

Comparative Analysis Of Lateral Load Resistance Systems In High-Rise Buildings Using Outriggers And Belt Trusses

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ABSTRACT

High-rise buildings are increasingly constructed in urban areas because of rapid population growth and limited land availability. As building height increases, lateral loads caused by earthquakes and wind become critical factors affecting structural stability and serviceability. This study presents a comparative analysis of lateral load-resisting systems in a 50-storey reinforced concrete building modeled in ETABS. The structural configurations include a conventional core wall system, single and double outrigger systems, single and double belt truss systems, and combined outrigger-belt truss systems. The models were analyzed under seismic and wind loads according to IS 1893:2016 and IS 875 (Part 3):2015. The performance of each configuration was evaluated using maximum storey displacement and inter-storey drift, and the best-performing systems were further compared across hard, medium, and soft soil conditions. The results show that the use of outriggers and belt trusses considerably enhances lateral stiffness and reduces lateral deformation compared with the conventional core wall model. Among the studied alternatives, the double combined outrigger with belt truss system placed at the 10th and 20th stories produced the most effective response, with the greatest reduction in seismic displacement, wind displacement, and drift. The findings provide a practical reference for selecting and optimizing lateral load-resisting systems in high-rise buildings subjected to seismic and wind actions.

Keywords: High-rise buildings; outrigger system; belt truss; lateral load resistance; ETABS; seismic analysis; wind analysis; storey displacement; storey drift; structural stability.

I. INTRODUCTION

High-rise buildings are an essential part of modern urban development because they accommodate growing populations while improving land-use efficiency. These structures also contribute to economic activity, integrated infrastructure, and the development of compact urban spaces. However, their increased height makes lateral load resistance a critical design requirement.

Tall buildings must remain stable and serviceable under natural forces such as earthquakes and wind. Limited lateral movement is acceptable and reflects structural flexibility, but excessive sway may cause discomfort, non-structural damage, structural distress, or even collapse. The response of a high-rise building depends on its stiffness distribution, mass, structural system, and seismic context.

Outrigger systems and belt trusses are commonly adopted to control the lateral response of tall buildings. Outriggers connect the central core to perimeter columns, thereby mobilizing tension and compression in the outer columns and reducing overturning effects. Belt trusses connect perimeter columns around the building and are frequently combined with outriggers to improve force transfer and drift control.



Figure 1. Outriggers connected with perimeter columns.

II. LITERATURE REVIEW

Previous studies consistently indicate that outrigger and belt truss systems improve the lateral performance of high-rise structures. Khadka et al. [1] reported that the combined use of outriggers and belt trusses increases lateral stiffness more effectively than outriggers alone. Tobber et al. [2] proposed a controlled rocking outrigger core wall system for improved seismic resilience, while Habrah et al. [3] developed analytical design curves for optimizing outrigger locations. Zhou et al. [4] addressed construction-stage scheduling of outrigger installation in super-tall structures, and Ussher et al. [5] compared different lateral systems for wind-induced serviceability in tall timber structures. Other studies by Kim et al. [6], Shan et al. [7], Rathore et al. [8], Shingade et al. [9], Shareef et al. [10], and Karande et al. [11] show that the location and number of outriggers have a significant effect on displacement, drift, and global stiffness.

The literature highlights the need for a systematic comparison of single and double outrigger, belt truss, and combined systems in a tall reinforced concrete building, including their performance under different soil conditions. This study addresses that requirement using ETABS analysis of a 50-storey building.

III. METHODOLOGY

3.1 Study objectives

- To evaluate the structural efficiency of four lateral-resisting configurations: standalone core wall, belt truss system, outrigger system, and combined outrigger-belt truss system.
- To compare displacement and drift variations across different soil conditions for the best-performing lateral load-resisting systems.

3.2 Building and material description

Table 1. Building and material description.

Parameter	Value
Geometry	Square plan
Location	Bhuj, Gujarat
Center-to-center distance between columns	5 m on each side
Number of stories	50
Storey height	3 m
Total building height	150 m
Concrete grade	M50
Reinforcement grade	Fe 550 and Fe 415
Steel grade for outriggers and belt trusses	Fe 345
Column sections	1000 mm x 1000 mm from base to 16th storey; 850 mm x 850 mm from 17th to 32nd storey; 700 mm x 700 mm from 33rd to 50th storey
Beam section	300 mm x 450 mm
Outrigger and belt truss section	ISMB 600
Shear wall thickness	500 mm
Slab thickness	175 mm
Unit weight of RCC	25 kN/m ³

3.3 Loading and analysis parameters

The slab dead load due to floor finish was taken as 1 kN/m². Live load was taken as 3 kN/m² on all floors and 1.5 kN/m² on the roof. Exterior wall loading was calculated for 12 mm glass with density 24.517 kN/m³, giving 0.8826 kN/m. Interior wall loading was calculated using 200 mm AAC block masonry with density 6.865 kN/m³, giving 4.12 kN/m.

Wind loading was assigned for Bhuj, Gujarat, with wind speed of 50 m/s according to IS 875 (Part 3):2015. Seismic analysis was carried out according to IS 1893 (Part 1):2016 for Zone V, with zone factor 0.36, importance factor 1.2, response reduction factor 3, soil type I, and 5% damping. The approximate fundamental period was 2.7 s, and dynamic analysis was therefore adopted.

Table 2. External pressure coefficients.

WIND ANGLE (θ)	Cpe FOR SURFACE	Cpe FOR SURFACE	Cpe FOR SURFACE	Cpe FOR SURFACE
WIND ANGLE (θ)	A	B	C	D
0	0.95	-1.25	-0.7	5
90	-0.7	-0.7	0.95	-1.25

Table 3. Final external pressure coefficients.

WIND ANGLE (θ)	Cpe FOR SURFACE	Cpe FOR SURFACE	Cpe FOR SURFACE	Cpe FOR SURFACE
WIND ANGLE (θ)	A	B	C	D
0	1.65	-1.95	-1.4	4.3
90	-1.4	-1.4	1.65	-1.95

3.4 Structural modeling in ETABS

ETABS 22 Ultimate was used for modeling and analysis. The model was prepared using Indian codes, metric SI units, defined material and section properties, fixed base supports, manually assigned live, floor, wall, wind, and seismic loads, response spectrum functions, P-delta effects, and dynamic load cases in the principal directions.

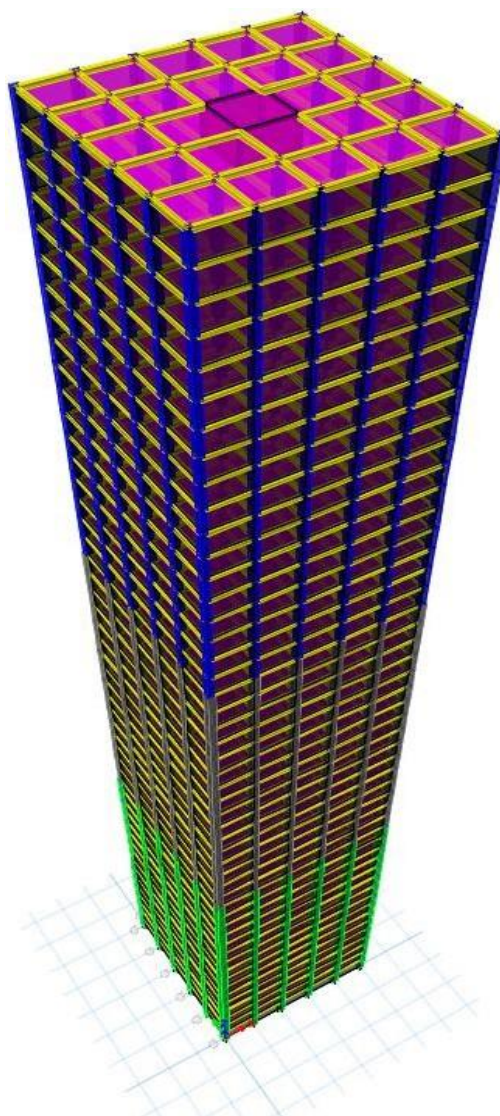


Figure 5. Three-dimensional ETABS model of the high-rise structure.

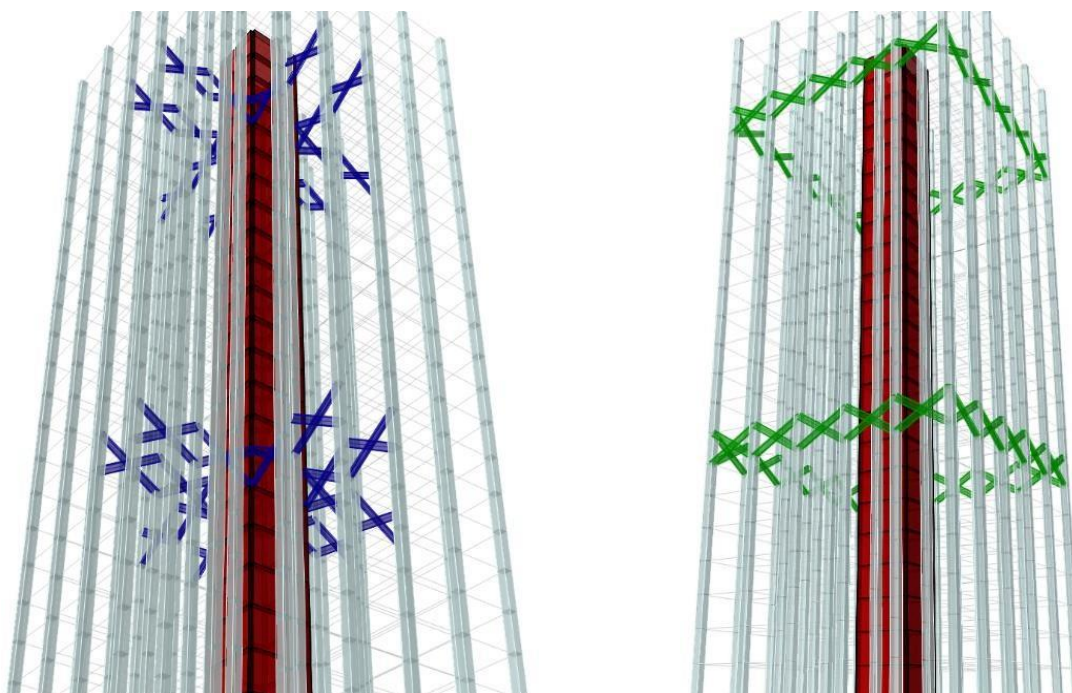


Figure 6. Outrigger and belt truss placed view.

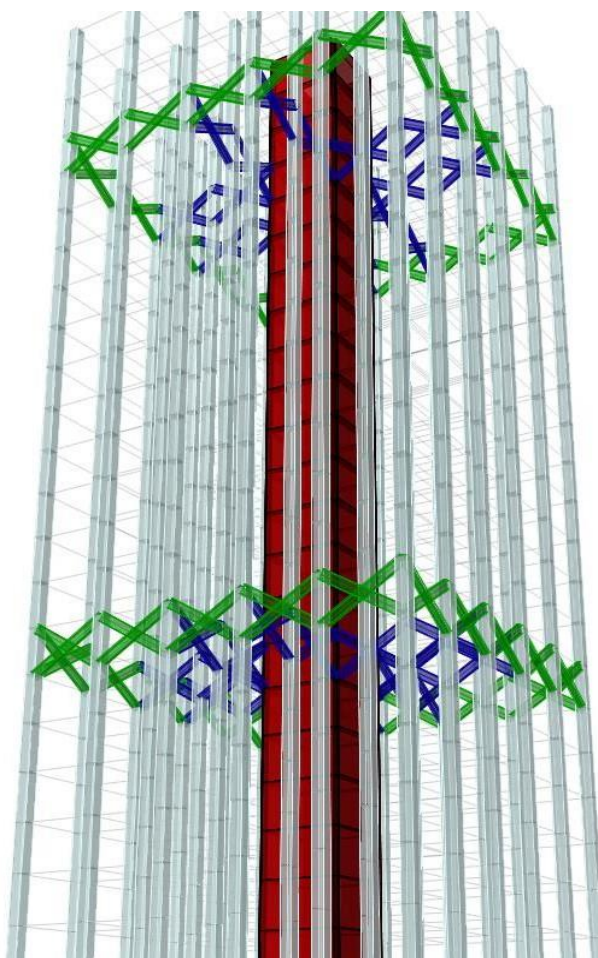


Figure 7. Combined outrigger with belt truss placed view.

Table 4. Structural models analyzed.

Sl.no	MODEL	TYPE
1	CONVENTIONAL	CANTILEVER
2	OUTRIGGER SYSTEM @ 5TH STORY	SINGLE OUTRIGGER SYSTEM AT VARYING LOCATION
3	OUTRIGGER SYSTEM @ 10TH STORY	SINGLE OUTRIGGER SYSTEM AT VARYING LOCATION
4	OUTRIGGER SYSTEM @ 15TH STORY	SINGLE OUTRIGGER SYSTEM AT VARYING LOCATION
5	OUTRIGGER SYSTEM @ 20TH STORY	SINGLE OUTRIGGER SYSTEM AT VARYING LOCATION
6	OUTRIGGER SYSTEM @ 25TH STORY	SINGLE OUTRIGGER SYSTEM AT VARYING LOCATION
7	OUTRIGGER SYSTEM @ 30TH STORY	SINGLE OUTRIGGER SYSTEM AT VARYING LOCATION
8	OUTRIGGER SYSTEM @ 35TH STORY	SINGLE OUTRIGGER SYSTEM AT VARYING LOCATION
9	OUTRIGGER SYSTEM @ 40TH STORY	SINGLE OUTRIGGER SYSTEM AT VARYING LOCATION
10	OUTRIGGER SYSTEM @ 45TH STORY	SINGLE OUTRIGGER SYSTEM AT VARYING LOCATION
11	OUTRIGGER SYSTEM @ 50TH STORY	SINGLE OUTRIGGER SYSTEM AT VARYING LOCATION
12	ONE @ 5TH STORY & OTHER @ 10TH STORY	TWO OUTRIGGERS AT VARYING LOCATION
13	ONE @ 5TH STORY & OTHER @ 15TH STORY	TWO OUTRIGGERS AT VARYING LOCATION
14	ONE @ 5TH STORY & OTHER @ 20TH STORY	TWO OUTRIGGERS AT VARYING LOCATION
15	ONE @ 5TH STORY & OTHER @ 25TH STORY	TWO OUTRIGGERS AT VARYING LOCATION
16	ONE @ 10TH STORY & OTHER @ 20TH STORY	
17	ONE @ 10TH STORY & OTHER @ 30TH STORY	
18	ONE @ 15TH STORY & OTHER @ 25TH STORY	
19	ONE @ 20TH STORY & OTHER @ 30TH STORY	
20	ONE @ 20TH STORY & OTHER @ 50TH STORY	
21	BELT TRUSS SYSTEM @ 10TH STORY	SINGLE BELT TRUSS SYSTEM @ VARYING LOCATION
22	BELT TRUSS SYSTEM @ 15TH STORY	SINGLE BELT TRUSS SYSTEM @ VARYING LOCATION
23	BELT TRUSS SYSTEM @ 20TH STORY	SINGLE BELT TRUSS SYSTEM @ VARYING LOCATION
24	BELT TRUSS SYSTEM @ 25TH STORY	SINGLE BELT TRUSS SYSTEM @ VARYING LOCATION
25	ONE BT@ 5TH STORY & OTHER @ 20TH STORY	TWO BELT TRUSS @ VARYING LOCATION
26	ONE BT@ 10TH STORY & OTHER @ 20TH STORY	TWO BELT TRUSS @ VARYING LOCATION
27	ONE BT@ 20TH STORY & OTHER @ 30TH STORY	TWO BELT TRUSS @ VARYING LOCATION
28	ONE COMBINED OUTRIGGER WITH BELT TRUSS @ 15TH STORY	ONE COMBINED OUTRIGGER WITH BELT TRUSS @ VARYING LOCATION
29	ONE COMBINED OUTRIGGER WITH BELT TRUSS @ 20TH	ONE COMBINED OUTRIGGER WITH BELT TRUSS @

Sl.no	MODEL	TYPE
	STORY	VARYING LOCATION
30	ONE COMBINED OUTRIGGER WITH BELT TRUSS @ 25TH STORY	ONE COMBINED OUTRIGGER WITH BELT TRUSS @ VARYING LOCATION
31	ONE COMBINED OUTRIGGER WITH BELT TRUSS @ 5TH STORY & OTHER @ 15TH STORY	TWO COMBINED OUTRIGGER WITH BELT TRUSS @ VARYING LOCATION
32	ONE COMBINED OUTRIGGER WITH BELT TRUSS @ 10TH STORY & OTHER @ 20TH STORY	TWO COMBINED OUTRIGGER WITH BELT TRUSS @ VARYING LOCATION
33	ONE COMBINED OUTRIGGER WITH BELT TRUSS @ 20TH STORY & OTHER @ 30TH STORY	TWO COMBINED OUTRIGGER WITH BELT TRUSS @ VARYING LOCATION

Table 5. Best-performing models compared under different soil conditions.

Sl.no	BEST PERFORMING MODELS	SOIL CONDITION
1	CONVENTIONAL MODEL WITH CORE SHEAR WALL	SOIL TYPE I (HARD SOIL)
2	OUTRIGGER SYSTEM @ 20TH STORY	SOIL TYPE I (HARD SOIL)
3	ONE @ 10TH STORY & OTHER @ 20TH STORY	
4	BELT TRUSS SYSTEM @ 20TH STORY	
5	ONE BT@ 10TH STORY & OTHER @ 20TH STORY	
6	ONE COMBINED OUTRIGGER WITH BELT TRUSS @ 20TH STORY	
7	ONE COMBINED OUTRIGGER WITH BELT TRUSS @ 10TH STORY & OTHER @ 20TH STORY	
8	CONVENTIONAL MODEL WITH CORE SHEAR WALL	SOIL TYPE II (MEDIUM SOIL)
9	OUTRIGGER SYSTEM @ 20TH STORY	SOIL TYPE II (MEDIUM SOIL)
10	ONE @ 10TH STORY & OTHER @ 20TH STORY	SOIL TYPE II (MEDIUM SOIL)
11	BELT TRUSS SYSTEM @ 20TH STORY	SOIL TYPE II (MEDIUM SOIL)
12	ONE BT@ 10TH STORY & OTHER @ 20TH STORY	SOIL TYPE II (MEDIUM SOIL)
13	ONE COMBINED OUTRIGGER WITH BELT TRUSS @ 20TH STORY	SOIL TYPE II (MEDIUM SOIL)
14	ONE COMBINED OUTRIGGER WITH BELT TRUSS @ 10TH STORY & OTHER @ 20TH STORY	SOIL TYPE II (MEDIUM SOIL)
15	CONVENTIONAL MODEL WITH CORE SHEAR WALL	SOIL TYPE III (SOFT SOIL)
16	OUTRIGGER SYSTEM @ 20TH	SOIL TYPE III (SOFT SOIL)

Sl.no	BEST PERFORMING MODELS	SOIL CONDITION
	STORY	
17	ONE @ 10TH STORY & OTHER @ 20TH STORY	SOIL TYPE III (SOFT SOIL)
18	BELT TRUSS SYSTEM @ 20TH STORY	SOIL TYPE III (SOFT SOIL)
19	ONE BT@ 10TH STORY & OTHER @ 20TH STORY	SOIL TYPE III (SOFT SOIL)
20	ONE COMBINED OUTRIGGER WITH BELT TRUSS @ 20TH STORY	SOIL TYPE III (SOFT SOIL)
21	ONE COMBINED OUTRIGGER WITH BELT TRUSS @ 10TH STORY & OTHER @ 20TH STORY	SOIL TYPE III (SOFT SOIL)

IV. ANALYSIS AND RESULTS

A total of 47 models were analyzed using different lateral load-resisting configurations. Because the building has a square configuration, no major variation was observed between the X and Y directions under seismic and wind loading. The results were evaluated mainly using maximum storey displacement and maximum storey drift.

4.1 Conventional core wall model

The conventional model with core shear wall was used as the baseline model for comparison.

Table 6. Conventional cantilever model results.

DESCRIPTION	MAX STORY DISP (mm)	MAX STORY DISP (mm)	MAX STORY DISP (mm)	MAX STORY DISP (mm)	MAX STORY DRIFT	MAX STORY DRIFT
DESCRIPTION	DUE TO SEISMIC	DUE TO SEISMIC	DUE TO WIND	DUE TO WIND	DUE TO SEISMIC	DUE TO SEISMIC
DESCRIPTION	R.Sx	R.Sy	Wx (0°)	Wy (90°)	R.Sx	R.Sy
CONVENTIONAL MODEL WITH CORE SHEAR WALL	255.14	255.14	60.084	60.084	0.002244	0.002244

4.2 Single outrigger system

Ten models were analyzed by placing a single outrigger system at different locations at every fifth storey. The results show that the outrigger at the 20th storey gave the best overall performance among the single-outrigger alternatives.

Table 7. Displacement and drift values for single outrigger systems at varying locations.

DESCRIPTION	MAX STORY DISP (mm)	MAX STORY DISP (mm)	MAX STORY DRIFT
SINGLE OUTRIGGER SYSTEM AT VARYING LOCATION	DUE TO SEISMIC	DUE TO WIND	DUE TO SEISMIC
SINGLE OUTRIGGER SYSTEM AT VARYING LOCATION	R.Sx or R.Sy	Wx (0°) or Wx (90°)	R.Sx or R.Sy
CONVENTIONAL MODEL	255.14	60.08	0.002244
OUTRIGGER SYSTEM @ 5TH STORY	229.47	57.16	0.002063
OUTRIGGER SYSTEM @ 10TH STORY	220.78	53.91	0.002006

DESCRIPTION	MAX STORY DISP (mm)	MAX STORY DISP (mm)	MAX STORY DRIFT
OUTRIGGER SYSTEM @ 15TH STORY	221.36	52.24	0.001969
OUTRIGGER SYSTEM @ 20TH STORY	220.52	52.14	0.001880
OUTRIGGER SYSTEM @ 25TH STORY	222.66	52.83	0.002006
OUTRIGGER SYSTEM @ 30TH STORY	222.95	53.91	0.002123
OUTRIGGER SYSTEM @ 35TH STORY	234.08	55.26	0.002193
OUTRIGGER SYSTEM @ 40TH STORY	239.20	56.60	0.002222
OUTRIGGER SYSTEM @ 45TH STORY	244.28	57.77	0.002238
OUTRIGGER SYSTEM @ 50TH STORY	248.12	58.64	0.002240

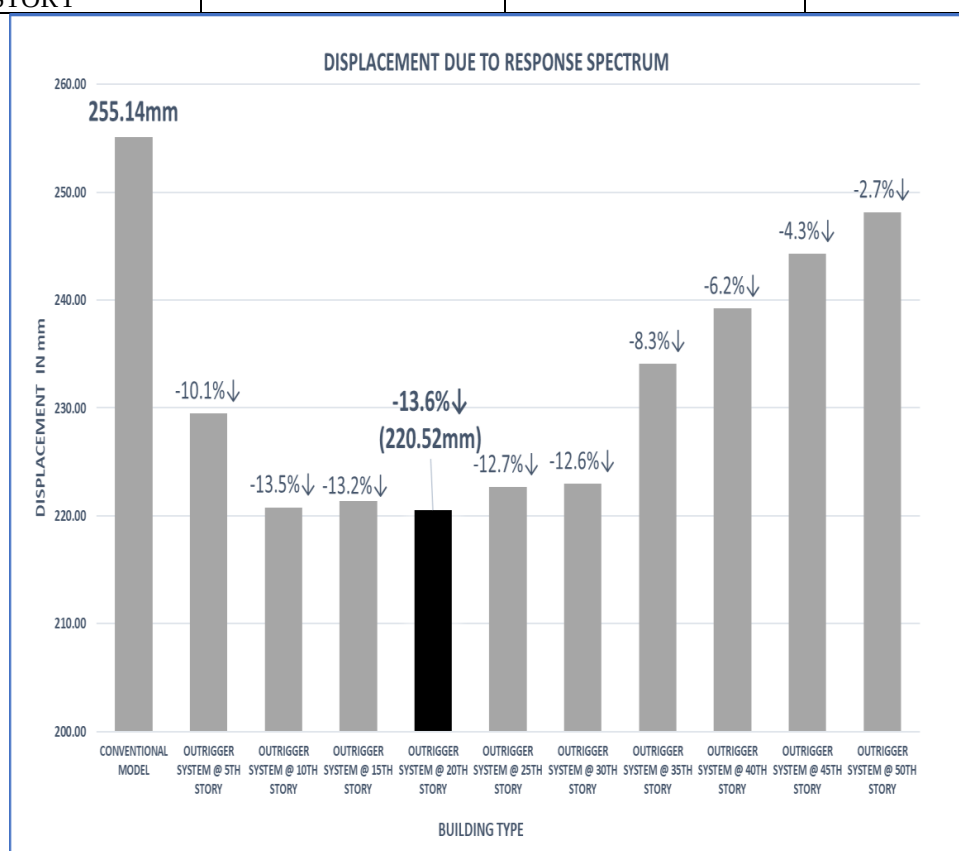


Figure 8. Percentage reduction in displacement due to response spectrum loading for single outrigger systems.

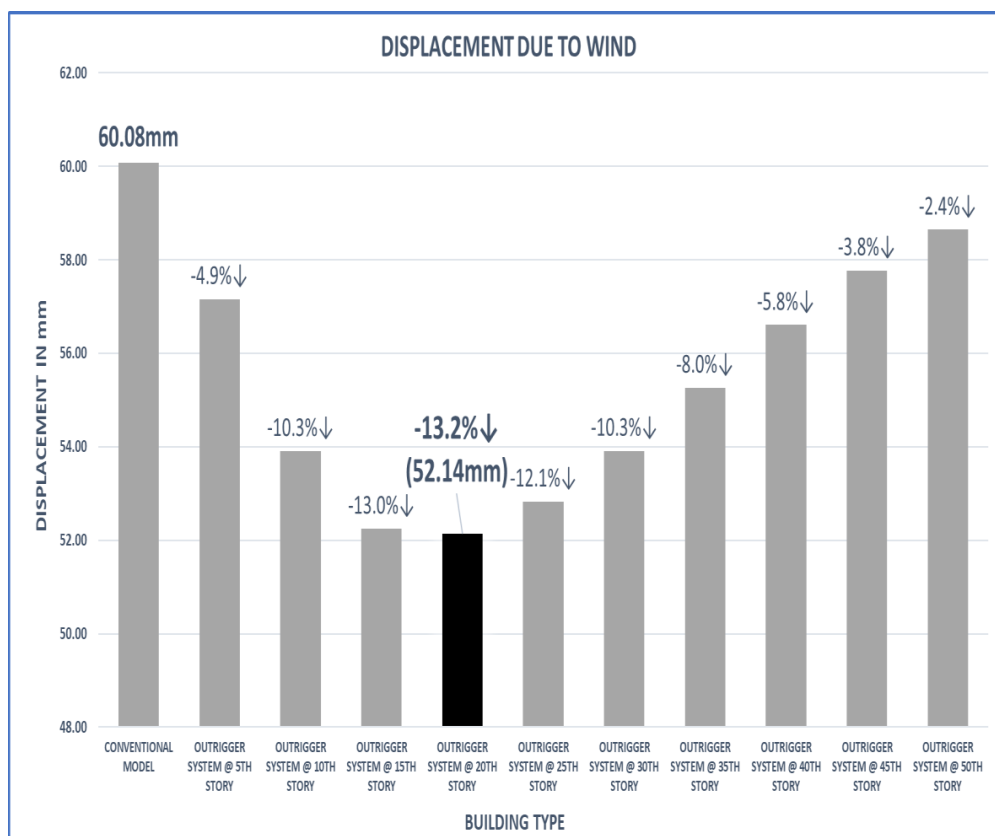


Figure 9. Percentage reduction in displacement due to wind loading for single outrigger systems.

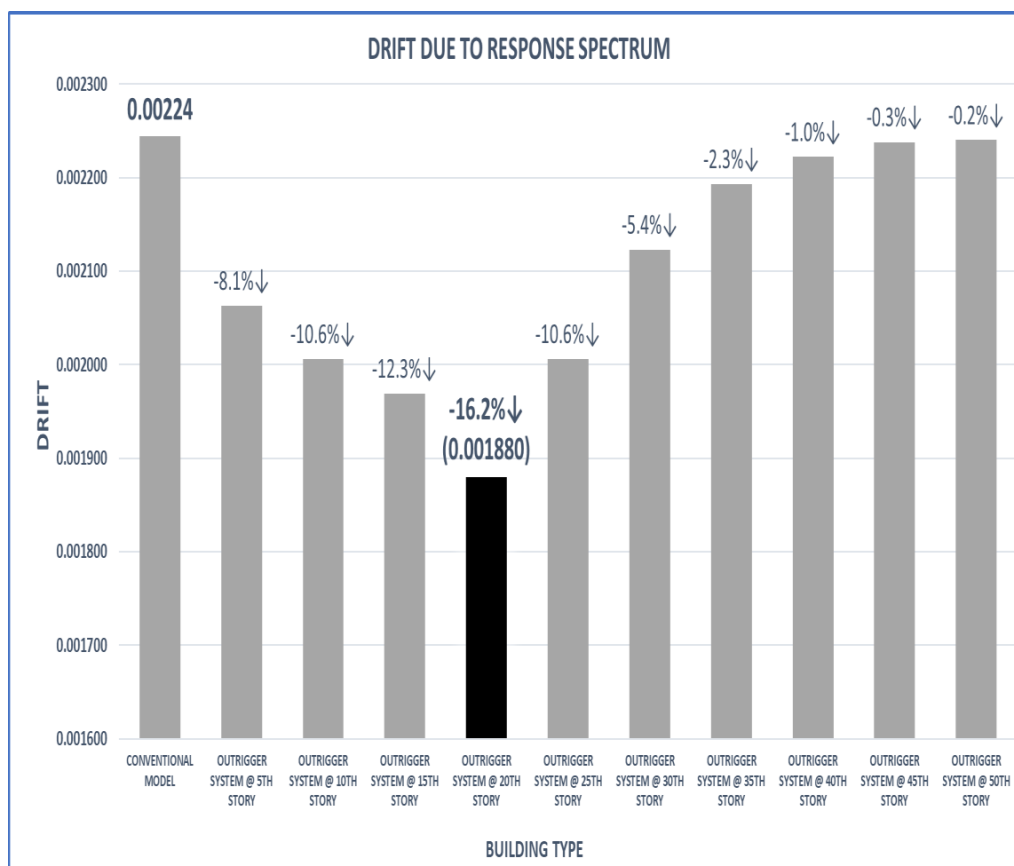


Figure 10. Percentage reduction in drift due to response spectrum loading for single outrigger systems.

4.3 Double outrigger system

Nine models were analyzed using two outriggers at different positions. The model with one outrigger at the 10th storey and the other at the 20th storey provided the best overall response for displacement and drift.

Table 8. Displacement and drift values for double outrigger systems at varying locations.

DESCRIPTION	MAX STORY DISP (mm)	MAX STORY DISP (mm)	MAX STORY DRIFT
TWO OUTRIGGERS AT VARYING LOCATION	DUE TO SEISMIC	DUE TO WIND	DUE TO SEISMIC
TWO OUTRIGGERS AT VARYING LOCATION	R.Sx or R.Sy	Wx (0°) or Wx (90°)	R.Sx or R.Sy
CONVENTIONAL MODEL	255.14	60.08	0.002244
ONE @ 5TH STORY & OTHER @ 10TH STORY	202.029	52.24	0.001873
ONE @ 5TH STORY & OTHER @ 15TH STORY	201.098	50.16	0.001841
ONE @ 5TH STORY & OTHER @ 20TH STORY	200.346	49.71	0.001759
ONE @ 5TH STORY & OTHER @ 25TH STORY	203.994	50.18	0.001822
ONE @ 10TH STORY & OTHER @ 20TH STORY	195.427	47.52	0.001773
ONE @ 10TH STORY & OTHER @ 30TH STORY	198.702	48.25	0.001851
ONE @15TH STORY & OTHER @ 25TH STORY	200.504	47.74	0.001723
ONE @ 20TH STORY & OTHER @ 30TH STORY	204.650	47.64	0.001790
ONE @ 20TH STORY & OTHER @ 50TH STORY	215.910	50.91	0.001865

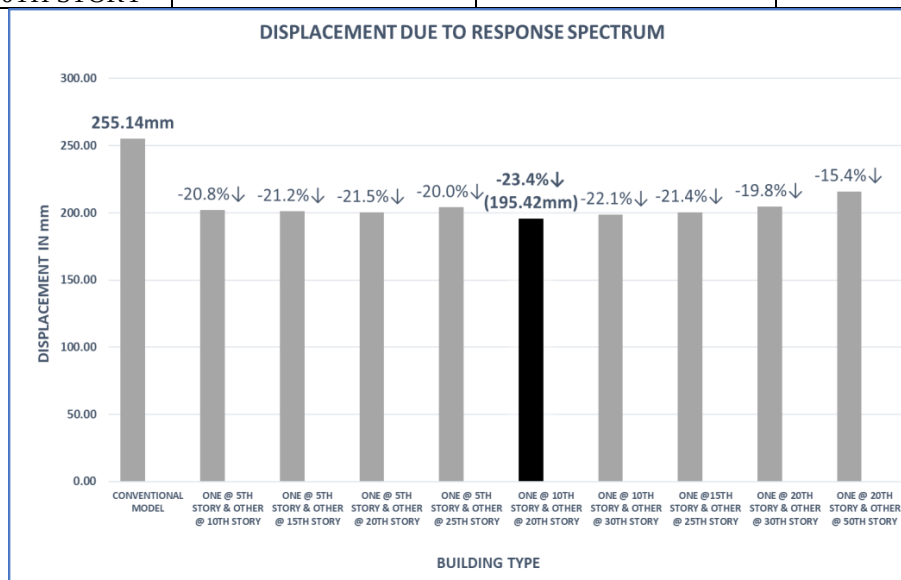


Figure 11. Percentage reduction in displacement due to response spectrum loading for double outrigger systems.

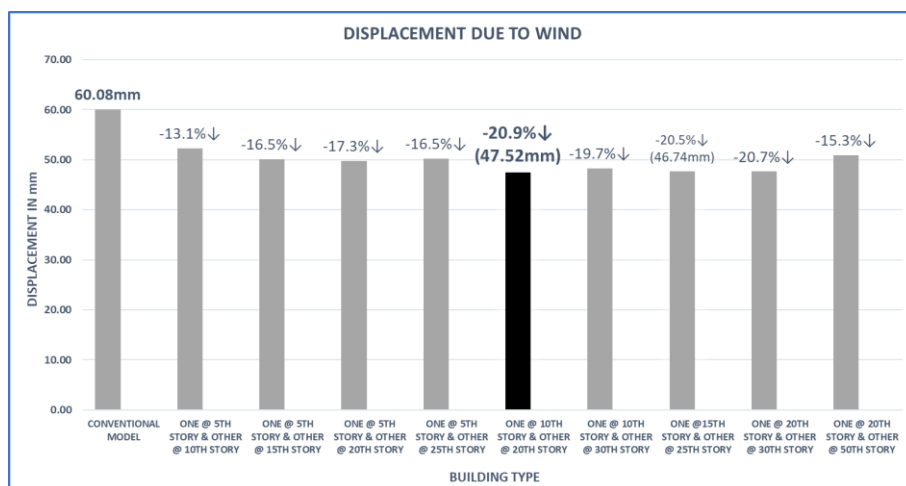


Figure 12. Percentage reduction in displacement due to wind loading for double outrigger systems.

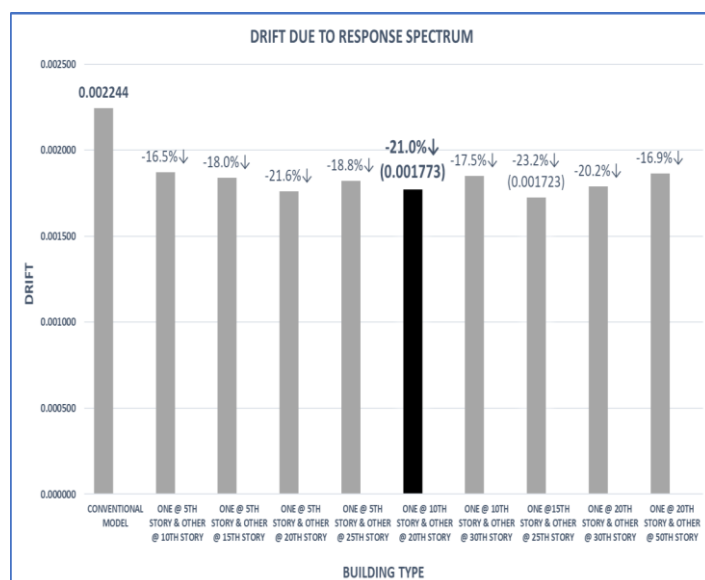


Figure 13. Percentage reduction in drift due to response spectrum loading for double outrigger systems.

4.4 Single belt truss system

Four models were analyzed using a single belt truss at different locations. The belt truss at the 20th storey achieved the best performance among the single belt truss alternatives.

Table 9. Displacement and drift values for single belt truss systems at varying locations.

DESCRIPTION	MAX STORY DISP (mm)	MAX STORY DISP (mm)	MAX STORY DRIFT
SINGLE BELT TRUSS SYSTEM @ VARYING LOCATION	DUE TO SEISMIC	DUE TO WIND	DUE TO SEISMIC
SINGLE BELT TRUSS SYSTEM @ VARYING LOCATION	R.Sx or R.Sy	Wx (0°) or Wx (90°)	R.Sx or R.Sy
CONVENTIONAL MODEL	255.14	60.084	0.002244
BELT TRUSS SYSTEM @ 10TH STORY	227.701	54.989	0.002052
BELT TRUSS SYSTEM	227.52	53.536	0.002007

DESCRIPTION	MAX STORY DISP (mm)	MAX STORY DISP (mm)	MAX STORY DRIFT
@ 15TH STORY			
BELT TRUSS SYSTEM @ 20TH STORY	227.492	53.378	0.001917
BELT TRUSS SYSTEM @ 25TH STORY	230.702	53.849	0.002041

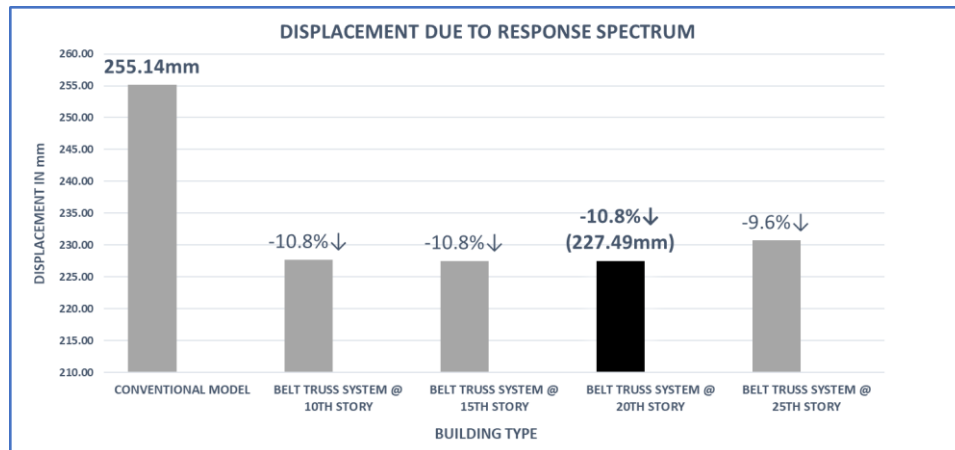


Figure 14. Percentage reduction in displacement due to response spectrum loading for single belt truss systems.

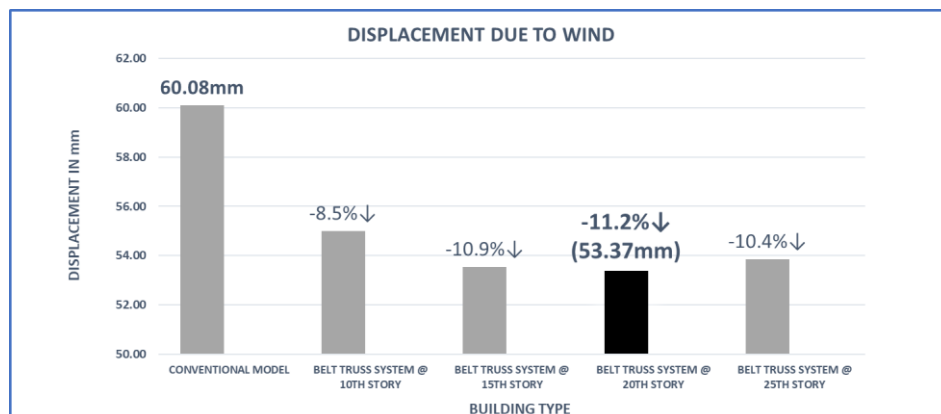


Figure 15. Percentage reduction in displacement due to wind loading for single belt truss systems.

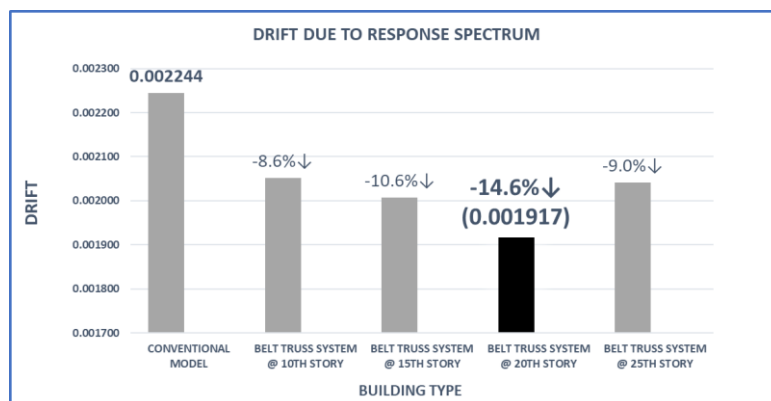


Figure 16. Percentage reduction in drift due to response spectrum loading for single belt truss systems.

4.5 Double belt truss system

Three models were analyzed with two belt trusses. The model with belt trusses at the 10th and 20th stories showed the best performance for the considered parameters.

Table 10. Displacement and drift values for two belt truss systems at varying locations.

DESCRIPTION	MAX STORY DISP (mm)	MAX STORY DISP (mm)	MAX STORY DRIFT
TWO BELT TRUSS @ VARYING LOCATION	DUE TO SEISMIC	DUE TO WIND	DUE TO SEISMIC
TWO BELT TRUSS @ VARYING LOCATION	R.Sx or R.Sy	Wx (0°) or Wx (90°)	R.Sx or R.Sy
CONVENTIONAL MODEL	255.14	60.08	0.002244
ONE BT@ 5TH STORY & OTHER @ 20TH STORY	209.792	51.346	0.001817
ONE BT@ 10TH STORY & OTHER @ 20TH STORY	205.3	49.348	0.001825
ONE BT@ 20TH STORY & OTHER @ 30TH STORY	211.11	49.184	0.001843

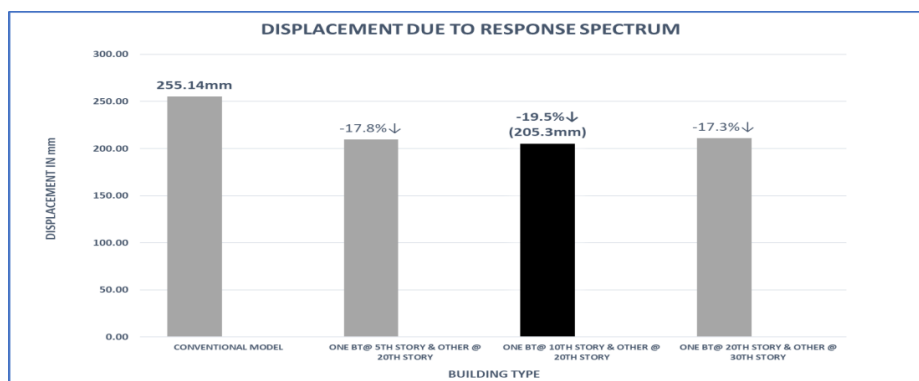


Figure 17. Percentage reduction in displacement due to response spectrum loading for two belt truss systems.

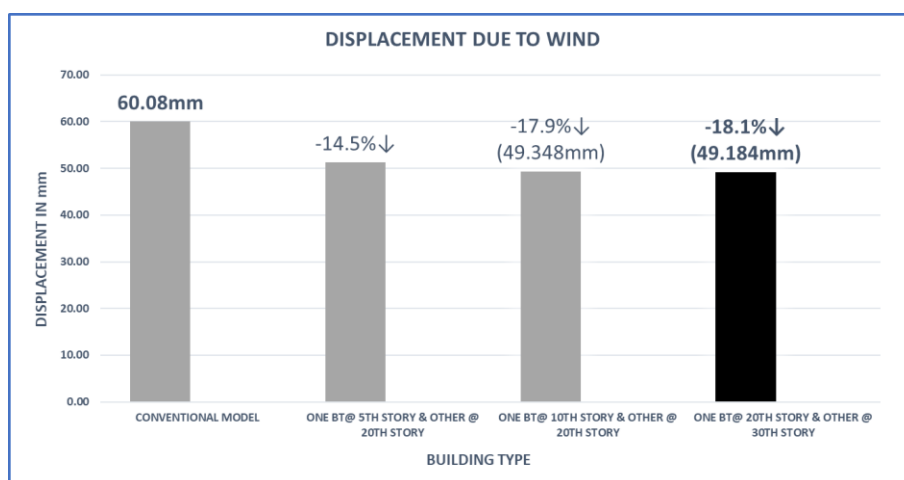


Figure 18. Percentage reduction in displacement due to wind loading for two belt truss systems.

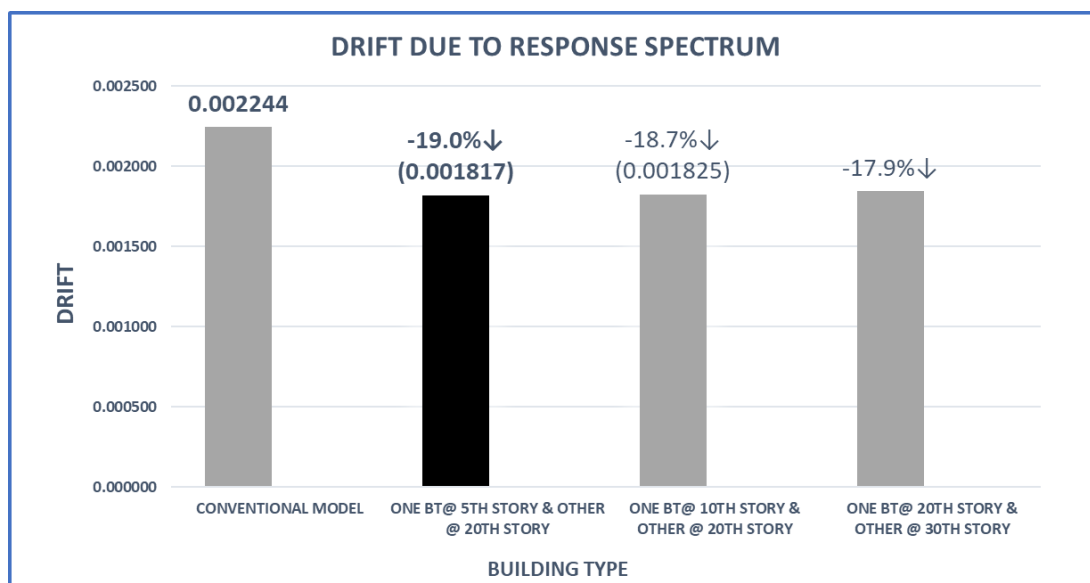


Figure 19. Percentage reduction in drift due to response spectrum loading for two belt truss systems.

4.6 Single combined outrigger with belt truss

Three models were analyzed using a single combined outrigger with belt truss system. The combined system placed at the 20th storey showed the best performance among the single combined alternatives.

Table 11. Displacement and drift values for one combined outrigger with belt truss system at varying locations.

DESCRIPTION	MAX STORY DISP (mm)	MAX STORY DISP (mm)	MAX STORY DRIFT
ONE COMBINED OUTRIGGER WITH BELT TRUSS @ VARYING LOCATION	DUE TO SEISMIC	DUE TO WIND	DUE TO SEISMIC
ONE COMBINED OUTRIGGER WITH BELT TRUSS @ VARYING LOCATION	R.Sx or R.Sy	Wx (0°) or Wx (90°)	R.Sx or R.Sy
CONVENTIONAL MODEL	255.14	60.08	0.002244
ONE COMBINED OUTRIGGER WITH BELT TRUSS @ 15TH STORY	212.732	49.785	0.001901
ONE COMBINED OUTRIGGER WITH BELT TRUSS @ 20TH STORY	211.823	49.623	0.001816
ONE COMBINED OUTRIGGER WITH BELT TRUSS @ 25TH STORY	216.905	50.4	0.001951

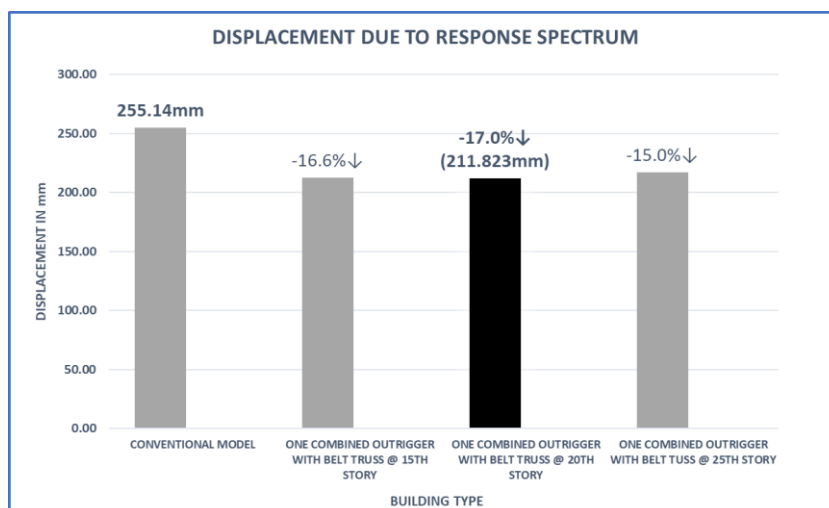


Figure 20. Percentage reduction in displacement due to response spectrum loading for one combined outrigger with belt truss.

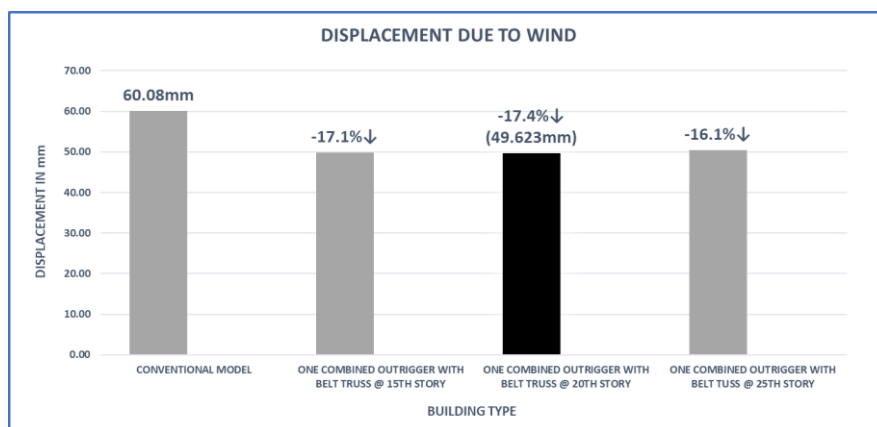


Figure 21. Percentage reduction in displacement due to wind loading for one combined outrigger with belt truss.

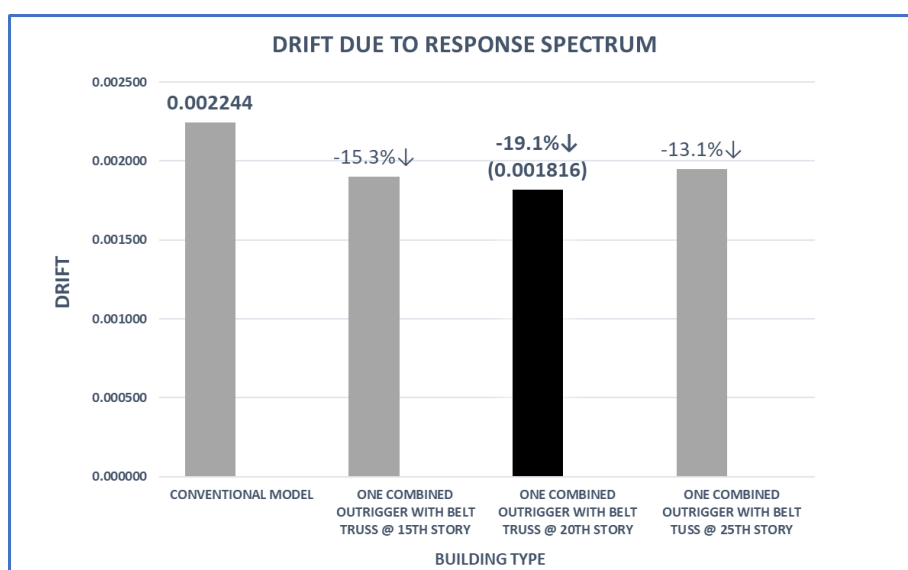


Figure 22. Percentage reduction in drift due to response spectrum loading for one combined outrigger with belt truss.

4.7 Double combined outrigger with belt truss

Three models were evaluated using double combined outrigger and belt truss systems. The arrangement with systems at the 10th and 20th stories gave the best overall performance.

Table 12. Displacement and drift values for two combined outrigger with belt truss systems at varying locations.

DESCRIPTION	MAX STORY DISP (mm)	MAX STORY DISP (mm)	MAX STORY DRIFT
TWO COMBINED OUTRIGGER WITH BELT TRUSS @ VARYING LOCATION	DUE TO SEISMIC	DUE TO WIND	DUE TO SEISMIC
TWO COMBINED OUTRIGGER WITH BELT TRUSS @ VARYING LOCATION	R.Sx or R.Sy	Wx (0°) or Wx (90°)	R.Sx or R.Sy
CONVENTIONAL MODEL	255.14	60.08	0.002244
ONE COMBINED OUTRIGGER WITH BELT TRUSS @ 5TH STORY & OTHER @ 15TH STORY	182.681	47.142	0.001722
ONE COMBINED OUTRIGGER WITH BELT TRUSS @ 10TH STORY & OTHER @ 20TH STORY	176.579	43.526	0.001677
ONE COMBINED OUTRIGGER WITH BELT TRUSS @ 20TH STORY & OTHER @ 30TH STORY	188.82	43.696	0.001705

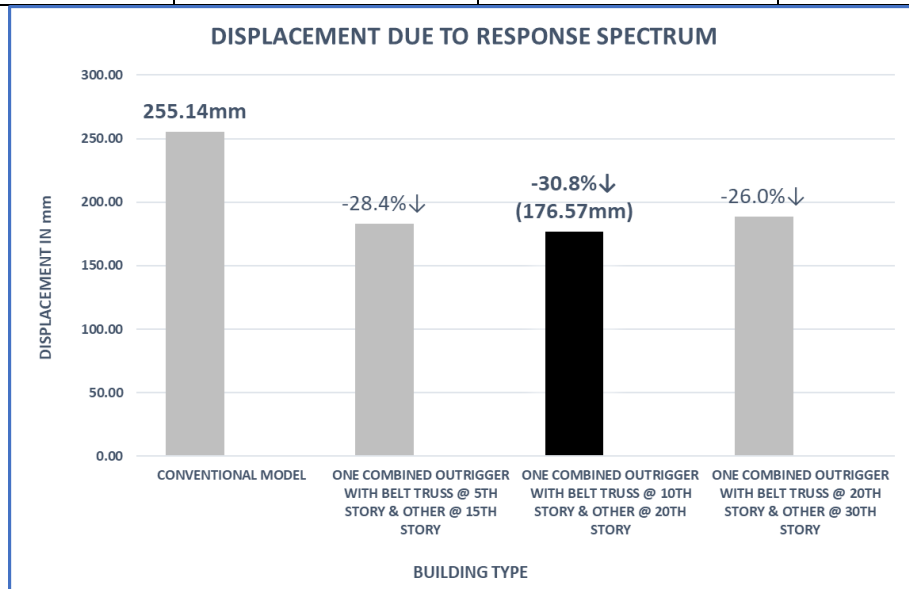


Figure 23. Percentage reduction in displacement due to response spectrum loading for two combined outrigger with belt truss systems.

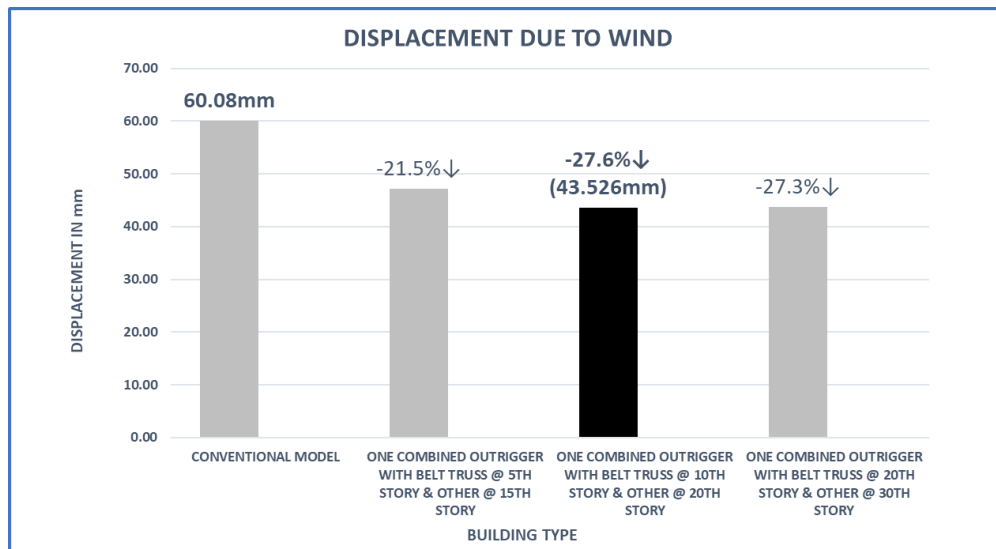


Figure 24. Percentage reduction in displacement due to wind loading for two combined outrigger with belt truss systems.

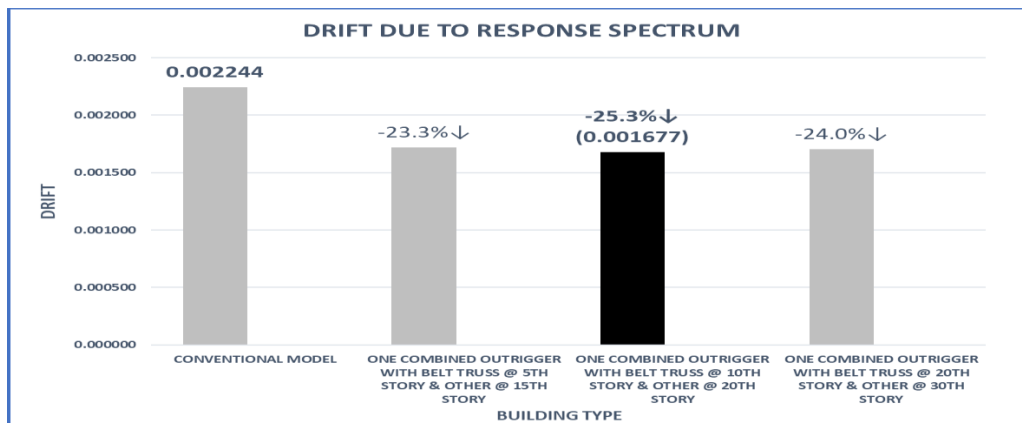


Figure 25. Percentage reduction in drift due to response spectrum loading for two combined outrigger with belt truss systems.

4.8 Comparison under soil conditions

The best-performing systems from each category were compared under hard, medium, and soft soil conditions. In all soil types, the double combined outrigger with belt truss system placed at the 10th and 20th stories provided the minimum deflection and storey drift.

Table 13. Comparison of displacement and drift values under hard soil condition.

DESCRIPTION	MAX STORY DISP (mm)	MAX STORY DISP (mm)	MAX STORY DRIFT
SOIL TYPE I (HARD SOIL)	DUE TO SEISMIC	DUE TO WIND	DUE TO SEISMIC
SOIL TYPE I (HARD SOIL)	R.Sx or R.Sy	Wx (0°) or Wx (90°)	R.Sx or R.Sy
CONVENTIONAL MODEL WITH CORE SHEAR WALL	255.140	60.084	0.0022440
OUTRIGGER SYSTEM @ 20TH STORY	222.520	52.144	0.0018800
ONE @ 10TH STORY &	195.427	47.520	0.0017730

DESCRIPTION	MAX STORY DISP (mm)	MAX STORY DISP (mm)	MAX STORY DRIFT
OTHER @ 20TH STORY			
BELT TRUSS SYSTEM @ 20TH STORY	227.492	53.378	0.0019170
ONE BT@ 10TH STORY & OTHER @ 20TH STORY	205.300	49.348	0.0018250
ONE COMBINED OUTRIGGER WITH BELT TRUSS @ 20TH STORY	211.823	49.623	0.0018160
ONE COMBINED OUTRIGGER WITH BELT TRUSS @ 10TH STORY & OTHER @ 20TH STORY	176.579	43.811	0.0016770

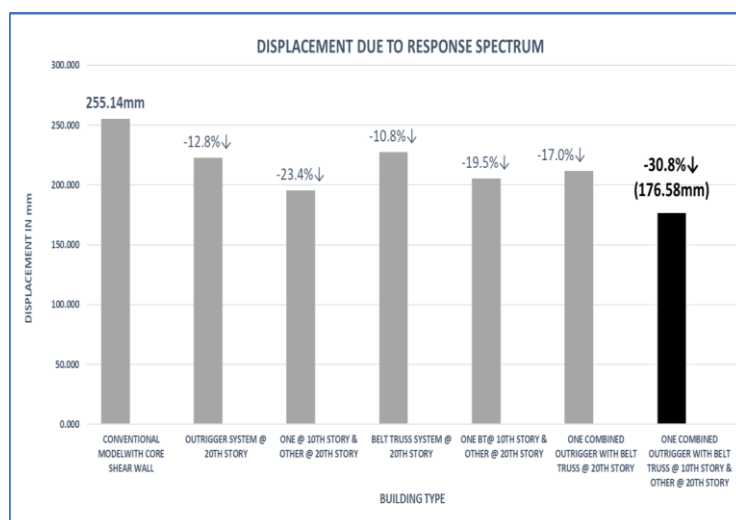


Figure 26. Percentage reduction in displacement due to response spectrum loading for best-performing models under hard soil.

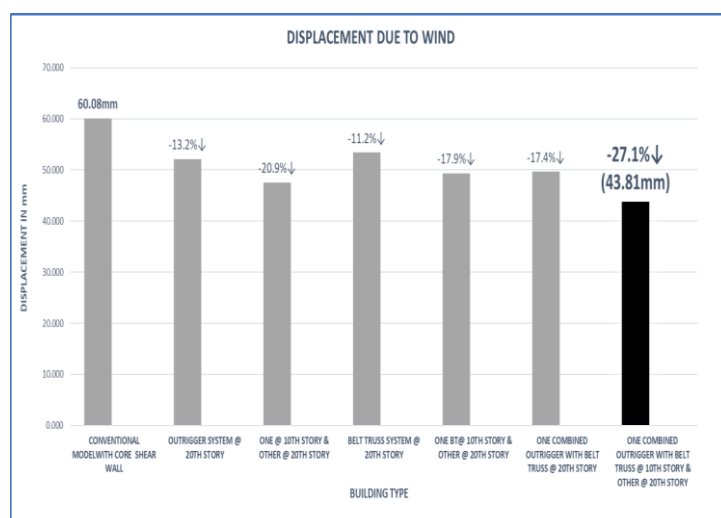


Figure 27. Percentage reduction in displacement due to wind loading for best-performing models under hard soil.

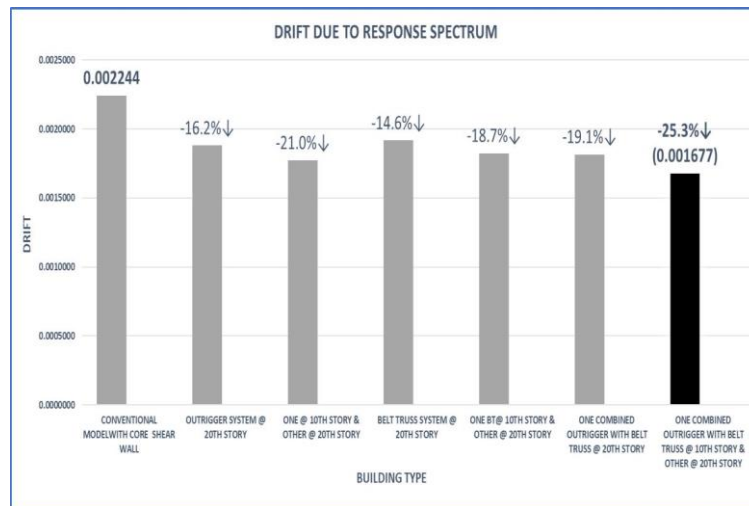


Figure 28. Percentage reduction in drift due to response spectrum loading for best-performing models under hard soil.

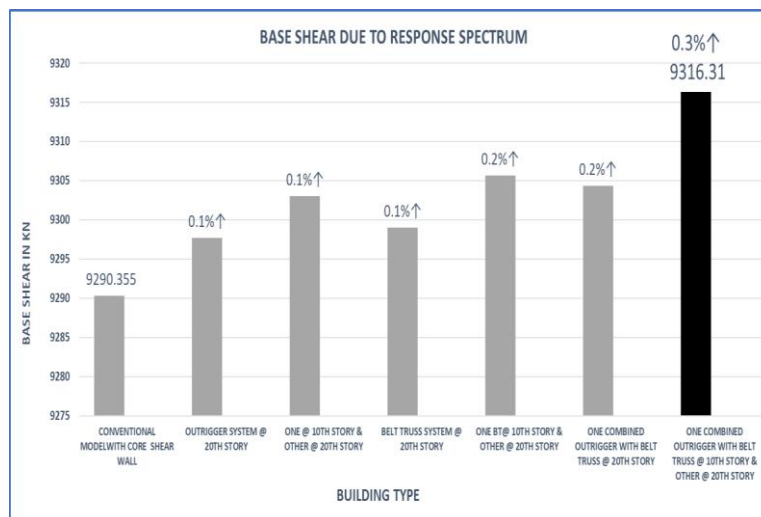


Figure 29. Percentage increase in base shear due to response spectrum loading for best-performing models under hard soil.

Table 14. Comparison of displacement and drift values under medium soil condition.

DESCRIPTION	MAX STORY DISP (mm)	MAX STORY DISP (mm)	MAX STORY DRIFT
SOIL TYPE II (MEDIUM SOIL)	DUE TO SEISMIC	DUE TO WIND	DUE TO SEISMIC
SOIL TYPE II (MEDIUM SOIL)	R.Sx or R.Sy	Wx (0°) or	R.Sx or R.Sy
SOIL TYPE II (MEDIUM SOIL)	R.Sx or R.Sy	Wx (90°)	R.Sx or R.Sy
CONVENTIONAL MODEL WITH CORE SHEAR WALL	270.432	60.084	0.0023760
OUTRIGGER SYSTEM @ 20TH STORY	237.105	52.143	0.0020000
ONE @ 10TH STORY & OTHER @ 20TH STORY	206.469	47.520	0.0018690
BELT TRUSS SYSTEM	242.527	53.378	0.0020380

DESCRIPTION	MAX STORY DISP (mm)	MAX STORY DISP (mm)	MAX STORY DRIFT
@ 20TH STORY			
ONE BT@ 10TH STORY & OTHER @ 20TH STORY	216.858	49.348	0.0019260
ONE COMBINED OUTRIGGER WITH BELT TRUSS @ 20TH STORY	226.301	49.623	0.0019360
ONE COMBINED OUTRIGGER WITH BELT TRUSS @ 10TH STORY & OTHER @ 20TH STORY	186.360	43.811	0.0017660

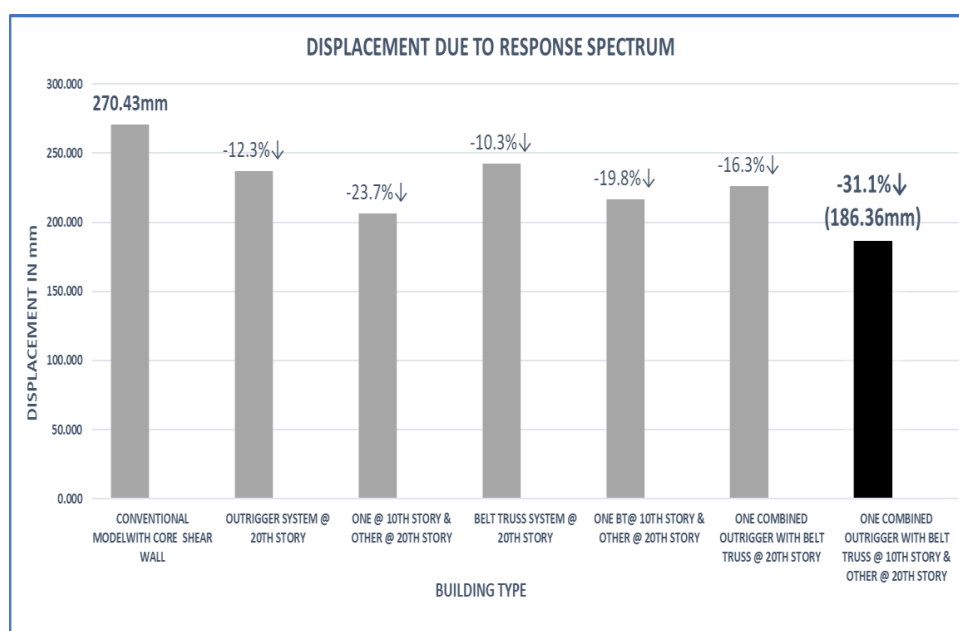


Figure 30. Percentage reduction in displacement due to response spectrum loading for best-performing models under medium soil.

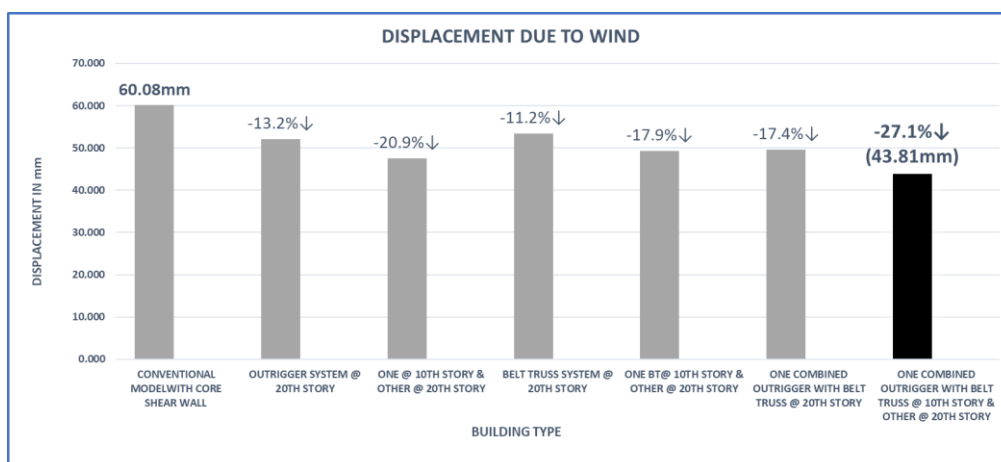


Figure 31. Percentage reduction in displacement due to wind loading for best-performing models under medium soil.

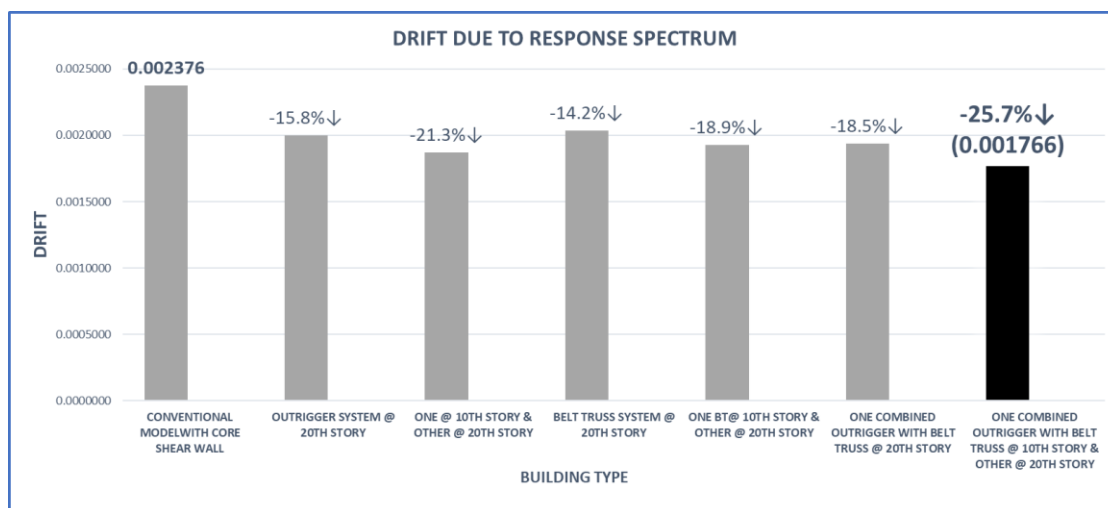


Figure 32. Percentage reduction in drift due to response spectrum loading for best-performing models under medium soil.

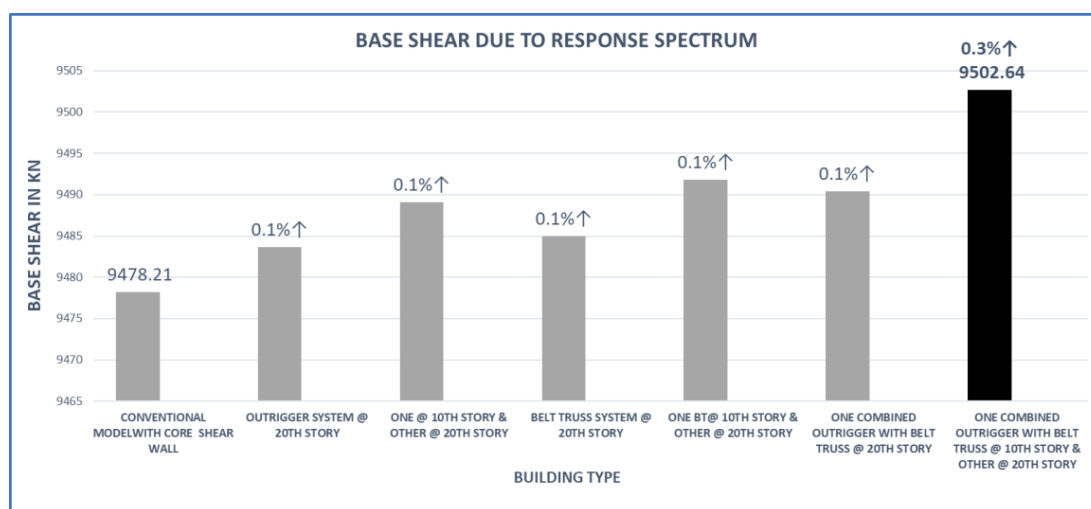


Figure 33. Percentage increase in base shear due to response spectrum loading for best-performing models under medium soil.

Table 15. Comparison of displacement and drift values under soft soil condition.

DESCRIPTION	MAX STORY DISP (mm)	MAX STORY DISP (mm)	MAX STORY DRIFT
SOIL TYPE III (SOFT SOIL)	DUE TO SEISMIC	DUE TO WIND	DUE TO SEISMIC
SOIL TYPE III (SOFT SOIL)	R.Sx or R.Sy	Wx (0°) or	R.Sx or R.Sy
SOIL TYPE III (SOFT SOIL)	R.Sx or R.Sy	Wx (90°)	R.Sx or R.Sy
CONVENTIONAL MODEL WITH CORE SHEAR WALL	340.340	60.084	0.0029870
OUTRIGGER SYSTEM @ 20TH STORY	298.819	52.143	0.0025170
ONE @ 10TH STORY & OTHER @ 20TH STORY	259.825	47.520	0.0023480
BELT TRUSS SYSTEM @ 20TH STORY	305.544	53.378	0.0025640

DESCRIPTION	MAX STORY DISP (mm)	MAX STORY DISP (mm)	MAX STORY DRIFT
ONE BT@ 10TH STORY & OTHER @ 20TH STORY	272.870	49.348	0.0024190
ONE COMBINED OUTRIGGER WITH BELT TRUSS @ 20TH STORY	285.503	49.623	0.0024380
ONE COMBINED OUTRIGGER WITH BELT TRUSS @ 10TH STORY & OTHER @ 20TH STORY	234.320	43.811	0.0022170

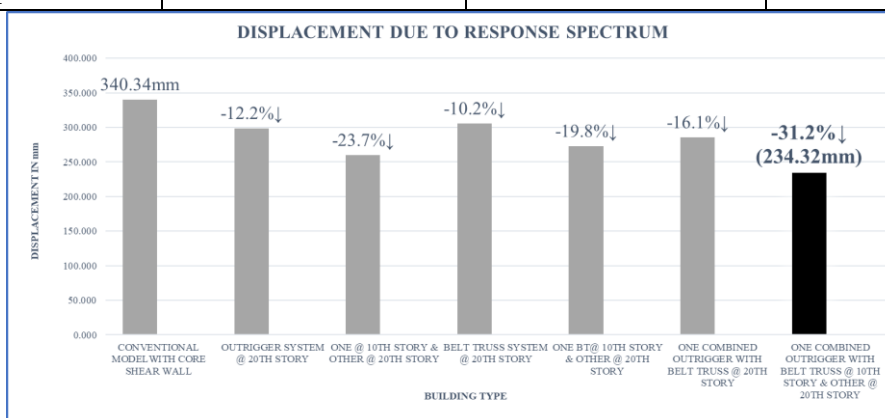


Figure 34. Percentage reduction in displacement due to response spectrum loading for best-performing models under soft soil.

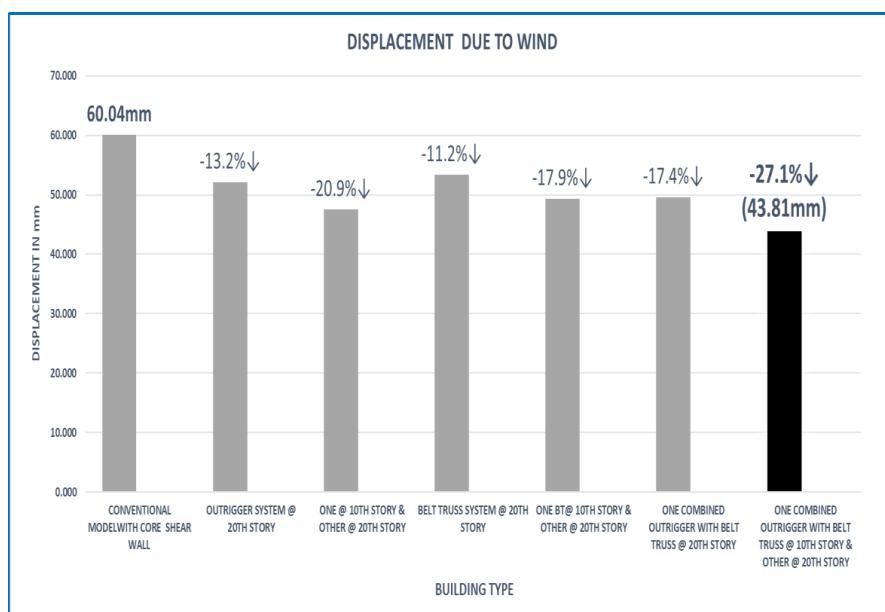


Figure 35. Percentage reduction in displacement due to wind loading for best-performing models under soft soil.

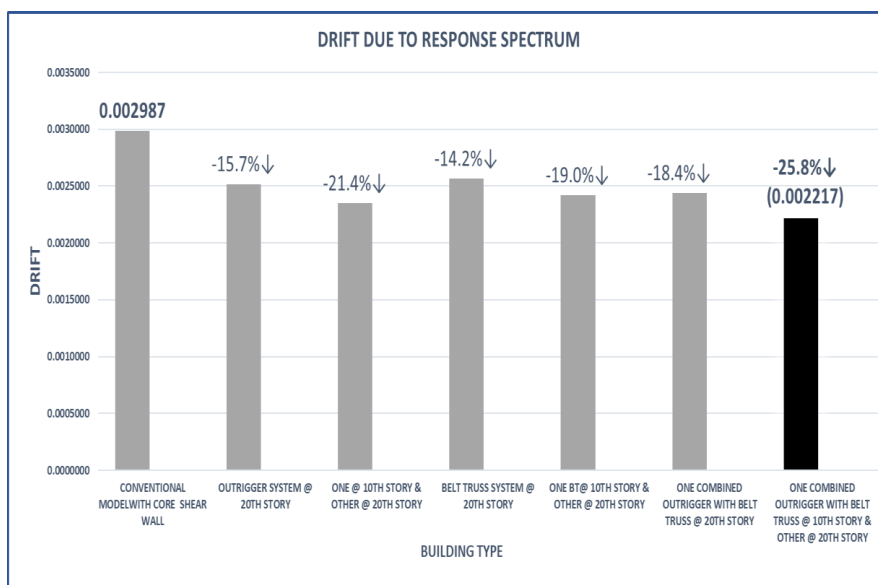


Figure 36. Percentage reduction in drift due to response spectrum loading for best-performing models under soft soil.

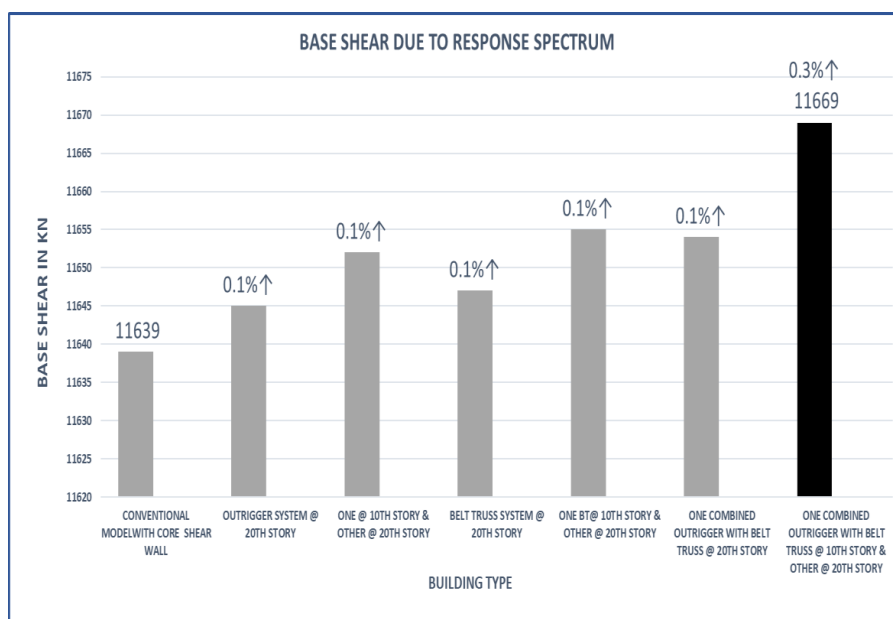


Figure 37. Percentage increase in base shear due to response spectrum loading for best-performing models under soft soil.

4.9 Discussion

The response trends indicate that the optimum position of the lateral load-resisting system is critical. A single outrigger at the 20th storey, a double outrigger at the 10th and 20th stories, a single belt truss at the 20th storey, and a double belt truss at the 10th and 20th stories were found to be the strongest configurations within their respective categories. The combined outrigger-belt truss system improved stiffness more effectively than using either system alone. The double combined system at the 10th and 20th stories consistently produced the lowest displacement and drift under seismic and wind loading. The soil-condition comparison also shows that displacement and drift increase from hard soil to soft soil, while the relative superiority of the double combined system remains consistent.

V. CONCLUSION AND FUTURE SCOPE

5.1 Conclusion

- The use of lateral load-resisting systems significantly reduces structural displacement and storey drift when the systems are placed at optimum locations.
- For the single outrigger system, the maximum displacement reduction was 13.6% under response spectrum loading and 13.2% under wind loading when the outrigger was placed at the 20th storey. The maximum drift reduction was 16.2% compared with the cantilever model.
- For the double outrigger system, the maximum displacement reduction was 23.4% under response spectrum loading and 20.9% under wind loading when outriggers were placed at the 10th and 20th stories. Storey drift was reduced by 21% compared with the cantilever model.
- For the single belt truss system, the maximum displacement reduction was 10.8% under response spectrum loading and 11.2% under wind loading when the belt truss was located at the 20th storey. The maximum drift reduction was 14.6%.
- For the double belt truss system, displacement was reduced by 19.5% under response spectrum loading and 18.1% under wind loading when belt trusses were placed at the 10th and 20th stories. The drift reduction was 19%.
- For the single combined outrigger and belt truss system, the maximum displacement reduction was 17% under response spectrum loading and 17.4% under wind loading when placed at the 20th storey. The maximum drift reduction was 19.1%.
- For the double combined outrigger and belt truss system, the maximum displacement reduction reached 30.8% under response spectrum loading and 27.6% under wind loading when the systems were placed at the 10th and 20th stories. The storey drift reduction was 25.3%.
- Among all analyzed models, the double combined outrigger and belt truss system at the 10th and 20th stories showed the best overall performance. Similar behavior was observed under medium and soft soil conditions.
- The base shear showed a slight increase, with a maximum increment of 0.3% observed in the model with the double combined outrigger and belt truss system at the 10th and 20th stories. This variation remained nearly constant across the soil conditions.

5.2 Scope for further research

- The optimum location of outrigger systems in mass-irregular buildings can be investigated in future studies.
- Further research can develop approximate formulae describing the behavior of structures with outrigger systems.

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