15SP15°SW	3397557
35	M15SP20°SW	6762542
36	M15SPSB0°SW	6556722
37	M15SPSB5°SW	7920491
38	M15SPSB10°SW	11645736
39	M15SPSB15°SW	3368323
40	M15SPSB20°SW	13315816
41	M20SP0°	1933576
42	M20SP5°	1082201
43	M20SP10°	814191
44	M20SP15°	870449
45	M20SP20°	5071581
46	M20SPSB0°	1933576
47	M20SPSB5°	1010519
48	M20SPSB10°	830036
49	M20SPSB15°	865905
50	M20SPSB20°	1085046
51	M20SP0°SW	8168653
52	M20SP5°SW	10871463
53	M20SP10°SW	10860225
54	M20SP15°SW	2791766
55	M20SP20°SW	10890228
56	M20SPSB0°SW	10863152
57	M20SPSB5°SW	8631528
58	M20SPSB10°SW	7468200
59	M20SPSB15°SW	7468155
60	M20SPSB20°SW	13225164

CONCLUSION

- The Step-Back with Set-Back (SPSB) configuration consistently outperforms the Step-Back (SP) design in controlling roof displacement across all building heights. For instance, in the G+10 models, M10SPSB20° recorded a 35.63% increase in displacement, compared to a 40.07% reduction in M10SP20°, indicating that the set-back addition significantly enhances deformation capacity and energy absorption.
- The integration of shear walls into SPSB models leads to a substantial increase in displacement capacity. The M10SPSB20°SW model showed a 142.90% increase over the baseline, highlighting the synergy between shear walls and SPSB geometry in enhancing flexibility and ductility, particularly under lateral loads.
- In taller buildings (G+20), the benefits of SPSB configurations become more pronounced. The M20SPSB10° model achieved the highest displacement increase of 342.11%, demonstrating the effectiveness of combining step-back and set-back features in high-rise structures to absorb and dissipate seismic energy.

- Base shear analysis indicates that the highest values occur at 5° angles. In G+10 models, M10SPSB5° reached 15204 kN, marking a 313.71% increase over the baseline. This suggests increased lateral stiffness at moderate inclinations, although base shear tends to reduce at higher angles due to increased flexibility.
- Shear wall integration significantly improves base shear performance, especially in SPSB models. The M20SPSB5°SW configuration registered the highest base shear value (21299 kN), a 266.78% increase, proving highly effective for seismic and wind load resistance in high-rise structures.
- The addition of shear walls notably reduces the structural time period, which correlates with increased stiffness. For example, M10SP0° had a time period of 0.844 s, which dropped to 0.51 s in M10SP0°SW, confirming that shear walls make structures more rigid and dynamically efficient under seismic loading.
- Without shear walls, SPSB models tend to exhibit longer time periods, indicating greater flexibility. The M20SPSB10° model had the highest time period of 3.05 seconds, suggesting that this configuration, while enhancing energy absorption, may require supplemental stiffness for stability under certain loading conditions.
- Stiffness analysis reveals dramatic improvements with the use of shear walls. For instance, in G+10 buildings, M10SP0°SW achieved a stiffness of 9.2 million kN/m, compared to only 1.49 million kN/m in its non-shear wall counterpart, a more than 500% increase, affirming the critical role of shear walls in structural rigidity.
- Even without shear walls, SPSB models typically match or slightly exceed the stiffness of SP configurations. For example, M15SPSB0° had a stiffness of 1.97 million kN/m, identical to M15SP0°, and increased at higher angles, showing that the geometry itself contributes to rigidity, even before wall inclusion.
- Across displacement, base shear, time period, and stiffness, the most balanced and effective structural behavior was observed in SPSB models with shear walls at 5° to 10° angles. This range consistently offered improved ductility, strength, and stability, making it a recommended design

choice for mid- to high-rise buildings in seismic zones.

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