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Comparative Analysis of Structural Performance of Plain and Step-back RCC Building

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Abstract

This study compares the performance and structural response of two buildings: a 4 Storey RCC building built on plain ground, and a Step-back RCC building, built on a sloping ground. The step-back model has a single bay in the lowermost floor and 2 bays at every other level along one direction. Two models were developed in FEM tool ETABS. Both buildings were analysed by 3 methods, Equivalent Static Method, Response Spectrum Analysis, and Pushover Analysis following the guidelines in NBC 105:2020 code. Key response parameters such as storey drift, storey shears, modal mass participation, fundamental time period, and various performance point parameters were evaluated. The findings suggest that despite being stiffer, the step-back building showed similar maximum displacement values along weaker direction, indicating higher inter-storey drift values. The storey shear values continuously increased from top storey to bottom for the plain RCC building, but for the step-back building, there was a sudden change in nature of storey shear between 1st and 2nd storey due to the supports provided at differing levels. The results of model analysis indicate that step-back configuration is stiffer than plain one. Non-linear pushover analysis shows that plain building can withstand higher base shear and displacements at performance point. These results suggest that more precautions is necessary during step-back building construction to ensure stability and safety.

Keywords: *Step-back building, RCC, ETABS, Seismic Performance*

1. Introduction

Reinforced cement concrete (RCC) frame buildings are widely employed in Nepal, especially in hilly and urban areas. Such constructions are often built with symmetric plans and erected on flat sites. Nevertheless, there are many cases when buildings incorporate different irregularities due to site limitations, architectural needs, and other functional reasons.

One of the most widespread irregularity in Nepal is building with step-backs, meaning that its floor area gradually reduces when building elevation rises, providing the building with stair like appearance. Buildings having step-backs are rather popular in Nepal, especially in its hilly and mountainous zones, since such areas have natural slopes. Therefore, the study of step-back buildings has become a necessity.

The structures on slopes are structurally weaker than flat land structures owing to their geometrical irregularities and varying height of the columns. Stepback and setback architectural styles increase vulnerability to earthquakes due to structural irregularity, which was proven by Kumar in 1996. The results from Sreerama and Ramancharla (2013) indicate that stiffer and shorter columns experience higher lateral forces causing brittle shear failure. Birajdar and Nalawade (2004) found that the difference between the centers of mass and stiffness causes high torsional forces in slope buildings. Slope buildings failed during the Gorkha earthquake in 2015. According to Tiwary et al. (2014), RC structures failed due to soft stories, shear failure, and irregular plan geometry. Shear walls and bracing have been considered appropriate countermeasures to such problems according to Danish et al. (2013) and Amini et al. (2012) (Chettri & Adhikari, 2021).

Prior investigations demonstrate that buildings located on sloping terrain have different responses compared to buildings on flat terrain when subjected to earthquakes owing to their non-uniform mass and stiffness distribution. It was also observed that the base shear, displacement, and time period of step-back and setback arrangements were significantly affected by the above arrangements. Shear walls and bracing systems can contribute to better seismic response by minimizing drift and structural loads. In addition, it is also pointed out that SSI effect causes displacement and time period to increase on account of soil flexibility. Nevertheless, there has been a dearth of research conducted on low-rise RC buildings designed according to MRT criteria on sloping terrain in Nepal (Shrestha et al., 2023).

The torsional irregularity is an important aspect which affects the seismic performance of multi-storey structures. This aspect has been highlighted by various authors like Thaskeen and Shajee (2016) and Pajgade and Guptha (2015), where it has been stated that the presence of eccentricity and irregularity causes torsion which in turn results in greater displacement and forces. The studies carried out by Arvindreddy and Fernandes (2015) and Mohamed and Abbas (2015) reveal that torsional irregularity should be taken into consideration during static as well as dynamic analysis due to its significant effect on drift and modal response (Lamichhane et al., 2021).

For buildings located on sloping ground, the Nepal National Building Code (NBC 105:2020) states that the problems caused by the irregular shape of the footing and differences in stiffness between various levels are significant considerations. As per the building code, a slope building with irregular configuration is classified as a vertically irregular structure where differences in height of columns and stepped footing could enhance the demands on buildings due to earthquakes. The importance of torsion, inter-storey drift, and stability considerations from the effect of sliding and overturning should be analyzed thoroughly. For slope building design, NBC recommends considering real soil-structure interaction (NBC, 2020).

It should be known that buildings made of reinforced concrete constructed on slopes will have varying reactions in seismic loads than on normal plains. Previous research works have indicated that slope inclination, soil rigidity, and shear walls have significant impacts on base shears, storey drifts, and bending moments. Researchers have always noted the occurrence of the short column problem in slopes whereby shorter columns receive higher forces, making them less resilient to earthquakes. In comparisons between RCC and steel buildings, RCC buildings provide higher rigidity and low storey drifts while steel buildings present low base shears owing to their light seismic weight (Siva et al., 2020).

The buildings erected on slopes are more vulnerable to earthquakes because of mass and stiffness irregularities, resulting in increased shearing and twisting loads. From literature, it has been seen that step-back and split foundations tend to have poor performance, whereas step-back set-back buildings have relatively higher safety against earthquake loading. The effect of soil-structure interaction in the case of slope foundation is seen to increase displacement and period while decreasing the base shear (Poudel & Adhikari, 2025).

This paper seeks to fill this gap through the detailed analysis of the performance of two ETABS-modelled RCC structures: (i) a regular structure that has a rectangular layout for all its floors, and (ii) an irregular structure, which also uses the same upper-floor layout, but a smaller layout at the lower level resulting in a step-like structure. Both structures use the same number of bays (5 bays, A to E grid), story height, material, and loadings, such that any differences in the performance can be attributed to irregularity alone.

1.1 Objectives of the Study

The specific Objective of this study are:

i. To develop ETABS models of a plain (Regular) and a step-back (irregular) RCC building with identical structural parameters.

ii. To compare story shear, lateral displacement, natural time period and non-linear behaviour of the two building models.

2. Materials and Methods

This part discusses the structural form of the two models for buildings, the material assumptions taken into account, the loading pattern, the analysis procedures that have been used, and the approach used in comparing their earthquake resistance performance. An approach is provided to illustrate the sequence of activities involved.

2.1 Description of Building Models

This study considered two reinforced concrete frame buildings: a plain (regular) building and a step-back (irregular) building. The buildings are assumed to be have the same grid layout, two bays in the longitudinal direction (Grid 1 through 3) and four bays in the transverse directions (Grid A through E), as shown in Figure 1.

Structural Configuration

a) Height of floor : 3.2 m
b) Number of Storey : G+4
c) Floor plan size : 13.1 m x 26 m
d) No. of bay in X-direction: 2
e) No. of bay in Y-direction: 4
f) Grade of Concrete: M25
g) Rebar: HYSD 500
h) Steel: Fe250

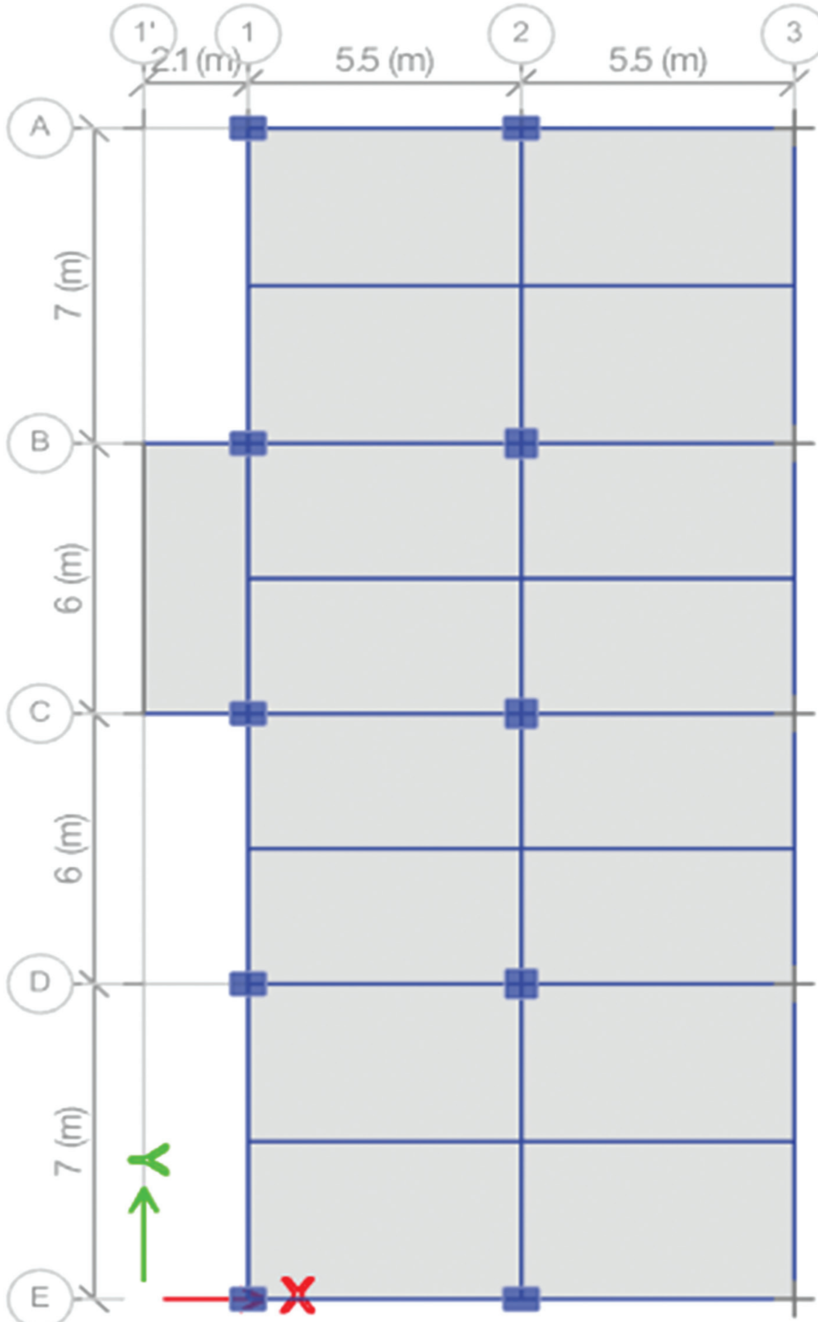

Figure 1: Plan of Selected Building

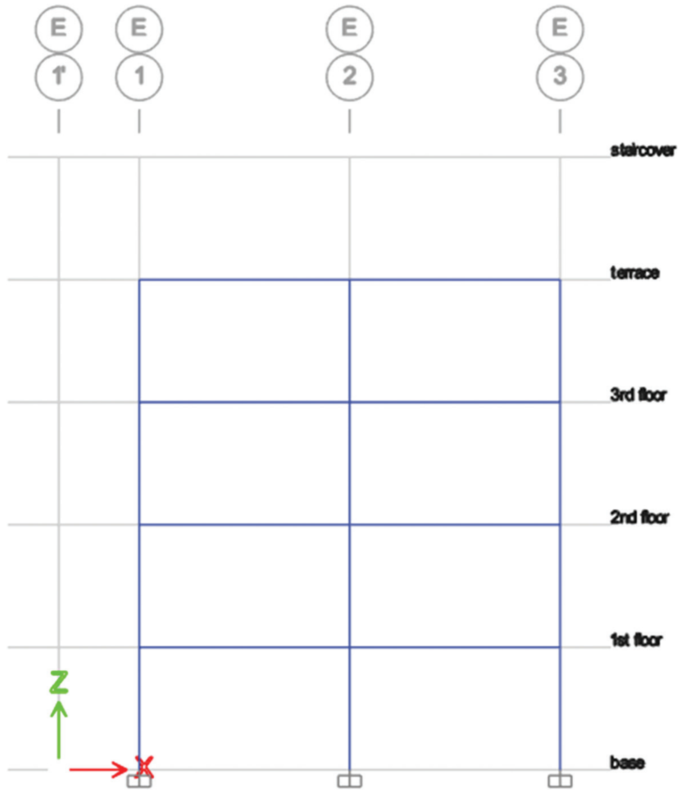

Figure 2: Elevation View of Plain Building Model

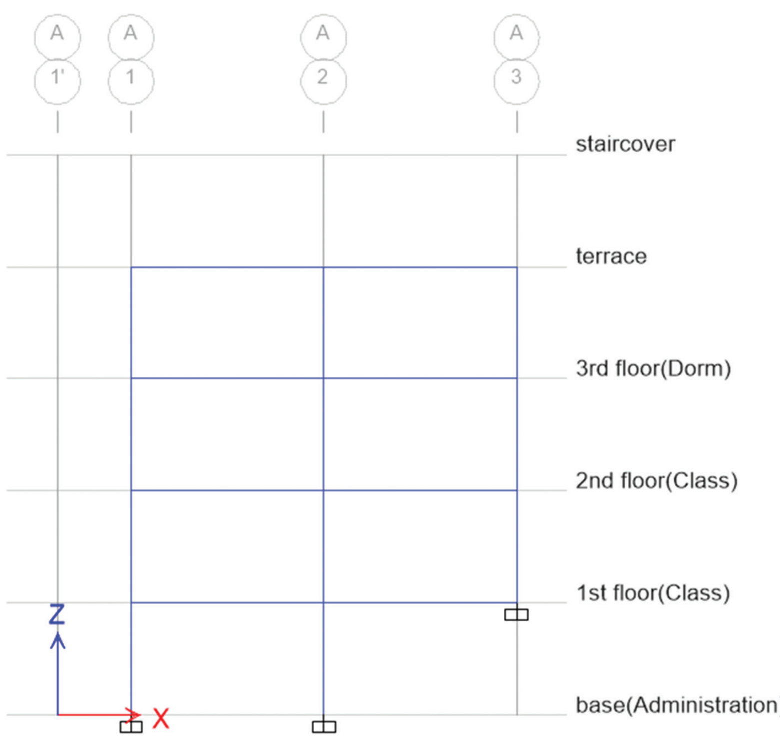

Figure 3: Elevation View of Step- Back Building Model

Loading Data

a) Outer wall Load: 12 kN/m

b) Partition wall Load: 1.91 kN/m^2 on slab, 8 kN/m on beams

c) Live load: 3 kN/m^2 on rooms, 4 kN/m^2 on stair and passage

d) Floor finish: 1.55 kN/m^2

2.2 Section Properties

The beam (Primary and Secondary), and Column sections used in the models are mentioned in the table:

Table 1: Size of Beams selected in RCC and Step-back Model

Floor	Primary Beam(mm)	Secondary Beam(mm)	Grade of concrete and rebar
1st	350×550	300×425	
2nd	350×550	300×425	
3rd	350×550	300×425	M25 & HYSD500
Terrace	250×400	200×300	
Staircover	250×400	200×300	

Table 2: Size of Columns Selected in RCC and Step-back Model

Grid	Size(mm)	Grade of concrete and Rebar
B2, C2, D2 all floor	625×625	M25 & HYSD500
All other columns	700×500	

Note: only for Step-back Model, No column in the grid 3 of 1st floor of the building (i.e. A3, B3, C3, D3, E3)

2.3 Selected Site Characteristics

Table 3: Site Characteristics

Site Subsoil Category	Soil Type D (Kathmandu)
Seismic Zoning Factor(Z)	0.35 (Kathmandu)
Importance Class	II (Commercial Building)
Importance Factor	1.25

2.4 Assumptions

1. The foundation is assumed to be fixed and the soil-structure interaction is not considered.
2. The infill walls are not considered in the model but their load have been distributed on beams.

2.5 Method of Analysis

Three methods of analysis have been used in this study. They are:

Equivalent Static Analysis (ESA): Equivalent Static Analysis is a simplified seismic analysis technique used in structural engineering to estimate earthquake forces on a building. The guidelines in NBC 105:2020 have been used for ESA and calculation of design base shear. The product of the floor mass and the height above the base determines how the base shear was distributed along the building's height. This technique has been used in both structures because they are within the code's height and regularity restrictions.

Response Spectra Analysis (RSA): Response Spectrum Analysis is a linear dynamic analysis technique. For structures with irregular configuration this method is more suitable than ESA. RSA has been carried out using the design spectrum outlined in NBC 105:2020. At least 12 modes were identified such that the sum of the modal participation mass is at least 90 percent of the total seismic mass in the horizontal directions. The results of modal analyses were summed up using the Complete Quadratic Combination method.

Pushover analysis: Pushover analysis is a nonlinear static procedure used in structural engineering to assess a building's seismic performance by gradually applying increasing lateral loads until the structure reaches failure. Pushover Analysis is performed by assigning user-defined hinges to the members of the structure, such as beams and columns, which can undergo plastic deformation under loading. The non-linear model is prepared first, and then the structure is pushed under gravity in the load pattern of the fundamental mode until it reaches the target displacement. Pushover Analysis has been performed in accordance to the FEMA440 Equivalent Linearization Guidelines.

2.6 Performance Parameters Evaluated

The following response characteristics were analyzed for both the plain and step-back models of buildings based on Equivalent Static Analysis and Response Spectra Analysis:

1. Story Shear: Horizontal loads for each story that help evaluate the horizontal loading along the height of the structure.
2. Lateral Displacements (Story Displacements): Absolute horizontal displacements at the levels of each story that are used to determine the total displacement.
3. Natural Time Period and Mode Shapes: Fundamental time period and mode shapes obtained through RSA analysis.
4. Pushover analysis: Base shear and spectral displacements at performance point.

2.7 Methodological Framework

The overall methodology follows a sequential analytical framework:

1. Structural model development in ETABS for both buildings.
2. Assignment of material properties and loading conditions.
3. Execution of ESA, RSA and pushover analysis.
4. Extraction of performance parameters
5. Comparative evaluation of results to identify the influence of geometric irregularity (step-back) on seismic behavior.

All results are interpreted against the acceptance criteria specified in NBC 105:2020.

3. Results and Discussion

3.1 Lateral Displacement (Story Displacement)

Table 5: Lateral displacements of Plain RCC Building (RS_x and RS_y load Cases)

Story	RS_x	RS_y
	X-Dir (mm)	**Y-Dir (mm)**
staircover	64.236	43.039
terrace	58.625	49.976
3rd floor	43.85	38.745
2nd floor	26.95	24.89
1st floor	9.648	9.406
base	0	0

Table 6: Lateral Displacements of step-back Building (RS_x and RS_y load Cases)

Story	RS_x	RS_y
	X-Dir (mm)	**Y-Dir (mm)**
staircover	65.916	13.123
terrace	53.879	13.262
3rd floor	33.782	8.826
2nd floor	13.519	3.89
1st floor	0	0
base	0	0

Since the first story of the step-back building has been modelled as rigidly supported, the deflection at this level as well as the base is zero. Despite this, the top story displacements along the X direction are almost the same for both configurations. This suggests that the step-back building experiences higher interstory drift values, making it more vulnerable along this direction. The displacements and drifts are much less along the Y direction.

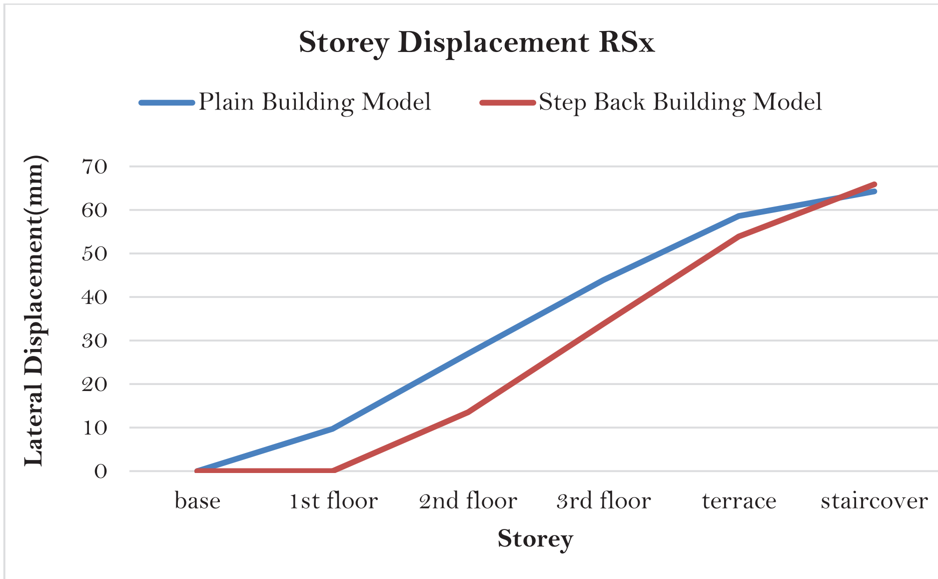

Figure 4: Storey Displacement for RS_x

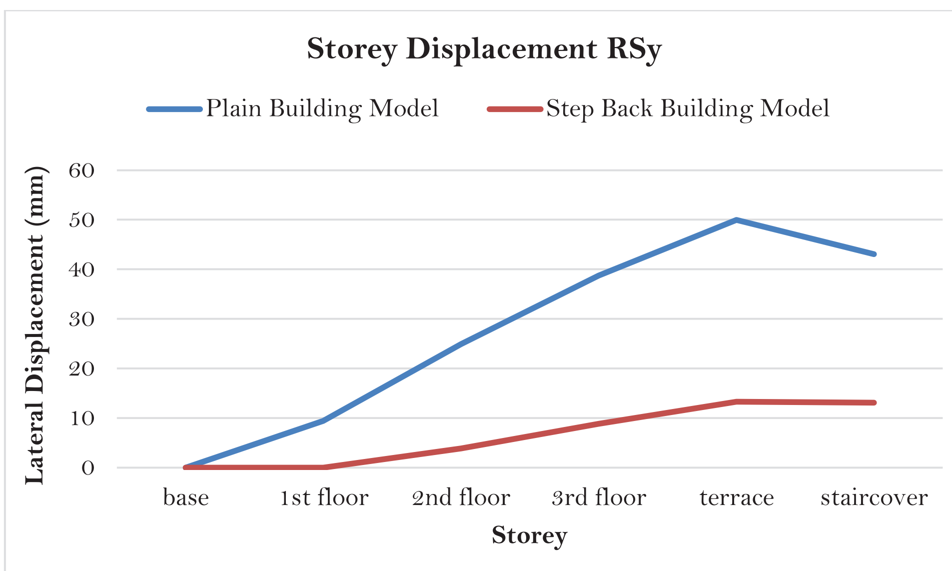

Figure 5: Storey Displacement for RS_y

3.2 Storey Shear

Table 4: Story Shear of Plain and Step-back Buildings

Story	Elevation(m)	Shear force	
		Plain Building (kN)	Step-back Building (kN)
staircover	16	-246.21	-230.21
terrace	12.8	-1015.70	-969.22
3rd floor	9.6	-1899.60	-1847.93
2nd floor	6.4	-2464.81	-2437.83
1st floor	3.2	-2723.95	1113.14

The storey shears experienced by the plain building and the step-back building are as shown in Table 3. The story shears for the plain building are slightly larger than those of the step-back building. The sudden change in the nature of shear force between the first and second floors is caused by the fixed supports modelled at the first story level of the step-back configuration

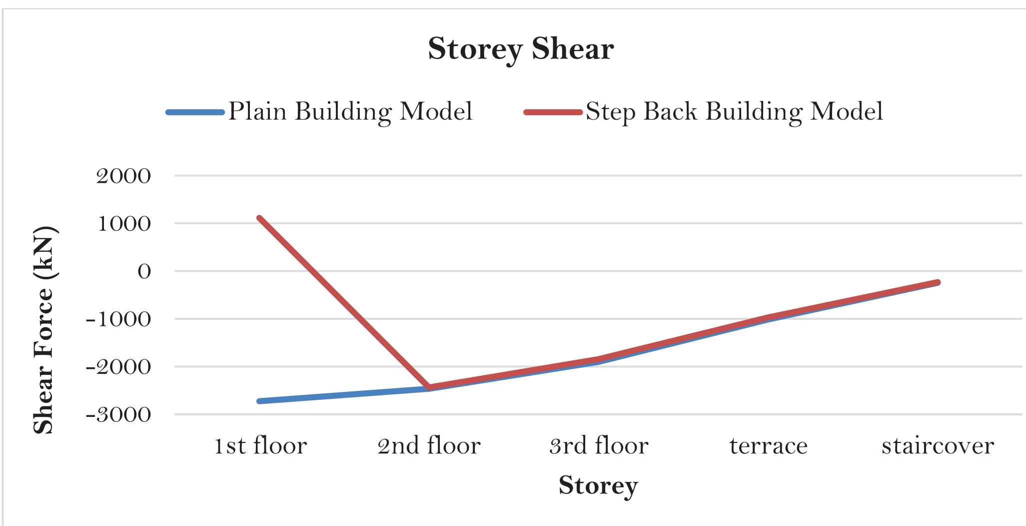

Figure 6: Storey Shear

3.3 Modal Analysis

Table 7: Modal mass Participation ratios for Plain and Step-back buildings

Plain Building				
Mode	Period(sec)	UX	UY	SumRZ
1	0.811	0.748	0.0057	0.0103
2	0.752	0.0152	0.4282	0.3558
3	0.653	0.0005	0.3577	0.7768

Step-back Building				
Mode	**Period(sec)**	**UX**	**UY**	**SumRZ**
1	0.633	0.6391	0.0125	0.0083
2	0.587	0.0192	0.529	0.1529
3	0.517	0.0006	0.1441	0.6954

The time periods and modal mass participation ratios along the three principal directions for the first three modes are shown in Table 4. The fundamental period of vibration for the step-back building is lesser than that of the plain building. This is due to the fixed supports at the first story level, which makes the step-back building much stiffer, reducing the time period.

3.4 Pushover analysis

Table 8: Performance parameter at performance point for both building Configuration

Parameter	Plain Building	Step-back Building
Shear(kN)	9322.6702	7374.6008
Displacement (mm)	186.063	72.747
Sa (g)	0.665644	0.743963
Sd (mm)	123.969	44.491

The results show that the plain building can withstand larger base shear and deflections compared to the step-back building. Although the spectral acceleration at the performance point is higher for the step-back building, the spectral displacement is lower. The position of the first hinge suggests that more forces are transmitted to the columns on the first story in the step-back configuration

4. Conclusions

1. The deflection at the first story level is zero for the step-back configuration.
2. Step-back configuration experiences much higher drift values along the weaker X-direction, leaving it vulnerable
3. Story shear changes in nature for the step-back building
4. Fundamental time period for the step-back configuration is lower than the plain building, suggesting stiffer nature.
5. The base shear and displacements at performance point are lower for the step-back configuration compared to plain

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