Seismic Performance Assessment of Reinforced Concrete Tube Structural System Using Nonlinear Time-History Analysis

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***Abstract*—This study investigates the seismic performance of a 20-storey reinforced concrete tube-in-tube building subjected to near-fault pulse-like ground motions through nonlinear time-history analysis (NLTHA). A 3D finite element model was developed in 3D model software for a symmetric 24 m × 24 m plan (total height 60 m). The outer framed tube comprises 450 mm × 450 mm peripheral columns at 3.0 m centres connected by 300 mm × 500 mm spandrel beams; the inner core is a 300 mm thick RC shear wall box (6 m × 6 m) with special boundary elements per IS 13920:2016. Five ground motions are scaled in categories. Eigenvalue analysis yielded T_1 = 1.342 s with 95.07% cumulative modal mass in 12 modes. Medium pulse excitations governed all demand parameters: peak inter-storey drift ratio (IDR) of 0.607% at Storey 12, mean roof displacement of 263 mm, and maximum base shear of 21,034 kN. All IDR values comply with the IS 1893:2016 life-safety limit of 2.0%. The results confirm that pulse-period proximity to the structural fundamental period is the primary driver of seismic demand in tube-in-tube systems.**

***Index Terms*—Inter-storey drift ratio; IS 1893:2016; Near-fault ground motion; Nonlinear time-history analysis; Tube-in-tube structure.**

I. INTRODUCTION

The rapid urbanisation of global cities has placed extraordinary demands on structural engineering, particularly in seismically active regions. Among the structural systems adopted for high-rise construction, the tube-in-tube (TIT) configuration represents one of the most efficient systems for reinforced concrete (RC) buildings. The concept, first conceptualised by Fazlur Rahman Khan in the 1960s, leverages two concentric tubular systems an outer perimeter tube and an inner core tube to resist lateral and gravity loads with exceptional efficiency [1].

Seismic performance assessment of such systems has emerged as a pressing research frontier. While IS 1893:2016 provides baseline prescriptive guidance, it does not fully capture the complex nonlinear dynamic response mechanisms that govern the behaviour of these structures under strong near-fault ground shaking. Near-fault pulse-like ground motions impose fundamentally different seismic demands on tall structures compared to ordinary far-field records, as the concentrated seismic energy in high-amplitude velocity pulses can interact with the natural periods of high-rise buildings, triggering near-resonance conditions [2].

The present study addresses this gap through a finite element investigation of a 20-storey RC tube-in-tube building subjected to 21 near-fault pulse-like ground motions. The key objectives are:

1. determination of natural periods and modal mass participation using eigenvalue analysis;
2. evaluation of IDR under near-fault excitation and verification of IS 1893:2016 drift limits;
3. computation of base shear demands across low, medium, and high pulse categories; and
4. investigation of translational-torsional coupling arising from closely spaced modal periods.

II. LITERATURE REVIEW

Comprehensive advances in nonlinear modeling of RC structural systems have been documented extensively. Kolozvari et al. [3] demonstrated that coupling of shear and flexural deformations is critical for accurately predicting the behaviour of slender RC walls. Lu and Henry [4] showed that conventional fiber-section models can overestimate the ductility capacity of heavily loaded RC walls at high axial load ratios typical of high-rise buildings.

Research specifically addressing tube-in-tube seismic behaviour has grown since 2015. Li et al. [5] demonstrated that the load-sharing ratio between the outer tube and inner core changes significantly during inelastic deformation. Saab and Mwafy [6] found that near-fault ground motions with forward-directivity pulses produce significantly higher story drift demands than far-field records, particularly in upper storeys where higher-mode response is concentrated. Zhang et al. [7] established that adequate collapse margins exist for 20-storey tube-in-tube structures under the FEMA P-695 framework, while taller structures show reduced margins under near-fault excitation.

Khashaee et al. [8] conducted a comparative study across ASCE 7, Eurocode 8, and NZS 3101, finding that structures designed to NZS 3101 exhibit the most favourable seismic performance due to stringent ductility requirements. Mohammed and Abed [9] investigated combined seismic and wind loading, establishing that wind-governed designs may exhibit inferior ductility performance at MCE levels if detailing requirements are relaxed.

III. MODELLING AND METHODOLOGY

A. Structural Configuration

The structure is a symmetrical 20-storey RC building with plan dimension 24 m × 24 m and uniform bay spacing of 3.0 m in both directions (8 × 8 bay configuration). Uniform storey height is 3.0 m throughout, giving a total building height of 60 m. The inner shear wall core occupies the central 6 m × 6 m zone with 300 mm wall thickness. Peripheral columns are spaced at 3.0 m on centres. The three-dimensional model was developed in ETABS v19.0 conforming to IS 456:2000, IS 875 (Parts 1-3), IS 1893 (Part 1):2016, IS 13920:2016, and IS 1786:2008.

Table I: Structural and geometric properties

No.	Parameter
1	Structure Type
2	Number of Storeys
3	Total Building Height
4	Plan Dimension
5	Bay Spacing
6	Inner Core Size
7	Storey Height
8	Slab Thickness
9	Peripheral Column
10	Core Column
11	Beam Dimensions
12	Spandrel Beam
13	Shear Wall Thickness
14	Concrete — Frame
15	Concrete — Shear Wall
16	Reinforcing Steel
17	Floor Live Load
18	Roof Live Load
19	Superimposed Dead Load

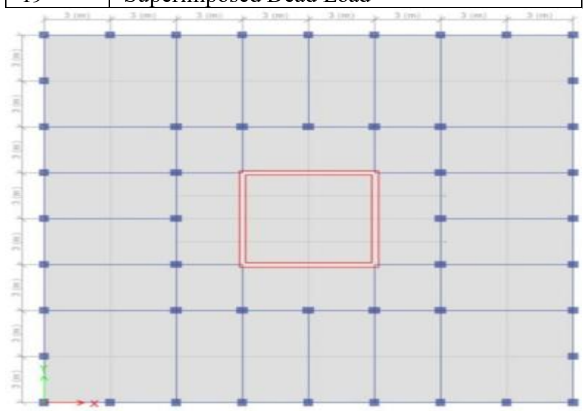

Fig. 1. Typical Floor Plan of the 20-Storey Tube-in-Tube Building (ETABS v19.0)

B. Material Properties

Table II: Material Properties — M40 (Frame) and M30 (Shear Walls)

Property	M40 (Frame)	M30 (Core Wall)	Unit
fck	40	30	N/mm²
Ec = 5000√fck	31,623	27,386	N/mm²
Poisson's Ratio (ν)	0.2	0.2	—
Unit Weight (γc)	25	25	kN/m³
Shear Modulus (G)	13,176	11,411	N/mm²

Table III: Material Properties — FE 500 HYSD Steel

Property	Value	Unit
Yield Strength (fy)	500	N/mm²
Ultimate Tensile Strength	545	N/mm²
Modulus of Elasticity (Es)	2,00,000	N/mm²
Poisson's Ratio	0.3	—
Unit Weight (γs)	78.5	kN/m³

C. Seismic Design Parameters

Seismic forces are computed using the Response Spectrum Method (RSM) per IS 1893 (Part 1):2016. The design horizontal seismic coefficient is given by:

$$Ah = (Z / 2) \times (I / R) \times (Sa / g) \quad \ldots \quad (1)$$

$$VB = Ah \times W \quad \ldots \quad (2)$$

Table IV: Seismic Design Parameters (IS 1893:2016)

Parameter	Adopted Value
Seismic Zone	Zone V
Zone Factor (Z)	0.36
Importance Factor (I)	1.0
Response Reduction Factor (R)	5.0 (SMRF with Shear Wall)
Soil Type	Type II — Medium Soil
Damping (RSA)	5%
Damping (NLTHA)	2% Rayleigh (1st and 3rd modes)
Fundamental Period (T_1)	1.342 s (ETABS Modal Analysis)
Modes Considered	12 modes (≥ 90% mass participation)

D. Load Combinations

Table V: Load Combinations
(IS 456:2000 / IS 1893:2016)

No.	Combination
1	1.5 (DL + IL)
2	1.2 (DL + IL + EQX)
3	1.2 (DL + IL − EQX)
4	1.2 (DL + IL + EQY)
5	1.2 (DL + IL − EQY)
6	1.5 (DL + EQX)
7	1.5 (DL − EQX)
8	1.5 (DL + EQY)
9	1.5 (DL − EQY)
10	0.9 DL + 1.5 EQX
11	0.9 DL − 1.5 EQX
12	0.9 DL + 1.5 EQY
13	0.9 DL − 1.5 EQY

E. Analysis Methods

Table VI: Summary of analysis methods employed

Analysis Type	Purpose
Modal Analysis	Determine natural frequencies, mode shapes, and T_1
Response Spectrum Analysis	Primary lateral load analysis using IS 1893:2016 design spectrum; CQC combination
Nonlinear Static (Pushover)	Capacity curve evaluation; assessment of plastic hinge formation
Nonlinear Time History (NLTHA)	Dynamic response under near-fault pulse-like ground motions

Model validation: The ETABS fundamental period T_1 = 1.342 s is compared with the IS 1893:2016 empirical formula:

$$T_1 = 0.09 \times H / \sqrt{D} = 0.09 \times 60 / \sqrt{24} = 1.102 \text{ s} \quad (3)$$

The ETABS period of 1.342 s is higher than the empirical value, as expected the empirical formula provides a conservative lower-bound estimate that excludes stiffness contributions from non-structural elements.

IV. RESULTS AND DISCUSSION

A. Modal Analysis Results

Eigenvalue extraction revealed a fundamental period of T_1 = 1.342 s. Modes 1–3 have closely spaced periods (1.342 s, 1.284 s, 1.191 s), indicating translational-torsional coupling that necessitates Complete Quadratic Combination (CQC) for modal superposition. Cumulative modal mass reaches 95.07% within 12 modes, satisfying the IS 1893:2016 threshold of 90%. The sharp period drops from Mode 3 (1.191 s) to Mode 4 (0.397 s) a 67% reduction reflects the dual-stiffness behaviour characteristic of tube-in-tube systems.

Table VII: Modal analysis results natural periods, frequencies, and mass participation

Mode	Period (s)	Freq. (Hz)	ω (rad/s)	Cum. Mass (%)
1	1.342	0.745	4.682	53.1
2	1.284	0.779	4.895	64.55
3	1.191	0.840	5.276	73.55
4	0.397	2.519	15.829	88.30
5	0.399	2.506	15.746	89.1
6	0.349	2.865	18.001	89.1
7	0.238	4.202	26.402	89.1
8	0.212	4.717	29.638	93.25
9	0.168	5.952	37.4	93.4
10	0.164	6.098	38.318	93.55
11	0.142	7.042	44.247	94.60
12	0.129	7.752	48.709	95.07

B. Ground Motion Selection

Five scaled ground motions are downloaded from PEER NGA Data.

C. Storey Displacement

Mean storey displacement profiles exhibit a cantilever-type deformation pattern for all three pulse categories. Medium pulse excitations produce the largest roof displacement of 263 mm, marginally exceeding the IS 1893:2016 permissible limit of 240 mm (H/250 = 60,000/250). Low pulse produces 227 mm (compliant) and high pulse yields the smallest displacement at 130 mm.

Table IX: Mean Storey Displacement (MM) Three Pulse Categories

Storey	Low	Medium	High
0	0	0	0
2	8.8	5.5	3.3
4	19.8	11	16.5
6	35.2	24.2	30.8
8	57.2	49.5	52.8
10	90.2	85.8	74.8
12	129.8	123.2	90.2
14	167.2	159.5	104.5
16	200.2	192.5	115.5
18	228.8	220	129.8
20	227.0	263	130

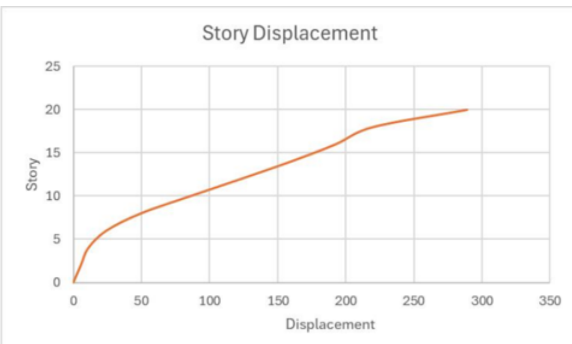

Fig. 4. Mean Storey Displacement Profiles Low, Medium, and High Pulse Categories

D. Inter-Storey Drift Ratio (IDR)

Mean inter-storey drift ratios (IDR) for all three pulse categories are presented in Table X. All values are within the IS 1893:2016 life-safety limit of 2.0% (IDR = 0.020). The peak IDR of 0.00607 (0.607%) occurs at Storey 12 under medium pulse excitation, compared to 0.00465 (0.465%) for low pulse and 0.00263 (0.263%) for high pulse records. The IDR profiles exhibit peak drift values concentrated in Storeys 11–14, consistent with combined first- and second-mode response typical of tube-in-tube systems.

Table X: Mean Inter-Storey Drift Ratio (IDR) Dimensionless Ratio

Storey	Low Drift Ratio	Medium Drift Ratio	High Drift Ratio
20	0.00703	0.00230	0.0045
18	0.00953	0.00917	0.00477
16	0.011	0.011	0.00367
14	0.01247	0.0121	0.00477
12	0.0132	0.01247	0.00513
10	0.011	0.0121	0.00753
8	0.00733	0.00843	0.00733
6	0.00513	0.0044	0.00477
4	0.00367	0.00183	0.0044
2	0.00293	0.00183	0.0011

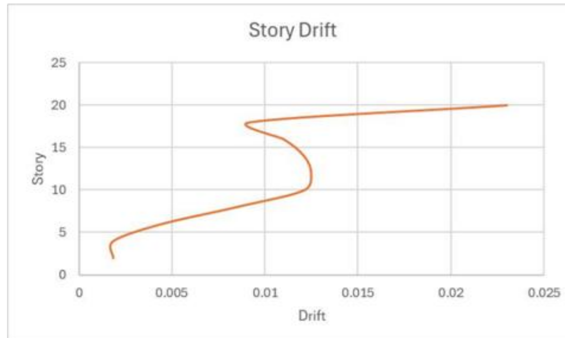

Fig. 5. Inter-Storey Drift Ratio (IDR) Profiles — Low, Medium, and High Pulse Ground Motion Groups

E. Storey Shear Forces

Table XI presents the maximum positive and negative storey shear forces (kN) for each pulse category. Shear forces increase monotonically from roof to base in all cases, confirming the absence of any soft-storey or weak-storey mechanism. Maximum base shear forces are 21,034 kN (medium pulse), 12,952 kN (low pulse), and 8,445 kN (high pulse). Medium pulse produces approximately 62% greater base shear than low pulse excitation.

Table XI: Storey Shear Forces (KN) — Maximum Positive (+) And Negative (−) Values

Storey	X_max	X_min
20	3,566	-3566
19	6,918	-6918
18	9,611	-9611
17	11,650	-11650
16	13,078	-13078
15	14,050	-14050
14	14,968	-14968
13	16,222	-16222
12	17,346	-17346
11	18,545	-18545
10	19,767	-19767
9	20,393	-20393
8	20,441	-20441
7	20,021	-20021
6	19,953	-19953
5	20,743	-20743
4	22,606	-22606

3	24,119	-24119
2	25,061	-25061
1	25,451	-25451

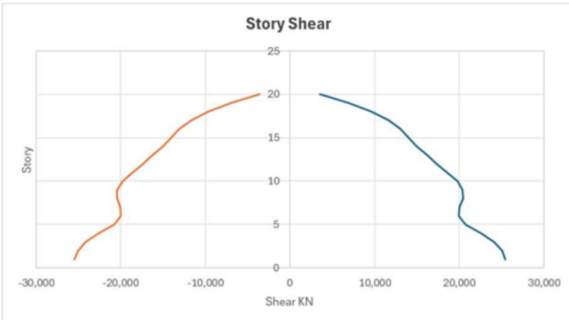

Fig. 6. Storey Shear Force Profiles

The directional asymmetry between positive and negative peak shear values (7–12%) reflects the unidirectional character of near-fault velocity pulses and unsymmetric inelastic force redistribution. Medium pulse records exhibit elevated spectral displacement demands across T = 1.0–2.0 s, overlapping directly with T_1 = 1.342 s and the closely spaced T_2–T_3 modes, explaining the governing seismic demands for this category.

V. CONCLUSIONS

1. The fundamental period T_1 = 1.342 s and cumulative modal mass of 95.07% within 12 modes satisfy the IS 1893:2016 threshold, confirming adequate model completeness.
2. Modes 1–3 exhibit closely spaced periods (1.342 s,
1.284 s, 1.191 s), indicating translational–torsional coupling; CQC combination and accidental eccentricity checks per IS 1893:2016 Clause 7.8 are mandatory.
3. A sharp period reduction of 67% from Mode 3 to Mode 4 (1.191 s → 0.397 s), with cumulative modal mass jumping from 73.55% to 88.30%, confirms significant higher-mode contribution characteristic of tube-in-tube systems.
4. Medium pulse records ($0.8 \le Tp/T_1 \le 1.2$) produce the highest drift and shear demands due to near-resonance with the fundamental period. Medium pulse governs seismic design.
5. Mean roof displacements are 227 mm (low), 263 mm (medium), and 130 mm (high pulse). Low and high values comply with IS 1893:2016 limit of 240 mm; medium pulse marginally exceeds due to mid-height drift concentration.
6. Peak IDR is 0.607% at Storey 12 under medium pulse; 0.465% (low); 0.263% (high pulse). All values are within the IS 1893:2016 life-safety limit of 2.0%.
7. Localised drift amplification at Storeys 11–14 under medium pulse results from combined first- and second-mode contributions — a critical concern for near-fault seismic design of tall tube-in-tube structures.
8. Maximum base shears are 21,034 kN (medium), 12,952 kN (low), and 8,445 kN (high pulse). Shear forces increase monotonically from roof to base; no soft-storey mechanism is observed.
9. Positive and negative peak shears differ by 7–12%, attributable to unidirectional near-fault velocity pulses. Connection and foundation designs must account for this asymmetry.
10. The tube-in-tube system performs satisfactorily under all near-fault ground motions considered. Pulse-period proximity to the structural fundamental period is the primary driver of seismic demand.

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