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Commercial Building with Vertical Irregularities Using Etabs Software

Girish Kumar G M[1], Pruthvi Rani K M[2], Pramod K S[3]
[1,2]Assistant Professor, Structural Engineering, S J M Institute of Technology, Chitradurga, Karnataka, India
[3]PG – Structural Engineering, S J M Institute of Technology, Chitradurga, Karnataka, India.
Email: *girishgowdru27@gmail.com[1], pruthviranikm@sjmit.ac.in[2], pramodks8187@gmail.com[3]*

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Abstract
Building on hilly slopes is always a challenge because the natural ground profile forces engineers to adopt unconventional building forms like step-back or step-back & set-back structures. These designs often create vertical irregularities, since the columns rest at different heights, which makes the structure more vulnerable to torsional effects and increased shear during an earthquake. To understand this behavior, the present study uses the Response Spectrum Method to analyses step-back and step-back & set-back frames. The focus is on key seismic responses such as fundamental time period, lateral displacement, inter-storey drift, and base shear in columns for buildings of different heights. The results clearly show that step-back & set-back frames perform better under earthquake loads compared to simple step-back frames, as they control displacement, reduce story drift, and distribute base shear more effectively.

1. Introduction

Studied the "Effect of Vertical Irregularities on Seismic Performance of Multi-Storey RC Buildings". The researchers analyzed G+9 RC frame models incorporating vertical stiffness irregularities using response spectrum and pushover analysis. Their study revealed that sudden stiffness reduction at intermediate stories produced significant increase in inter-storey drift ratios and plastic hinge concentrations. They concluded that irregular structures exhibit more pronounced vulnerability than regular buildings and recommended additional lateral load-resisting elements such as shear walls to strengthen weak levels S. K. Dubey, R. K. Singh,et al. (2016). As more and more people flock to cities, commercial buildings such as malls, theatres, and hotels need to be high-rise. Moreover, they need to be functional and architecturally stylish. To optimize site utilization and design flexibility, designers use vertical irregularities, setbacks, floor height variations, and sudden stiffness changes in building geometry. This may complicate the construction since buildings at varying heights distribute weight unevenly, therefore these considerations must be considered when constructing structures. This uneven distribution leads to much greater stress concentrations. It also leads to abrupt changes in displacement between the stories. All this leads to such buildings being more vulnerable during earthquakes. The analysis of a G+8 commercial building with vertical irregularities using ETABS software is done in this project which shows the importance of detailed analysis and design for performance and safety. The analysis evaluates the most important performance parameters, including story displacement, drift, base shear, and modal participation. The Equivalent Static Method and Response Spectrum Method, adopted by IS standards, are used to assess the impact of irregularities on overall stability in multi-storey structures. These irregularities, such as differences in story heights, setbacks, discontinuity of load-bearing members, or changes in mass and stiffness, significantly impact the stability and seismic behavior of these structures. These irregularities can cause stress concentration, abrupt displacement changes, and localized damage, which are crucial considerations in earthquake-resistant design [1].

Vertical Irregularities in Commercial Buildings:

Vertical irregularity refers to significant changes in stiffness, strength, geometry, or mass along the height of a building, which disturb the uniform distribution of seismic forces. As per IS 1893:2016 (Indian Standard for earthquake-resistant design) and ASCE 7 (American code), a building is said to have vertical irregularity if sudden changes occur between adjacent stories in terms of stiffness, mass, or geometry.

Literatures

M. K. Sharma, V. Patel,et al. (2020) explored "Seismic Analysis of Vertically Geometric Irregular Buildings". Models with different number of stories were subjected to nonlinear dynamic analyses and response spectra. Abrupt changes in vertical geometry were found to induce higher-mode participation, leading to torsional irregularities and localized stress concentration. The effect was most severe under near-fault pulse-like ground motions. Authors suggested avoiding sudden vertical discontinuities in practice and recommended transitional stiffness members where geometric changes are unavoidable [2].

Mehar, P. Khatri,et al. (2017) investigated the "Seismic Behavior of Setback Buildings with Vertical Irregularities". Using ETABS software, different setback configurations were modeled and compared against a regular frame. The findings indicated that setback levels cause drift concentration and redistribution of shear, leading to increased demand on structural members located at the setback. Torsional response was also observed to be more severe when setbacks combined with plan asymmetry. The study emphasized that code provisions may underestimate demands at setback levels and hence advanced dynamic analysis is essential [3].

1.1. Staggered Setback Building

A staggered setback building is a type of vertical irregularity in which the floor plan or elevation of a building reduces in size at different levels, but not in a uniform or continuous manner. Instead, the setbacks occur at irregular heights and positions, creating a "staggered" or step-like profile. This is commonly seen in commercial or high-rise buildings for architectural aesthetics, functional requirements, or zoning regulations. A staggered setback refers to a vertical irregularity where certain stories of a building recede or step back from the main building line in a non-uniform pattern, resulting in discontinuities along the height. Unlike a uniform setback, the staggered arrangement creates abrupt changes in mass and stiffness distribution

1.2. Setback Irregularity

Setback irregularity is a type of vertical irregularity in buildings where the floor area is reduced suddenly at certain heights, creating a "step-like" profile. This is a common occurrence in commercial or high-rise structures when the design, zoning regulations, or aesthetic preferences result in lower storeys being smaller than higher stories. A building is considered to have setback (vertical geometric) irregularity if: The horizontal dimension of the lateral force resisting system in any story is more than 130% of that in the story above. In simpler terms, if the building width or length suddenly reduces at a certain height, it qualifies as a setback irregularity.

2. Method

Selection of a G+8 commercial building with vertical irregularities and staggered setback building (setback, soft story, or mass irregularity).

Objective: In order to determine how seismic performance metrics are affected by vertical irregularities [4]

Earthquake analysis types

- Equivalent static method
- Respose spectrum
- Time history

2.1. Model Data

Details of the model designed in ETABS is provided in the table 1 It has 8 storeys vertical irregularity building model. 5X4 bays are placed in X and Y directions. Spacing is 4 m along X direction and 3 meter along Y Directions Shown in Figure 1 - 3.

Table 1 Table of Base Model Data

No. of Bays in X & Y Direction	Bays 5 Bays x 4 Bays
Spacing in X & Y Direction	X Direction 4m
	Y Direction 3m
Storeys	G+8 Storey
Material Grade	M30
	Rebar Fe 550
Member Sizes	Column Size 300X650mm
	Beam 300X550mm
Shear wall	250mm
	Slab Thickness 150mm
Load Details	Live Load 4KN/m2
	Floor finish 1.54KN/m2
	Wall load 9.8KN/m
Story height	Plinth To 5th Storey 3.2m
	5th To 8th Story 3.4 M
Seismic Analysis	Equivalent Static Analysis
	Response spectrum Analysis
Total building height	29.6m
Response reduction factor R	5
Zone factor	Iv
Soil type	Iii
Importance factor (I)	1.2
Time period td x direction	0.6075
Time period td y direction	0.7014

2.2. Figure: - Plan

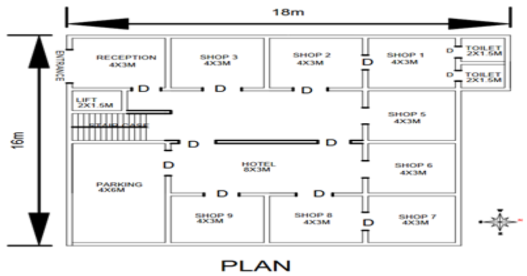

Figure 1 3d Model of Regular Building View

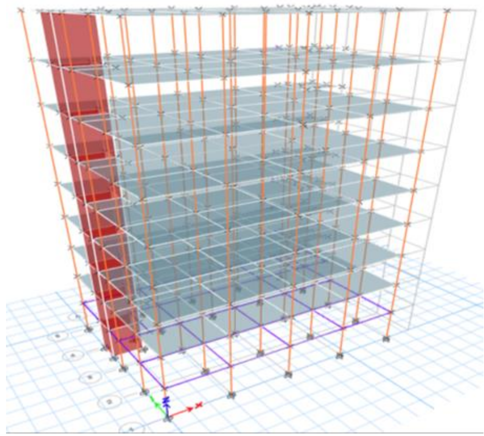

Figure 2 3d Model of Regular Building View

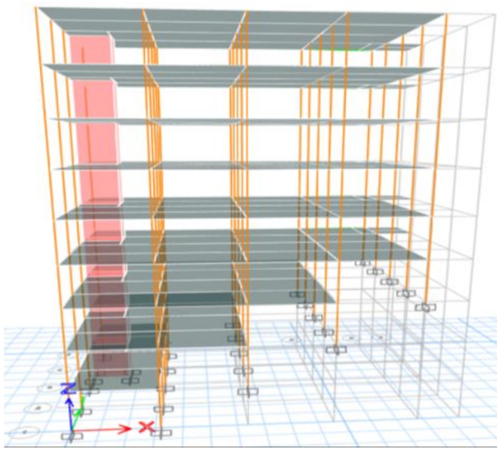

Figure 3 3d Model of Regular Building View

3. Results and Discussion

3.1. Modal Analysis

Modal analysis is essential for analysing a building structure's natural vibrations, including frequencies, mode shapes, and modal mass participation ratios. It forms the basis for advanced dynamic analyses like Response Spectrum Analysis (RSA). The project utilized ETABS for modal analysis of a G+8 commercial building with vertical irregularities to assess its seismic performance Shown in Table 2.

3.1.1. Mode Vs Time Period

Table 2 Mode Vs Time Period

Mode	Model 1	Model 2
1	1.188	0.874
2	0.979	0.821
3	0.781	0.713
4	0.394	0.28
5	0.301	0.256
6	0.237	0.221
7	0.222	0.162
8	0.156	0.136
9	0.155	0.128
10	0.136	0.112
11	0.122	0.104
12	0.113	0.09

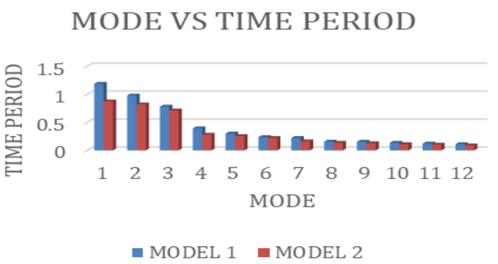

Figure 4 Mode Vs Time Period

From the table it is clear that the first mode time period of Model 1 (1.188 sec) is greater than that of Model 2 (0.874 sec). This means Model 1 is more flexible, whereas Model 2 behaves stiffer. As we move to higher modes, the time periods gradually reduce for both models, which is a natural trend since higher modes capture smaller and more localized vibrations Shown in Figure 4.

3.1.2. Displacement in X Direction

Displacement is the lateral shift of a structural structure resulting from seismic forces [5]. It is one of the most important parameters in earthquake-resistant design because excessive displa cement may lead to structural and non-structural damage Shown in Figure 5.

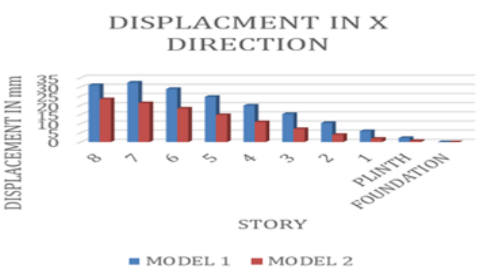

Figure 5 Displacement Vs Storey X Direction

Table 3 Displacement in X Direction

Story	Model 1	Model 2
8	31.17	23.42
7	32.53	21.26
6	29.011	18.32
5	24.75	14.79
4	19.99	10.91
3	15.358	7.17
2	10.47	3.99
1	6.027	1.89
Plinth	2.27	0.62
Foundation	0	0

From the displacement values in the X direction, it is observed that Model 1 shows larger displacements at all stories compared to Model 2 [6]. For example, at the top storey, Model 1 reaches 31.17 mm while Model 2 records only 23.42 mm. This indicates that Model 1 is more flexible and undergoes higher lateral movement, whereas Model 2, being stiffer due to vertical irregularities, resists displacement more effectively. A smoother increase of displacement from plinth to roof can be seen, which reflects proper load transfer, but excessive displacement in Model 1 may cause non-structural damages during seismic events Shown in Table 3.

3.1.3. Displacement in Y Direction

Displacement is the lateral movement of a building structure under the action of seismic forces. It is one of the most important parameters in earthquake-resistant design because excessive displacement may lead to structural and non-structural damage Shown in Table 4.

Table 4 Displacement in Y Direction

Story	Model 1	Model 2
8	52.638	26.79
7	49.539	24.452
6	44.826	20.678
5	38.802	15.75
4	31.92	11.45
3	25.268	8.41
2	18.29	5.15
1	11.342	2.98
Plinth	4.674	1.05
Foundation	0	0

In the Y direction, displacements are higher than in the X direction for both models, showing that the building is more flexible along Y. At the roof, Model 1 records 52.68 mm while Model 2 shows 26.79 mm [7]. Once again, Model 1 consistently undergoes larger displacements, highlighting its flexible nature, while Model 2 demonstrates reduced lateral movement due to increased stiffness. The values decrease steadily towards the foundation, confirming that seismic forces are well-distributed. However, higher Y-direction displacements must be carefully checked against serviceability limits Shown in Figure 6.

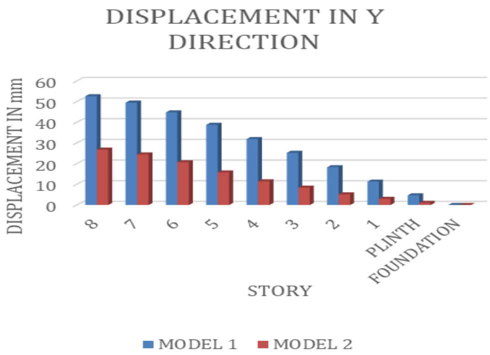

Figure 6 Displacement Vs Storey in Y Direction

3.1.4. Storey Drift in X Direction

The storey drift is the difference in the displacement of successive storey. Storey drift is a localised failure between floors, signifying a specific failure within defined parameters. It ascends to the building's midpoint and thereafter declines towards the top. Elevated drift values are seen at setback and soft-storey levels as a result of vertical imperfections [8]. The RSA findings underscore these impacts more prominently than the ESA. The maximum drift values comply with the H/250 limit established by IS 1893.2016 Shown in Table 5

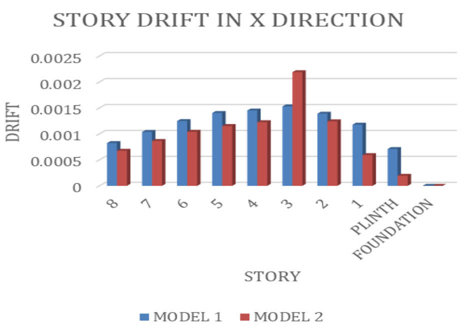

Figure 7 Storey Drift Vs Storey in X Direction

Table 5 Storey Drift in X

Story	Model 1	Model 2
8	0.000823	0.000674
7	0.001038	0.000864
6	0.001248	0.001041
5	0.001403	0.001151
4	0.00145	0.001225
3	0.001529	0.002188
2	0.001389	0.001242
1	0.001178	0.000592
Plinth	0.000709	0.000194
Foundation	0	0

Model 1 has somewhat elevated drift values compared to Model 2 over the majority of levels, with a peak drift of 0.001529 occurring at the 3rd story. Both versions adhere to the permitted limitations of IS 1893 (H/250), guaranteeing protection against structural damage. Increased drifts at intermediate floors indicate a concentration of distortion at setback or soft-storey levels, necessitating meticulous details to prevent collapse Shown in Figure 7.

3.1.5. Storey Drift in Y Direction

Storey drift is the variation in displacement between consecutive storeys, signifying localised failure between levels. It ascends to the midpoint of the structure and thereafter descends towards the roof [9]. Vertical imperfections result in increased drift values at setback and soft-storey levels. The RSA findings underscore these impacts more prominently than the ESA. The maximum drift values are within the allowable limit prescribed by IS 1893 (H/250) Shown in Table 6.

Table 6 Storey Drift in Y Direction

Story	Model 1	Model 2
8	0.000911	0.000688
7	0.001386	0.00111
6	0.001772	0.001449
5	0.002024	0.001665
4	0.002079	0.001657
3	0.002181	0.001622
2	0.002171	0.000862
1	0.002084	0.00061
Plinth	0.001349	0.000328
Foundation	0	0

In the Y–direction, the maximum story drift for both models occurs at the 3rd storey. Model 1 records a drift of 0.0015, while Model 2 shows a higher value of 0.0021. This clearly indicates that the vertical irregularities in Model 2 make the structure more flexible, resulting in greater lateral movement at this level [10]. Even though the values are within the permissible limits of IS 1893, the higher drift in Model 2 highlights the added risk of deformation in irregular buildings. This emphasizes the importance of adopting proper structural detailing and lateral load–resisting measures to ensure safety during seismic events Shown in Figure 8.

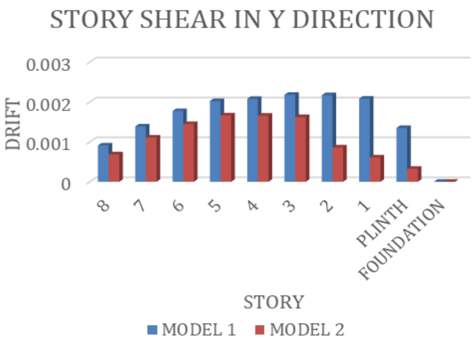

Figure 8 Storey Drift Vs Storey in Y direction

3.1.6. Base Shear in X Direction

Base shear is the shear force at base or foundation level. The table presents a detailed summary of the basic shear values for different models. For the G+8 building with vertical irregularities, the analysis shows that the base shear is concentrated at the foundation and is slightly amplified compared to a regular plan due to stiffness discontinuities and torsional coupling. Response Spectrum Analysis (RSA) is a technique that employs higher vibration modes and torsional effects to produce base shear in the X direction, used for the construction of foundations and load-resisting components [11]. The base shear distribution reveals that peak pressures are concentrated at the building's base and diminish progressively towards the upper floors. For the irregular building, shear concentration is slightly higher near discontinuity levels. RSA results yield slightly larger base shear compared to ESA due to the influence of multiple vibration modes Shown in Table t.

Table 7 Base Shear in X Direction

Model 1	2159.194
Model 2	1893.72

The base shear values indicate that Model 1 (2056.28 KN) attracts more seismic force compared to Model 2 (1803.34 KN). This is due to the increased flexibility of Model 1, which results in higher mass participation and overall force transfer at the foundation. Model 2, being stiffer, experiences slightly lower base shear. The results show that base shear is maximum at the foundation and decreases progressively at upper storeys, which is expected in seismic load transfer Shown in Figure 9.

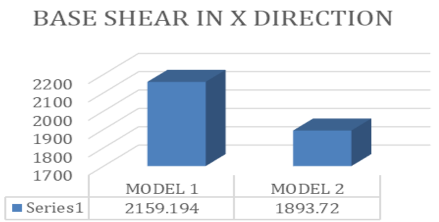

Figure 9 Base Shear in X Direction

3.1.7. Base Shear in Y Direction

For the G+8 building with vertical irregularities, the analysis shows that the base shear is concentrated at the foundation and is slightly amplified compared to a regular plan due to stiffness discontinuities and torsional coupling [12]. Response Spectrum Analysis (RSA) is a method that uses higher vibration modes and torsional effects to generate higher base shear in the X direction, which is crucial for designing foundations and primary lateral load-resisting elements like frames, shear walls, and core. The following table indicates the base shear value for different models Shown in Table 8.

Table 8 Base Shear in Y Direction

Model 1	2056.28
Model 2	1803.54

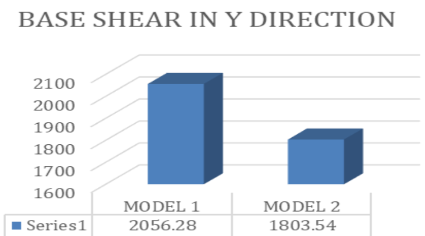

Figure 10 Base Shear in Y Direction

The maximum base shear in the Y–direction for Model 1 is 2056.28 kN, whereas for Model 2 it is 1803.54 kN. This shows that Model 1 attracts a higher seismic force compared to Model 2. The difference arises mainly due to the variation in structural stiffness caused by vertical irregularities. A stiffer model (Model 2) tends to reduce overall displacement but simultaneously modifies the seismic force distribution. In summary, Model 1 experiences greater seismic demand, while Model 2 demonstrates reduced base shear, indicating improved energy dissipation but also highlighting the sensitivity of irregular buildings to seismic action Shown in Figure 10.

3.1.8. Storey Shear in X Direction

Storey shear in the X direction represents the cumulative horizontal seismic force acting on each floor level when earthquake loading is applied along the X-axis. The analysis shows that storey shear values are maximum at the base and gradually reduce towards the top storeys. In the G+8 commercial building with vertical irregularities, a non-uniform reduction trend is observed due to stiffness discontinuities at setback levels. RSA generates somewhat elevated storey shear values compared to ESA owing to heightened mode effects, while base shear denotes the shear force at the foundational level Shown in Table 9.

Table 9 Storey Shear in X Direction

Story	Model 1	Model 2
8	587.72	523.76
7	1091.28	972.51
6	1472.9	1312.59
5	1749.469	1559.06
4	1937.11	1726.29
3	2056.5	1832.68
2	2123.8	1834.34
1	2154.032	1157.45
Plinth	2154.49	565.21
Foundation	2159.09	302.025

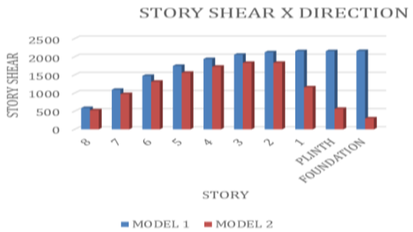

Figure 11 Base Shear in X Direction

The maximum story shear in the X–direction is observed at different levels for the two models. Model 1 reaches its peak of 2159.09 kN at the 1st storey, while Model 2 records its maximum of 1834.35 kN at the 3rd storey. This difference shows how vertical irregularities affect the way seismic forces are distributed through the height of the building. Model 1, with a higher base shear at the lower level, indicates a more uniform load transfer to the foundation. In contrast, Model 2 shifts its peak shear to an intermediate storey, reflecting localized stiffness variations due to irregularities. Such irregular force concentration requires careful design checks, as it may increase demand on structural elements at that level Shown in Figure 11.

3.1.9. Storey Shear in Y Direction

Storey shear in the Y direction represents the cumulative horizontal seismic force acting on each floor level when earthquake loading is applied along the Y-axis. The analysis shows that storey shear values are maximum at the base and gradually reduce towards the top storeys. In the G+8 commercial building with vertical irregularities, a non-uniform reduction trend is observed due to stiffness discontinuities at setback levels. Response Spectrum Analysis (RSA) produces slightly higher storey shear values compared to ESA, as RSA accounts for higher mode effects Base shear is the shear force at base or foundation level. The following table indicates the base shear value for different models Shown in Table 10.

Table 10 Storey Shear in Y Direction

Story	Model 1	Model 2
8	559.73	498.82
7	1039.31	926.2
6	1402.76	1250.82
5	1666.16	1484.82
4	1844.87	1644.088
3	1958.57	1745.41
2	2022.67	1746.99
1	2051.45	1038.77
Plinth	2056.169	756.758
Foundation	2056.28	588.6

The story shear distribution in the Y direction shows that Model 1 consistently carries higher shear compared to Model 2 at almost all levels. For instance, at the 5th storey, Model 1 resists 1666.16 kN while Model 2 resists 1484.82 kN. This means Model 1 attracts larger seismic demand along Y. Both models show a gradual increase in shear from top to bottom, peaking at the foundation level (2056.28 kN for Model 1 and 1756.78 kN for Model 2). The smoother profile of Model 1 indicates better distribution, whereas Model 2 reflects localized effects of irregularities Shown in Figure 12.

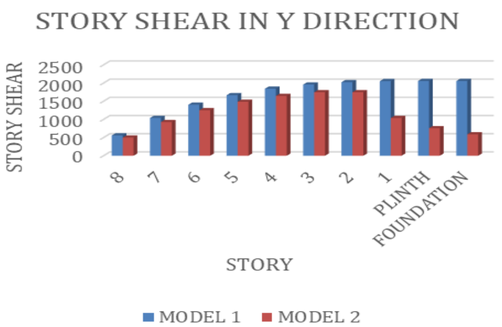

Figure 12 **Base Shear in Y Direction**

3.2. Results

- The maximum lateral displacement of Model-2 was higher than Model-1 across the entire height of the structure.
- Significant drift amplification occurred at the irregular storey of Model-2 due to stiffness discontinuity.
- Base shear demand was higher in Model-2 because of increased modal mass participation and reduced stiffness.
- The fundamental time period of Model-2 was higher than that of Model-1, indicating a more flexible dynamic response.
- Torsional rotation was observed in Model-2, leading to non-uniform displacement and uneven force distribution across the plan.
- Overall, Model-1 (regular building) demonstrated better seismic performance, while Model-2 (vertical irregular building) showed higher vulnerability under earthquake loading

3.3. Discussion

The seismic analysis clearly indicates that vertical irregularities significantly influence the distribution of lateral forces in a multi-storey commercial building. In the regular building model, the storey displacement and storey drift values follow a smooth and gradual pattern from the base to the roof, demonstrating uniform stiffness distribution and effective resistance against earthquake forces. In contrast, the vertically irregular model exhibits a sudden rise in displacement and drift near the location of soft storey, floating column and setback levels, indicating localized weakness in lateral load transfer. The base shear capacity of the irregular building is found to be lower than that of the regular structure, implying a reduction in lateral load-resisting efficiency due to discontinuities. The modal analysis shows that the irregular structure experiences higher participation in torsional and translational modes, which increases dynamic instability during earthquake loading. The storey drift ratio in the irregular building exceeds the permissible limits recommended by IS 1893:2016, particularly at the storey with vertical discontinuity. This highlights a potential vulnerability during strong seismic ground motion. The results confirm that when architectural and commercial requirements demand vertical irregularities, additional stiffening measures such as shear walls, bracing systems, strong columns and enhanced lateral systems are necessary to maintain structural safety. Overall, the study emphasizes that vertical irregular buildings can be constructed safely, but they must be designed with careful consideration of seismic behaviour and stiffness distribution, instead of relying solely on conventional design practices.

Conclusion

- Model 1 exhibits higher base shear (2056.28 kN in Y) compared to Model 2 (180 kN), indicating stiffer resistance in the more regular configuration.
- Story drift in Model 1 is lower (0.0015 at story 3) than Model 2 (0.0021 at story 3), showing that vertical irregularities increase lateral displacement.
- Story shear values highlight that irregular buildings experience force concentration at certain stories; for example, Model 1 has 2159.09 kN at story 1, while Model 2 has 1834.348 kN at story
- The comparison demonstrates that vertical irregularities can lead to uneven

distribution of seismic forces throughout the structure.

- Irregular structures are more prone to significant displacements and drift at crucial levels, requiring meticulous design attention.

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