Evaluation of Seismic Performance of Tall Structural Systems Using Nonlinear Time History Analysis

Naveen N[1], Dr. N.Jayaramappa[2]

[1]P.G. Student, department of Civil Engg. , Major: Structural Engineering, University of Visvesvaraya College of engineering, Karnataka, India,
[2]Professor, department of Civil Engg. , University of Visvesvaraya College of engineering, Karnataka, India.

Abstract - *This dissertation presents a comparative seismic analysis of seven high-rise structural systems through time history analysis of 40-storey reinforced concrete buildings. The study evaluates Moment-Resisting Frame (MRF), Shear Wall-MRF (SW-MRF), Diagrid (DG), Outrigger (OT), Belt Truss (BTS), Bundled Tube (BT), and Tube-in-Tube (TT) configurations, each 140 meters tall with a 56m × 56m plan, designed for Seismic Zone V per IS 1893:2016. Modal analysis, equivalent static analysis, and time history analysis were performed in ETABS using six historical earthquake records. Results indicate that Tube-in-Tube demonstrates superior base shear resistance, while exterior systems (Diagrid, Bundled Tube, and Tube-in-Tube) and in interior structures (shear wall- moment resisting frames) provide better lateral displacement control.*

***Key Words*: Time History Analysis, High-rise structural systems, Seismic performance, Moment-resisting frames, Shear-wall Moment-resisting frames, Diagrid structures, Tube-in-tube systems**

1. INTRODUCTION

The design of structural systems for tall buildings represents one of the most challenging and sophisticated aspects of modern structural engineering. As buildings ascend to greater heights, the structural system must efficiently resist not only accumulated gravity loads but also increasingly dominant lateral forces from wind and seismic activities. The selection of an appropriate structural system is fundamentally governed by the principle of "premium for height," which recognizes that lateral load effects increase exponentially with building height, necessitating different structural configurations for different height ranges.

1.1 Classification of structural system

Structural systems for tall buildings are broadly classified into two categories: Interior Structures and Exterior Structures, based on the primary location of lateral load-resisting elements. Interior structural systems are characterized by lateral load-resisting elements located primarily within the building's interior core or distributed throughout the internal structure. These include Rigid Frame systems (Moment-Resisting Frames), Shear Wall-Frame Interaction Systems, Core-Outrigger Systems with belt trusses, and Buttressed Cores. Exterior structural systems position the primary lateral load-resisting elements at or near the building perimeter, creating highly efficient structural configurations. These include Framed Tube systems, Braced Tube systems, Bundled Tube structures, Diagrid Systems, Tube-in-Tube structures, and Space Trusses.

1.2 Objective of the study

Among various analytical methods, time history analysis has emerged as a critical tool in structural engineering, particularly for evaluating the dynamic response of high-rise buildings subjected to diverse loading conditions such as seismic events, wind forces, and other transient effects. Time history analysis captures the actual response of structures subjected to real earthquake ground motions, accounting for frequency content, duration, and phasing effects. This study aims to provide comprehensive comparative analysis of seven contemporary structural systems using rigorous nonlinear dynamic analysis methods, contributing to the advancement of safer and more resilient high-rise buildings.

2. PRELIMINARY DATA CONSIDERED FOR ANALYSIS

Building Models and Geometry

Seven 40-storey reinforced concrete high-rise building models were developed representing different lateral load-resisting systems:

Table -1: 7 STRUCTURAL SYSTEMS NOMENCLATURE

S.L. No.	Structural System	Nomenclature
1	Moment Resisting Frame	MRF
2	Shear Wall-Moment Resisting Frame	SW-MRF
3	Diagrid Structure	DG
4	Outrigger Structure	OT
5	Belt Truss System	BTS
6	Bundled Tube Structure	BT
7	Tube-in-Tube Structure	TT

Building Dimensions:
- Total Height: 140 m (40 storeys)
- Storey Height: 3.5 m
- Plan Dimension: 56 m × 56 m (square)
- Bay Width: 5 m

Material Properties and Sections

Concrete and Steel Properties:
- Grade of Concrete: M40, M55
- Compressive Strength of Concrete: 40, 55 N/mm^2
- Modulus of Elasticity (Concrete): 31,622 N/mm^2
- Grade of Steel (Reinforcement): Fe 550
- Rebar Strength: 550 N/mm^2

Section Dimensions (Common for all systems):
- Beam: 600 mm × 900 mm (Rectangular RCC section)
- Column: 1200 mm × 1200 mm (Rectangular RCC section)
- Slab: 150 mm thickness
- Core (Central shear wall): 600 mm thickness

Special Elements:
- Diagrid (DG): CHS 1000 × 40 mm
- Outrigger (OT): 600 mm thickness wall
- Belt Truss System (BTS): RHS 600 × 1000 × 30 mm

Loading Conditions

Gravity Loads (as per IS 875-1987 Part I & II):
- Super Imposed Dead Load: 1.5 kN/m^2
- Live Load: 4.0 kN/m^2
- Mass Source: 100% dead load + 50% live load

Seismic Load Parameters (as per IS 1893-2016):
- Seismic Zone: Zone V
- Zone Factor (Z): 0.36
- Soil Type: Soft Soil
- Importance Factor (I): 1.2
- Response Reduction Factor (R): 5
- Damping Ratio: 5%

Wind Load Parameters (as per IS 875-1987 Part III):
- Wind Speed: 50 m/sec
- Risk Coefficient (K_1): 1.0
- Terrain Roughness: Category 4
- Topography Factor (K_3): 1.0
- Importance Factor: 1.0

Earthquake Records for Time History Analysis

Table-2: Earthquake Record

S. No.	Earthquake	Peak Ground Acceleration
1	Bhuj	1.038 m/s^2 (0.106 g)
2	Chi-Chi	4.617 m/s^2 (0.471 g)
3	Kobe	5.679 m/s^2 (0.579 g)
4	Loma Prieta	4.694 m/s^2 (0.478 g)
5	Northridge	2.519 m/s^2 (0.257 g)
6	Uttarkashi	2.480 m/s^2 (0.253 g)

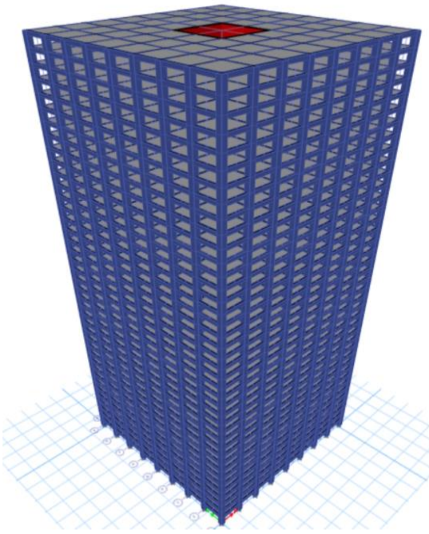

Fig -1: 3D View of MRF

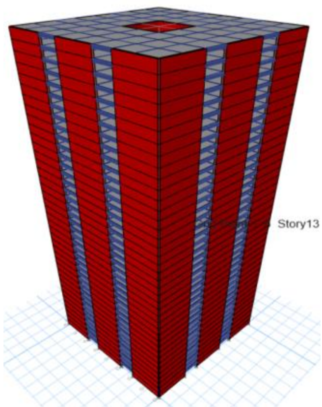

Fig -2: 3D View of SW-MRF

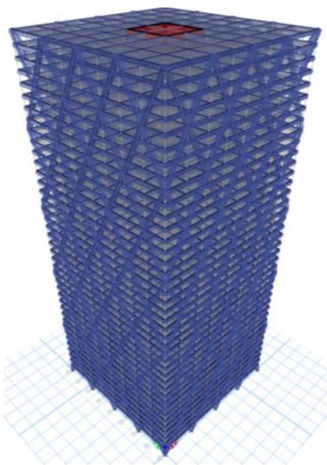

Fig -3: 3D View of DG

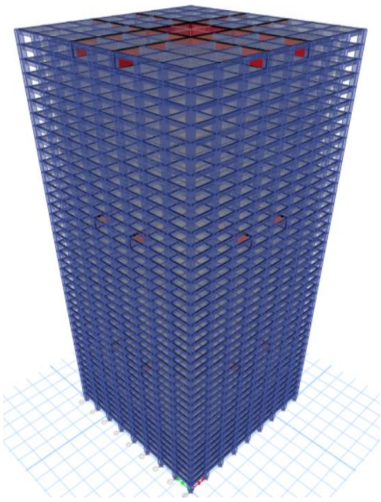

Fig -4: 3D View of OT

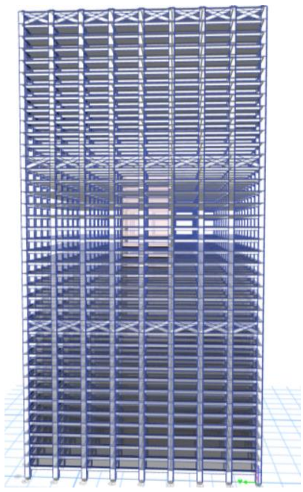

Fig -5: 3D View of BTS

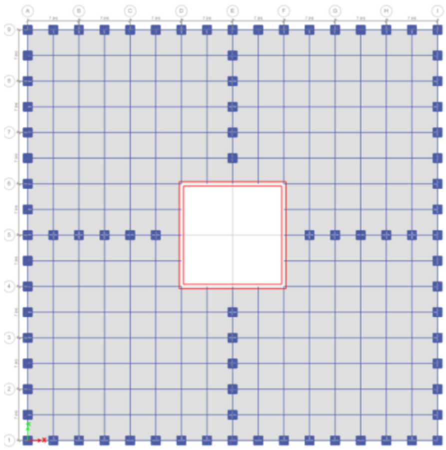

Fig -6: Plan View of BT

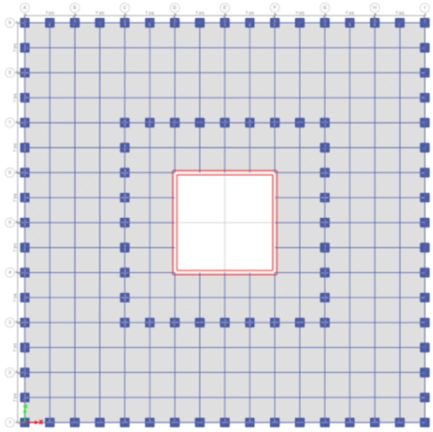

Fig -7: Plan View of BT

3. RESULTS AND DISCUSSION

3.1 Modal Analysis

Table-3: MODE 1 TIME PERIOD OF ALL STRUCTURES

S. No.	Model	Computed Period (s)	IS 1893:2016 (s)
1	MRF	2.645	1.684
2	SW-MRF	2.086	1.684
3	DG	2.130	1.684
4	OT	2.220	1.684
5	BTS	2.599	1.684
6	BT	2.448	1.684
7	TT	2.329	1.684

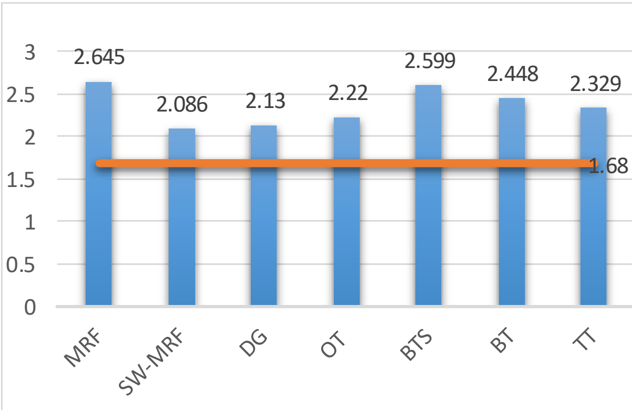

Chart -1: Modal time period of all structure

3.2 Base Shear from Time History Analysis

Table-4: MAX BASE SHEAR (10^6) IN kN

Model	BJ	CH	KB	LP	NR	UK
MRF	0.090	0.208	0.376	0.390	0.554	0.111
SW-MRF	0.121	0.287	0.686	0.419	0.683	0.252
DG	0.124	0.319	0.577	0.425	0.686	0.217
OT	0.102	0.285	0.701	0.394	0.851	0.138
BTS	0.100	0.265	0.474	0.443	0.902	0.116
BT	0.158	0.440	0.781	0.708	1.663	0.207
TT	0.185	0.492	1.225	0.767	1.690	0.216

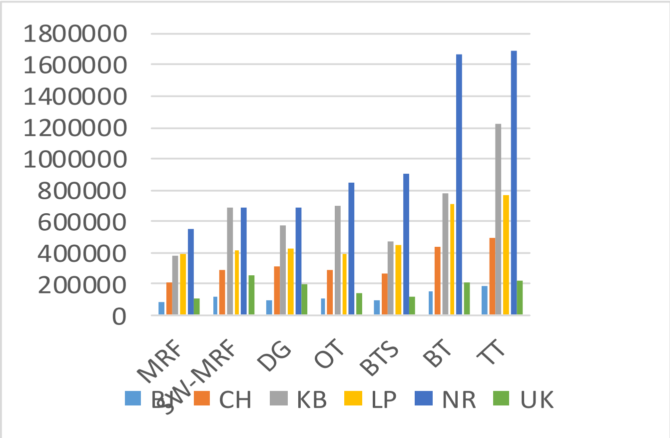

Chart -2: Max Base shear of All Structure

3.3 Storey Displacement

Table-5: MAX STOREY DISPLACEMENT IN (mm)

Model	BJ	CH	KB	LP	NR	UK
MRF	140.6	90.2	412.2	297.7	1751.8	140.2
SW-MRF	101.4	110.6	533.0	186.7	764.2	132.5
DG	100.4	108.6	580.0	187.9	879.2	117.2
OT	110.5	96.0	577.8	222.0	1058.5	109.0
BTS	135.6	91.5	420.5	291.2	1692.4	135.3
BT	121.5	94.3	452.6	263.1	1491.8	120.2
TT	105.6	96.6	543.7	248.4	1229.6	114.1

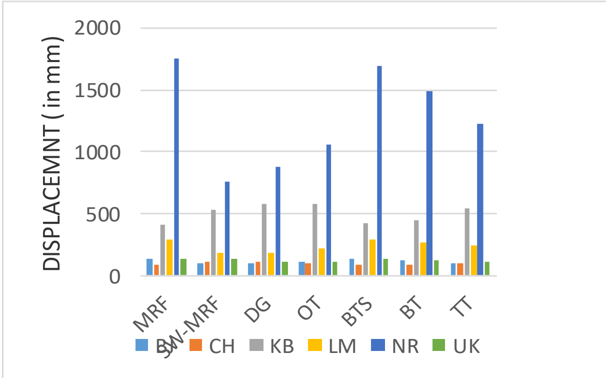

Chart -3: Max Displacement of All Structure

3.4 Inter Storey Drift Ratio

Table-6: MAX INTER STOREY DRIFT RATIO (10^{-3})

Model	BJ	CH	KB	LP	NR	UK
MRF	1.42	2.19	6.31	4.36	15.82	1.65
SW-MRF	1.05	2.16	5.39	2.03	6.75	1.45
DG	1.13	2.63	6.72	2.92	8.28	1.59
OT	1.12	1.93	7.06	3.4	9.99	1.41
BTS	1.6	2.3	6.92	4.9	17.54	1.82
BT	1.2	1.98	5.93	4	13.45	1.53
TT	0.93	1.92	6.79	3.8	10.82	1.49

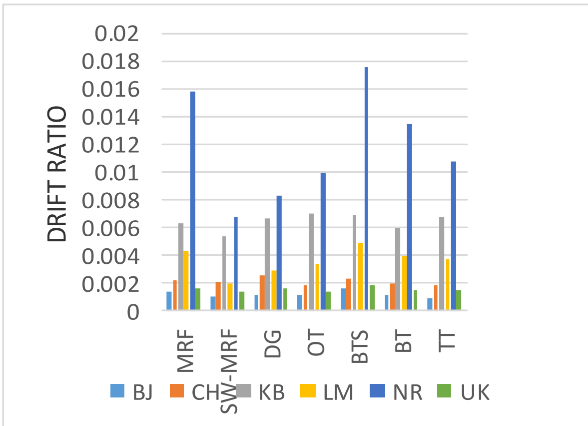

Chart -4: Max Inter Storey Drift of All Structure

4. CONCLUSIONS

Modal Analysis

MRF exhibits maximum flexibility (2.645s period) requiring 6-7 modes for 90% mass capture, while SW-MRF is most stiff (2.086s period) achieving efficiency at mode 5, with IS 1893:2016 empirical formula systematically underestimating dynamic flexibility across all systems.

Base Shear Response

Time history analysis reveals base shear substantially exceeds equivalent static values, with MRF experiencing lowest demand (90,000-5,55,000kN) and Tube-in-Tube/Bundled Tube systems attracting maximum forces (1,80,000–16,90,000 kN), validating the necessity of multi-record analysis over single-earthquake assessment.

Lateral Displacement

Spectral period compatibility governs displacement response more than peak ground acceleration, with Northridge inducing maximum displacement (700–1760 mm) and flexible systems (MRF, BTS) showing inherently higher displacements due to longer natural periods compared to stiffer systems (SW-MRF, Diagrid and Tube-in-Tube).

Drift Ratio and Damage Control

Northridge produces highest drift ratios (0.006–0.016), with Moment resisting frame (0.01582) achieving poorest performance and SW-MRF, Diagrid, outrigger and Tube-in-Tube delivering best control (0.00675, 0.00828, 0.00999 and 0.01082), representing from 30%-57% reduction relative to MRF.

System Ranking & Performance

Tube-in-Tube achieves optimal balance establishing definitive ranking as **TT > SW-MRF > DG > OT > BT > BTS > MRF**, confirming that structural system configuration governs seismic performance more critically than member strength and distributed lateral load paths deliver most resilient performance.

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