PERFORMANCE BASED DESIGN OF SHEAR WALL STRUCTURES USING PUSHOVER ANALYSIS

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Abstract - *This study analyses the seismic performance of RCC buildings (G+10, G+15, and G+25) in Seismic Zones IV and V under medium soil conditions. Using ETABS 2021, buildings were assessed through Equivalent Static, Response Spectrum, and Pushover Analysis. Shear walls with varying reinforcement percentages—0.25% to 1% for Zone IV and 1% to 3% for Zone V—were examined to evaluate their impact on structural stability. Key seismic parameters, including base shear, performance points, story drift, displacement, and time period, were compared. Results indicated that taller buildings required higher reinforcement ratios to meet seismic demands. Zone IV structures performed well with 0.25%–0.75% reinforcement, while Zone V required up to 3% for stability. This study provides insights into optimizing reinforcement strategies for earthquake-resistant RCC buildings.*

Key Words: Performance-Based Design, Pushover Analysis, Seismic Resilience, Shear Wall Structures, Earthquake Engineering, Seismic Zone IV & V, Steel Reinforcement, Reinforcement Optimization.

1. INTRODUCTION

Performance-Based Design (PBD) is a modern approach in structural engineering that focuses on predicting how structures will behave under specific conditions, particularly during earthquakes. Unlike traditional methods that primarily aim to meet minimum safety standards, PBD establishes clear performance objectives, such as operational continuity, immediate occupancy, life safety, and prevention of collapse. This approach enables engineers to design structures that not only prioritize safety but also ensure usability after seismic events, offering a more comprehensive and tailored design solution.

A core component of PBD is Pushover Analysis, a nonlinear static procedure used to evaluate a structure's seismic performance. This method involves incrementally applying lateral loads to the structure, simulating increasing seismic forces until the structure reaches failure. Through this process, critical weak points are identified, and the overall capacity of the structure to resist seismic loads is assessed. The insights provided by Pushover Analysis allow engineers to optimize designs, ensuring greater resilience and structural reliability during earthquakes. By integrating PBD with tools like Pushover Analysis, engineers can create buildings that effectively withstand seismic demands, reducing damage and safeguarding occupants.

1.1 Performance Levels in Performance-Based Design

Performance-Based Design (PBD) is an advanced methodology in structural engineering that prioritizes predicting a building's performance during seismic events rather than merely adhering to traditional design codes. Unlike conventional approaches, which emphasize compliance with basic safety requirements, PBD focuses on achieving specific, measurable performance objectives tailored to the building's intended use, location, and importance. This shift from code compliance to performance-driven design provides a refined and adaptable approach to earthquake-resistant construction, ensuring structures remain functional, resilient, and safe even under extreme seismic conditions.

PBD organizes performance objectives into four distinct levels, each reflecting a different degree of damage tolerance and usability. These levels serve as clear design targets and offer a flexible framework to address diverse building requirements based on their roles and significance.

Operational Level (O): This is the highest performance standard, requiring buildings to remain fully operational with no significant damage after minor earthquakes. Structures designed to this level, such as hospitals, emergency response centres, and data hubs, must ensure uninterrupted functionality of essential services. The design minimizes damage to both structural and non-structural components, allowing immediate use without the need for repairs. This level is particularly critical for infrastructure that plays a vital role in post-earthquake recovery and public safety.

Immediate Occupancy (IO): At the Immediate Occupancy level, buildings are designed to sustain minimal damage during moderate earthquakes, ensuring they can be used immediately after the event. While minor cosmetic damage may occur, the structural integrity and primary functionality remain intact. This level is essential for offices, residential complexes, and public safety facilities where quick recovery and continuity of use are priorities. The design ensures the safety of occupants while maintaining the building's usability, significantly reducing downtime and repair costs.

Life Safety (LS): The Life Safety level prioritizes protecting human life during severe earthquakes. Buildings designed to this standard may sustain significant damage but are engineered to prevent collapse, allowing occupants to evacuate safely. This level is commonly applied to schools, commercial establishments, and residential buildings where occupant safety is paramount. Although repairs may be extensive, the design ensures the structure can fulfil its primary purpose of safeguarding lives during the seismic event.

Collapse Prevention (CP): Collapse Prevention represents the minimum acceptable performance level, focusing on preventing total structural failure during major earthquakes. Buildings at this level may experience extensive damage but are designed to remain standing long enough to allow safe evacuation of occupants. This standard is often applied to older structures or those with budgetary or other constraints preventing higher performance levels. While these buildings may be unfit for occupancy after the earthquake, they are designed to mitigate catastrophic risks by avoiding life-threatening collapses.

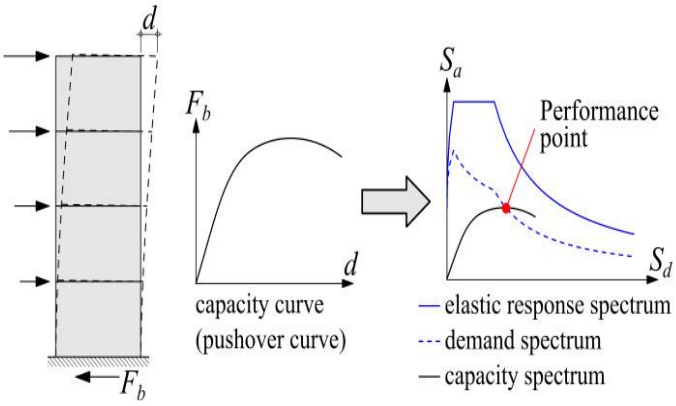

Fig -1: Procedure for PBD

1.2 Role of Plastic Hinges in Pushover Analysis Design

Plastic hinges play a critical role in pushover analysis by indicating locations of inelastic deformation in structural elements like beams and columns. As lateral forces are applied, these hinges form at specific points, allowing energy to be dissipated through plastic deformation. This mechanism is essential for managing seismic loads, as it helps identify structural weaknesses that could compromise performance during earthquakes.

By analysing the formation and behaviour of plastic hinges, engineers can optimize designs to meet key performance objectives, such as life safety and collapse prevention. Strategically incorporating these insights into the design process ensures that buildings are more resilient to seismic events, minimizing structural damage while safeguarding occupants. Understanding and addressing the anticipated locations of plastic hinges enables engineers to enhance a structure's ability to withstand earthquakes, ensuring both safety and functionality are maintained under extreme conditions.

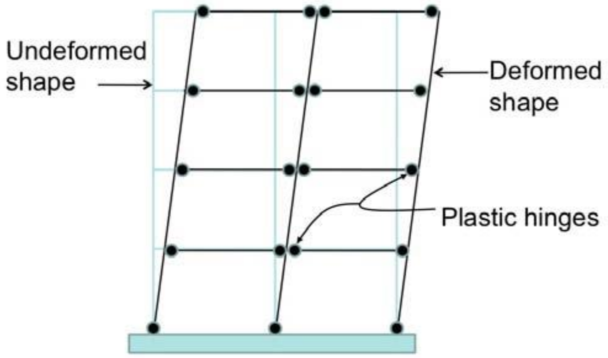

Fig -2: Plastic Hinge Formations

2. OBJECTIVES OF STUDY

1. To analyse RCC buildings (G+10, G+15, G+25) using actual plan in ETABS 2021.
2. To conduct Equivalent Static, Response Spectrum, and Pushover Analysis on each model to assess their seismic performance.
3. To evaluate key parameters such as performance points, modal mass participation, base shear, storey drift, and storey displacement for the analysed models.
4. To assess the influence of varying steel reinforcement percentages (0.25%, 0.5%, 0.75%, and 1%) for Seismic Zone IV and (1%, 1.5%, 2.5%, and 3%) for Seismic Zone V on seismic parameters and structural behaviour.
5. To compare the seismic performance of G+10, G+15, and G+25 buildings and evaluate the impact of building height on stability and drift control.

3. METHODOLOGY

This study aims to analyse and compare the seismic performance of RCC buildings of varying heights (G+10, G+15, and G+25) under seismic loading conditions in Seismic Zones IV and V with medium soil. The models were developed using ETABS 2021 and analysed with Equivalent Static, Response Spectrum, and Pushover Analysis. Different shear wall thicknesses and reinforcement percentages (0.25%, 0.5%, 0.75%, and 1% for Zone IV, and 1%, 1.5%, 2.5%, and 3% for Zone V) were applied to assess their influence on seismic behaviour, structural stability, material optimization, and overall earthquake resistance of the buildings.

3.1 Modelling Process in ETABS

Fig -3: ETABS Steps Flowchart

3.2 Model data

Material Properties:

1. Grade of Concrete: M35
2. Grade of Steel: Fe550
3. Density of RCC: 25 kN/m³
4. Density of Steel: 78.5 kN/m³
5. Density of Light Weight Block Work: 10 kN/m³

Storey Details:

G+10 Building:

1. Plan Size: As Per Plan
2. Height of Building: 30 m
3. Slab Thickness: 150 mm
4. Floor to Floor Height: 3.0 m
5. Shear Wall Thickness:
    i) From Storey Base to 5th: 300 mm
6. Beam Size: 230 mm x 550 mm, 230 mm x 650 mm, 230 mm x 750 mm (Sizes used as per structural framing requirements)

G+15 Building:

1. Plan Size: As Per Plan
2. Height of Building: 45 m
3. Slab Thickness: 150 mm
4. Floor to Floor Height: 3.0 m
5. Shear Wall Thickness:
    i) From Storey Base to 5th: 350 mm
    ii) From Storey 6th to 10th: 300 mm
    iii) From Storey 11th to 15th: 300 mm
6. Beam Size: 230 mm x 550 mm, 230 mm x 650 mm, 230 mm x 750 mm (Sizes used as per structural framing requirements)

G+25 Building:

1. Plan Size: As Per Plan
2. Height of Building: 75 m
3. Slab Thickness: 150 mm
4. Floor to Floor Height: 3.0 m
5. Shear Wall Thickness:
    i) From Storey Base to 5th: 400 mm
    ii) From Storey 6th to 10th: 350 mm
    iii) From Storey 11th to 15th: 230 mm
    iv) From Storey 16th to 25th: 230 mm
6. Beam Size: 230 mm x 550 mm, 230 mm x 650 mm, 230 mm x 750 mm (Sizes used as per structural framing requirements)

Loading on Structure:

Live Load:
a) Floor: 3 kN/m²
b) Terrace: 1.5 kN/m²
Dead Load:
a) 3.75 kN/m²
Wall Load:
a) Floors: 0.23 x (3.0 – 0.55) x 10 = 5.7 kN/m
b) Terrace: 0.23 x 1.2 x 10 = 2.8 kN/m

Seismic Parameters (As Per IS 1893 part-1 2016):
Seismic Zone (Z): IV & V (As Per Clause 6.4.2)
Soil Category: II [Medium Soil] (As Per Clause 6.4.2)
Response Reduction Factor (R): 5 [SMRF] (As Per Clause 7.2.6)
Importance Factor (I): 1.2 (As Per Clause 7.2.3)
Damping: 5% (As Per Clause 7.2.4)

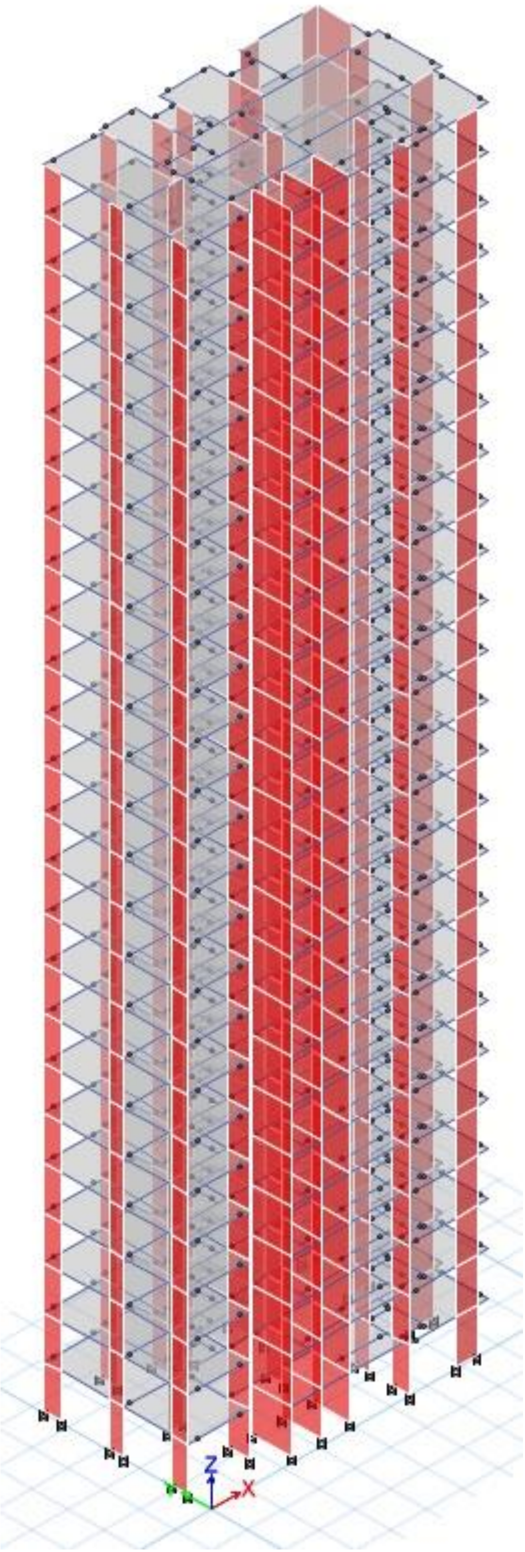

Fig -4: 3D View of G+25 Model

4. RESULTS AND DISCUSSIONS

4.1 Modal Mass Participation

Table -1: Modal Mass Participation Ratios for 30m Building (G+10) for Zone IV & Zone V

Case	Mode	UX	UY	RZ
Modal Ritz	1	0.752	0	0
	2	0	0.624	0.074
	3	0	0	0.649

Table -2: Modal Mass Participation Ratios for 45m Building (G+15) for Zone IV & Zone V

Case	Mode	UX	UY	RZ
Modal Ritz	1	0.729	0	0
	2	0	0.623	0.061
	3	0	0	0.643

Table -3: Modal Mass Participation Ratios for 75m Building (G+25) for Zone IV & Zone V

Case	Mode	UX	UY	RZ
Modal Ritz	1	0.706	0	0
	2	0	0.642	0.035
	3	0	0	0.650

4.2 Time Period

Table -4: Time Period for Model No. 01, Model No. 02, Model No. 03 (in seconds) for Zone IV & Zone V

Mode	Model No. 01 G+10 30m	Model No. 02 G+15 45m	Model No. 03 G+25 75m
1	1.434	2.256	4.117
2	1.018	1.725	3.443
3	0.991	1.611	3.021
4	0.42	0.728	1.374
5	0.272	0.485	0.995
6	0.255	0.472	0.961
7	0.209	0.382	0.741
8	0.131	0.239	0.493
9	0.127	0.238	0.488
10	0.114	0.217	0.478
11	0.103	0.164	0.347
12	0.102	0.146	0.309
13	0.089	0.134	0.286
14	0.087	0.129	0.26
15	0.083	0.128	0.213

4.3 Base Shear

Table -5: Base Shear (Vb) Calculation for X and Y Direction (in kN) for Zone IV

Sr No	Description	Model No.01 G+10 30m	Model No. 02 G+15 45m	Model No. 03 G+25 75m
1	DL	30325.55 kN	45501.32 kN	76736.30 kN
2	LL	5091.01 kN	7919.35 kN	13576.04 kN
3	25% LL	1272.753 kN	1979.838 kN	3394.010 kN
4	Total Seismic Weight, W (D.L + 25% L.L)	31598.31 kN	47481.16 kN	80130.318 kN
5	$T_x = \frac{0.075h^{0.75}}{\sqrt{A_w}} \geq \frac{0.09h}{\sqrt{d}}$	1.322 sec	1.665 sec	2.288 sec
6	$T_y = \frac{0.075h^{0.75}}{\sqrt{A_w}} \geq \frac{0.09h}{\sqrt{d}}$	0.784 sec	1.166 sec	1.944 sec
7	Sa/g for x direction = 1.36/Tx	1.029	0.817	0.594
8	Sa/g for y direction = 1.36/Ty	1.736	1.166	0.700
9	Z/2	0.12	0.12	0.12
10	I/R	0.24	0.24	0.24
11	Ahx = Z/2 x Sa/g x I/R	0.030	0.024	0.017
12	Ahx = Z/2 x Sa/g x I/R	0.050	0.034	0.020
13	$V_{BX} = A_h W$	936.048 kN	1116.962 kN	1371.741 kN
14	$V_{BY} = A_{hy} W$	1579.633 kN	1594.976 kN	1614.478 kN

Table -6: Base shear in X and Y Direction (in kN)

Sr. No.	Storey	Model No. 01 G+10	Model No. 02 G+15	Model No. 03 G+25
01	Base Shear (EQX)	924.972 kN	1106.571 kN	1363.0995 kN
02	Base Shear (EQY)	1561.703 kN	1580.138 kN	1604.306 kN

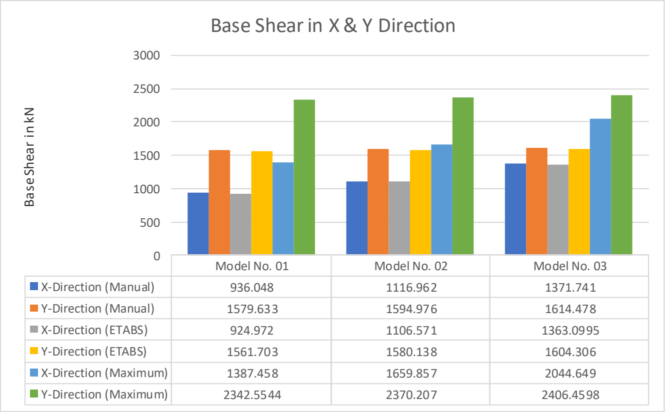

Chart -1: Base Shear in X & Y Direction for Zone IV

4.4 Storey Displacement

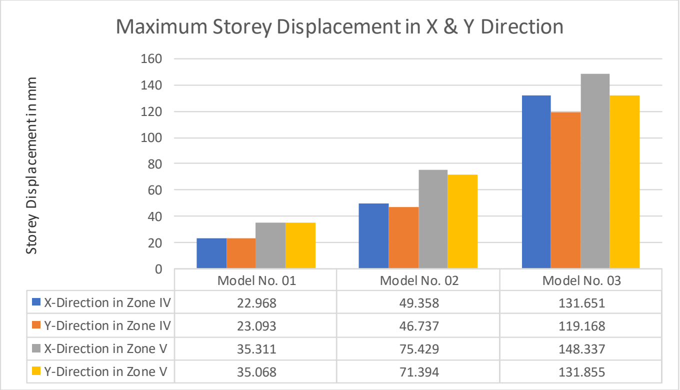

Chart -2: Maximum Storey Displacement in X & Y Direction for Zone IV & Zone V

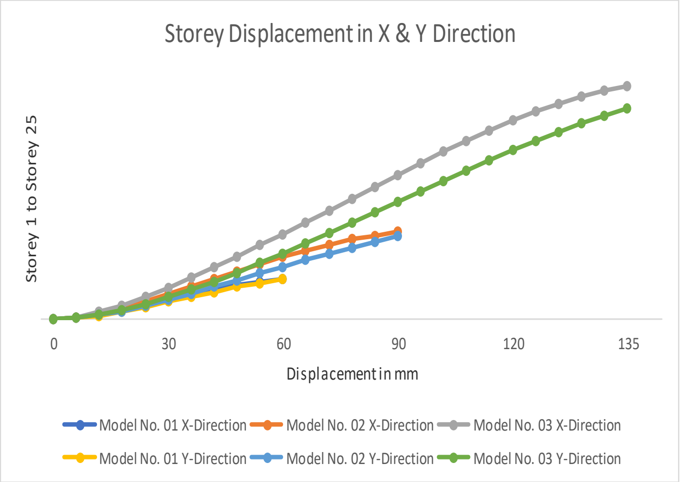

Chart -3: Storey Displacement in X & Y Direction for Zone IV

4.5 Storey Drift

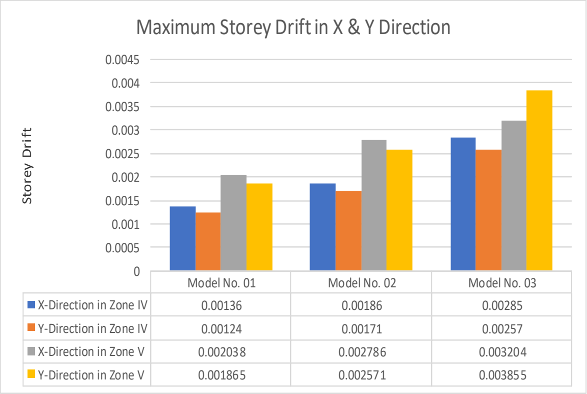

Chart -4: Maximum Storey Drift in X & Y Direction for Zone IV & Zone V

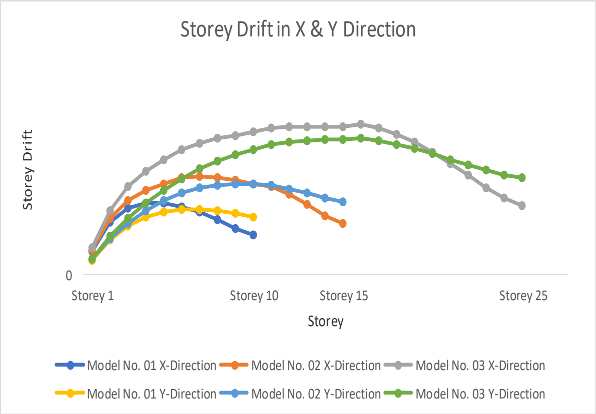

Chart -5: Storey Drift in X & Y Direction for Zone IV

4.6 Pushover-Based Reinforcement Analysis

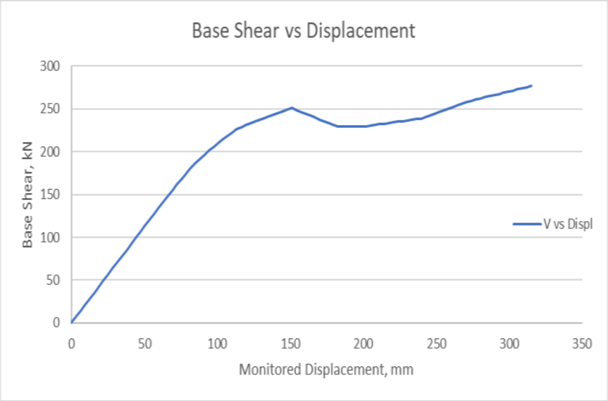

Chart -6: Base Shear vs Monitored Displacement for Shear Wall LW3 with 0.75% Reinforcement for Model No. 03 for Zone IV

Table -7: Optimization of Steel Reinforcement Based on Pushover Analysis for Zone IV

Shear Wall ID	Model	Required Reinforcement %	Provided Reinforcement %
C16	G+10	0.49%	0.25%
C2A	G+10	0.63%	0.5%
LW1	G+10	0.95%	0.75%
C16	G+15	0.5%	0.25%
C13	G+15	0.64%	0.5%
LW3	G+15	0.92%	0.75%
C2	G+15	1.18%	1%
C7	G+25	0.83%	0.25%
C2A	G+25	0.85%	0.5%
LW3	G+25	1.07%	0.75%
C1	G+25	1.61%	1%

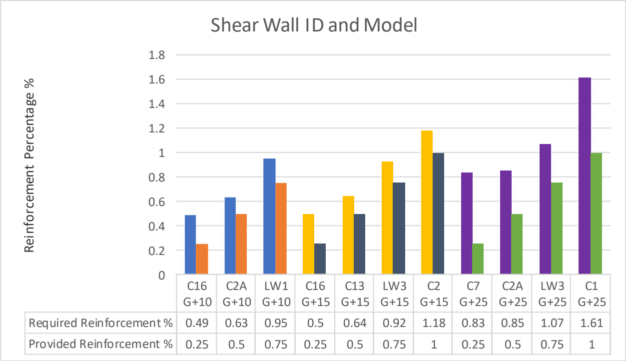

Chart -7: Comparison of Required and Provided Steel Reinforcement Percentages for Shear Walls in G+10, G+15, and G+25 Models for Zone IV

5. CONCLUSIONS

Following are the conclusions obtained from these studies:

1. Seismic demands increase with building height and seismic intensity. Taller buildings (G+25) in Zone V experience significantly higher forces, necessitating greater stiffness, strength, and drift control compared to those in Zone IV.
2. In Zone IV, reinforcement between 0.5%–1% was sufficient for shear walls across different building heights. However, in Zone V, higher reinforcement levels were required—2.5%–3% for taller buildings (G+15, G+25) and 1%–2.5% for shorter buildings (G+10).
3. In Zone IV, shorter buildings (G+10, G+15) maintained adequate seismic performance even with lower reinforcement percentages (0.25%–0.5%), enabling material efficiency. In contrast, Zone V required increased reinforcement even for shorter buildings due to higher seismic demands.

4. Base shear, storey drift, displacement, and hinge formation were influenced by both building height and reinforcement levels, emphasizing the need for tailored design approaches for different seismic zones.
5. Pushover analysis proved valuable in performance-based design, identifying optimal reinforcement configurations to balance safety and material efficiency—0.75%–1% for taller buildings in Zone IV and 2.5%–3% in Zone V.
6. Modal mass participation and time period analyses highlighted height-dependent dynamic behaviour. Taller buildings in higher seismic zones require precise reinforcement strategies to ensure structural resilience and compliance with seismic safety standards.

6. FUTURE SCOPE

This research area has vast scope for the future studies. Some are discussed below:

1. A detailed study on how different soil-structure interaction effects influence the seismic performance of shear walls in varying soil conditions.
2. Conducting a more detailed non-linear time-history analysis using real earthquake records to assess structural response under dynamic loading conditions.
3. Exploring the use of advanced reinforcement techniques, such as fibre-reinforced concrete, hybrid reinforcement, or high-performance steel, for improved seismic resilience.
4. Investigating effective retrofitting strategies for existing shear wall structures to enhance seismic resistance without significant material and financial costs.
5. Performing a comparative cost-benefit and environmental impact analysis of optimized reinforcement strategies versus conventional methods to enhance sustainability and efficiency.

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