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SEISMIC AND WIND PERFORMANCE OF OUTRIGGER AND BELT TRUSS SYSTEMS IN A 50-STOREY HIGH-RISE BUILDING: A PARAMETRIC STUDY UNDER VARYING SOIL CONDITIONS

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ABSTRACT

This study presents a comprehensive parametric investigation on the effectiveness of various lateral load resisting systems for a 50-storey reinforced concrete high-rise building located in Bhuj, classified under Seismic Zone V according to Bureau of Indian Standards IS 1893 (Part 1): 2016. A total of 33 structural configurations were developed and analyzed using ETABS, including single and double outrigger systems, single and double belt truss systems, and hybrid configurations combining outriggers with belt trusses positioned at different floor levels. Dynamic analysis was performed using the Response Spectrum Method (RSA), while wind effects were evaluated in accordance with IS 875 (Part 3): 2015. Structural performance was assessed based on maximum story displacement, inter-storey drift, and base shear response under both seismic and wind loading conditions. Subsequently, the optimum configuration from each structural category was further examined under three different soil conditions, namely Type I (Hard Soil), Type II (Medium Soil), and Type III (Soft Soil), to evaluate soil–structure interaction effects on overall building response. The analytical results indicate that the double combined outrigger with belt truss system positioned at the 10th and 20th storeys demonstrates superior structural efficiency among all models considered. This configuration achieved a reduction of 30.8% in seismic displacement, 27.6% in wind displacement, and 25.3% in story drift, while producing only a marginal increase of 0.3% in base shear. The findings confirm the significant potential of combined outrigger–belt truss systems in enhancing the stability and serviceability performance of tall buildings in high seismic regions.

KEYWORDS: High-Rise Building, Outrigger System, Belt Truss, Lateral Load Resisting System, Response Spectrum Analysis, Story Drift, Seismic Performance, Wind Analysis, ETABS, Soil Type Effect

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1. INTRODUCTION

High-rise buildings have become indispensable in modern urban environments, accommodating growing populations within limited land. However, they face severe challenges from lateral forces induced by earthquakes and wind, causing sway, overturning moments, and inter-story drift. Excessive lateral displacement leads to structural damage and occupant discomfort.

The Bhuj earthquake of January 26, 2001 (Mw 7.7) tragically demonstrated the consequences of inadequate lateral resistance — over 19,000 lives were lost and approximately 170,000 people were injured. This underscored the urgent need for robust lateral systems in seismically active zones such as Bhuj, Gujarat (Seismic Zone V).

Since the 1980s, outrigger systems have emerged as a preferred strategy for tall buildings. An outrigger is a stiff horizontal element connecting the central shear core to peripheral columns, mobilizing those columns as tension-compression couples

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to resist overturning moments and substantially reduce lateral drift. Belt trusses, which horizontally tie peripheral columns without direct core connection, serve as virtual outriggers and are commonly deployed alongside outriggers for enhanced stiffness. This study evaluates 33 structural configurations of these systems on a 50-storey building in Bhuj using ETABS 22 dynamic analysis.

2. LITERATURE REVIEW

Khadka et al. (2023) examined a 32-storey building with outrigger and belt truss under seismic forces. The combined system significantly improved lateral stiffness over standalone outriggers. Optimal placement at the top floor and 16th floor yielded best deflection performance, with minimum story drift at the 16th story.

Rathore et al. (2023) studied a 100-storey building with one to four outriggers. Using four outriggers produced a 25% reduction in earthquake-induced displacement and 26% under wind. Story drift reductions of 22% (seismic) and 27% (wind) were recorded.

Shingade et al. (2023) analysed a 40-storey RCC structure in multiple earthquake zones. Displacement reductions were 16.5% (outrigger), 18% (belt truss), and 21% (combined) under seismic loading. Wind displacement reduced by 31%, 30%, and 35%, respectively.

Shareef et al. (2022) found that outriggers at the 10th and 40th floors of a 50-storey Zone V building reduced displacement by 49% and inter-story drift by 51%. Placement at the 20th and 30th floors yielded only 6% displacement reduction, highlighting placement sensitivity.

Karande et al. (2022) evaluated eleven configurations and found the 20th story optimal for a single outrigger (24.4% and 28.9% reduction in X and Y directions). Dual outriggers at the 6th and 20th stories achieved 33.9% and 39.8% reductions.

3. OBJECTIVES

The primary objectives of this study are:

1. Evaluate the structural response of a 50-storey building under seismic and wind lateral loads using a conventional cantilever core model as baseline.
2. Investigate the effectiveness of single/double outrigger, single/double belt truss, and combined systems placed at varying story locations.
3. Identify the optimal story location for each lateral resisting system configuration.
4. Compare best-performing configurations across three soil types (Hard, Medium, Soft) as per IS 1893 (Part 1): 2016.
5. Evaluate changes in base shear due to incorporation of lateral systems.

4. MATERIALS AND METHODS:

4.1 Building Configuration

The study building is a 50-storey square-plan RCC structure in Bhuj, Gujarat. Total height: 150 m; floor-to-floor: 3 m; column spacing: 5 m. Structural analysis was performed using ETABS 22 Ultimate with Indian standard codes (IS 456: 2000 for concrete; IS 800: 2007 for steel).

Table 1: Structural and Material Properties

Parameter	Value
Concrete Grade	M50
Rebar Grade	HYSD 550 & HYSD 415 (Fe 550 / Fe 415)
Outrigger / Belt Truss	Fe 345 Steel — ISMB 600 Section
Column: Base to 16th Story	1000 × 1000 mm
Column: 17th to 32nd Story	850 × 850 mm
Column: 33rd to 50th Story	700 × 700 mm
Beam Section	300 × 450 mm
Shear Wall Thickness	500 mm
Slab (Shell Thin)	175 mm
Unit Weight of RCC	25 kN/m³

4.2 Loading

Table 2: Loading Summary

Load Type	Value / Code
Dead Load (floor finish)	1 kN/m² — IS 875 Part 1
Live Load (floors)	3 kN/m² — IS 875 Part 2
Live Load (roof)	1.5 kN/m² — IS 875 Part 2
Exterior wall (Glass 12 mm)	0.883 kN/m
Interior wall (AAC 200 mm)	4.12 kN/m
Wind Speed / Terrain	50 m/s, Category 4 — IS 875 Part 3: 2015

Seismic Zone Factor (Z)	0.36 — Zone V, IS 1893 Part 1: 2016
Importance Factor (I)	1.2
Response Reduction Factor (R)	3
Damping	5%

M25 grade concrete (target mean strength 31.6 MPa) was designed as per IS 10262:2019. The water-to-binder (w/b) ratio was maintained at 0.45. Six mixes were prepared: M0 (control, 100% OPC), M1 (10% RHA), M2 (10% FA), M3 (20% RHA), M4 (20% FA), and M5 (10% RHA + 10% FA). Cube specimens (150×150×150 mm) for compressive strength, cylinders (150×300 mm) for split tensile strength, and beams (100×100×500 mm) for flexural strength were cast in triplicate for each mix and curing period (7, 28, 56 days).

4.3 Analysis Method

The approximate fundamental natural period Ta = $0.09h/\sqrt{d} = 0.09 \times 150/\sqrt{25} = 2.7$ sec > 0.4 sec, mandating dynamic analysis per Clause 6.4.3 of IS 1893 (Part 1): 2016. Response Spectrum Analysis (RSA) was adopted with the CQC modal combination method, Modal Eigen vectors, and 5% damping in X, Y, and Z directions. P-delta effects were incorporated iteratively with a dead load scale factor of 1.5. Scale factors for the dynamic spectra were computed per Clause 7.7.3 to match static base shear.

4.3 Model Configuration

Table 3: Summary of Models Analyzed

Category	No. of Models	Story Locations Studied
Conventional Cantilever (Baseline)	1	—
Single Outrigger	10	5th, 10th, 15th, 20th … 50th (every 5th)
Double Outrigger	9	Various two-story combinations
Single Belt Truss	4	10th, 15th, 20th, 25th
Double Belt Truss	3	5th+20th, 10th+20th, 20th+30th
Single Combined (OBT)	3	15th, 20th, 25th
Double Combined (OBT)	3	5th+15th, 10th+20th, 20th+30th

5. RESULTS AND DISCUSSION:

5.1 Baseline Conventional Cantilever Core:

The square-plan building showed symmetric response in X and Y directions. Baseline values are: Max Story Displacement (Seismic) = 255.14 mm, (Wind) = 60.08 mm; Max Story Drift (Seismic) = 0.002244.

5.2 Single Outrigger at Varying Locations

Among 10 single-outrigger positions, the 20th story was optimal: seismic displacement = 220.52 mm (−13.6%), wind displacement = 52.14 mm (−13.2%), drift = 0.001880 (−16.2%). Performance degraded progressively as outrigger placement moved higher, confirming that mid-height positioning maximizes core moment reduction.

5.3 Double Outrigger at Varying Locations

The best configuration placed outriggers at the 10th and 20th stories: seismic displacement = 195.43 mm (−23.4%), wind = 47.52 mm (−20.9%), drift = 0.001773 (−21.0%). Concentrating both units in the lower-to-mid zone provides superior core restraint compared to spreading them vertically.

5.4 Belt Truss Systems

Single belt truss at the 20th story: seismic displacement = 227.49 mm (−10.8%), wind = 53.38 mm (−11.2%), drift = 0.001917 (−14.6%). Double belt truss at 10th and 20th stories: seismic = 205.30 mm (−19.5%), wind = 49.35 mm (−17.9%), drift = 0.001825 (−18.7%). The belt truss alone performs modestly less than the outrigger system, lacking direct core connectivity.

5.5 Combined Outrigger with Belt Truss (OBT)

Single OBT at 20th story: seismic = 211.82 mm (−17.0%), wind = 49.62 mm (−17.4%), drift = 0.001816 (−19.1%). Double OBT at 10th and 20th stories: seismic = 176.58 mm (−30.8%), wind = 43.53 mm (−27.6%), drift = 0.001677 (−25.3%). This was the highest-performing configuration in the entire study, surpassing all other systems by a significant margin.

5.6 Soil Condition Comparison

The best-performing configurations were re-evaluated across all three soil types. The double combined OBT system at 10th and 20th stories remained optimal across all conditions, demonstrating robustness to varying foundation soils.

5.7 Base Shear

All configurations produced only marginal base shear increases. The maximum increase was 0.3% in the double combined OBT system across all soil conditions. This confirms that significantly improved lateral performance is obtained without adverse amplification of seismic demand.

Table 4: Summary of Best Models Hard Soil

System	Seismic Disp. (mm)	Wind Disp. (mm)	Story Drift	% Reduction
Conventional	255.14	60.08	0.002244	—
Single Outrigger @ 20th	220.52	52.14	0.00188	−13.6%
Double Outrigger 10th+20th	195.43	47.52	0.001773	−23.4%
Single Belt Truss @ 20th	227.49	53.38	0.001917	−10.8%
Double Belt Truss 10th+20th	205.3	49.35	0.001825	−19.5%
Single Combined OBT @ 20th	211.82	49.62	0.001816	−17.0%
Double Combined OBT 10th+20th	176.58	43.53	0.001677	−30.8%

Table 5: Seismic Displacement (mm) across Soil Types

Configuration	Hard Soil (I)	Medium Soil (II)	Soft Soil (III)
Conventional Core	255.14	270.43	340.34
Single Outrigger @ 20th	220.52 (−13.6%)	237.11 (−12.3%)	298.82 (−12.2%)
Double Outrigger 10th+20th	195.43 (−23.4%)	206.47 (−23.7%)	259.83 (−23.7%)
Single Belt Truss @ 20th	227.49 (−10.8%)	242.53 (−10.3%)	305.54 (−10.2%)
Double Belt Truss 10th+20th	205.30 (−19.5%)	216.86 (−19.8%)	272.87 (−19.8%)
Single Combined OBT @ 20th	211.82 (−17.0%)	226.30 (−16.3%)	285.50 (−16.1%)
Double Combined OBT 10th+20th	176.58 (−30.8%)	186.36 (−31.1%)	234.32 (−31.2%)

Table 6: Story Drift (Seismic) across Soil Types

Configuration	Hard Soil (I)	Medium Soil (II)	Soft Soil (III)
Conventional Core	0.002244	0.002376	0.002987
Single Outrigger @ 20th	0.001880 (−16.2%)	0.002000 (−15.8%)	0.002517 (−15.7%)
Double Outrigger 10th+20th	0.001773 (−21.0%)	0.001869 (−21.3%)	0.002348 (−21.4%)
Single Belt Truss @ 20th	0.001917 (−14.6%)	0.002038 (−14.2%)	0.002564 (−14.2%)
Double Belt Truss 10th+20th	0.001825 (−18.7%)	0.001926 (−18.9%)	0.002419 (−19.0%)
Single Combined OBT @ 20th	0.001816 (−19.1%)	0.001936 (−18.5%)	0.002438 (−18.4%)
Double Combined OBT 10th+20th	0.001677 (−25.3%)	0.001766 (−25.7%)	0.002217 (−25.8%)

6. CONCLUSIONS:

The following conclusions are drawn from the numerical investigation:

a. Lateral resisting systems substantially reduce both story displacement and drift. The magnitude of reduction depends on system type and placement location.
b. Single outrigger at the 20th story: seismic displacement −13.6%, wind −13.2%, drift −16.2%.
c. Double outrigger at 10th+20th: seismic −23.4%, wind −20.9%, drift −21.0%.
d. Single belt truss at 20th story: seismic −10.8%, wind −11.2%, drift −14.6%.
e. Double belt truss at 10th+20th: seismic −19.5%, wind −18.1%, drift −19.0%.
f. Single combined OBT at 20th story: seismic −17.0%, wind −17.4%, drift −19.1%.
g. Double combined OBT at 10th+20th: seismic −30.8%, wind −27.6%, drift −25.3% — the best-performing system overall, consistently optimal across hard, medium, and soft soil conditions.
h. Base shear increases were negligible (maximum 0.3%), confirming structural efficiency with minimal added seismic demand.

7. SCOPE FOR FUTURE RESEARCH

a. Optimum outrigger placement in buildings with mass and stiffness irregularities.
b. Development of closed-form analytical formulae for outrigger placement optimisation.
c. Time-history analysis using recorded Bhuj 2001 ground motions.
d. Nonlinear pushover and dynamic analysis of the combined OBT system for extreme seismic events.
e. Cost-benefit analysis of combined OBT systems versus conventional solutions.

8. DECLARATIONS

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Conflict of Interest

The authors declare that they have no conflict of interest.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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