Seismic Performance Evaluation of an Existing 3-Story RCC Building Using Pushover Analysis

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Abstract

This study presents a seismic performance evaluation of an existing 3-story reinforced concrete (RCC) building located in Kathmandu using nonlinear static (pushover) analysis in ETABS. The building was originally designed according to IS 1893:2002, and the assessment is carried out in compliance with NBC 105:2020 to evaluate whether the building satisfies the requirements of the updated code. Actual structural details, material properties and hinge assignments are incorporated to accurately model the building's behavior under lateral loading. The performance point is determined using FEMA 440 Equivalent Linearization procedures, and the building's capacity is assessed through capacity curves.

The analysis reveals that the existing structure satisfies the Immediate Occupancy (IO) performance level in the X-direction and Life Safety (LS) in the Y-direction, indicating acceptable performance under design-level seismic forces. A modified model with an additional one story shows a decrease in base shear capacity and an increase in displacement, with performance levels reducing to LS in the X-direction and Collapse Prevention (CP) in the Y-direction. These findings suggest that while vertical extension is structurally feasible, it compromises the seismic performance, particularly in the Y-direction. The study emphasizes the need for careful evaluation and retrofitting strategies when considering structural modifications in seismically active regions.

Introduction

Nepal is situated in a seismically active zone where the Indian and Eurasian tectonic plates meet, making it extremely susceptible to frequent and potentially devastating earthquakes. The catastrophic Gorkha Earthquake in 2015 highlighted this vulnerability, leading to extensive destruction and significant loss of life. Rapid and unplanned urban growth, along with a rising population especially in the Kathmandu Valley, has resulted in a heightened risk during future seismic occurrences [1].

In an effort to improve seismic safety, the Nepalese government has updated its seismic code NBC 105 in 2020, introducing more advanced and performance-based design approaches. However, numerous existing buildings were designed using older standards, such as IS 1893:2002, IS 1893:2016, NBC 105:1994 and may not fulfill the safety and performance requirements outlined in the new code [2].

Nonlinear static procedures, such as pushover analysis, are useful for assessing the seismic adequacy of these structures, offering insights into their capacity and possible failure mechanisms [1].

Over the years, numerous studies have explored the application of pushover analysis to evaluate the seismic performance of existing reinforced concrete buildings. This method has proven effective in identifying structural vulnerabilities and guiding retrofitting decisions.

In the research by Golghate et al., a nonlinear static (pushover) analysis was performed on a four-storey reinforced concrete building located in seismic Zone IV of India. The study demonstrated how pushover analysis helps assess the building's seismic performance through capacity spectrum, plastic hinge formation, and performance level evaluation based on FEMA-356 and ATC-40 guidelines [3]. In the study by Hakim et al., a reinforced concrete building in Saudi Arabia—originally designed for gravity loads only—was analyzed using pushover techniques. The research highlighted the building's inadequate seismic performance in the Haql region while showing acceptable performance levels in Makkah, Jeddah, and Gizan, based on ATC-40 guidelines [4]. Similarly, Handana et al. emphasized the importance of Performance Based Seismic Evaluation (PBSE) for assessing aging or vulnerable structures. Using nonlinear static pushover analysis, their study showed how gradual lateral loading leads to plastic hinge formation, helping to understand structural behavior and improve seismic resilience planning [5]. The study by A. Cinitha et al. investigated the seismic performance of 4-storey and 6-storey RC buildings designed as Ordinary Moment Resisting Frames (OMRF) and Special Moment Resisting Frames (SMRF) according to IS 456:2000 and IS 1893:2002. Nonlinear static (pushover) analysis was conducted using SAP2000, incorporating user-defined plastic hinge properties derived from Eurocode 8 to simulate realistic structural behavior. The results indicated that plastic hinge length significantly affects the displacement capacity, with code-conforming buildings maintaining performance within the Collapse Prevention level. Additionally, OMRF buildings were found to be more vulnerable than SMRF, with the vulnerability index effectively identifying the extent and location of structural damage [6].

Objective

The building under study is an existing three-story structure originally designed as per the provisions of IS 1893:2002. The objective of this analysis is to evaluate its current seismic performance against the updated requirements of the Nepal Building Code, NBC 105:2020. To achieve this, a nonlinear static pushover analysis was performed using the response spectrum defined in NBC 105:2020 as the demand curve. This approach helps determine whether the existing structure meets the performance criteria outlined in ATC-40 code.

Nonlinear Static Pushover Analysis

Pushover analysis is a nonlinear static analysis method used to evaluate a building's seismic performance. It involves incrementally applying lateral loads to a structural model until a target displacement is reached, allowing engineers to study the structure's behavior under progressively increasing seismic forces. This method helps identify the formation of plastic hinges, determine the order of failure in structural components, and estimate the overall load-bearing capacity of the building [7, 8]. The analysis can be performed using either a force-controlled or displacement-controlled

method, depending on the nature of the load and the anticipated structural response. Force-controlled analysis is suitable when the magnitude of the load is known and the structure is expected to resist it effectively. In contrast, displacement-controlled analysis is used when achieving a specific deformation is the goal, or when the exact load magnitude is not known in advance.

Capacity Spectrum

The Capacity Spectrum Method (CSM) is a commonly used technique in performance-based seismic analysis. It assesses a building's ability to withstand earthquake forces by comparing its capacity curve with the seismic demand curve. The capacity curve, obtained from pushover analysis (base shear versus roof displacement), is transformed into the Acceleration Displacement Response Spectrum (ADRS) format. The seismic demand is similarly represented as a demand spectrum in ADRS format. By overlaying these two spectra on a single graph, the performance point, the intersection of the capacity and demand curves can be identified, representing the building's expected maximum displacement during a design-level earthquake [9].
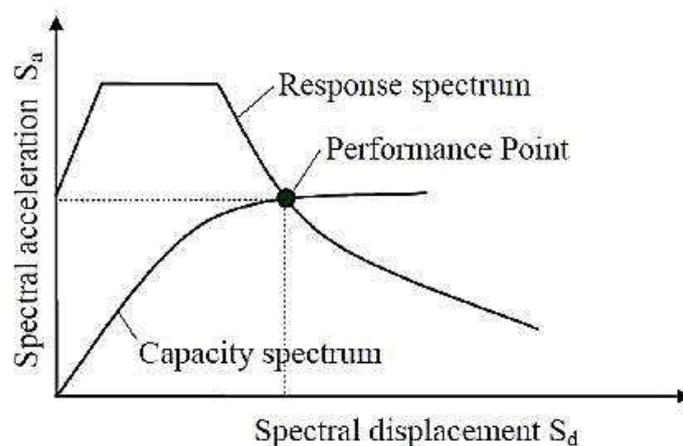

Figure 24 Capacity Spectrum Method to find performance point

The ATC-40 (1996) introduced the Capacity Spectrum Method (CSM), which uses an equivalent linearization approach to evaluate seismic performance. In this method, the pushover curve is transformed into a capacity spectrum by converting each point into modal spectral coordinates. FEMA 440 (2005) later enhanced this method by introducing a more efficient way to approximate the pushover curve using a bilinear approximation. It also refined the formulas used to calculate the effective period and effective damping [10]. Software like ETABS has this method built-in. It allows engineers to perform pushover analysis, convert the data to ADRS format, apply FEMA 440 EL, and graphically find the performance point [11]. In this research, the built-in FEMA 440 EL feature in ETABS is used to assess the seismic performance of the building and determine its performance level.

Structural Performance level

The performance level of the structure is determined based on the capacity spectrum. After the performance point is obtained, then the level of structure performance is determined by referring to the provisions of ATC-40 as shown in Table 1 [9, 12].
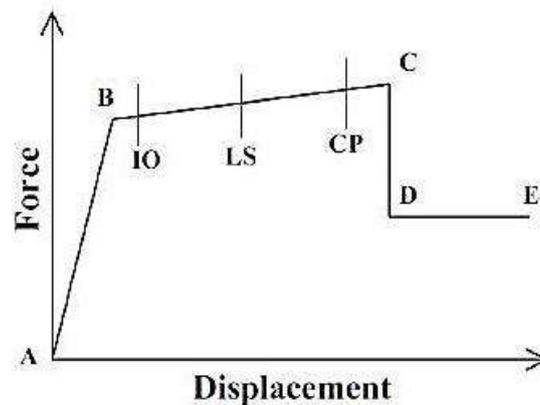

Figure 25 Force Deformation for Pushover Analysis

Table 5 Performance Levels as per ATC-40 guidelines

Parameters	Performance Level			
	Immediate Occupancy (IO)	Damage Control (DC)	Life Safety (LS)	Collapse Prevention (CP)
Maximum Total Drift	0.01	0.01-0.02	0.02	0.33 Vi/Pi

The three performance levels—Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP)—define the severity of structural damage and safety following an earthquake. At the IO level, the building experiences only minor damage and temporary drift, allowing it to be safely reoccupied with minimal or no repairs. The LS level indicates moderate damage and some permanent deformation; while the structure remains stable, it requires repairs or reinforcement before it can be reoccupied. At the CP level, the building endures significant damage and large displacements, avoiding collapse but remaining unsafe for use and generally considered irreparable [13].

Methodology

This study conducts a pushover analysis of an existing three-story reinforced concrete (RCC) building using ETABS 20, in accordance with the guidelines outlined in ATC 40 to evaluate its seismic performance. The same building is modeled based on original architectural and structural drawings, incorporating existing member sizes and reinforcement details, but assessed using the updated seismic provisions of NBC 105:2020.
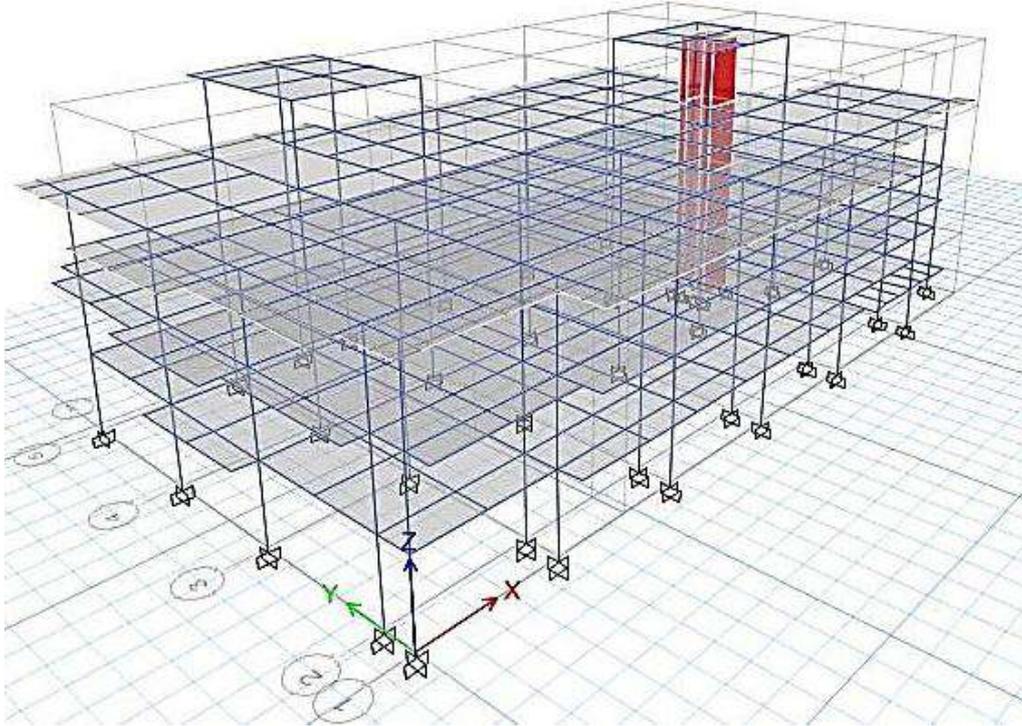
Figure 26 3-story Building Model

Building Details

The building is a regular three storey moment resisting reinforced concrete frame system with a lift. The building is used for office purpose. Detailed information about the material and structural components of the building—namely columns, main beams, and slabs are described below in Table 2. Accurate specifications of these elements, such as member sizes and reinforcement details, are essential for conducting an effective pushover analysis, as they ensure that the structural model closely represents the actual existing building for more reliable results.

Table 6 Building Parameters

Number of stories	3
Floor to floor height	3.3m
Plan Dimension:	36m (X-direction)
	18.975m (Y-direction)
Total Height	13.2m (including Staircase Cover)
Beam size	300x600, 300x500
Column size	350x600, 450x450
Thickness of slab	125mm
Soil Type	D

Zone Factor	0.35
Concrete Grade	M25
Steel Grade	HYSD 500
Loadings:	
Normal Live Load	3KN/m^2 (on floor); 4KN/m^2 (on staircase part)
Roof Live Load	1.5 KN/m^2
Floor Finish	1.5KN/m^2
Solar Panel Load	1KN/m^2 (on Third floor roof)
Equipment Load	3KN/m^2

The seismic coefficients used to calculate the base shear are determined according to NBC 105:2020 [14]. For the Ultimate Limit State (ULS), the coefficient is found to be 0.13125, while for the Serviceability Limit State (SLS), it is 0.126. These values are based on parameters specified in the code, including an importance factor (I) of 1.0, a ductility factor (R) of 4, over strength factors of 1.5 for ULS and 1.24 for SLS, soil classification as Type D, and a seismic zone factor (Z) of 0.35.

Nonlinear Modelling

Non-linear material properties are assigned to the materials used. M25 concrete and HYSD500 steel were used in the building.

Figure 27 Non-linear material properties of steel HYSD500

Figure 28 Non-linear material properties of concrete grade M25

In this study, non-linear behavior is modeled by assigning concentrated plastic hinges and fiber hinges at locations 10% from the member length at both ends of beams and columns, respectively. Geometric non-linearity is also considered through the inclusion of P-delta effects. Flexural M3 plastic hinges are assigned at both ends of the main beams using the auto hinge properties in accordance with ASCE 41-13 provisions available in ETABS v20 [11]. For columns, fiber P-M2-M3 hinges are used to capture material-level non-linearity, allowing for the representation of coupled axial and biaxial bending behavior. The reinforcement details for both beams and columns are input based on the actual construction drawings. Hinges are not assigned to secondary beams or the lift shear wall, assuming their behavior remains elastic.

A nonlinear gravity load case is defined by applying the full dead load along with 30% of the live load. Displacement-controlled pushover analyses are conducted in both the +X and +Y directions, with a target roof displacement of 300 mm. From these analyses, pushover curves are generated, and the performance point is determined using the FEMA 440 Equivalent Linearization (EL) method. This is then compared with the demand spectrum specified in NBC 105:2020 for soil type D as shown in Figure 6. Lastly, inter-story drift values are evaluated against the performance criteria outlined in ATC-40 (Immediate Occupancy, Life Safety, and Collapse Prevention) to assess the structural performance.
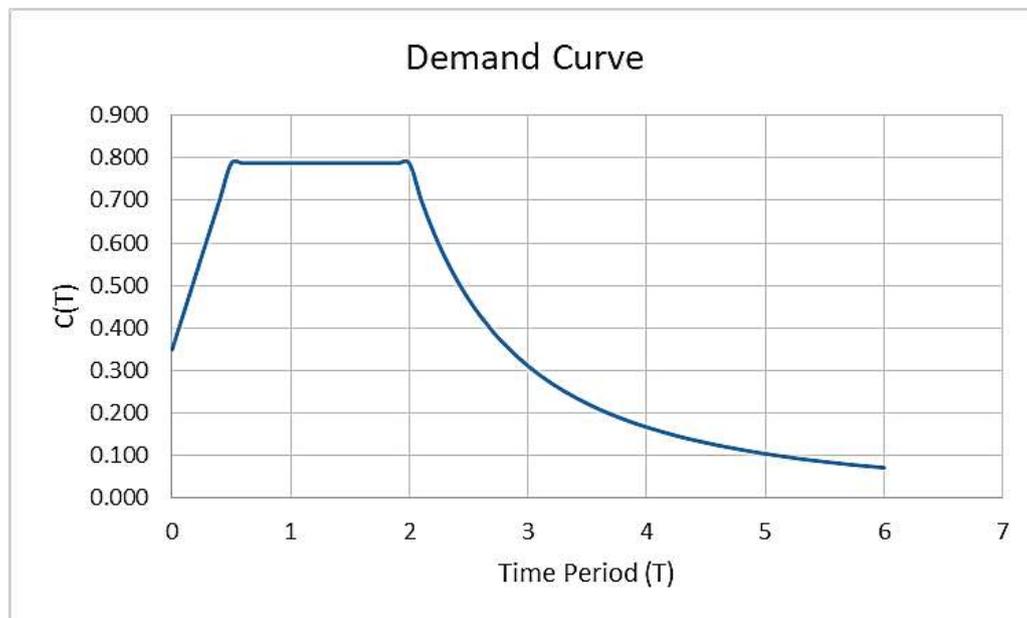

Figure 29 Demand Curve as per NBC 105:2020 for Soil Type D

To determine the structure's ability to support an additional floor, a fourth story with a height of 3.3 meters is introduced to the existing 3-story building. This new floor uses the same column, beam, and slab dimensions as those on the third floor. A roof live load of 1.5 kN/m² is applied to the newly added top floor. The pushover analysis is then performed again for the modified structure.

Results and discussion

Pushover Curve:

Pushover curves for the building in both X and Y-direction are shown in figure 7 and 8.
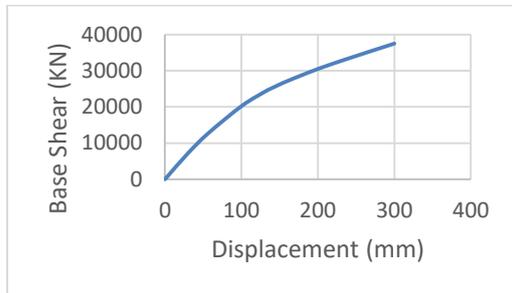

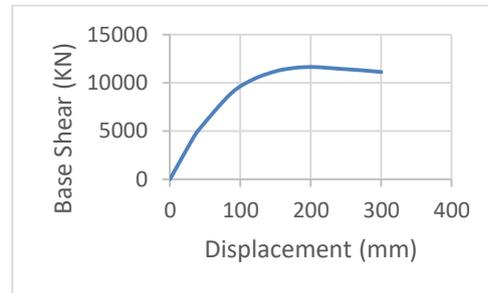*Figure 30 Pushover Curve in X-direction (without floor addition)*

Figure 31 Pushover Curve in Y-direction (without floor addition)

In the initial case, without the additional roof load, the structure reaches a maximum displacement of 300 mm in the X-direction, corresponding to a base shear of 37488.196 KN. The pushover curve in this direction exhibits a steady rise in base shear with increasing displacement, suggesting greater stiffness and a higher lateral load-carrying capacity before yielding.

In contrast, the Y-direction shows a maximum displacement of 198.018 mm with a corresponding base shear of 11633.708 KN. The pushover curve in this direction reaches its peak displacement earlier, indicating that the structure yields at a lower displacement compared to the X-direction.
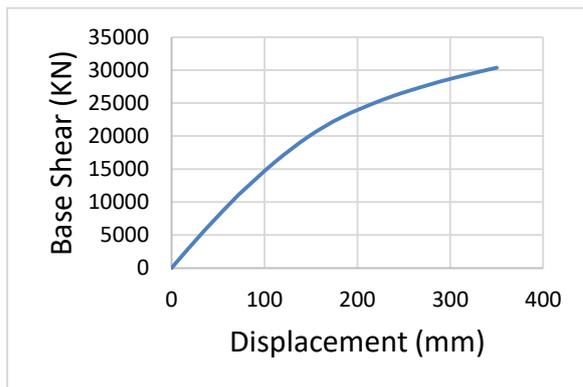

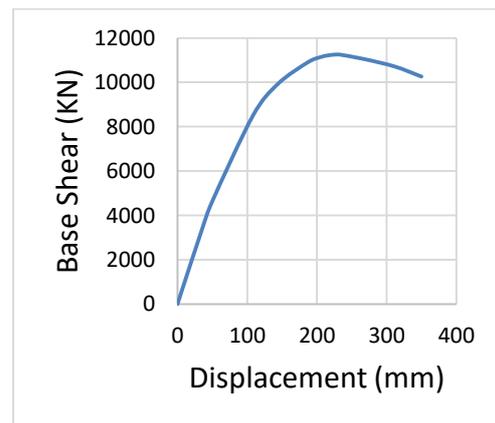*Figure 32 Pushover Curve in X-direction (with floor addition)*

Figure 33 Pushover Curve in Y-direction (with floor addition)

After the addition of a floor, the target displacement at the roof level is taken as 350 mm. In the X-direction, the structure now reaches the target displacement of 350 mm, with a corresponding base shear of 30364.226KN. In the Y-direction, the maximum displacement increases to 229.40 mm, and the associated base shear slightly reduces to 11254.66 KN. This reduction in base shear, along with

increased displacement in both directions, reflects the effect of added mass and height on the seismic response of the building.

Structural Performance Level

The performance points in both directions are identified using the Capacity Spectrum Method in ETABS with the FEMA 440 EL approach, comparing the capacity spectrum with the demand spectrum defined in NBC 105:2020 for soil type D. The performance point for building for pushover in X and Y direction is marked by the intersection between the capacity (the green line) and the single demand (red line).
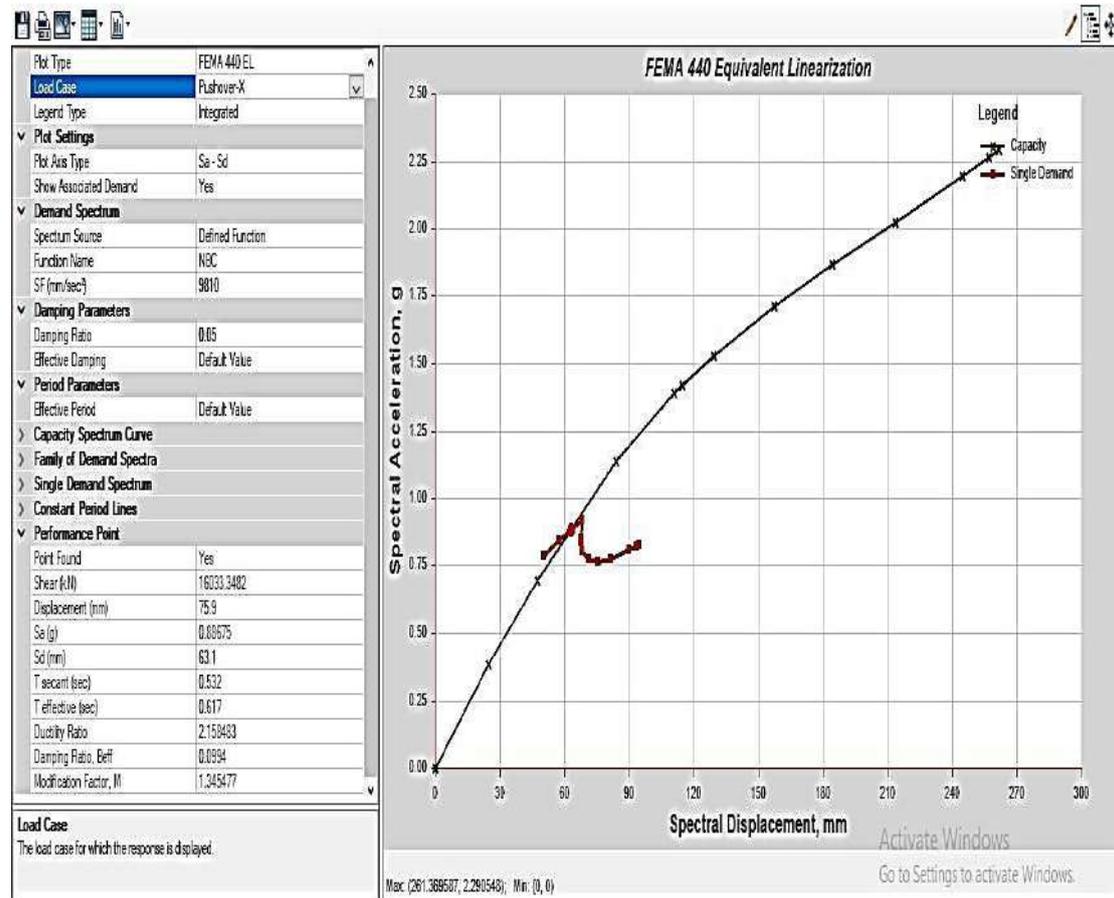

Figure 34 Capacity Spectrum Curve for Pushover in X-direction (without floor addition)
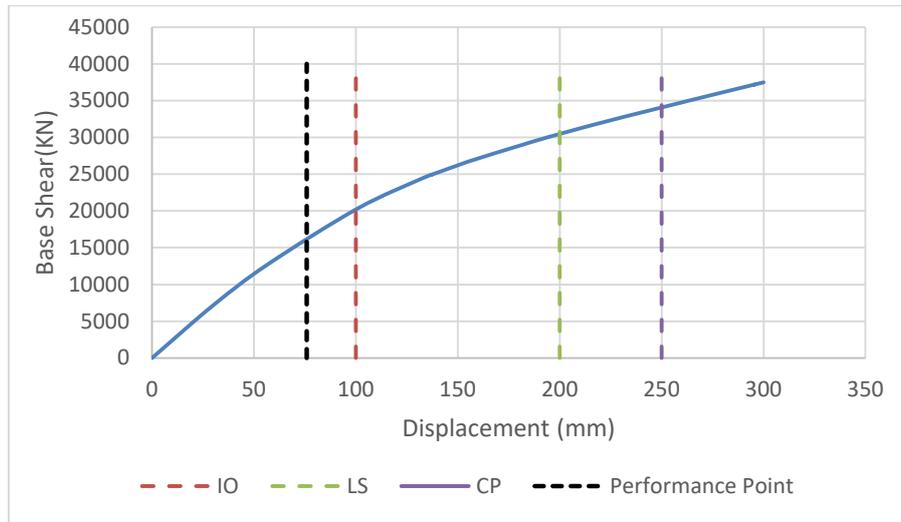
Figure 35 Performance point for Pushover X direction (without floor addition)

In the initial condition without roof load addition, For Pushover in X-direction, performance point is found at displacement (D_{max}) 75.9mm and the corresponding base shear is 16033.3432KN. Maximum total drift is $D_{max}/h = (75.9/9900) = 0.0076 < 0.01$ (IO). Based on ATC-40, this condition is included in the level of Immediate Occupancy. This indicates that the building performs well under seismic loading in the X-direction, with minimal expected damage and higher safety.
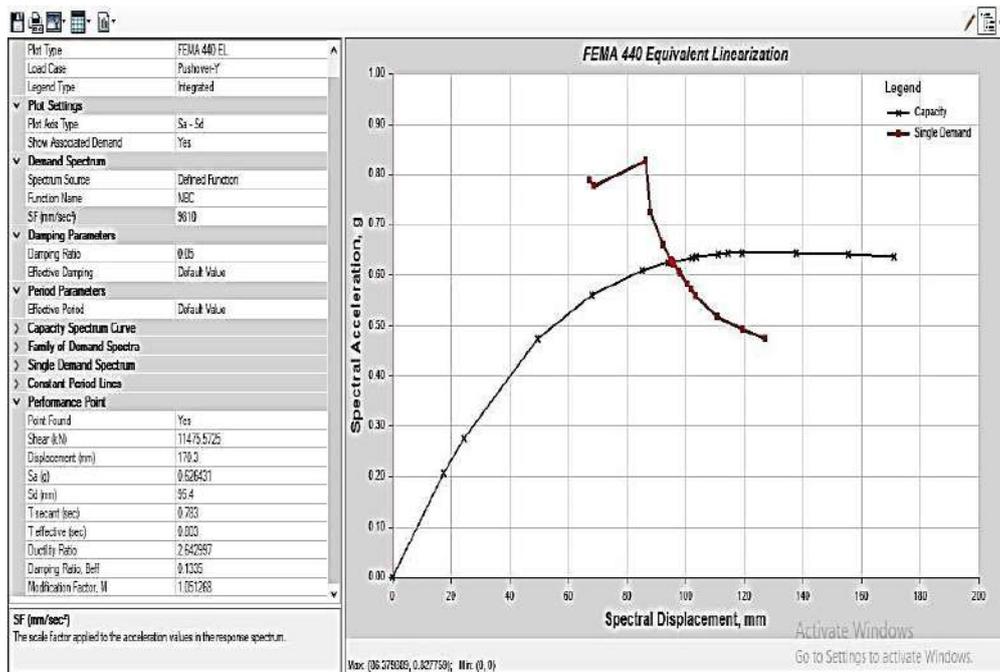

Figure 36 Capacity Spectrum Curve for Pushover in Y-direction (without floor addition)
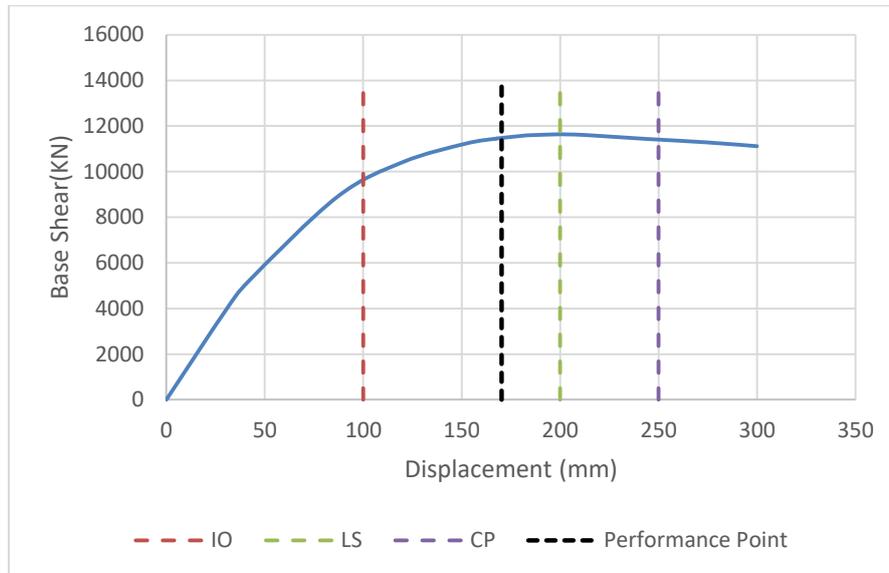
Figure 37 Performance point for Pushover Y direction (without floor addition)

Similarly, For Pushover in Y-direction, performance point is found at 170.3mm and corresponding base shear is 11475.572KN. Maximum total drift is $D_{max}/h = (170.3/9900) = 0.017 < 0.02$ (LS). According to ATC-40, this condition is included in the level of Life Safety. While the building may experience some damage in this direction, it is still within the LS level, where structural safety is maintained, but significant damage may be present.
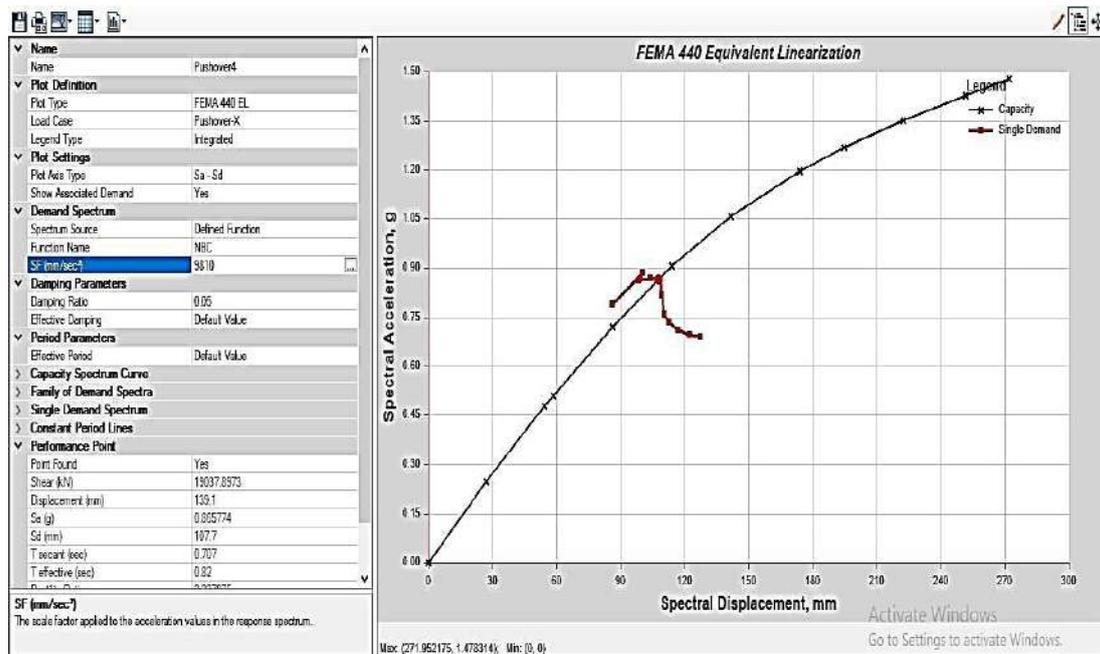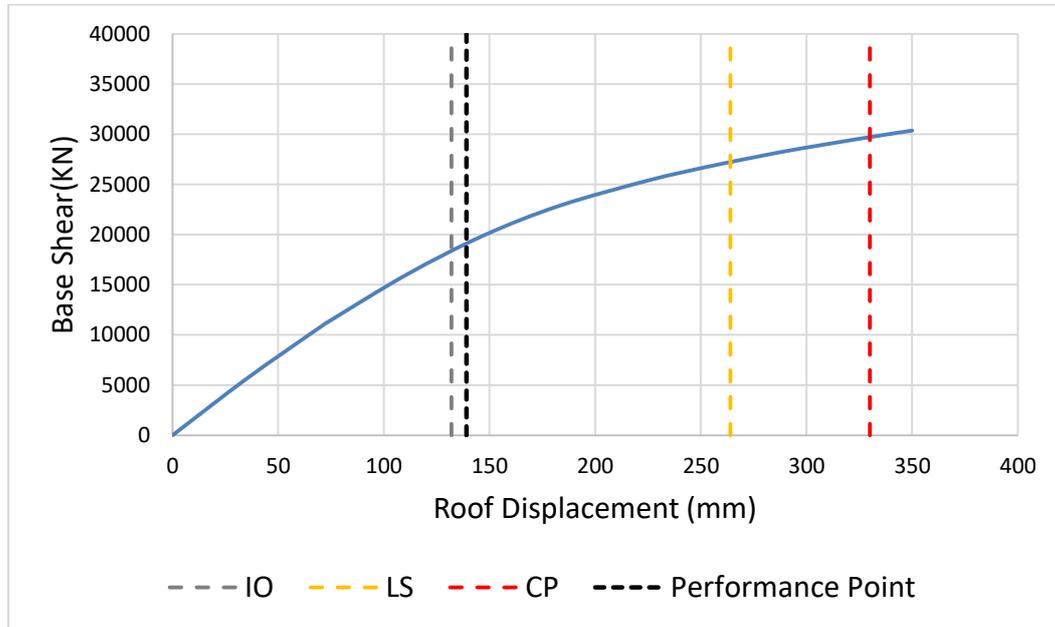
Figure 38 Capacity Spectrum Curve for Pushover in X-direction (with floor addition)

Figure 39 Performance point for Pushover X direction (with floor addition)

With the addition of the floor, the performance in the X-direction changes noticeably. The new performance point is found at a displacement of 139.1 mm and a base shear of 19037.89 KN. The drift ratio becomes $D_{max}/h = 139.1/13200 = 0.0105$, which places the building within the Life Safety (LS) level. Although this still ensures life safety, it marks a downgrade from the original Immediate Occupancy level, implying increased vulnerability.
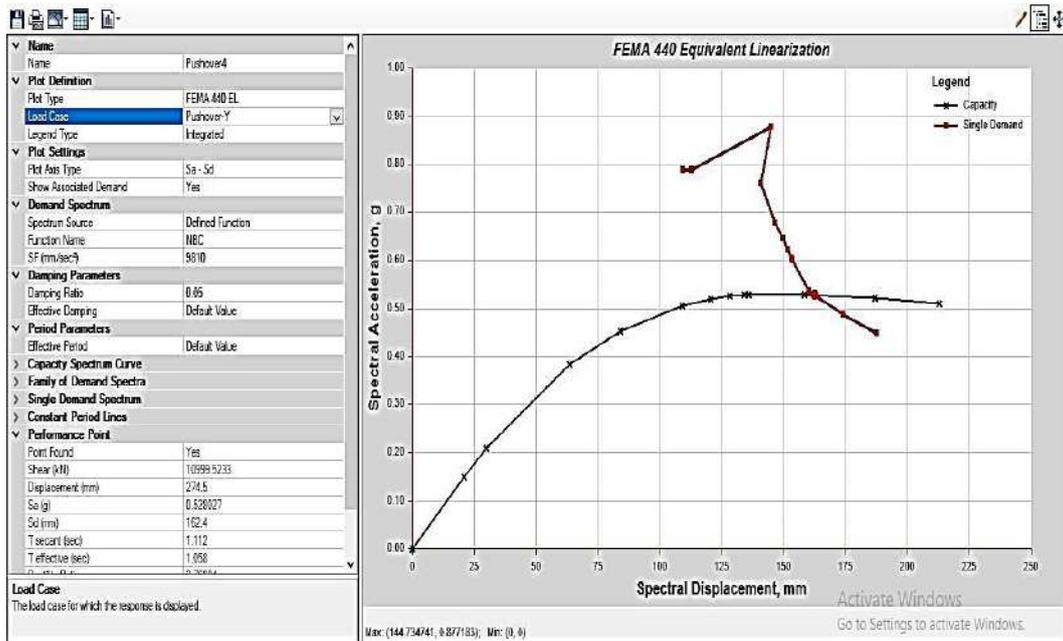
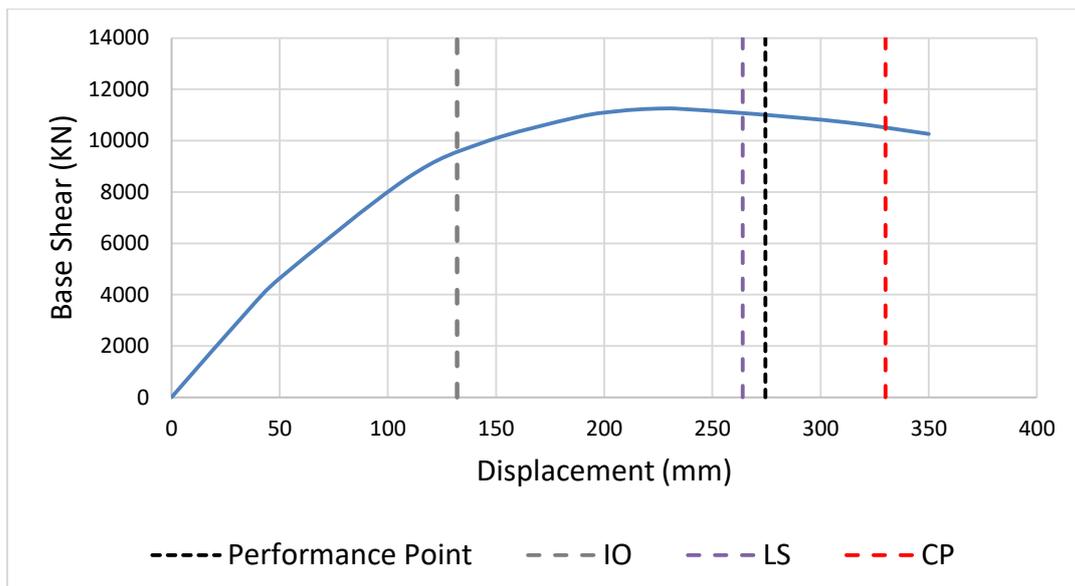*Figure 40 Capacity Spectrum Curve for Pushover in Y-direction (with floor addition)*

Figure 41 Performance point for Pushover Y direction (with floor addition)

In the Y-direction, the updated performance point occurs at 274.5 mm displacement and a base shear of 10999.52 KN. The drift ratio rises to 0.0207 ($D_{max}/h = 274.5/13200$), which falls under the Collapse

Prevention (CP) level of ATC-40. This significant increase in drift suggests that although collapse may be prevented, the structure is likely to sustain extensive damage in this direction under severe seismic loading.

Table 7 Comparison of Results for Building with and without floor addition

S.N.	Without floor addition	With floor addition
1.	Pushover Curve	Pushover Curve
	In X-direction,	In X-direction,
	D_{max} = 300mm	D_{max} = 350mm
	V_{max} = 37488.196KN	V_{max} = 30364.226KN
	In Y-direction,	In Y-direction,
	D_{max} = 198.018mm	D_{max} = 229.40mm
	V_{max} = 11633.708KN	V_{max} = 11254.66KN
2.	Structure Performance Level	Structure Performance Level
	In X-direction,	In X-direction,
	D = 75.9mm	D = 139.1mm
	V = 16033.343KN	V = 19037.89KN
	Max Drift = 0.0076 < 0.01 (IO)	Max Drift = 0.0105 < 0.02 (LS)
	In Y-direction,	In Y-direction,
	D = 170.3mm	D = 274.5mm
	V = 11475.572KN	V = 10999.52KN
	Max Drift = 0.017 < 0.02 (LS)	Max Drift = 0.0207 < 0.025 (CP)

In the pushover curve analysis, the original 3-story structure demonstrates higher base shear capacities in both directions, indicating stronger lateral load resistance. In the X-direction, the target displacement was set to 300 mm for the original building and 350 mm after adding a floor. In both cases, the building was able to reach the given displacement without failing. This means that even after the floor was added, the structure could still deform as expected, although the base decreases from 37488.196 KN to 30364.226 KN, marking a 19.01% reduction in base shear capacity. Similarly, in the Y-direction, the displacement rises from 198.018 mm to 229.40 mm, and the base shear slightly decreases from 11633.708 KN to 11254.66 KN, resulting in a 3.26% decrease. These changes reflect a reduction in structural stiffness and lateral strength due to the added mass and height.

Furthermore, the structural performance level also declines with the added floor. Initially, the building achieves an Immediate Occupancy (IO) level in the X-direction with a drift ratio of 0.0076, but after the addition, the performance shifts to Life Safety (LS) with an increased drift of 0.0105. In the Y-direction, the original structure meets the Life Safety (LS) level with a drift of 0.017; however, after adding the floor, the drift increases to 0.0207, reaching the Collapse Prevention (CP) level. This performance downgrade indicates that the building, in its current form, may not be adequate to resist seismic forces safely after vertical expansion, especially in the Y-direction, where the structural response becomes significantly more vulnerable.

Conclusion

Based on the results of the nonlinear static (pushover) analysis carried out in both X and Y directions, it can be concluded that the existing 3-story RCC building demonstrates adequate seismic performance under current conditions. The performance levels achieved—Immediate Occupancy (IO) in the X-direction and Life Safety (LS) in the Y-direction—indicate that the structure is capable of withstanding moderate to strong seismic events with limited damage and maintained structural integrity.

However, upon the addition of an extra floor with similar structural configuration and updated loading conditions, the seismic performance of the building shows a noticeable decline. The base shear capacity in the X-direction reduces by approximately 20 percent and in the Y-direction by about 4 percent, indicating a significant reduction in lateral load resistance due to increased mass and height. Consequently, the performance level shifts to Life Safety (LS) in the X-direction and further degrades to Collapse Prevention (CP) in the Y-direction, highlighting a reduction in structural safety and an increased risk of damage under seismic loading.

Therefore, while the original structure performs well, the vertical expansion compromises its seismic resilience, particularly in the Y-direction. Any proposal for additional story construction compliance with seismic performance requirements and safety standards.

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