|| Volume 9 || Issue 9 || September 2025 || ISSN (Online) 2456-0774
INTERNATIONAL JOURNAL OF ADVANCE SCIENTIFIC RESEARCH AND ENGINEERING TRENDS

Investigating the Influence of Vertical Irregularities on Structural Integrity

[1] SANSKRITI NAGAR, [2]MAHROOF AHMED

[1]M. Tech Scholar, Department of Civil Engineering, Sushila Devi Bansal College of Engineering Indore

[2]Assistant Professor, Department of Civil Engineering, Sushila Devi Bansal College of Engineering Indore

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Abstract: Earthquakes are among the most destructive natural hazards, and structural failures during strong seismic events have demonstrated the vulnerability of buildings with irregularities. This research investigates the influence of vertical irregularities on reinforced concrete (RC) buildings, including stiffness irregularities (soft storey), vertical geometric irregularities (setbacks), mass irregularities, and combined irregularities. Using SAP2000, a series of 19 models—both with and without infill walls—were developed and analyzed under seismic loads following IS 1893 (Part 1):2002 and IS 456:2000. The study applies linear static analysis, nonlinear static pushover analysis, and linear dynamic response spectrum analysis to evaluate seismic performance. Results highlight the critical impact of soft storey and setback irregularities on displacement, base shear, and hinge formation, while infill walls are found to significantly enhance performance. The findings emphasize the need for careful consideration of vertical irregularities in seismic design and suggest directions for improving resilience in earthquake-prone regions.

Keywords: *Vertical Irregularities; Seismic Analysis; Pushover Analysis; Response Spectrum; RC Frames; SAP2000*

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I.INTRODUCTION:

Earthquakes represent one of the most severe and unpredictable natural hazards, often resulting in catastrophic damage to buildings, infrastructure, and human life. The seismic performance of a building is primarily governed by its geometry, stiffness distribution, mass arrangement, and structural system. Historically, post-earthquake damage assessments have revealed that buildings with regular and symmetrical configurations generally demonstrate better resistance to seismic forces than those with irregularities in plan or elevation. Regular structures distribute seismic forces more evenly, ensuring uniform stiffness and strength, whereas irregular structures tend to concentrate stresses at discontinuities, making them highly vulnerable during strong ground shaking. In practice, however, architectural and functional requirements frequently necessitate the construction of irregular buildings. Variations such as open ground storeys for parking, setbacks for urban design, mass concentration due to service floors, or construction on sloping ground are becoming increasingly common. While these features enhance functionality and aesthetics, they introduce vertical irregularities that alter the natural period, mode shapes, and lateral load distribution of the structure, leading to unpredictable seismic behavior. Recognizing this, international and national seismic codes, including IS 1893 (Part 1): 2002, Eurocode 8, and FEMA 356, classify irregularities and prescribe appropriate analytical approaches. Among them, vertical irregularities have been identified as particularly detrimental because they create abrupt changes in stiffness, mass, or geometry along the height of the building. These discontinuities can trigger soft storey mechanisms, torsional amplification, weak-storey failures, and excessive inter-storey drifts, which are among the leading causes of collapse during earthquakes. This study focuses on the systematic investigation of vertical irregularities in RC buildings. It considers multiple irregularity types — stiffness irregularities (soft storey), vertical geometric irregularities (setbacks), mass irregularities (plan and elevation), and combined irregularities, both with and without infill walls. Using SAP2000 as the analytical tool, the models are subjected to linear static, nonlinear static (pushover), and linear dynamic (response spectrum) analyses in accordance with IS 1893 (Part 1): 2002.

II.OBJECTIVES OF THE STUDY

The main objectives of this study are:

- To compare the seismic response of regular and irregular RC buildings.
- To analyze the effect of soft storey, setback, mass irregularity, and sloping ground on seismic performance.
- To evaluate the role of infill walls in enhancing seismic resistance.
- To assess performance using linear static, nonlinear pushover, and response spectrum analyses.

III.METHODLOGY AND MODELLING APPROACH

3.1 General: A hypothetical building is considered, and various irregularities are introduced to study their effects.

- A regular structure refers to a building without any irregularities, being symmetrical in plan with uniform strength, stiffness, and mass distribution.
- An irregular structure, as defined by IS 1893 (Part 1): 2002, refers to a building that has discontinuities or asymmetry in strength, stiffness, or mass distribution

3.2 List of models taken for study.

3.2.1 Buildings without infill walls.

- Regular building
- Building with soft storey effect at ground level
- Building with soft storey effect at intermediate level
- Building with set backs
- Building with mass irregularity in plan

- Building with mass irregularity in elevation
- Building with combined effect of soft storey and set backs
- Building with combined effect of setbacks and mass irregularity
- Building with combined effect of soft storey at ground level setbacks and mass irregularity
- Building with Sloping ground effect.

3.2.2 Building with infill walls.

- Regular building
- Building with soft storey effect at ground level
- Building with soft storey effect at intermediate level
- Building with set backs
- Building with mass irregularity in plan
- Building with mass irregularity in elevation
- Building with combined effect of soft storey and set backs
- Building with combined effect of setbacks and mass irregularity
- Building with combined effect of soft storey at ground level setbacks and mass irregularity

3.3 Typical features for the models considered.

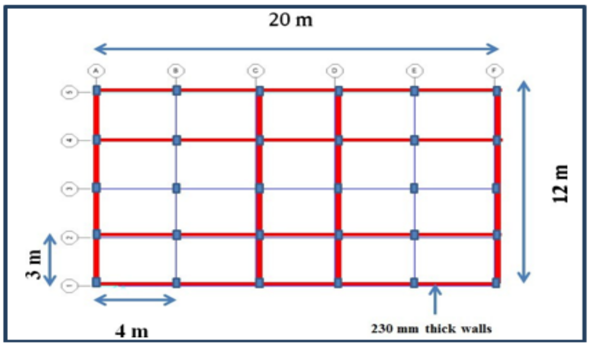
Type of the Building	Residential Building
Location of the Building	Delhi
Seismic Zone	Zone-4
No. of Storey	G+10
Plan area	20m x12 m
Grade of concrete	M 30
Grade of steel	Fe 415
Beam size	300mm x 600mm
Column size	350mm x 600mm
Slab thickness	125 mm
Wall thickness	230 mm
Density of concrete	25 kn/m^3
Density of masonry	20 kn/m^3
Yield strength of steel	415 N/m^2
Zone factor	.24
Type of soil	Medium

3.4 Complete breakdown of a regular building.

Building without any irregularities, and is symmetrical in plan, strength, stiffness and mass assignment.

3.4.1 Plan details

Figure 3. 1 Plan details of the building at typical floors.



Plan area	20 m X 12 m
Bay width -x	4m
Bay width -y	3m

It is assumed that all highlighted beams have 230 mm thick walls, while the beams that are not highlighted do not carry any walls above them on any floor, except at the roof level(Figure 3.1).

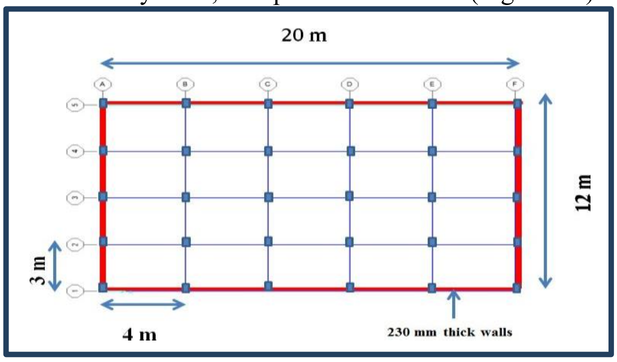


Figure 3. 2 Plan details of the building at roof level.

Building featuring a soft storey at mid-level without infill walls.

All specifications regarding building type, materials used, section properties, loading conditions, plan area, and soil type remain the same as discussed in the previous sections. The only changes are in the geometrical parameters and time period due to the increased height. The height of the 5th storey is increased, and the wall load is removed.

Variation in geometry

Regular building Soft storey at intermediate level

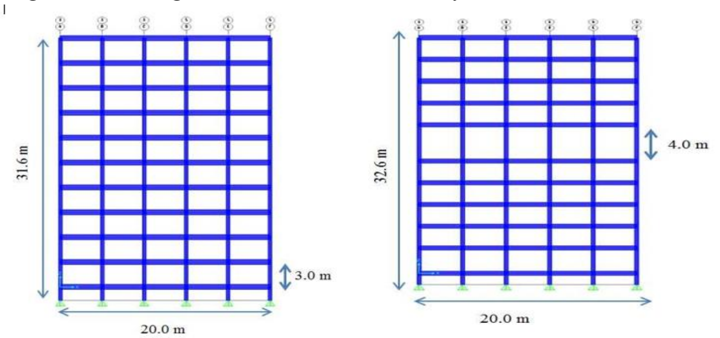


Figure 3.3 Soft storey at intermediate level.

Building with soft storey at mid-level without infill walls.

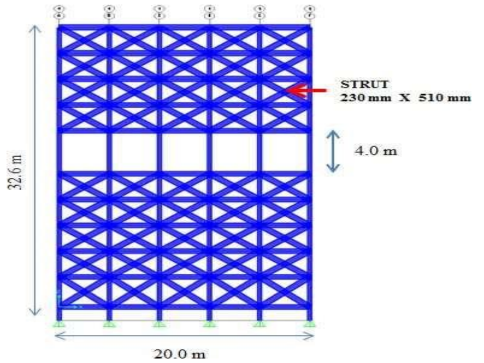


Figure 3.4 Strut modeling in building with soft storey at intermediate level

Building with setback configurations without infill walls

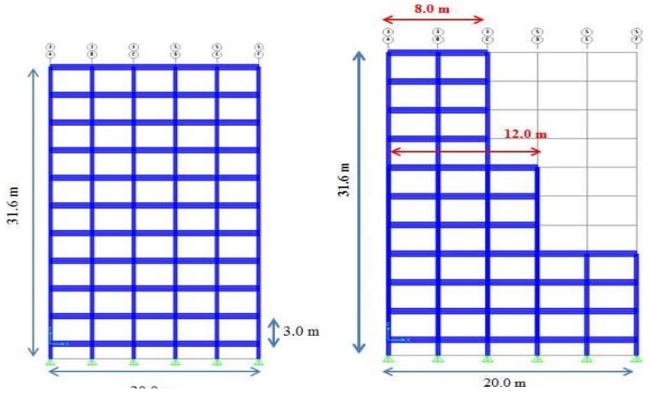


Figure 3.5 Setback modeling

Building with mass irregularity in plan without infill walls.

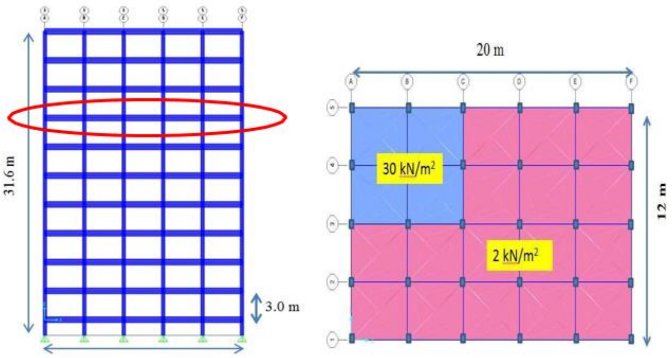
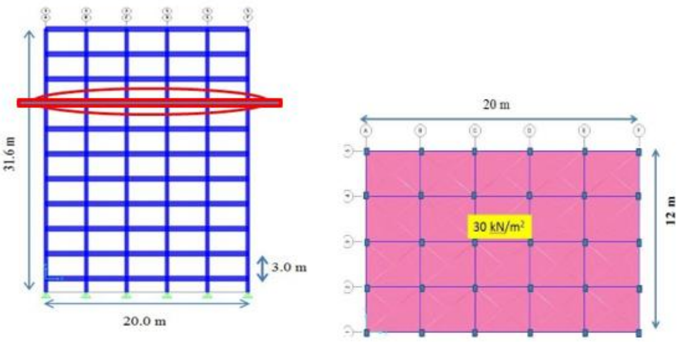


Figure 3.6 Inducing mass irregularity in plan

Building with mass irregularity in elevation without infill walls.



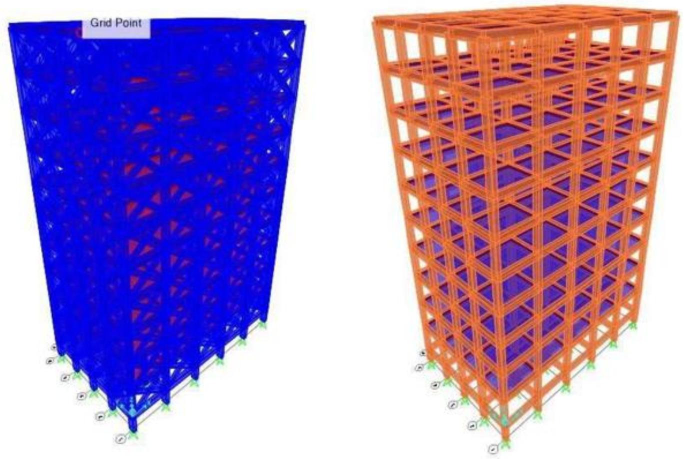


Figure 3.7 Inducing mass irregularity in elevation

3-D view of models with and without infill walls.

Figure 3.8 3-D view of models with and without infill walls.

IV.RESULT AND DISCUSSION

4.1 Modal mass participation.

Modes upto which 90%modal mass participation is obtained, number of modes varies when irregularities varies.

Table 4.1 Number of modes till which 90% modal mass participation is obtained.

TYPE OF STRUCTURE	MODELLING METHOD	90% MODAL MASS PARTICIPATION	MODES
REGULAR BUILDING	NO INFILL	X	4
		Y	5
	INFILL	X	4
		Y	5
GROUND LEVEL SOFT STOREY	NO INFILL	X	4
		Y	5
	INFILL	X Y	1
			2
INTERMEDIATE LEVEL SOFT STOREY	NO INFILL	X	4
		Y	5
	INFILL	X	4
		Y	5
SET BACK	NO INFILL	X	7
		Y	8
	INFILL	X	4
		Y	6
MASS IRREGULARITY IN ELEVATION	NO INFILL	X	4
		Y	5
MASS IRREGULARITY IN PLAN	NO INFILL	X	4
		Y	5
	INFILL	X	4
		Y	5
SET BACK + SOFT STOREY	NO INFILL	X	4
		Y	6
	INFILL	X Y	1
			3
SET BACK +SOFT STOREY +MASS IRREGULARITY IN PLAN	NO INFILL	X	4
		Y	5
	INFILL	X Y	1
			3
SLOPING GROUND EFFECT I	NO INFILL	X	4
		Y	5
SLOPING GROUND EFFECT II	NO INFILL	X	6
		Y	9

Time period of structures with and without infill walls.

Time period of structures with and without infill walls have been collected and percentage variation between time period of a structure without infill walls and of a structure with infill walls is calculated to consider the effect of infill walls on our structure.

Table 4.2 Percentage variation in time period of a structure with and without infill walls.

TYPE OF STRUCTURE	DIRECTION	TIME PERIOD		PERCENTAGE VARIATION %
		NO INFILL	INFILL	
REGULAR BUILDING	X	1.35	0.70	48.3
	Y	1.05	0.67	36.2
GROUND LEVEL SOFT STOREY	X	1.48	1.06	28.6
	Y	1.14	0.91	19.9
INTERMEDIATE LEVEL SOFT STOREY	X	1.38	0.94	32.0
	Y	1.08	0.89	17.6
SET BACK	X	1.09	0.72	34.1
	Y	0.95	0.71	25.4
MASS IRREGULARITY IN PLAN	X	1.36	0.86	37.1
	Y	1.06	0.82	22.5
SET BACK + SOFT STOREY	X	1.21	0.86	28.9
	Y	1.05	0.81	22.9
SET BACK +SOFT STOREY +MASS IRREGULARITY IN PLAN	X	1.23	0.87	28.7
	Y	1.06	0.82	22.8

4.2Shear force at the base and Critical performance point

The base shear values obtained from the linear static analysis and the performance points from the pushover analysis for all the structures analyzed are compiled in the following table. The table also shows the residual force that the structure can withstand before ultimate failure. Additionally, the percentage variation between the performance points obtained from the pushover analysis and the base shear values from the linear static analysis is calculated.

Table 4.3 Performance point and Base shear values for all cases considered for study.

TYPE OF STRUCTURE	MODELLING METHOD	PERFORMANCE POINT			BASE SHEAR (kN)	RESIDUAL FORCE (kN)	PRECENTAGE VARIATION %
		CASE	FORCE (kN)	DISPLACEMENT (mm)			
REGULAR BUILDING	NO INFILL	PUSH X	2550	50	1396	1154	45.3
		PUSH Y	2621	42	1396	1225	46.7
	INFILL	PUSH X	4043	41	2197	1846	45.7
		PUSH Y	4591	42	1702	2889	62.9
GROUND LEVEL SOFT STOREY	NO INFILL	PUSH X	2166	58	1312	854	39.4
		PUSH Y	2272	47	1312	960	42.3
	INFILL	PUSH X	2628	44	2047	581	22.1
		PUSH Y	3043	42	1587	1456	47.8
INTERMEDIATE LEVEL SOFT STOREY	NO INFILL	PUSH X	2459	53	1256	1203	48.9
		PUSH Y	2531	42	1256	1275	50.4
	INFILL	PUSH X	5378	50	1870	3508	65.2
		PUSH Y	5314	41	1670	3644	68.6
SET BACK	NO INFILL	PUSH X	2567	46	972	1595	62.1
		PUSH Y	2335	41	972	1363	58.4
	INFILL	PUSH X	3838	27	1569	2269	59.1
		PUSH Y	4998	32	1403	3595	71.9
MASS IRREGULARITY IN PLAN	NO INFILL	PUSH X	2671	43	1499	1172	43.9
		PUSH Y	2756	44	1499	1257	45.6
	INFILL	PUSH X	3923	41	2285	1638	41.8
		PUSH Y	6056	42	2043	4013	66.3
SET BACK + SOFT STOREY	NO INFILL	PUSH X	2112	51	847	1265	59.9
		PUSH Y	1901	46	847	1054	55.4
	INFILL	PUSH X	2485	35	1395	1090	43.9
		PUSH Y	2644	40	1248	1396	52.8
SET BACK +SOFT STOREY +MASS IRREGULARITY IN PLAN	NO INFILL	PUSH X	2117	38	863	1254	59.2
		PUSH Y	1907	43	863	1044	54.7
	INFILL	PUSH X	2494	36	1420	1074	43.1
		PUSH Y	2656	41	1270	1386	52.2
SLOPING GROUND EFFECT I	NO INFILL	PUSH X	2421	40	1303	1118	46.2
		PUSH Y	2504	42	1303	1201	48.0
SLOPING GROUND EFFECT II	NO INFILL	PUSH X	4534	40	615	3919	86.4
		PUSH Y	4649	42	615	4034	86.8

4.4 Structural performance capacity.

Graphical representation of capacity of structures with and without infill walls.

Effect of infill walls – The structure's capacity is significantly higher when the effect of infill walls is taken into account. The percentage variation is clearly shown in the table above. Several graphs are plotted to compare the capacity of the structure with and without considering the effect of infill walls.

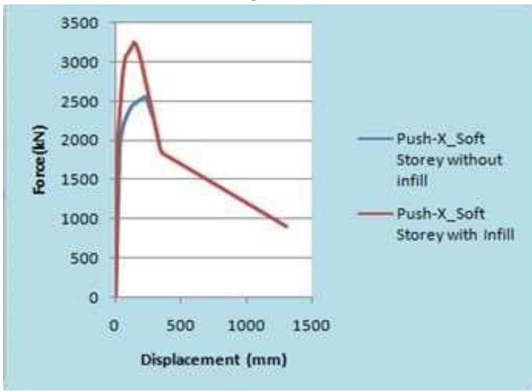


Figure 4.1 Capacity of building with soft storey at ground level with and without infill walls in x- direction

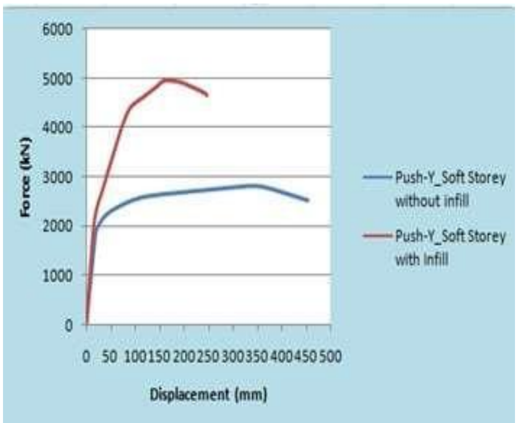


Figure 4.2 Capacity of building with soft storey ground level with and without infill walls in x- direction

|| Volume 9 || Issue 9 || September 2025 || ISSN (Online) 2456-0774
INTERNATIONAL JOURNAL OF ADVANCE SCIENTIFIC RESEARCH
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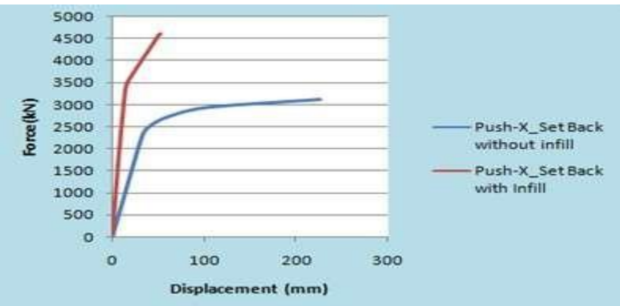


Figure 4.3 Capacity of building with setbacks with and without infill walls in x- direction

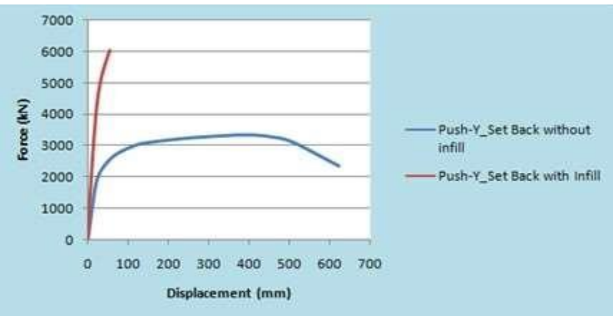


Figure 4.4 Capacity of building with setbacks with and without infill walls in y- direction.

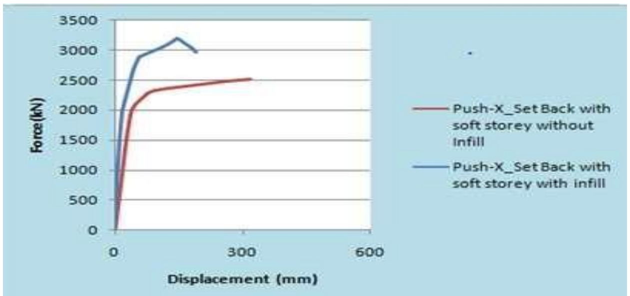


Figure 4.5 Capacity of building with setbacks and soft storey with and without infill walls in x- direction

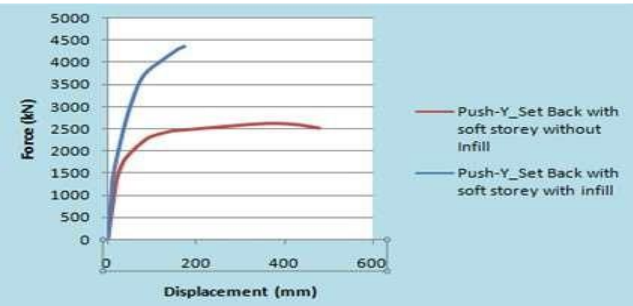


Figure 4.6 Capacity of building with setbacks and soft storey with and without infill walls in y- direction

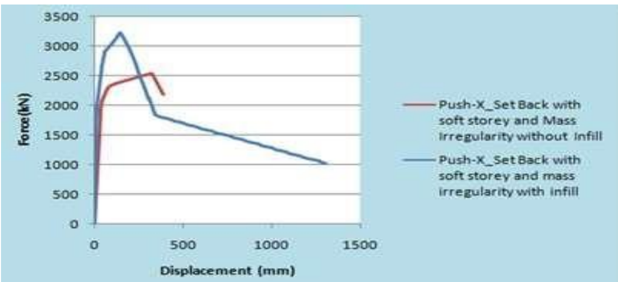


Figure 4.7 Capacity of building with setbacks, soft storey and mass irregularity in plan with and without infill walls in x- direction

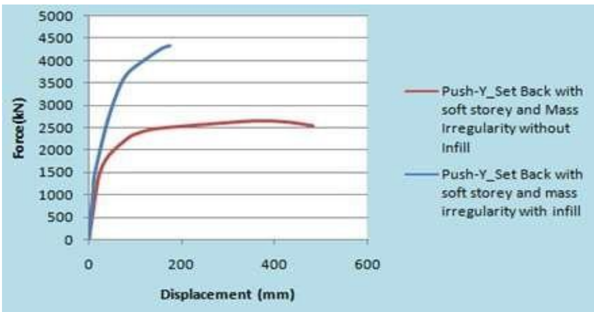
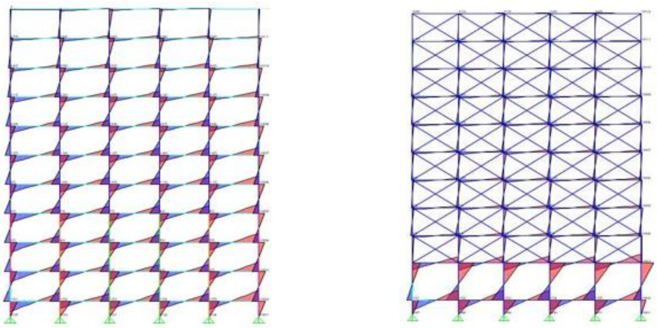


Figure 4.8 Capacity of building with setbacks, soft storey and mass irregularity in plan with and without infill walls in y- direction.

Investigation of moment and force distribution in beams and columns at the soft storey level.

In building with soft storey at ground level both with and without infill walls, moments and forces in beams and columns is studied.



Without infill walls With infill walls

Figure 4.9 Forces in beams and columns in building with soft storey at ground level with and and without infill walls

AS PER IS-1893 2002, if there is a soft storey in a building and while designing we are neglecting the effect of infill walls, the column and beams of the soft storey are to designed for 2.5 times the storey shear and moments under seismic loads.

As per my study:-

Variation of moments in column and beams Between regular building without infill walls and building with soft storey and infill walls are,

Moments in column = 2.4 times Moments in beams = 1.58 times.

V.CONCLUSION

Based on the comprehensive analysis of 19 structural models (regular and irregular, with and without infill walls) using Equivalent Static Analysis, Nonlinear Pushover Analysis, and Response Spectrum Analysis in SAP2000, the following conclusions are drawn:

1. These irregularities introduced torsional effects and led to non-uniform load distribution, which increased vulnerability under seismic loading.
2. Structures with combined irregularities (e.g., soft storey + setback + mass) exhibited the worst seismic performance, with

higher displacements, reduced ductility, and premature hinge formations.

3. Presence of infill walls significantly improved the overall seismic performance.
4. Infill walls contributed to increased stiffness, reduced displacements by 25–40%, and delayed hinge formation, thereby enhancing the collapse resistance of the building.
5. However, if not uniformly distributed, infills can also introduce irregularities of their own.
6. Base shear capacity was consistently higher in regular structures compared to irregular ones under both static and dynamic analyses.
7. Among all irregularities studied, soft storey and setback conditions were the most detrimental to seismic safety.
8. Mass irregularities had less impact individually, but when combined with other irregularities, their effect became severe.
9. The findings strongly emphasize the need for special seismic provisions in design codes (e.g., IS 1893, IS 456) for irregular buildings.
10. Regular structures, or those with uniformly distributed stiffness and mass, remain inherently safer against seismic events.

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