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SEISMIC ANALYSIS OF BUILDING WITH VERTICAL IRREGULARITY

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Abstract: Rapid urbanization and limited land availability in metro cities have led to a surge in the construction of multi-story buildings. tall buildings often face challenges such as vertical and mass irregularity, which can affect their stability during seismic events. Vertical irregularities (like sudden changes in stiffness) and mass irregularities (uneven weight distribution) increase vulnerability, making proper design and compliance with seismic codes essential. This highlights the need for advanced engineering solutions to balance urban growth with earthquake-resistant construction.

This study examines the seismic performance of vertically irregular RC buildings (G+4, G+9, G+14) in Zone V (IS 1893:2016), focusing on mass irregularity effects. Using ETABS, models are analyzed via Equivalent Static and Response Spectrum Methods to assess base shear, storey displacement, and inter-storey drift. Results reveal structural vulnerabilities caused by irregularities, guiding safer designs for seismic zones while addressing limitations of standard analysis approaches for irregular structures.

I. INTRODUCTION

As India has witnessed vigorous earthquakes in past years. The main challenge is to design a structure in a such a way that it should resist the lateral loads and gravitational loads, like wind loads, Earthquake loads etc. As the height of the structure increases the intensity of these loads on the building also increase. The construction of high-rise buildings requires careful planning and strong and good quality materials and workmanship to ensure the building is safe, strong and durable. The common problem in this type of building is that presence of irregularities in the structure due to various reasons such as parking in ground floor, any party or seminar hall in any of the adjacent floor, apart from that the other reason may be architectural aspect, the shape of the building is irregular.

Indian standard has designated the structure as regular or irregular. A structure is said to be regular when it has simple and regular geometry and has uniform mass distribution and uniform stiffness in plane and elevation. A structure is said to be irregular when it has discontinuities as mentioned in IS 1893 (Part 1): 2016, Table- 4 (Plan irregularities) and Table- 5 (Vertical irregularities). For the structure to perform well during the earthquake the structure should have robust structural configuration, lateral stiffness, lateral strength and adequate ductility. Buildings with simple regular geometry and uniformly distributed mass and stiffness in plan and in elevation, suffer much less damage, than buildings with irregular configurations. The cause for the failure of the structure begins with the points of weakness. This weakness is due to the irregularities. The major reason for the failure is vertical irregularities. As the height varies intensity of the load increases and it also impacts the stiffness of the structure.

II. VERTICAL IRREGULARITY

Vertical irregularity is characterized by vertical discontinuities in the distribution of mass, stiffness and strength. Buildings with simple regular geometry and uniformly distributed mass and stiffness in plan and in elevation, suffer much less damage, than buildings with irregular configurations, so the design and analysis is to be made to eliminate irregularities by modifying architectural planning and structural configurations. Below are the different types of vertical irregularities.

2.1 Stiffness Irregularity

Stiffness irregularity is also known as soft storey, condition in multistory buildings where a story has less lateral stiffness than the story above or below it. Storey in which lateral stiffness is less than 70% of that in the storey above or less than 80% of the average of the lateral stiffness of the three storeys above.

2.2 Vertical Geometric Irregularity

Vertical geometric irregularity is a structural irregularity that occurs when the horizontal dimension of a story's seismic force-resisting system is more than 125% of the adjacent story's dimension. This can happen in any two earthquake directions that are perpendicular to each other.

2.3 Mass Irregularity

IS 1893 2016 defines mass irregularity as any floor's mass exceeding 150% of adjacent floors, or significant deviation from symmetrical mass distribution. This creates uneven seismic forces, potentially causing stress concentrations, torsion, and excessive drifts during earthquakes. The code mandates special design measures in Zones III-V to ensure structural safety through enhanced analysis and detailing for such irregular buildings.

III. OBJECTIVE

- To understand the behavior of the RC structure with irregularities.
- To study the effect of vertical geometric irregularity and performance level of the structure.
- To obtain the Seismic performances of different irregular buildings located in severe earthquake zone (v).
- FE Analysis involving Modal Analysis, Equivalent Static Analysis and Response Spectrum Analysis to be performed on all the models.
- Comparison of the results between regular and vertical irregular frame on the basis of base shear, storey drift & displacement and time period.

IV. METHODOLOGY

1. Literature review to be carried out regarding the behavior of the vertical irregular structure and seismic design of these structures.
2. Validation is carried out for a preferred thesis.
3. Stories having G+4, G+9 and G+14 are modelled for both regular and irregular structure.
4. Structure which is regular is considered as bare frame and irregular structure as vertical irregularity.
5. Finite Element Analysis involves Modal, Equivalent Static and Response Spectrum analyses are performed to obtain time period, base shear, storey displacement and Storey drift.
6. Compare the results with regular and irregular building to find the critical amongst all models.

V. PRESENT STUDY

A multi-storey RC frame building having G+4, G+9 and G+14 storey are considered to have geometric irregularities and mass irregularities. Seismic analysis of the structure is done by using ETABS software in which Modal analysis and Equivalent Static Method and Response Spectrum Method is considered to analysis the model. Therefore, all the results are compared to check the critical model among all the models.

VI. PROJECT DESCRIPTION

Table 6.1 Details for the Modelling

Description	Data		
Storey	G+4	G+9	G+14
Floor hight	3 mtr		
Number of bays in ‘x’ and ‘y’ direction:	5		
Bay width	5 mtr		
Grade of concrete (f_{ck})	M25		
Grade of steel (f_y)	Fe 500		
Young’s modulus of concrete (Es)	25 Mpa		
Density of concrete	25 Mpa		
Slab thickness	150 mm		
Soil type	Medium (Type II)		
Zone	V		
Support	Fixed support		
Importance factor	1.2		
Response reduction factor	5		
Damping ratio	5%		
Beam size	300 X 600		
Column size	300X400	400X400	450X450
	600X600	650X650	700X700
Load combinations	1. 1.2(DL + LL ± EQX) 2. 1.2(DL + LL ± EQY) 3. 1.5(DL ± EQX) 4. 1.5(DL ± EQY) 5. 0.9DL ±1.5 EQX 6. 0.9DL ±1.5 EQY 7. 1.5(DL±LL)		

Table 6.2: Nomenclature for the Models.

SI.NO	Description	Nomanculture
	G+4	
1	Regular building, LL of 3 kN/m2	5R
2	Irregular-1 building, LL of 9 kN/m2 at 3-4 FL, 3 kN/m2 on remaining FL	5VR1M1
3	Irregular-1 building, LL of 9 kN/m2 at 1-2 FL, 3 kN/m2 on remaining FL	5VR1M2
4	Irregular-2 building, LL of 9 kN/m2 at 3-4 FL, 3 kN/m2 on remaining FL	5VR2M1
5	Irregular-2 building, LL of 9 kN/m2 at 1-2 FL, 3 kN/m2 on remaining FL	5VR2M2
6	Irregular-3 building, LL of 9 kN/m2 at 3-4 FL, 3 kN/m2 on remaining FL	5VR3M1
7	Irregular-3 building, LL of 9 kN/m2 at 1-2 FL, 3 kN/m2 on remaining FL	5VR3M2
8	Irregular-4 building, LL of 9 kN/m2 at 3-4 FL, 3 kN/m2 on remaining FL	5VR4M1
9	Irregular-4 building, LL of 9 kN/m2 at 1-2 FL, 3 kN/m2 on remaining FL	5VR4M2
	G+9	
10	Regular building, LL of 3 kN/m2	10R
11	Irregular-1 building, LL of 9 kN/m2 at 7-9 FL, 3 kN/m2 on remaining FL	10VR1M1
12	Irregular-1 building, LL of 9 kN/m2 at 4-6 FL, 3 kN/m2 on remaining FL	10VR1M2
13	Irregular-1 building, LL of 9 kN/m2 at 1-3 FL, 3 kN/m2 on remaining FL	10VR1M3
14	Irregular-2 building, LL of 9 kN/m2 at 7-9 FL, 3 kN/m2 on remaining FL	10VR2M1
15	Irregular-2 building, LL of 9 kN/m2 at 4-6 FL, 3 kN/m2 on remaining FL	10VR2M2
16	Irregular-2 building, LL of 9 kN/m2 at 1-3 FL, 3 kN/m2 on remaining FL	10VR2M3
17	Irregular-3 building, LL of 9 kN/m2 at 7-9 FL, 3 kN/m2 on remaining FL	10VR3M1
18	Irregular-3 building, LL of 9 kN/m2 at 4-6 FL, 3 kN/m2 on remaining FL	10VR3M2
19	Irregular-3 building, LL of 9 kN/m2 at 1-3 FL, 3 kN/m2 on remaining FL	10VR3M3
20	Irregular-4 building, LL of 9 kN/m2 at 7-9 FL, 3 kN/m2 on remaining FL	10VR4M1
21	Irregular-4 building, LL of 9 kN/m2 at 4-6 FL, 3 kN/m2 on remaining FL	10VR4M2
22	Irregular-4 building, LL of 9 kN/m2 at 1-3 FL, 3 kN/m2 on remaining FL	10VR4M3
	G+14	
23	Regular building, LL of 3 kN/m2	15R
24	Irregular-1 building, LL of 9 kN/m2 at 11-14 FL, 3 kN/m2 on remaining FL	15VR1M1
25	Irregular-1 building, LL of 9 kN/m2 at 6-10 FL, 3 kN/m2 on remaining FL	15VR1M2
26	Irregular-1 building, LL of 9 kN/m2 at 1-5 FL, 3 kN/m2 on remaining FL	15VR1M3
27	Irregular-2 building, LL of 9 kN/m2 at 11-14 FL, 3 kN/m2 on remaining FL	15VR2M1
28	Irregular-2 building, LL of 9 kN/m2 at 6-10 FL, 3 kN/m2 on remaining FL	15VR2M2
29	Irregular-2 building, LL of 9 kN/m2 at 1-5 FL, 3 kN/m2 on remaining FL	15VR2M3
30	Irregular-3 building, LL of 9 kN/m2 at 11-14 FL, 3 kN/m2 on remaining FL	15VR3M1
31	Irregular-3 building, LL of 9 kN/m2 at 6-10 FL, 3 kN/m2 on remaining FL	15VR3M2
32	Irregular-3 building, LL of 9 kN/m2 at 1-5 FL, 3 kN/m2 on remaining FL	15VR3M3
33	Irregular-4 building, LL of 9 kN/m2 at 11-14 FL, 3 kN/m2 on remaining FL	15VR4M1
34	Irregular-4 building, LL of 9 kN/m2 at 6-10 FL, 3 kN/m2 on remaining FL	15VR4M2
35	Irregular-4 building, LL of 9 kN/m2 at 1-5 FL, 3 kN/m2 on remaining FL	15VR4M3

LL: Live load; FL: Floor level

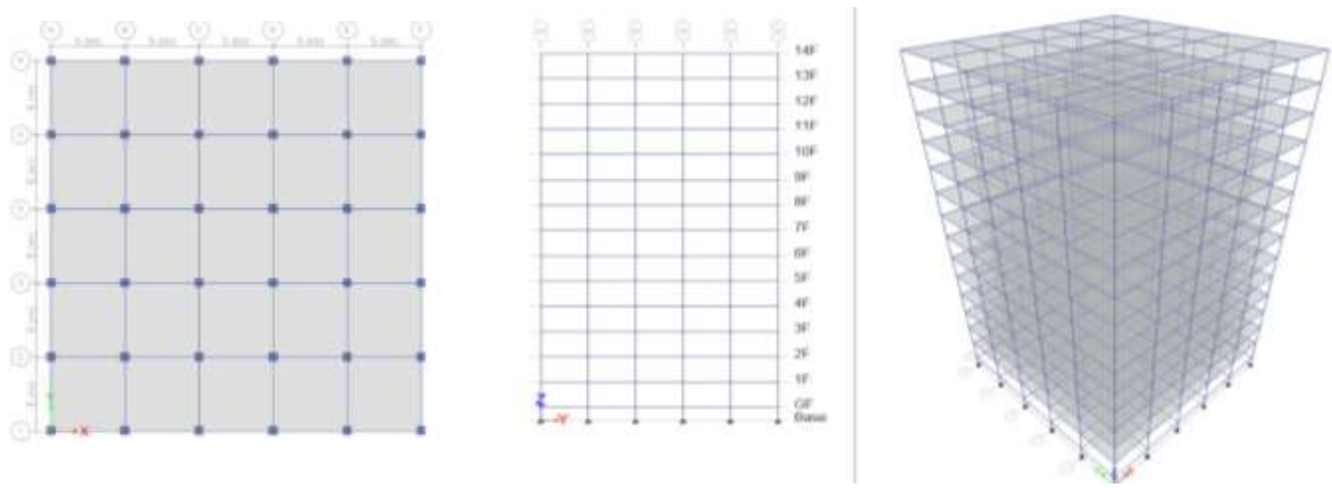


Figure 6.1 Plan view and elevation and 3D view of Regular building model

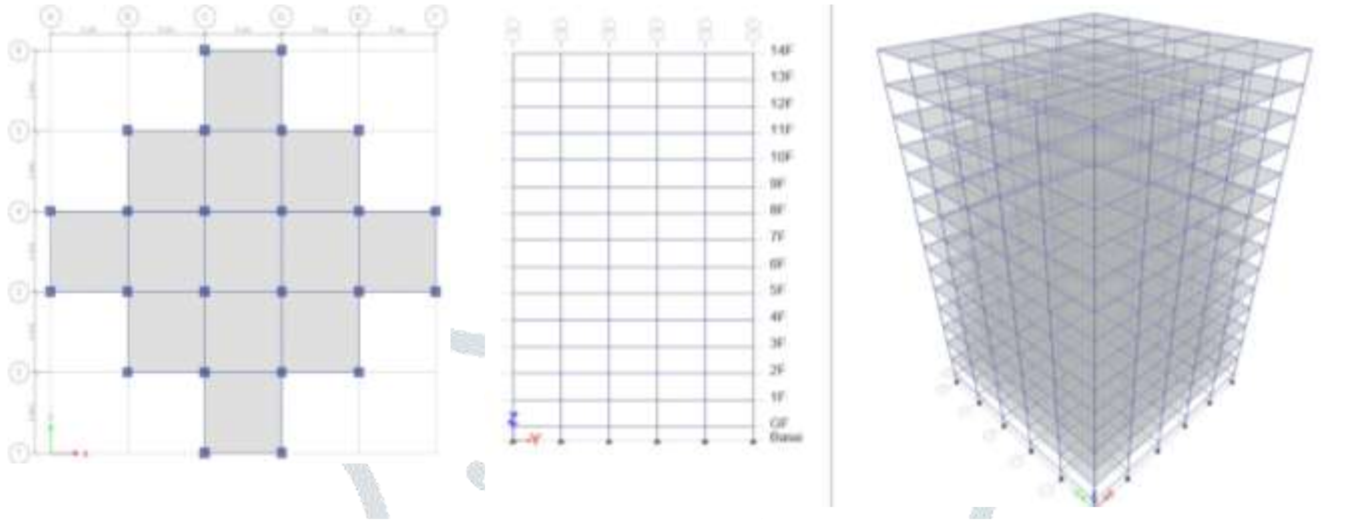


Figure 6.2 Plan view and elevation and 3D view of Irregular-1 building model

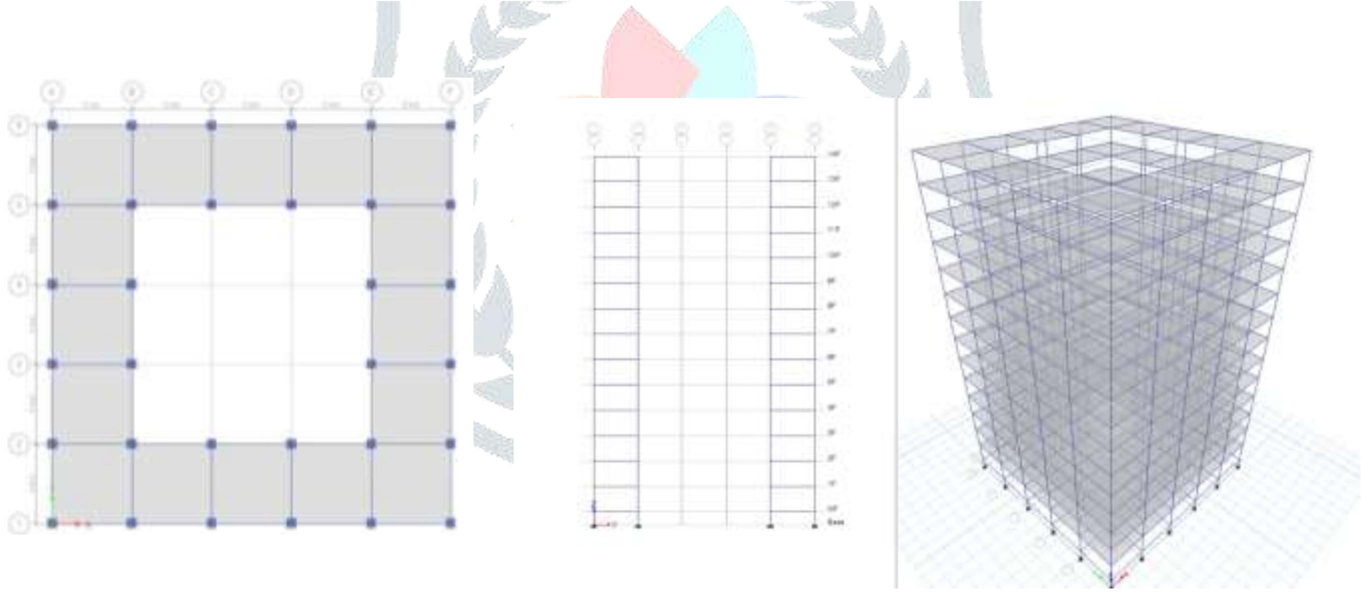


Figure 6.3 Plan view and elevation and 3D view of Irregular-2 building model

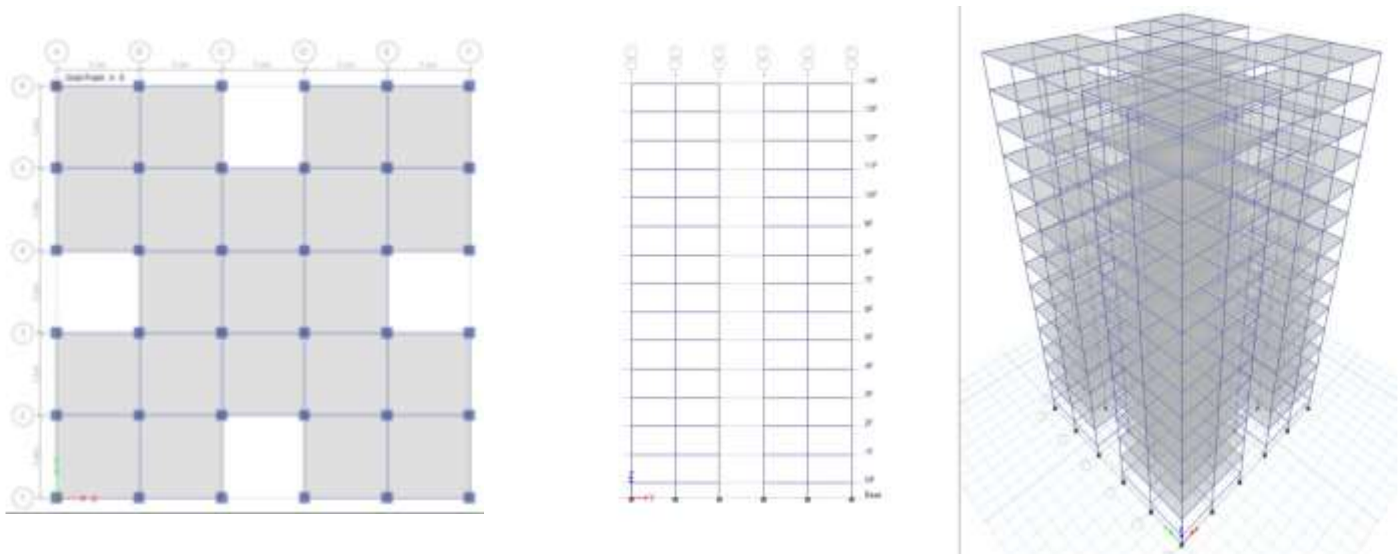
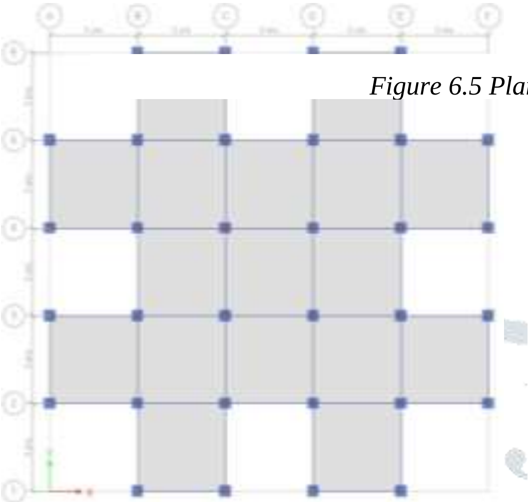


Figure 6.4 Plan view and elevation and 3D view of Irregular-3 building model



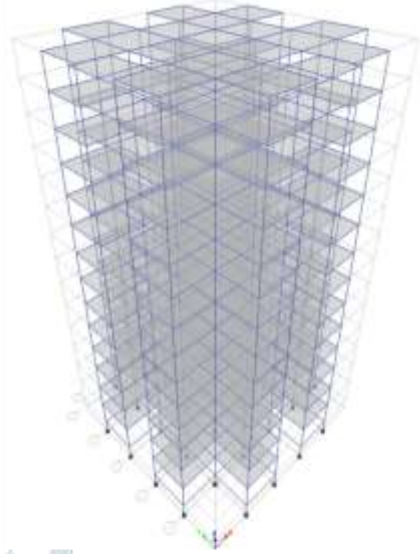


Figure 6.5 Plan view and elevation and 3D view of Irregular-4 building model

VII. Finite Element Analysis

Finite Element Analysis (FEA) has become the civil engineer's most trusted digital tool. This modeling technique transforms complex structures into smaller elements, each responding realistically to simulated stresses and environmental factors. FEA has been evolved from a specific verification tool to the backbone of modern structural design - predicting how suspension bridge cables fatigue under decades of traffic or how seismic waves might ripple through a structure's foundation. The precision is remarkable: we can now pinpoint stress concentrations within millimeters and optimize material usage. What truly sets FEA apart is its ability to test extreme scenarios safely - simulating everything from hundred-year storms to accidental impacts that we would never risk recreating physically. For old infrastructure, it serves as a reviewing tool, revealing hidden vulnerabilities before they become emergencies. As computational power grows, FEA continues to push boundaries, enabling smarter, more resilient designs while paradoxically making complex engineering solutions more accessible and cost-effective.

7.1 Load Case Details

The load case considered for this study is given in the table below

Table 6.1 Load case data

SI.No	Case	Data	SI.No	Case	Data
1	Live load	3 kN/m^2	4	Importance Factor	1.2
		9 kN/m^2	5	Response reduction Factor	5
2	Zone	V	6	Damping Ratio	5%
3	Zone Factor	0.36	7	Soil Type	II

VIII. Result and Discussion

8.1 Modal Analysis

The fundamental time period for G+4, G+9 and G+14 is obtained from modal analysis by consideration of mass and stiffness of the building. The time period calculated as per Cl. 7.6.2 IS 1893 part I: 2016 is given below.

$T = 0.075 \times h^{\mathbf{0.75}}$

- G+4: $0.075h^{0.75} = 0.075 \times 13.5^{0.75} = 0.528$ sec
- G+9: $0.075h^{0.75} = 0.075 \times 28.5^{0.75} = 0.925$ sec
- G+14: $0.075h^{0.75} = 0.075 \times 43.5^{0.75} = 1.27$ sec

The fundamental time period for G+4, G+9 and G+14 obtained by the software and as per the IS 1893 2016 is given in the table below

Table 8.1 Natural time period for all the models

Model	Time Period (Sec)		Model	Time Period (Sec)		Model	Time Period (Sec)	
	Program calculated	IS 1893 2016		Program calculated	IS 1893 2016		Program calculated	IS 1893 2016
5R	0.91	0.528	10R	1.51	0.925	15R	2.12	1.27
5VR1M1	0.99		10VR1M1	1.68		15VR1M1	2.42	
5VR1M2	1.02		10VR1M2	1.6		15VR1M2	2.36	
5VR2M1	1.01		10VR1M3	1.53		15VR1M3	2.23	
5VR2M2	0.92		10VR2M1	1.71		15VR2M1	2.39	
5VR3M1	1.03		10VR2M2	1.61		15VR2M2	2.33	
5VR3M2	0.91		10VR2M3	1.54		15VR2M3	2.21	
5VR4M1	0.95		10VR3M1	1.74		15VR3M1	2.44	
5VR4M2	0.87		10VR3M2	1.66		15VR3M2	2.38	
			10VR3M3	1.57		15VR3M3	2.25	
			10VR4M1	1.73		15VR4M1	2.4	
			10VR4M2	1.65		15VR4M2	2.34	
			10VR4M3	1.57		15VR4M3	2.22	

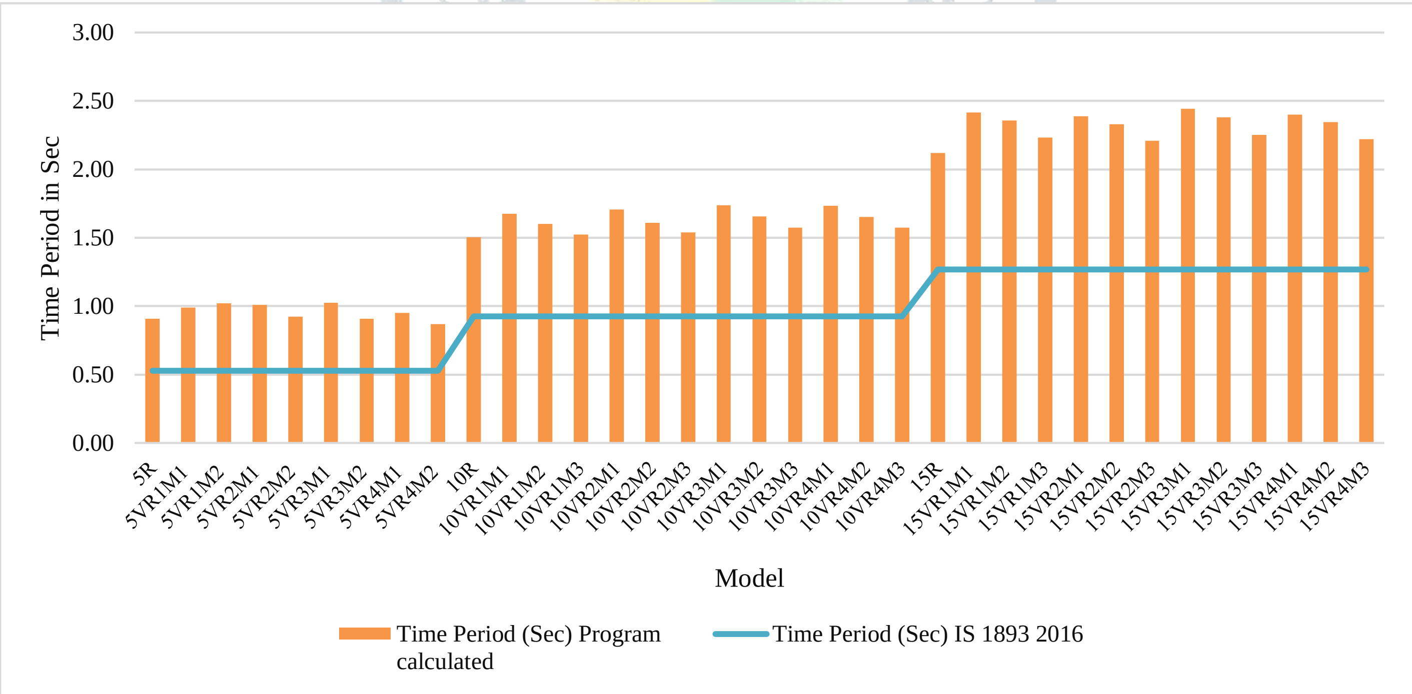


Figure 8.1 Chart showing time period for all the models

As per the above graph, below are the following observations.

1. The IS 1893:2016 formula consistently underestimates time periods by 40-92% compared to program-calculated values, making it overly conservative for seismic design.
2. Time periods increase proportionally with building height (0.87-1.03s for G+4, 1.51-1.74s for G+9, and 2.12-2.44s for G+15), confirming taller structures are more flexible.
3. Vertical irregularities increase time periods by 9-15% for G+4 models and up to 15-20% for taller buildings, with VR3 (geometric irregularity) showing maximum effect.
4. Models with irregularities at lower floors (M1) exhibit 5-12% longer periods than those with upper-floor irregularities (M2/M3), indicating foundation-level irregularities are most critical.
5. VR1 (mass irregularity) models consistently show higher time periods than regular structures, with the most severe case being 15VR1M1 at 2.42s vs 2.12s for 15R.
6. Dynamic analysis is essential for irregular/high-rise structures as static methods using code periods may miss critical modal responses.
7. All irregularity types (VR1-VR4) follow similar trends, but geometric irregularities (VR3) consistently show the most significant period increases.

8.2 Base Shear

Base shear for various models is given in the table below.

Table 8.2 Base shear results for various models

Model	Base Shear (kN)	Model	Base Shear (kN)
5R	3060.3	10VR3M3	4867.6
5VR1M1	2453.7	10VR4M1	4016.5
5VR1M2	2850.6	10VR4M2	4017.7
5VR2M1	3095.3	10VR4M3	4016.5
5VR2M2	3095.3	15R	4934.2
5VR3M1	3904.4	15VR1M1	3718.9
5VR3M2	3904.4	15VR1M2	3803.5
5VR4M1	3229.1	15VR1M3	3803.5
5VR4M2	3229.1	15VR2M1	4594.9
10R	4071.8	15VR2M2	4699.0
10VR1M1	3113.7	15VR2M3	4699.0
10VR1M2	3113.7	15VR3M1	5876.0
10VR1M3	3113.7	15VR3M2	6015.4
10VR2M1	3858.5	15VR3M3	6014.1
10VR2M2	3869.3	15VR4M1	4900.8
10VR2M3	3865.4	15VR4M2	5012.7
10VR3M1	4867.6	15VR4M3	5011.4
10VR3M2	4867.6		

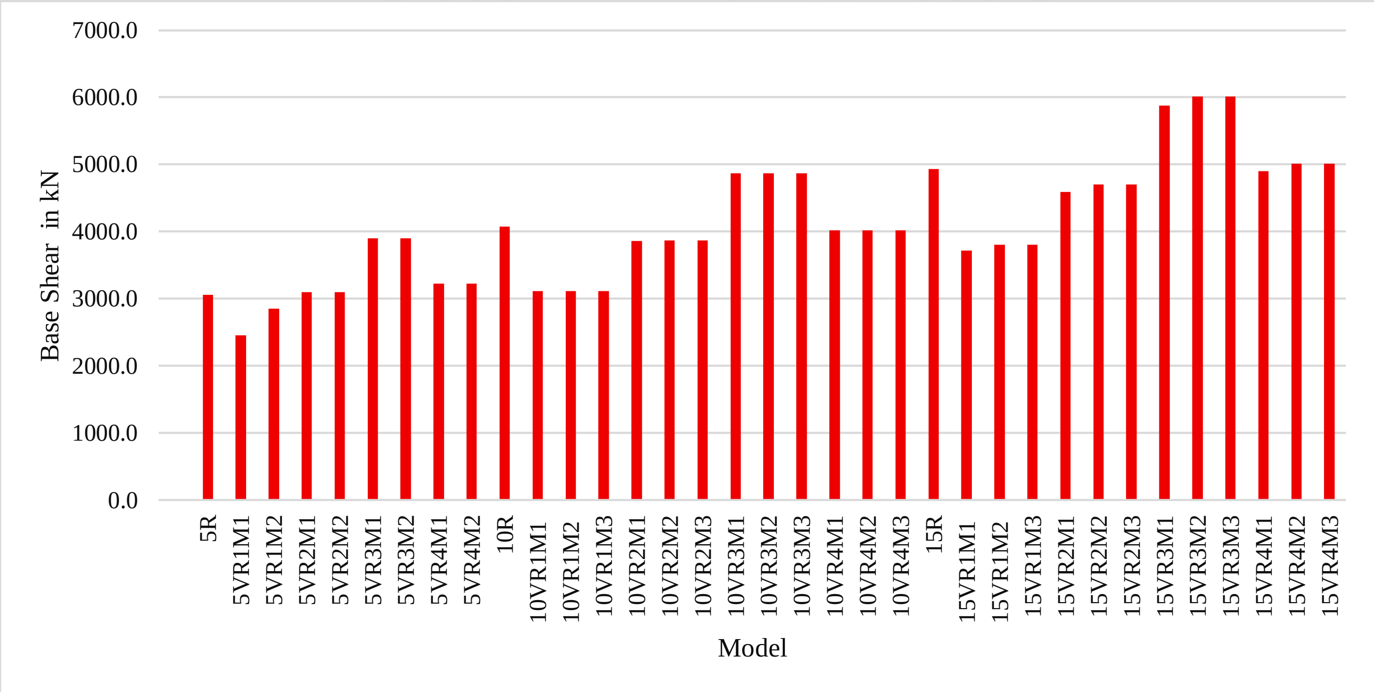


Figure 8.2 Base shear results for various models

As per the graph, below are the following observation.

1. Taller buildings show significantly higher base shear values, confirming increased seismic forces with building height.
2. Vertically irregular models consistently demonstrate 15-30% higher base shear compared to regular structures of same height (e.g., 5VR3M1: 3904 kN vs 5R: 3060 kN).
3. VR3 (geometric irregularity) models show the highest base shear across all heights (Peak: 15VR3M2 at 6015 kN), indicating greatest seismic vulnerability.
4. VR1 (mass irregularity) models exhibit 10-20% lower base shear than other irregular types, suggesting mass distribution plays a compensatory role.
5. Models with irregularities at lower floors (M1) show 5-12% higher base shear than upper-floor irregularities (M2/M3), emphasizing foundation-level criticality.
6. All values fall within expected ranges for Zone V seismicity, but irregular models exceed regular counterparts by up to 35%.
7. Structural elements in irregular buildings require 20-30% higher capacity than regular structures to accommodate increased seismic demands.
8. Dynamic analysis proves essential as equivalent static methods may underestimate forces in irregular configurations by 15-25%.

8.3 Top Displacement

Top displacement for the models is given in the table below.

Table 8.3 Top displacement for all models

Model	Top Displacement in mm	Model	Top Displacement in mm	Model	Top Displacement in mm
5R	49.05	10VR1M3	84.78	15VR1M2	142.10
5VR1M1	46.9	10VR2M1	98.47	15VR1M3	132.92
5VR1M2	51.2	10VR2M2	90.92	15VR2M1	141.76
5VR2M1	39.98	10VR2M3	86.18	15VR2M2	138.57
5VR2M2	35.78	10VR3M1	102.14	15VR2M3	129.84
5VR3M1	47.76	10VR3M2	96.34	15VR3M1	147.95
5VR3M2	41.39	10VR3M3	90.15	15VR3M2	144.29
5VR4M1	44.86	10VR4M1	101.56	15VR3M3	134.97
5VR4M2	40.05	10VR4M2	95.70	15VR4M1	143.72
10R	80.44	10VR4M3	89.99	15VR4M2	140.49
10VR1M1	95.28	15R	115.71	15VR4M3	131.53
10VR1M2	89.96	15VR1M1	145.32		

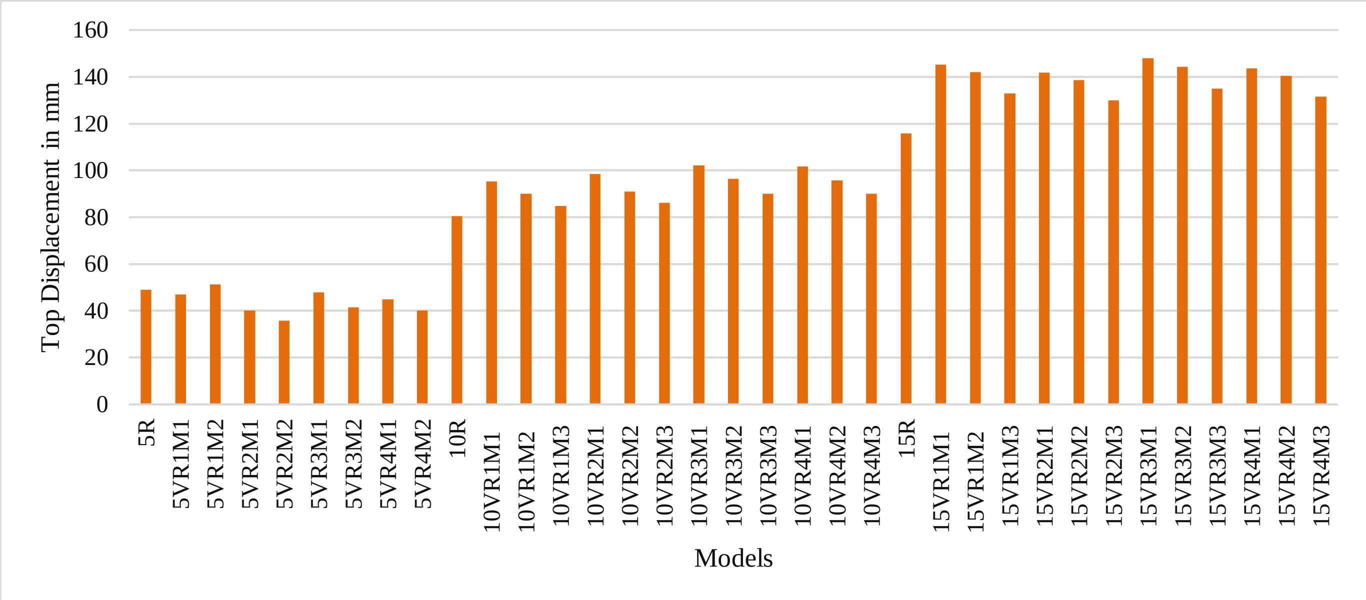


Figure 8.3 Top Storey Displacement for all models

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