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Analysis of High-Rise Building using ETABS

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ABSTRACT: High-rise RC buildings are highly sensitive to earthquake-induced lateral forces, which makes reliable seismic analysis essential. This paper presents the seismic analysis of a 14-storey (40.5 m high) RC high-rise building modelled in ETABS Ultimate 22.5.0 and analysed by the response spectrum method according to IS 1893 (Part 1):2016, with gravity loads as per IS 875. The building, built with M30 concrete, Fe500 steel, two beam sections, five column sections and 250 mm RC shear walls, is analysed for Seismic Zone II ($Z = 0.10$, soil type II) and Seismic Zone IV ($Z = 0.24$, soil type I). Time period, storey displacement, storey drift, storey shear, base shear, storey stiffness and overturning moment are evaluated, and the drift is checked against the code limit of 0.004 times the storey height. The fundamental period is 2.51 s in both zones. From Zone II to Zone IV the earthquake base shear rises from 963.0 kN to 1762.8 kN in X (1.83 times) and from 1281.6 kN to 2566.8 kN in Y (2.00 times), the roof displacement rises from 14.283 mm to 25.206 mm in X and from 12.965 mm to 22.928 mm in Y (1.76 to 1.77 times), and the maximum drift rises from 0.000480 to 0.000850 in X and from 0.000402 to 0.000714 in Y. The drift reaches at most 21 % of the limit. The increases are smaller than the zone-factor ratio of 2.4 because the Zone IV model uses stiffer soil (type I) than the Zone II model (type II), so the results show the combined effect of zone and soil, as discussed in Section IV. The wind base shear is reported for reference only, and the conclusions cover seismic response.

KEYWORDS: Base shear, ETABS, high-rise building, IS 1893:2016, response spectrum method, seismic zones, storey drift.

I. INTRODUCTION

Rapid urbanisation has raised the demand for tall residential, commercial and mixed-use buildings, which allow scarce urban land to serve a growing population. Greater height, however, brings greater exposure to earthquake and wind loading. Tall buildings are more flexible, have longer natural periods and respond more strongly to dynamic excitation than low-rise buildings, so gravity loads alone cannot establish their safety [1], [2], [3]. A thorough seismic analysis at the design stage is therefore indispensable, and in India the structural safety of tall concrete buildings is addressed specifically by IS 16700 [4].

During an earthquake the ground motion produces inertia forces over the height of the building, which appear as lateral displacement, storey drift, shear and bending moment and govern both safety and serviceability. Ductility, the capacity to deform inelastically without a significant loss of strength, largely decides whether a frame survives strong shaking [1], [5], [6], and Indian practice therefore couples the analysis code with a code for ductile detailing, IS 13920 [7].

Seismic hazard is not uniform across a country, and design codes therefore divide the territory into zones. IS 1893 (Part 1):2016 [8] places India in four seismic zones, II, III, IV and V, with zone factors Z of 0.10, 0.16, 0.24 and 0.36 respectively. A building in Zone IV is therefore designed for 2.4 times the seismic coefficient of an identical building in

Zone II, and the behaviour of the structure under different seismic intensities should be studied before the design is finalised [9].

The equivalent static method represents the earthquake by static lateral forces and suits regular, low-rise structures, whereas the response spectrum method combines the peak modal responses and is appropriate for tall buildings, in which higher modes contribute appreciably [1], [8], [10]. Time history and nonlinear static (pushover) procedures extend the analysis to inelastic behaviour at a higher computational cost [11], [12].

ETABS [13] builds three-dimensional models of multi-storey buildings, applies code-based loads and extracts displacement, drift, storey shear and modal properties. It has been widely used for seismic studies of tall buildings, covering seismic zones and shear wall locations [14], [15], seismic and wind loads [16], nonlinear static evaluation [17] and outrigger, belt truss and shear wall systems [18], [19] (see also [20]). These studies show that seismic response grows with the zone factor and that added lateral stiffness reduces displacement and drift.

The present paper analyses a 14-storey RC building, framed with two beam sections and five column sections and stiffened by RC shear walls, for Seismic Zone II and Seismic Zone IV. Choosing a low-intensity zone and a high-intensity zone makes the effect of the zone factor on the same structure easy to see and shows how the drift response of one member layout changes between the two zones. The analysis uses the response spectrum method in ETABS Ultimate 22.5.0 in accordance with IS 1893 (Part 1):2016. The two models use different soil types, so the comparison shows the combined effect of the zone factor and the soil type. Wind base shear is reported for reference only, so the conclusions cover seismic response.

A. Objectives of the Study

1. To model a 14-storey RC high-rise building in ETABS using the specified geometry, material grades and member sizes.
2. To perform response spectrum analysis as per IS 1893 (Part 1):2016 for Seismic Zones II and IV.
3. To evaluate and compare storey displacement, storey drift, storey shear, base shear, time period, frequency, storey stiffness and overturning moment in the two zones, and to compare the earthquake base shear with the wind base shear.
4. To check the storey drift against the code limit and report drift compliance in each zone; member strength design is outside the scope of this study.

II. LITERATURE REVIEW

The seismic behaviour of high-rise buildings has been studied extensively with ETABS; the studies relevant to the present work are reviewed below.

A. Effect of Seismic Zone

Several authors have examined how the same building responds in different zones. Ahamad and Pratap [14] analysed a G+20 building by response spectrum analysis in Zones II to V and found the largest displacement and storey drift in Zone V for every shear wall arrangement. Kumar et al. [15] reached the same conclusion for a G+10 building, reporting greater lateral displacement and drift in Zone V than in Zones III and IV and a higher storey shear in Zone V than in Zone III. Sathishkumar and Senthamilselvi [19] analysed a G+25 building in Zones II to V and found that displacement, drift and base shear increased progressively with the zone factor. Shear walls at the plan ends or corners [14], [19] and outrigger and belt truss systems [18], [21], [22] reduce displacement and drift, usually at the cost of a higher base shear, and pushover procedures and P-delta effects are treated in [11], [12], [16], [17], [24].

B. Research Gap

The reviewed studies show that seismic response grows with the zone factor and that added lateral stiffness reduces displacement and drift at the cost of a higher base shear. Since [14], [15] and [19] already cover Zones II to V, the present work is a building-specific compliance check: it analyses one 14-storey RC building in a low-intensity and a high-intensity

zone and checks drift, stiffness and overturning demand against IS 1893 (Part 1):2016 [8]. For each response parameter the governing theory and the expected zone-to-zone ratio are stated so that the ETABS results can be verified against first principles. Zone II is analysed with medium soil and Zone IV with hard soil, so the comparison covers the combined effect of zone and soil.

III. METHODOLOGY

The study follows a systematic procedure: definition of the building geometry and material properties, three-dimensional modelling in ETABS, assignment of loads and load combinations, modal and response spectrum analysis for Seismic Zones II and IV, and extraction and comparison of the response parameters. Fig. 1 shows the workflow.

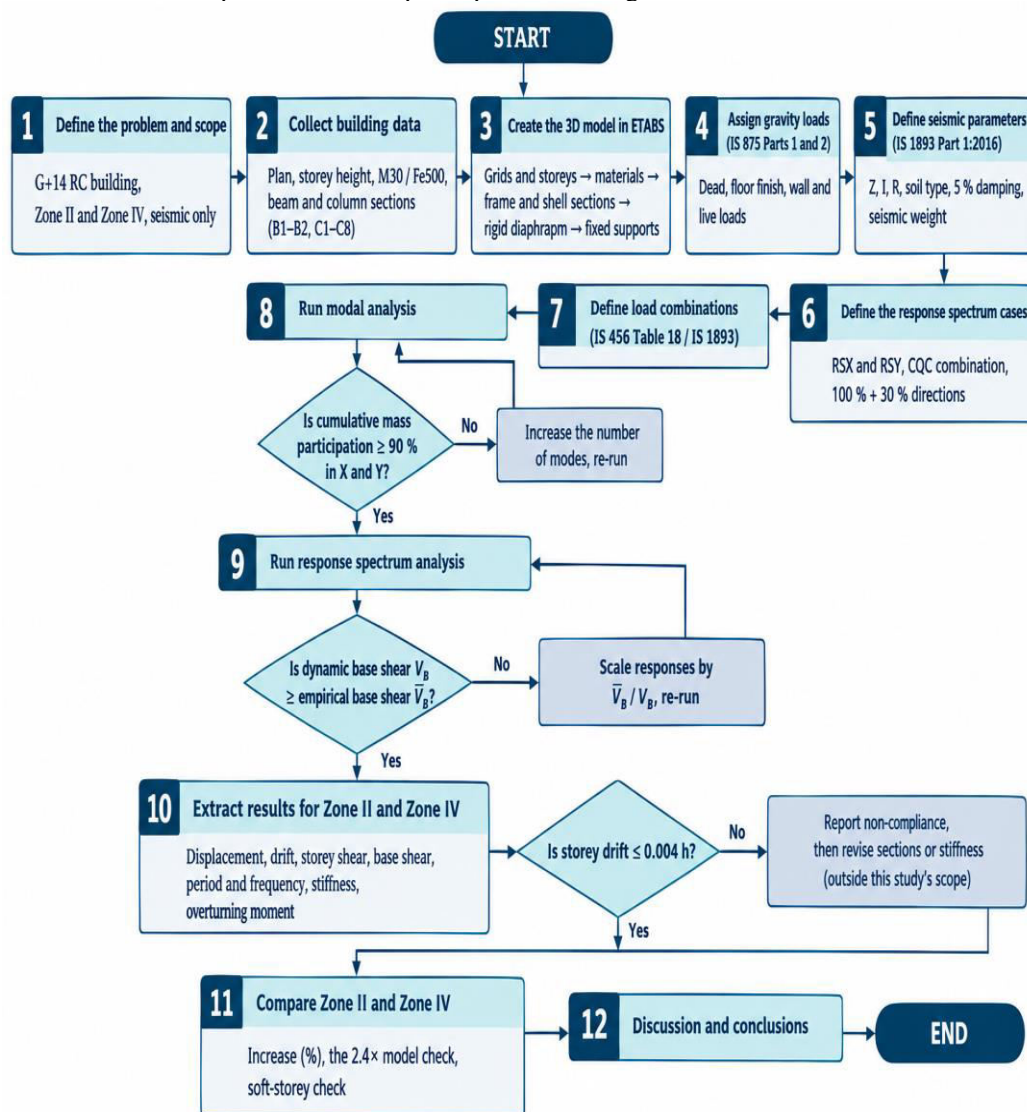


Fig.1. Flowchart of the methodology.

A. Description of the Building

The building is a 14-storey RC high-rise structure, 40.5 m high, in which the first storey (Story1) is 1.5 m high and the other thirteen storeys are 3 m high. The structural system is an RC frame of beams, columns and slabs, stiffened by RC shear walls, that resists both gravity and lateral loads. The general particulars are given in Table I. Concrete of grade M30 and reinforcing steel of grade Fe500 were used, and the members were proportioned in accordance with IS 456:2000 [25]; ductile detailing of such frames is governed by IS 13920:2016 [7]. A response reduction factor $R = 5$ was adopted for the structure [7], [8].

TABLE I GENERAL DETAILS OF THE BUILDING

Parameter	Value
Type of structure	RC frame with shear walls (dual system)
Plan dimensions	28.133 m $\times$ 18.036 m
Number of storeys	14 levels (Story1 to Story14)
Storey height	3.0 m (Story1 = 1.5 m)
Total height	40.5 m
Slab thickness	150 mm
Wall type and thickness	RC shear walls, 250 mm (M30)
Concrete / steel grade	M30 / Fe500
Support condition	Fixed base

Two beam sections and five column sections were used, together with RC shear walls 250 mm thick. Their sizes are listed in Table II, and their positions are shown in the plan in Fig. 2. [Table II to add columns for local-axis orientation, plan location and storey range of each column.]

TABLE II MEMBER SIZES

Member	Section (mm)
Beam B1	450 $\times$ 600
Beam B2	300 $\times$ 600
Column C1	350 $\times$ 1100
Column C2	450 $\times$ 1500
Column C3	450 $\times$ 1200
Column C4	450 $\times$ 1100
Column C5	500 $\times$ 1500
Shear walls W1 to W9	250 thick

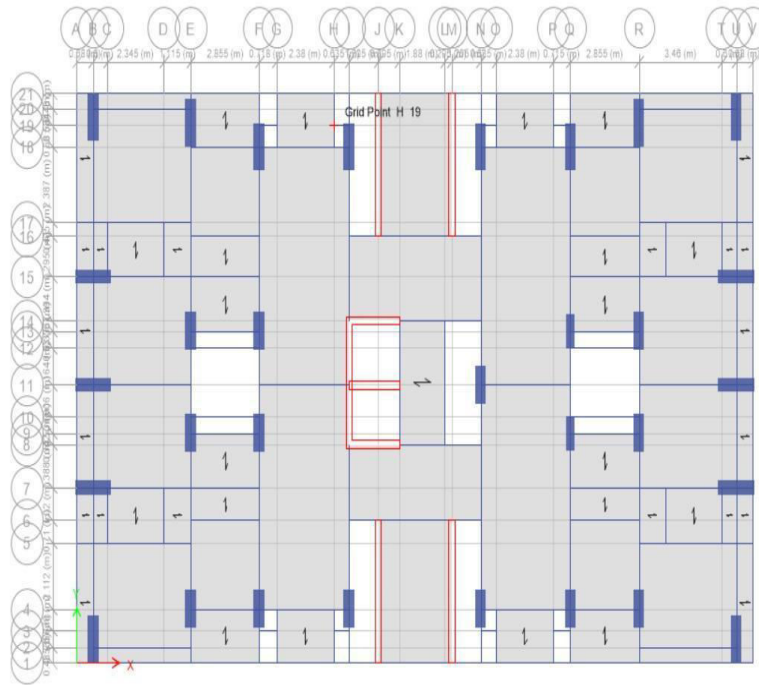


Fig.2. Plan of the building

B. Modelling in ETABS

The building was modelled in ETABS Ultimate 22.5.0 [13]. Beams and columns were modelled as frame elements, slabs as membrane elements and the 250 mm shear walls as thin shell elements, with a rigid diaphragm at each floor level and fixed supports at the foundation. The P-delta effect [24] was not included, infill walls were applied as line loads on the beams without stiffness, and gross section properties were used for all members.

The ETABS analysis settings were as follows: mass source dead load plus 25 % of the live load; modal case Eigen with 12 modes; damping ratio 5 %; response spectrum cases SPECTRAX and SPECTRAY for earthquake in X and Y; and wind load cases WINDX and WINDY as per IS 875 (Part 3) [27], used for reference only. The response spectrum results reported in this paper are the unscaled ETABS values. The scale factors required by (7) are 4.16 (X) and 2.50 (Y) for Zone II and 4.01 (X) and 2.20 (Y) for Zone IV, and they are derived in Section IV-D.

C. Loads and Load Combinations

Gravity loads comprise the self-weight of the structure, floor finish, wall loads and live loads, defined as per IS 875 (Parts 1 and 2) [26] and listed in Table III. Wind load cases WINDX and WINDY were defined as per IS 875 (Part 3) [27] and only the resulting base shear is reported, for reference; wind design and load combinations with wind are outside the scope of this study.

TABLE III GRAVITY LOADS APPLIED

Load	Intensity
Floor finish	1.5 kN/m ²
Wall load on beams	13 kN/m
Live load on floors	2 kN/m ²

The seismic weight W of each floor was taken as the full dead load plus a fraction of the imposed load, 25 % where the imposed load does not exceed 3 kN/m^2 and 50 % where it exceeds 3 kN/m^2 , as specified in IS 1893 (Part 1):2016 [8]; no imposed load is included on the roof. The load combinations of the code (IS 456:2000 [25], Table 18), given in Table IV, were used, where DL, LL and EL denote the dead, live and earthquake loads and the earthquake load acts in both horizontal directions with the sign reversed.

TABLE IV LOAD COMBINATIONS

No.	Combination
1	1.5 (DL + LL)
2	1.2 (DL + LL $\pm$ EL)
3	1.5 (DL $\pm$ EL)
4	0.9 DL $\pm$ 1.5 EL

The earthquake loads in the two orthogonal directions were combined using 100 % of the force in one direction and 30 % in the other, as required by the code [8]; explicitly, $EL = \pm EX \pm 0.3EY$ or $\pm 0.3EX \pm EY$, where EX and EY are the earthquake loads in the X and Y directions.

D. Response Spectrum Method

The response spectrum method is a linear dynamic procedure. The building is idealised as a multi-degree-of-freedom system, and its natural frequencies and mode shapes are obtained from an eigenvalue analysis. The peak response in each mode is read from the design response spectrum, and the modal values are combined to give the total response [1]. The number of modes was chosen so that at least 90 % of the total seismic mass is captured in each principal direction, as the code requires [8]. The modal responses were combined using the complete quadratic combination (CQC) rule [28], [29],

$$\lambda = \sqrt{\sum_{i=1}^n \sum_{j=1}^n \lambda_i \rho_{ij} \lambda_j} \quad (1)$$

where λ is the combined response quantity, λ_i and λ_j are the peak responses in modes i and j , and ρ_{ij} is the cross-modal correlation coefficient, and n is the number of modes considered. For modes with the same damping ratio ζ it is given by [28]

$$\rho_{ij} = \frac{8\zeta^2(1+r)^{\frac{3}{2}}}{[(1-r)^2 + 4\zeta^2 r(1+r)^2]} \quad (2)$$

where $r = \omega_j/\omega_i$ is the ratio of the circular frequencies of modes j and i . For well-separated modes the cross terms vanish and the CQC rule reduces to the square root of the sum of squares (SRSS),

$$\lambda = \sqrt{\sum_{i=1}^n \lambda_i^2} \quad (3)$$

The design horizontal seismic coefficient of IS 1893 (Part 1):2016 [8] is

$$A_h = \frac{Z}{2} \times \frac{I}{R} \times \frac{S_a}{g} \quad (4)$$

where Z is the zone factor, I the importance factor, R the response reduction factor, and S_a/g the design acceleration coefficient for the natural period and soil type. For any structure with $T \leq 0.10 \text{ s}$, A_h is not to be taken less than $Z/2$, whatever the value of I/R [8]. Other seismic codes, for example Eurocode 8 [30], likewise define the design action through a normalised elastic response spectrum that is scaled by the design ground acceleration and reduced by a behaviour factor. For medium soil and 5 % damping, S_a/g is given by [8]

$$\{S_a/g = 1 + 15T, 0 \leq T < 0.10 \quad S_a/g = 2.5, 0.10 \leq T < 0.55 \quad S_a/g = \frac{1.36}{T}, 0.55 \leq T < 4.00 \quad S_a/g = 0.34, T \geq 4.00 \quad (5)$$

where T is the natural period in seconds. The design base shear is

$$V_B = A_h W \quad (6)$$

where W is the seismic weight of the building. The code requires the base shear V_B^{dyn} obtained from the dynamic analysis to be at least the base shear V_B computed with the empirical fundamental period T_a ; if it is smaller, all response quantities are multiplied by the scale factor [8]

$$SF = \frac{V_B}{V_B^{\text{dyn}}} \quad (7)$$

where $V_B = A_h W$ evaluated with $T = T_a$. For an RC moment-resisting frame without brick infill panels the empirical period is [8]

$$T_a = 0.075h^{0.75} \quad (8)$$

where h is the height of the building in metres. For an RC frame with brick infill panels the code gives [8]

$$T_a = \frac{0.09h}{\sqrt{d}} \quad (9)$$

where d is the base dimension of the building at plinth level, in metres, along the direction of the lateral force considered. Equation (8) applies to a bare frame and (9) to a frame with infill; the appropriate expression is used for each direction. The seismic parameters adopted for the two zones are listed in Table V.

TABLE V SEISMIC PARAMETERS

Parameter	Zone II	Zone IV
Zone factor Z	0.10	0.24
Importance factor I	1.2	1.2
Response reduction factor R	5	5
Soil type	II (medium)	I (hard)
Damping ratio	5 %	5 %
Modal combination	CQC	CQC
Mass participation required	90 %	90 %
Directional combination	100 % + 30 %	100 % + 30 %
Seismic mass (kg)	17,180,132	17,180,682
Wind load (reference)	IS 875 (Part 3)	IS 875 (Part 3)

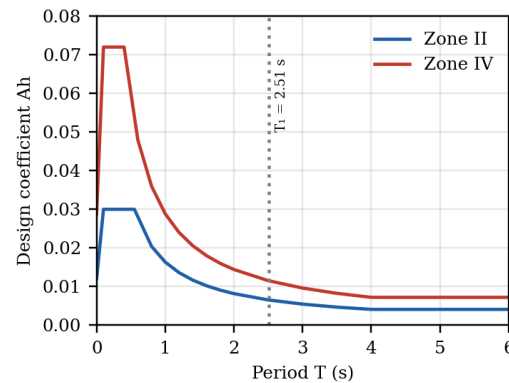


Fig.3.Design response spectra for Zone II and Zone IV

IV. RESULTS AND DISCUSSION

This section presents the response spectrum results of the 14-storey building for Seismic Zone II and Seismic Zone IV, taken from the ETABS reports of the two models for the cases SPECTRAX (earthquake in X) and SPECTRAY (earthquake in Y). The geometry, member sizes, loads and mass are the same in both models (seismic mass 17,180,132 kg and 17,180,682 kg, a difference of 0.003 %), and only the seismic parameters of the design spectrum change. For each parameter the governing theory is given first, followed by the table, figures and discussion. The ratio of the zone factors of Zone IV and Zone II is $0.24/0.10 = 2.4$. However, Zone II was analysed with medium soil (type II) and Zone IV with hard soil (type I), as listed in Table V, so the results show the combined effect of the zone factor and the soil type, not of the zone alone. At the fundamental period of 2.51 s the design coefficients are 0.006528 (Zone II) and 0.01152 (Zone IV), a ratio of $0.24/0.10 \times 1.00/1.36 = 1.76$, whereas on the short-period plateau ($T < 0.4$ s) the ratio is 2.4. First-mode quantities such as displacement and drift are therefore expected to increase by about 76 %, and base shear by a ratio between 1.76 and 2.4 depending on the contribution of the short-period modes, while the time period, frequency and storey stiffness, which depend only on mass and stiffness, are expected to be the same in both zones. In the tables, the ratio is the Zone IV value divided by the Zone II value.

A. Storey Displacement

Storey displacement is the absolute lateral movement of a floor relative to the base. A tall frame behaves like a vertical cantilever: displacement is zero at the fixed base and maximum at the terrace level. Excessive displacement endangers stability through P-delta effects [24] and can cause pounding with adjacent buildings.

For a single mode the peak displacement is the modal participation factor times the mode shape times the spectral displacement $S_d = S_a/\omega^2$. At a fixed period S_d is proportional to S_a , so the displacement of a given structure grows in the same proportion as the design spectrum, that is, with Z and the soil factor. IS 456:2000 [25] limits the lateral sway of a building under wind to $H/500$, which is 81 mm for the 40.5 m height of this building, and this value is used here only as an indicative check for earthquake displacement.

TABLE VI MAXIMUM STOREY DISPLACEMENT (MM)\

Storey	Level (m)	Zone II, X	Zone IV, X	Zone II, Y	Zone IV, Y
Story14	40.5	14.283	25.206	12.965	22.928
Story13	37.5	13.601	23.999	12.025	21.243
Story12	34.5	12.835	22.648	11.044	19.495
Story11	31.5	11.965	21.115	10.017	17.676
Story10	28.5	10.981	19.381	8.945	15.790
Story9	25.5	9.886	17.446	7.832	13.847
Story8	22.5	8.686	15.324	6.691	11.861
Story7	19.5	7.394	13.039	5.537	9.852
Story6	16.5	6.028	10.630	4.387	7.847
Story5	13.5	4.620	8.154	3.270	5.884
Story4	10.5	3.221	5.696	2.220	4.022
Story3	7.5	1.909	3.386	1.288	2.349
Story2	4.5	0.809	1.442	0.540	0.994

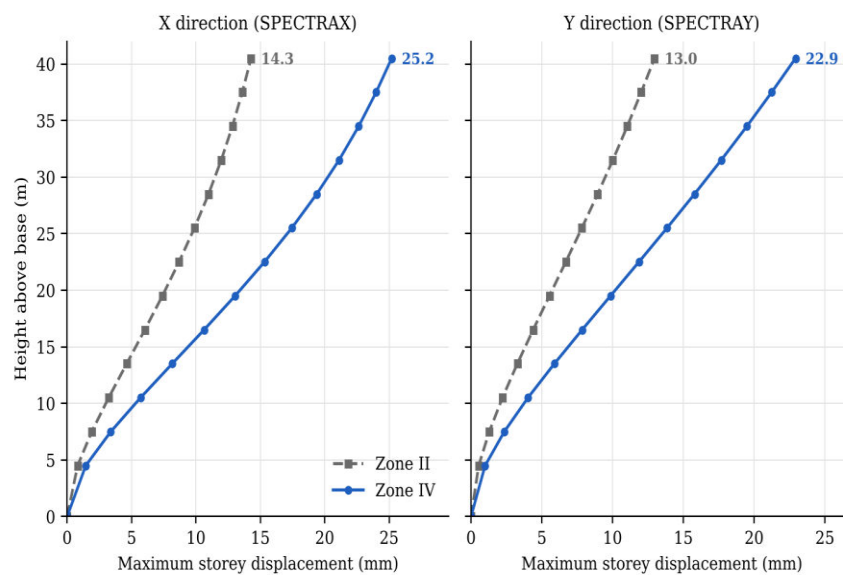


Fig.4. Maximum storey displacement along the height for Zone II and Zone IV

Displacement increases with height in both zones and is largest at the roof (Story14), as expected for a vertical cantilever (Fig. 4 and Table VI). The roof displacement is 14.283 mm (Zone II) and 25.206 mm (Zone IV) in X, and 12.965 mm and

22.928 mm in Y. Zone IV is 1.76 times Zone II in X and 1.77 times in Y at the roof, which matches the ratio of 1.76 between the design coefficients at the fundamental period. At the other storeys the ratio is 1.76 to 1.78 in X and 1.77 to 1.84 in Y, and it rises slightly towards the base in Y.

The roof displacement of the building is about 0.62×10^{-3} of its height in Zone IV (X), against the indicative limit of $H/500 = 2 \times 10^{-3}$ (81 mm), and both zones are well inside this value for the unscaled response. Displacements are larger in X than in Y because the first mode is a translation in X, with a longer period (2.513 s) than the first Y mode (1.838 s).

B. Storey Drift

Storey drift is the relative lateral displacement of two consecutive floors, usually expressed as a ratio to the storey height,

$$\theta_i = \frac{\delta_i - \delta_{i-1}}{h_i} \quad (10)$$

where δ_i and δ_{i-1} are the displacements of floors i and $i-1$ and h_i is the height of storey i . Drift is a key serviceability and safety measure because excessive drift damages non-structural elements such as partitions and facades and increases the second-order effects in columns. IS 1893 (Part 1):2016 [8] limits the storey drift under the design seismic force, taken with a partial load factor of 1.0, to 0.004 times the storey height. The drift check uses the response spectrum cases SPECTRAX and SPECTRAY with a load factor of 1.0. In a building with shear walls or a stiff core the drift is small at the base, largest in the middle storeys and smaller again towards the roof.

TABLE VII STOREY DRIFT (RATIO)

Storey	Level (m)	Zone II, X	Zone IV, X	Zone II, Y	Zone IV, Y
Story14	40.5	0.000274	0.000494	0.000333	0.000612
Story13	37.5	0.000308	0.000553	0.000350	0.000642
Story12	34.5	0.000345	0.000613	0.000367	0.000671
Story11	31.5	0.000380	0.000670	0.000383	0.000693
Story10	28.5	0.000410	0.000724	0.000394	0.000708
Story9	25.5	0.000436	0.000772	0.000401	0.000714
Story8	22.5	0.000458	0.000813	0.000402	0.000712
Story7	19.5	0.000474	0.000841	0.000397	0.000701
Story6	16.5	0.000480	0.000850	0.000383	0.000677
Story5	13.5	0.000472	0.000833	0.000358	0.000637
Story4	10.5	0.000439	0.000775	0.000317	0.000569
Story3	7.5	0.000367	0.000649	0.000254	0.000460
Story2	4.5	0.000234	0.000417	0.000159	0.000292
Story1	1.5	0.000083	0.000149	0.000049	0.000090

TABLE VIII MAXIMUM STOREY DRIFT AND CODE CHECK

Case	Max. drift	Storey	% of limit	Status
X, Zone II	0.000480 (1/2082)	Story6	12	OK
X, Zone IV	0.000850 (1/1176)	Story6	21	OK
Y, Zone II	0.000402 (1/2487)	Story8	10	OK
Y, Zone IV	0.000714 (1/1400)	Story9	18	OK

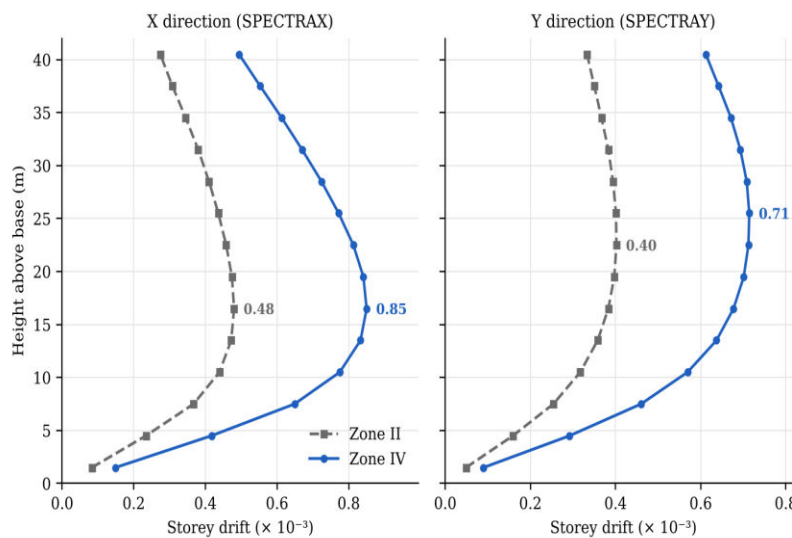


Fig.5. Storey drift along the height for Zone II and Zone IV.

Storey drift is small at the base, rises to a maximum in the middle storeys and then reduces towards the roof, which is the usual pattern for a building with shear walls or a stiff core (Fig. 5 and Table VII). The maximum drift in X is 0.000480 (1/2082) in Zone II and 0.000850 (1/1176) in Zone IV, both at Story6. In Y it is 0.000402 (1/2487) at Story8 in Zone II and 0.000714 (1/1400) at Story9 in Zone IV (Table VIII).

The Zone IV drift is about 1.8 times the Zone II drift at every storey (ratio range 1.76 to 1.84), consistent with the displacement ratio. Against the IS 1893 limit of 0.004, the maximum Zone II drift uses 12 % (X) and 10 % (Y) of the limit, and the maximum Zone IV drift uses 21 % (X) and 18 % (Y). The drift criterion is therefore satisfied in both zones with a large margin. These drifts are unscaled response spectrum results; the effect of the base shear scaling of (7) is given in Section IV-D.

C. Storey Shear

Storey shear is the total lateral seismic force acting at and above a given storey, that is, the sum of the floor forces Q_j from the top to that level,

$$V_i = \sum_{j=i}^n Q_j \quad (11)$$

It is largest at the base and decreases towards the top because each storey carries the inertia forces of the floors above it, and it governs the design of the vertical members.

TABLE IX STOREY SHEAR AT THE BOTTOM OF EACH STOREY (KN)

Storey	Zone II, X	Zone IV, X	Zone II, Y	Zone IV, Y
Story14	209.6	427.6	267.5	584.7
Story13	374.3	725.9	491.3	1051.1
Story12	468.9	860.7	620.9	1289.1
Story11	530.8	944.5	685.9	1368.8
Story10	580.6	1036.7	722.8	1383.1
Story9	620.9	1125.2	760.7	1409.0
Story8	657.5	1202.4	811.4	1478.9
Story7	699.4	1277.0	877.7	1599.1
Story6	746.9	1344.8	961.5	1777.8
Story5	799.2	1416.0	1060.3	2010.7
Story4	860.1	1524.6	1159.6	2256.5
Story3	920.9	1659.6	1236.9	2452.4
Story2	958.5	1751.4	1277.0	2555.0
Story1	963.0	1762.8	1281.6	2566.8

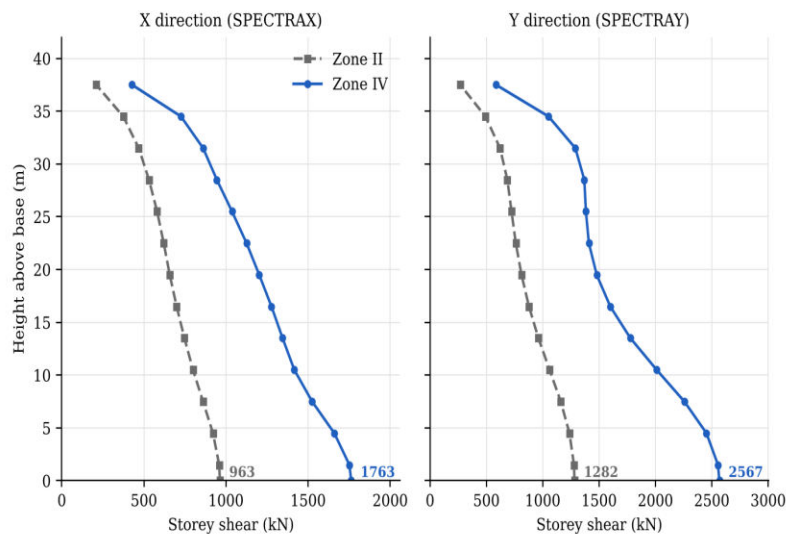


Fig. 6. Storey shear along the height for Zone II and Zone IV.

The storey shear is largest at the base in both zones, where it equals the base shear, and reduces towards the roof (Fig. 6 and Table IX). At Story14 it is 209.6 kN (Zone II) and 427.6 kN (Zone IV) in X, and 267.5 kN and 584.7 kN in Y. The Zone IV storey shear is 1.77 to 2.04 times the Zone II value in X and 1.82 to 2.19 times in Y. The ratio is lowest in the lower and

middle storeys (Story5 in X and Story7 in Y) and highest at Story14, where the higher modes contribute most; at the base it is 1.83 in X and 2.00 in Y.

D. Base Shear

Base shear is the total horizontal seismic force at the base of the structure, given by (6). For the same seismic weight, importance factor, response reduction factor and period, it is directly proportional to the zone factor and, through S_a/g , to the soil factor. In the response spectrum method the base shear of each mode follows from the spectral acceleration at that mode's period and the effective modal mass, and the modal values are combined by the CQC rule. The values in Table X are the unscaled response spectrum base shears from ETABS, and the wind base shear from IS 875 (Part 3) [27] is given for reference.

TABLE X BASE SHEAR (kN)

Load case		Zone II	Zone IV	Ratio
Earthquake, (SPECTRAX)	X	963.02	1762.82	1.83
Earthquake, (SPECTRAY)	Y	1281.58	2566.81	2.00
Wind, X (WINDX)		961.34	961.34	1.00
Wind, Y (WINDY)		1499.53	1499.53	1.00

The earthquake base shear in Zone IV is 1.83 times that of Zone II in X (963.0 kN to 1762.8 kN) and 2.00 times in Y (1281.6 kN to 2566.8 kN). The increase is less than the zone-factor ratio of 2.4 because the Zone IV model uses the stiffer soil type I, which has a lower spectral ordinate at long periods. The ratio is higher in Y (2.00) than in X (1.83) mainly because more of the Y-direction mass takes part in short-period modes (below 0.55 s), where the soil-type effect is smaller: about 22 % of the mass in Y against about 8 % in X, from the modal participation ratios.

The seismic weight of the building is 168,537 kN in Zone II (17,180,132 kg from dead load plus 25 % of the live load) and 168,542 kN in Zone IV (17,180,682 kg). The unscaled base shear in X is 963.0 kN in Zone II and 1762.8 kN in Zone IV, which is 0.57 % and 1.05 % of the seismic weight, and in Y it is 1281.6 kN and 2566.8 kN, which is 0.76 % and 1.52 %.

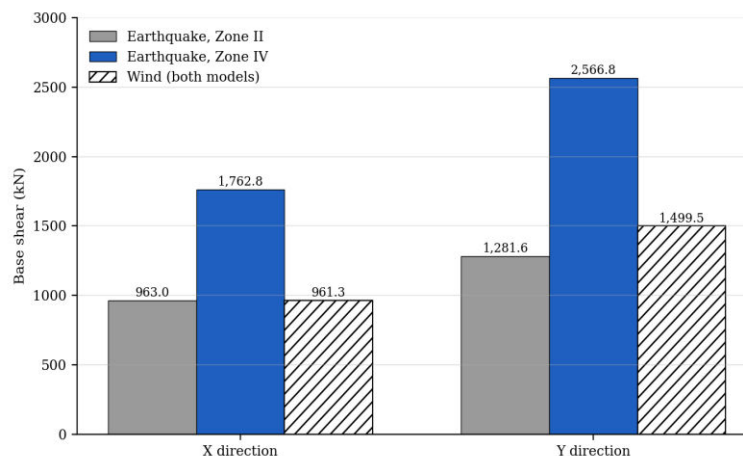


Fig.7. Earthquake and wind base shear (unscaled response spectrum results).

The wind base shear is the same in both models (961.3 kN in X and 1499.5 kN in Y). In Zone II the Y-direction wind base shear (1499.5 kN) is larger than the Y-direction earthquake base shear (1281.6 kN), so wind is the larger lateral load in that direction, while in X the two are practically equal (963.0 kN and 961.3 kN). In Zone IV earthquake governs in both directions. This comparison uses the unscaled earthquake values; after the scaling described below, the earthquake design base shear exceeds the wind base shear in every case.

The code requires the dynamic base shear to be not less than the design base shear $A_h W$ computed with the empirical period [8]. With the empirical period of (9), $T_a = 0.687$ s in X and 0.858 s in Y, and the design coefficient of (4), the design base shears of Table XI are obtained. The dynamic base shear is smaller than the design base shear in all four cases, so the response must be multiplied by the scale factors of (7): 4.16 (X) and 2.50 (Y) in Zone II and 4.01 (X) and 2.20 (Y) in Zone IV, which are the factors listed in Section III-B.

TABLE XI DYNAMIC AND DESIGN BASE SHEAR AND SCALE FACTORS

Case	Dynamic (kN)	T_a (s)	A_h	Design (kN)	SF
Zone II, X	963.02	0.687	0.02375	4,002.5	4.16
Zone II, Y	1281.58	0.858	0.01901	3,204.7	2.50
Zone IV, X	1762.82	0.687	0.04191	7,063.4	4.01
Zone IV, Y	2566.81	0.858	0.03356	5,655.5	2.20

Table XII shows the effect of the scaling on the roof displacement and the maximum drift, obtained by multiplying the unscaled values by the scale factors. After scaling, the design base shear of Zone IV is 1.76 times that of Zone II in both directions, equal to the ratio of the design spectra beyond 0.55 s, while the scaled displacement and drift ratios are about 1.70 in X and 1.56 in Y. The scaled maximum drift is 0.0020 in Zone II and 0.0034 in Zone IV in X, which is 50 % and 85 % of the limit of 0.004, and 0.0010 and 0.0016 in Y, which is 25 % and 39 %. The drift criterion is therefore still satisfied in both zones, but the margin in Zone IV (X) is much smaller than the unscaled results alone suggest. The scaled roof displacement in Zone IV (X), 101.1 mm, exceeds the indicative value $H/500 = 81$ mm, which is a wind sway limit of IS 456:2000 [25] and not an earthquake requirement of IS 1893.

TABLE XII EFFECT OF BASE SHEAR SCALING

Quantity	Zone II, X	Zone IV, X	Zone II, Y	Zone IV, Y
Roof displ., unscaled (mm)	14.283	25.206	12.965	22.928
Roof displ., scaled (mm)	59.4	101.1	32.4	50.4
Max. drift, unscaled	0.000480	0.000850	0.000402	0.000714
Max. drift, scaled	0.00200	0.00341	0.00101	0.00157
Scaled drift (% of limit)	50	85	25	39

E. Natural Time Period, Frequency and Mass Participation

The natural time period T is the time taken by the structure to complete one cycle of free vibration, and the natural frequency is its reciprocal,

$$f = \frac{1}{T} = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \quad (12)$$

where k is the stiffness and m the mass of the equivalent single-degree-of-freedom system; (12) is the single-degree-of-freedom relation and applies to the building only approximately. A taller or more flexible building has a longer period. The period depends only on mass and stiffness and is therefore independent of the seismic zone, because the zone factor changes the force but not the structure. The period from the modal analysis is compared with the empirical period of (8) or (9) as a check of the model, and the cumulative modal mass participation is checked to reach 90 % in each direction.

TABLE XIII MODAL TIME PERIODS AND FREQUENCIES (FIRST 12 MODES)

Mode	T, Zone II (s)	T, Zone IV (s)	f, Zone II (Hz)	f, Zone IV (Hz)
1	2.513	2.512	0.398	0.398
2	2.384	2.384	0.419	0.419
3	1.838	1.838	0.544	0.544
4	0.729	0.728	1.373	1.373
5	0.700	0.700	1.428	1.428
6	0.437	0.437	2.288	2.288
7	0.354	0.354	2.828	2.829
8	0.347	0.347	2.883	2.884
9	0.207	0.207	4.828	4.828
10	0.205	0.205	4.874	4.875
11	0.183	0.183	5.464	5.464
12	0.136	0.136	7.334	7.334

TABLE XIV MODAL MASS PARTICIPATION RATIOS (ZONE II)

Mode	UX	UY	RZ
1	0.7207	0.0002	0.0062
2	0.0064	0.0338	0.6914
3	0.00002	0.6379	0.0358

The time periods of the two models are practically identical (Table XIII). The fundamental period is 2.513 s in Zone II and 2.512 s in Zone IV, and the first 12 modes agree to within 0.001 s, which confirms that the seismic zone does not change the dynamic characteristics of the building. The 0.001 s difference comes from the very small difference in the total mass of the two models (17,180,132 kg and 17,180,682 kg, that is 0.003 %).

The fundamental mode is a translation in X (72.1 % of the mass, and 99 % of the modal direction factor in UX), the second mode (2.384 s) is torsion-dominated (RZ 69.1 % of the mass, 94 % of the direction factor in RZ), and the third mode (1.838 s) is a translation in Y (63.8 % of the mass, 95 % in UY), as shown in Table XIV. The torsional period is 95 % of the fundamental period, so the torsional coupling is strong. The modal period is more than twice the empirical period of (8), 1.20 s, and longer than the values of (9), 0.69 s in X and 0.86 s in Y, which is usual for a model without infill stiffness. The cumulative mass participation after 12 modes is 92.4 % in X and 89.4 % in Y in both models. X reaches 90 % at mode 9, but Y is just below the 90 % required by the code, so a few more modes should be included.

F. Storey Stiffness

The lateral stiffness of a storey is the storey shear divided by the storey drift,

$$k_i = \frac{V_i}{(\delta_i - \delta_{i-1})} \quad (13)$$

It shows how much resistance each storey offers to lateral deformation. IS 1893 (Part 1):2016 [8] classes a storey as soft [9] if its lateral stiffness is less than 70 % of that of the storey above or less than 80 % of the average of the three storeys above it.

TABLE XV STOREY STIFFNESS (kN/MM)

Storey	Zone II, X	Zone IV, X	Zone II, Y	Zone IV, Y
Story14	255	289	268	318
Story13	405	438	468	546
Story12	453	468	564	640
Story11	466	470	597	658
Story10	472	477	612	651
Story9	475	486	632	658
Story8	479	493	673	692
Story7	492	506	737	760
Story6	519	527	837	875
Story5	564	567	987	1,052
Story4	653	656	1,219	1,322
Story3	836	852	1,623	1,777
Story2	1,365	1,400	2,677	2,917
Story1	7,735	7,887	17,437	19,013

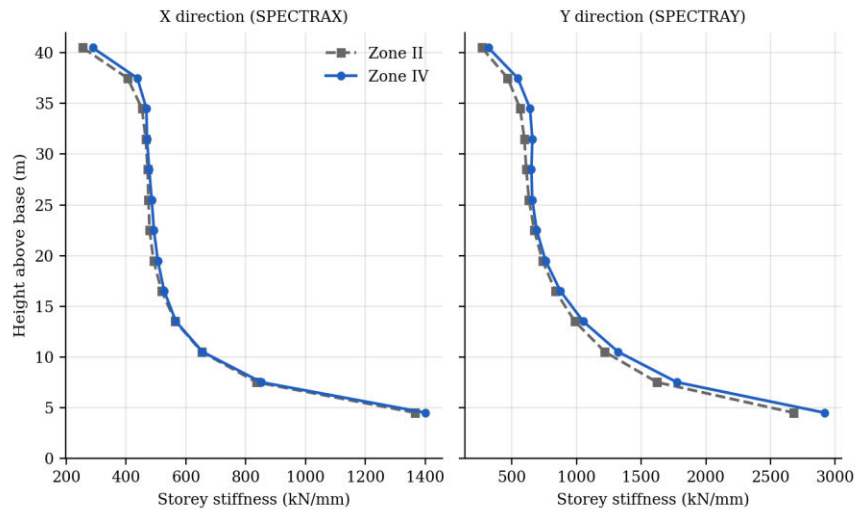


Fig.8. Storey stiffness along the height (Story1 is not plotted; see Table XV).

The storey stiffness, calculated from the storey shear of Table IX and the drift of Table VII with the storey height, is smallest at the top storey and increases towards the base (Fig. 8 and Table XV). In X it is 255 kN/mm in Zone II and 289 kN/mm in Zone IV at Story14, 564 and 567 kN/mm at Story5, and 7,735 and 7,887 kN/mm at Story1, which is far stiffer because it is only 1.5 m high. In Y the corresponding values are 268 and 318 kN/mm at Story14, 987 and 1,052 kN/mm at Story5, and 17,437 and 19,013 kN/mm at Story1, so the building is stiffer in Y than in X.

The stiffness of the structure is the same in both models. The Zone IV values differ from those of Zone II by 0 to 3 % in X below Story12 and by up to 13 % at Story14, and by 3 to 19 % in Y; each value is the ratio of a combined storey shear to a drift, and the small differences are attributed to the slightly different weight of the higher modes in the modal combination for the two design spectra. No storey has a stiffness below 70 % of that of the storey above (lowest ratio 1.00 in X and 0.99 in Y) or below 80 % of the average of the three storeys above (lowest ratio 1.02 in X and 1.01 in Y), in either zone, so the building has no soft storey in either direction.

G. Overturning Moment

The overturning moment at the base is the moment of the lateral floor forces about the base,

$$M_{OT} = \sum_{i=1}^n Q_i H_i \quad (14)$$

where Q_i is the lateral force at floor i and H_i its height above the base. It governs the axial forces in the columns and the demand on the foundation, and it increases with both the building height and the seismic intensity.

TABLE XVI OVERTURNING MOMENT AT THE BASE (kN·m)

Direction	Zone II	Zone IV	Ratio
X (about Y axis)	≈26,730	≈48,530	1.82
Y (about X axis)	≈34,720	≈67,500	1.94

The overturning moment is largest at the base and decreases to zero at the top. It was obtained from the storey shears of Table IX as the sum of the storey shear times the storey height, equivalent to (14), so it is an estimate from the combined

storey shears and not a value reported directly by ETABS. At the base it is about 26,730 kN·m about the Y axis (X-direction earthquake) in Zone II and about 48,530 kN·m in Zone IV, a ratio of 1.82, and about 34,720 kN·m and 67,500 kN·m about the X axis (Y-direction earthquake), a ratio of 1.94. These ratios follow the base shear ratios of 1.83 and 2.00.

H. Overall Comparison of Zone II and Zone IV

Table XVII summarises the results of the two zones.

TABLE XVII SUMMARY OF RESULTS, ZONE II AND ZONE IV

Parameter	Dir.	Zone II	Zone IV	Ratio
Fundamental period T_1 (s)	X	2.513	2.512	1.00
Period, Mode 3 (s)	Y	1.838	1.838	1.00
Base shear (kN)	X	963.02	1762.82	1.83
Base shear (kN)	Y	1281.58	2566.81	2.00
Wind base shear (kN)	X	961.34	961.34	1.00
Wind base shear (kN)	Y	1499.53	1499.53	1.00
Roof displacement (mm)	X	14.283	25.206	1.76
Roof displacement (mm)	Y	12.965	22.928	1.77
Maximum storey drift	X	0.000480	0.000850	1.77
Maximum storey drift	Y	0.000402	0.000714	1.78
Drift, share of limit	X	12 %	21 %	—
Drift, share of limit	Y	10 %	18 %	—
Overturning moment (kN·m)	X	≈26,730	≈48,530	1.82
Overturning moment (kN·m)	Y	≈34,720	≈67,500	1.94

Safety and serviceability. The storey drift is below the limit of 0.004 times the storey height in both zones, with the largest unscaled value (0.000850, Zone IV, X) at 21 % of the limit and the largest scaled value at 85 % of the limit, so the building meets the drift requirement of IS 1893 (Part 1):2016. No soft storey exists in either direction.

Effect of zone and soil. The time period, frequency and storey stiffness are practically the same in the two zones, as expected for quantities that depend only on mass and stiffness. Displacement and drift increase by about 1.76 to 1.8 times, in agreement with the ratio of 1.76 between the design spectra at the fundamental period, and base shear and storey shear increase by 1.83 to 2.00 times at the base because the short-period modes see a ratio closer to 2.4. The zone factor alone would give 2.4, so the lower ratios come from the stiffer soil of the Zone IV model; the comparison therefore gives the combined effect of zone and soil. The increase of response with the zone factor agrees with the trend reported in [14], [15] and [19].

Limitations. The strong torsional coupling (second mode at 95 % of the fundamental period) and the Y-direction mass participation of 89.4 % should be noted. The tables report unscaled results, except Tables XI and XII. For a comparison that isolates the effect of the seismic zone, both models should be run with the same soil type; the results would then scale by the zone-factor ratio of 2.4.

V. CONCLUSION

This paper presented the seismic analysis of a 14-storey RC high-rise building in ETABS Ultimate 22.5.0 by the response spectrum method according to IS 1893 (Part 1):2016, for Seismic Zone II and Seismic Zone IV. The building was modelled with M30 concrete, Fe500 steel, two beam sections, five column sections and 250 mm RC shear walls. The main conclusions are as follows.

1. The time period is the same in both zones: the fundamental period is 2.51 s (2.513 s in Zone II and 2.512 s in Zone IV), and the first 12 modes agree within 0.001 s. The first mode is a translation in X, the second mode (2.38 s) is torsional and the third mode (1.84 s) is a translation in Y.
2. The earthquake base shear increases from 963.0 kN in Zone II to 1762.8 kN in Zone IV in X (1.83 times) and from 1281.6 kN to 2566.8 kN in Y (2.00 times), less than the zone-factor ratio of 2.4 because the Zone IV model uses soil type I. The storey shear is largest at the base and Zone IV is 1.77 to 2.04 times Zone II in X and 1.82 to 2.19 times in Y.
3. The roof displacement increases from 14.283 mm to 25.206 mm in X and from 12.965 mm to 22.928 mm in Y (1.76 and 1.77 times), in agreement with the ratio of 1.76 between the design spectra at the fundamental period. Displacement is zero at the base and maximum at the roof.
4. The maximum storey drift increases from 0.000480 to 0.000850 in X (both at Story6) and from 0.000402 to 0.000714 in Y, which is 12 % and 21 % (X) and 10 % and 18 % (Y) of the limit of 0.004 times the storey height. After scaling by the factors of (7) the maximum drift in Zone IV (X) is 0.0034, 85 % of the limit, so the drift requirement is met in both zones.
5. The storey stiffness is practically the same in both zones and no soft storey exists in either direction. The overturning moment at the base increases by 1.82 times in X and 1.94 times in Y. The cumulative mass participation in Y is 89.4 % after 12 modes, so more modes should be used.
6. The wind base shear (961.3 kN in X and 1499.5 kN in Y) is reported for reference. Unscaled, wind exceeds earthquake only in Zone II in Y; after scaling, earthquake governs in every case. The two models use different soil types, so these conclusions cover seismic response and the combined effect of zone and soil.
7. Overall, the adopted 14-storey layout satisfies the drift requirement of IS 1893 (Part 1):2016 in both zones, with a wide margin for the unscaled response and a smaller margin, 85 % of the limit, for Zone IV in X after scaling. The increase of response from Zone II to Zone IV, about 1.76 times for displacement and drift and 1.83 to 2.00 times for base shear, is smaller than the zone-factor ratio of 2.4 because of the stiffer soil assumed in Zone IV.

VI. FUTURE SCOPE

1. The study can be extended to Zones III and V to give a complete comparison across all the seismic zones of IS 1893 (Part 1):2016.
2. Lateral load-resisting systems such as shear walls, outriggers, belt trusses, diagrids and bracing can be introduced and compared with the present frame [21], [22], [23].
3. Complete wind analysis, the combined effect of wind and earthquake loads, and the use of dampers or base isolation can be investigated [27], [30].
4. The comparison can be repeated with the same soil type in both zones to isolate the effect of the zone factor, and with more modes so that the mass participation in Y reaches 90 %.

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