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Performance-Based Design of Hospital Structures under Pushover

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Abstract- **This study evaluates the seismic performance of reinforced concrete (RC) hospital buildings of varying heights (G+6, G+9, and G+12) using a Performance-Based Seismic Design (PBSD) framework and nonlinear static pushover analysis. Three-dimensional models with identical plan geometry were developed in *SAP2000* and analyzed in both principal directions to determine base shear capacity, roof displacement, inter-storey drift, and hinge formation. Results indicate that increasing building height leads to higher lateral displacement demands, reduced lateral stiffness, and earlier plastic hinge formation, though all models maintained Immediate Occupancy (IO) performance levels. These findings highlight the effectiveness of PBSD and pushover analysis for critical healthcare infrastructure, enabling reliable assessment of safety, serviceability, and post-earthquake operability. The study underscores the importance of performance-based evaluation in guiding design strategies for resilient hospitals in high-seismic regions.**

Index Terms **— Performance-Based Seismic Design (PBSD), Nonlinear Static Pushover Analysis, Plastic Hinge Formation, Hospital Buildings, Seismic Performance, Reinforced Concrete Structures.**

I. INTRODUCTION

Hospitals are vital facilities that must remain safe and functional before, during, and after earthquakes. Unlike residential or commercial buildings, the failure of a hospital has far-reaching consequences because it disrupts medical services at the time of greatest need. Past earthquakes have clearly demonstrated this. For example, the 1971 San Fernando earthquake in California caused severe damage to the Veterans Administration Hospital, leading to a tragic loss of life. Similarly, the 2001 Bhuj earthquake in India highlighted how even buildings that did not collapse often became unusable owing to heavy structural and non-structural damage. These incidents underline the necessity of designing hospitals to protect occupants and ensure their continued operation after major seismic events.

The conventional approach to seismic design in most codes is Force-Based Design (FBD). In this method, the structures are analysed under equivalent static or dynamic forces that represent the effects of earthquakes. The design forces are reduced using a response reduction factor, which accounts for ductility, overstrength, and redundancy. Although this approach has been widely practiced, it has clear limitations. It evaluates buildings essentially under elastic conditions, and the inelastic response is indirectly considered through empirical factors. Consequently, FBD does not provide direct information about how and where damage will occur or whether performance objectives such as life safety or immediate occupancy are satisfied. This limitation is particularly critical for hospitals, where the expected performance is higher than that of ordinary buildings.

Hospitals also present unique design challenges that require careful consideration. In India, IS 1893 (Part 1): 2016 requires a higher importance factor for hospitals, recognizing their role as essential infrastructure in the healthcare system. However, code-based force design may underestimate the vulnerabilities of these structures. By applying PBSD principles through pushover analysis, it is possible to evaluate their true performance and identify whether strengthening measures are required. This approach not only improves structural resilience but also ensures post-disaster functionality, which is a priority for healthcare infrastructure in high-seismic zones such as the Himalayan belt and northeastern India.

This study focuses on hospital buildings with the same plan geometry, but different heights modelled as six-, nine-, and twelve-story reinforced concrete frames. Using SAP2000, nonlinear static pushover analyses were performed in both principal directions. The structural members were modelled with realistic material properties (M30 M35 concrete and Fe500 steel), and plastic hinges were defined according to the FEMA 356 recommendations. The performance of these models was compared in terms of base shear capacity, roof displacement, inter-story drift, and hinge formation patterns. The objective of this study was to determine how building height influences seismic performance and whether hospitals of different heights meet the required performance levels.

II. REVIEW OF LITERATURE

Krawinkler and Seneviratna *et al.* have examined the strengths and limitations of pushover analysis for seismic performance evaluation. They argued that pushover is a useful, low-cost tool for visualizing plastic hinge progression and collapse mechanisms in ordinary buildings but cautioned that pushover results can be strongly affected by the assumed lateral load pattern and may fail to capture higher-mode and torsional responses for tall or irregular structures. Their critique is important because it frames pushover analysis as a practical screening tool rather than a definitive substitute for nonlinear dynamic analysis. In practice, their observations have encouraged engineers to use pushover results mainly for preliminary design checks or retrofit evaluations rather than as the sole basis for performance predictions. This study also highlighted the importance of verifying pushover outcomes using alternative methods, such as modal pushover or time-history analysis, particularly when dealing with taller frames, where higher modes cannot be ignored. For the present study, their work suggests the careful selection of load patterns, attention to mode shapes, and conservative interpretation of hinge patterns, particularly as building height increases.

Villaverde *et al.* shifted the discussion from purely structural behavior to the importance of non-structural components in hospital functionality. He noted that hospitals are often left standing after earthquakes but become unusable because of damage to medical equipment, mechanical systems, or architectural elements. This highlights that performance-based design for hospitals must include not only structural safety but also the operability of essential services. His review also suggested that the anchorage of heavy equipment and careful design of secondary systems are as critical as frame strength. This perspective broadens the scope of PBSD and underscores why hospitals may require Immediate Occupancy as a performance target, as disruption of equipment or utilities can be as damaging as structural failure. For the present study, Villaverde's work is a reminder that while the analysis focuses on frames, the final interpretation must consider the operability of the hospital.

Ozkaynak *et al.* conducted a detailed pushover study on a reinforced concrete hospital building to evaluate its seismic performance. Their results showed that the building height and stiffness distribution had a strong influence on the hinge formation and drift concentration. In particular, taller hospital models exhibited earlier hinge formation in the lower stories, suggesting that vertical expansion without adequate detailing increases vulnerability. They also observed that although global collapse could be avoided, damage was often concentrated in critical locations, reducing the functional usability of the building after shaking. This finding is especially relevant for hospitals, where even a partial loss of operability undermines disaster response. Their study emphasized the need for careful detailing of columns and beam-column joints and supported the idea that pushover analysis can reveal weak zones before failure occurs.

Bhangle *et al.* More recently, Bhangle compared nonlinear static pushover with nonlinear response history analysis for RC buildings. The study acknowledged that response history analysis is more accurate but requires detailed ground motion data and significant computational effort. Pushover, on the other hand, remains an efficient tool for early-stage design and performance assessment. Bhangle concluded that pushover is particularly valuable for healthcare facilities, where quick assessment of multiple design options is often necessary. The research also highlighted that while pushover may not capture cyclic degradation or cumulative damage effects, its ability to provide displacement demand, hinge formation sequence, and performance levels makes it highly useful for practical design offices. Importantly, the paper emphasized that for hospitals and other lifeline structures, pushover serves as a cost-effective method to identify potential weaknesses early, allowing engineers to prioritize retrofitting or strengthening measures before resorting to more advanced analyses.

The study by Gore, Barbude, and Jadhav *et al*. explored the seismic performance of a G+10 RCC hospital building using pushover analysis across different Indian seismic zones (III, IV, and V). Their work is significant because it directly deals with hospitals, which are essential facilities that must remain operational during and after earthquakes. Unlike generic RC frame studies, their focus was on meeting the Immediate Occupancy (IO) performance level, which is a stricter requirement for healthcare facilities than for ordinary buildings. The authors modeled the hospital in SAP2000 and varied the seismic parameters according to the IS 1893:2016 provisions for each zone. Their findings highlighted that as the seismic zone changed from III to V, the base shear, roof displacement, and fundamental time period all increased gradually, reflecting the growing severity of the seismic demand. A key observation was that plastic hinges mostly developed in beams before columns, which aligned with the desired “weak beam–strong column” behavior. This finding emphasizes the importance of proper detailing to achieve ductile failure mechanisms in hospital structures. The study also assessed inter-storey drift ratios, noting that the structure generally remained within Immediate Occupancy limits for Zones III and IV. In Zone V, however, the drifts between the 3rd and 6th stories exceeded 1%, pushing the performance partly toward Life Safety (LS). Interestingly, while Zones III and IV achieved values slightly above 5 (as recommended by IS 1893:2016 for SMRFs), Zone V fell short. This discrepancy demonstrates that code assumptions may not always hold true in nonlinear performance evaluations, particularly for critical facilities.

The publication of FEMA 356 *et al*. was a turning point in the codification of performance-based design principles. It laid out explicit definitions for performance levels, such as Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP), and provided acceptance criteria and hinge modeling rules for nonlinear analysis. These guidelines provide engineers with a clear framework for interpreting pushover results in terms of practical performance objectives. Subsequently, FEMA 440 refined the equivalent linearization procedures originally used in FEMA 273/356 to better estimate displacement demands. The refinements improved the reliability of identifying the performance points, particularly in systems with significant nonlinearity. Together, these two documents remain widely referenced today because they translate theoretical concepts into usable tools for design and assessment. They also helped bridge the gap between academic research and practical engineering applications, making performance-based design accessible to design offices and consultants worldwide. In the present work, the hinge definitions and performance level criteria from FEMA are directly used to evaluate hospital models, ensuring that results can be compared against internationally accepted benchmarks.

Objectives of the present study

1. To perform nonlinear pushover analysis in both X and Y directions and determine: Capacity curves, Performance point using capacity spectrum method.
2. To determine performance points and performance levels (IO, LS, CP) for the selected hospital models and compare their ability to satisfy code-based performance requirements.
3. To investigate the influence of building height by analyzing hospital structures of varying stories (G+6, G+9, and G+12) while keeping plan dimensions constant. assess inter-storey, base shear capacity

III. METHODOLOGY

The present study adopts a Performance-Based Seismic Design (PBSD) framework to evaluate the seismic performance of reinforced concrete (RC) hospital buildings with constant plan geometry and varying heights. The analysis is carried out using nonlinear static pushover analysis, which has been recognized as a reliable tool for estimating the inelastic performance of buildings under seismic loading. The entire methodology is implemented in SAP2000 (v24.0.0) software.

In a displacement-controlled pushover, instead of applying incremental lateral forces, a target displacement is specified at a control point (usually at the roof level of the building). The building model is gradually pushed laterally until this target displacement is reached. The software records the corresponding base shear at each step. This produces the capacity curve (base shear vs. roof displacement), which is central to performance-based evaluation.

In real earthquakes, displacements (drifts) govern structural damage and performance, not just forces. Traditional force-controlled pushover may stop once strength capacity is exceeded, even if the structure could deform further. Displacement control ensures that the analysis captures the post-yield behavior (plastic hinge formation, degradation, ductility).This makes it more suitable for performance-based design of critical facilities like hospitals.

For this study, the roof joint at the center of mass is selected as the control node. The building is pushed laterally until the roof displacement reaches approximately 2% of the total building height, which is considered an appropriate limit for capturing the nonlinear range of structural behavior in reinforced concrete frames. By systematically reviewing base shear capacity, story drift behavior, performance point, and R-factor, the displacement-controlled pushover method ensures a comprehensive evaluation of the hospital buildings' seismic resilience.

IV. STRUCTURAL MODELING

1. General Information

a) Software used: SAP2000 (v24.0.0)
b) Type of structure: Reinforced Concrete (RC) Moment Resisting Frame (SMRF) R=5
c) Usage: Hospital building (critical facility, Importance Factor = 1.5)
d) Location/Seismic Zone: Zone V as per IS 1893 (Part 1): 2016

2. Geometry of the Building

a) Plan Layout: 5 × 5 bays, each bay measuring 6 m × 6 m
b) Floor-to-Floor Height: 3.3 m
c) Total Building Heights:
d) G+6 (23.1 m)
e) G+9 (33.0 m)
f) G+12 (42.9 m)
g) Symmetry: Regular and symmetric in plan (torsional irregularities avoided)
h) Diaphragm Assumption: Rigid diaphragm at each floor level

3. Material Properties

a) Concrete: M30 (fck = 30 MPa) , M35 (fck = 35 MPa)
b) Reinforcement Steel: Fe500
c) Unit Weight of Concrete: 25 kN/m³
d) Modulus of Elasticity of Concrete (Ec): $5000\sqrt{fck}$ = 27,386 MPa (approx.)
e) Modulus of Elasticity of Steel (Es): 2×10^5 MPa
f) Poisson's Ratio of Concrete: 0.2

4. Member Sections

a) Slab Thickness: 150 mm (modelled as shell elements)
b) Beams: 230 mm × 500 mm
c) Columns: 300 mm × 500 mm (Varying)
d) Walls/Shear Walls: Not provided (pure SMRF considered)

5. Loading Details

a) Dead Load (DL):
b) Self-weight of structural elements (automatically calculated in SAP2000)
c) Floor finishes (additional 1.0 kN/m² considered)
d) Live Load (LL):
e) 3.0 kN/m² (as per IS 875 Part 2 for hospitals)
f) Seismic Load (EL): As per IS 1893:2016
g) Seismic Zone: V
h) Importance Factor (I): 1.5
i) Response Reduction Factor (R): 5.0 (SMRF)
j) Soil Type: Medium soil (Type II)
e) Damping Ratio: 5%

6. Stiffness Modifiers

Applied as per IS 1893:2016 and IS 16700:2017 to account for cracking of RC sections.

7. Nonlinear Modelling Parameters

a) Hinge Properties:
b) Beams: Flexural hinges at both ends
c) Columns: Flexural + axial hinges as per FEMA 356
d) Location of Hinges: At 0.0L and 1.0L (ends of

members)

e) Acceptance Criteria: IO, LS, and CP levels as defined in FEMA 356

8. Pushover Setup

a) Control Node: Roof joint at center of mass
b) Loading Pattern:
c) Lateral load applied in X and Y directions
d) Mode shape distribution considered for accuracy
e) Target Displacement: 2% of total building height
f) Termination Criteria: Analysis stopped at target displacement or collapse mechanism

9. Assumptions

a) Soil–structure interaction not considered (fixed base).
b) Building plan is regular (no torsional irregularity).
c) Only structural components are modeled; non-structural elements like infill walls and equipment are not explicitly modeled but considered in interpretation of results.

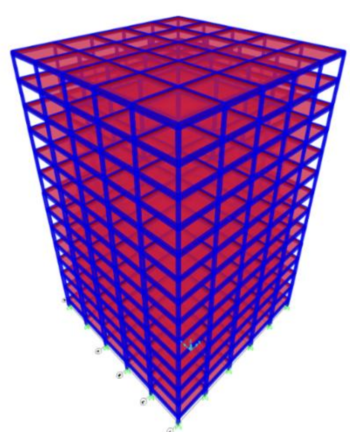


Fig. 1: 12 storey RCC building structure

V. RESULTS AND DISCUSSION

This study presents the results obtained from the nonlinear static pushover analysis of reinforced-concrete hospital buildings with varying heights (G+6, G+9, and G+12). The primary objective of this study was to evaluate the influence of building height on seismic performance by comparing the base shear capacity, performance point and Response reduction factor (R-factor).

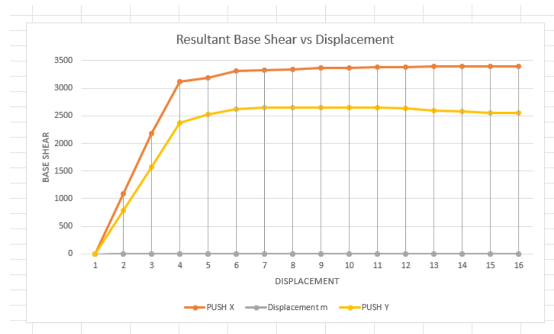


Fig 2: G+6 Resultant Base Shear vs Displacement

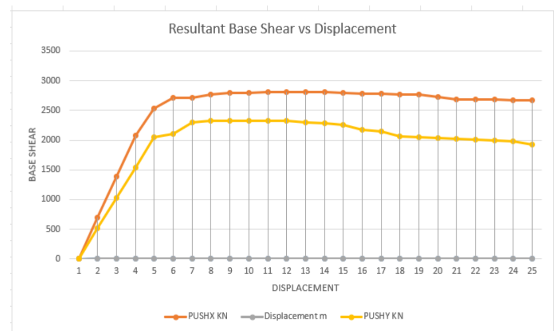


Fig 3: G+9 Resultant Base Shear vs Displacement

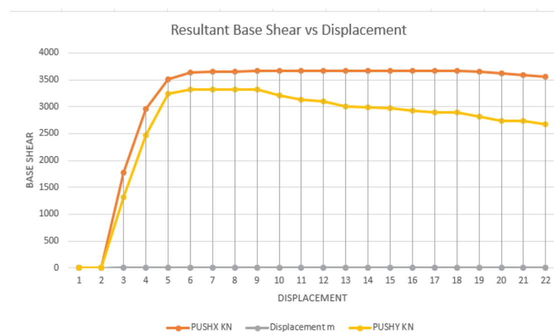


Fig 4: G+12 Resultant Base Shear vs Displacement

Across all three models, the capacity curves show the typical behavior of reinforced concrete (RC) frame structures under pushover loading:

Initial Linear Rise: At small displacements, the base shear increases linearly with displacement, indicating elastic behavior.

Yield Point: Around 3–4 displacement steps, yielding begins, and plastic hinges start to form.

Plastic Plateau: After yielding, the curves flatten, showing that the building sustains additional displacements with little increase in base shear.

Strength Degradation (in some cases): At higher displacements, especially in Y-direction curves, the base shear slightly decreases, signifying stiffness loss and potential hinge concentration in lower stories

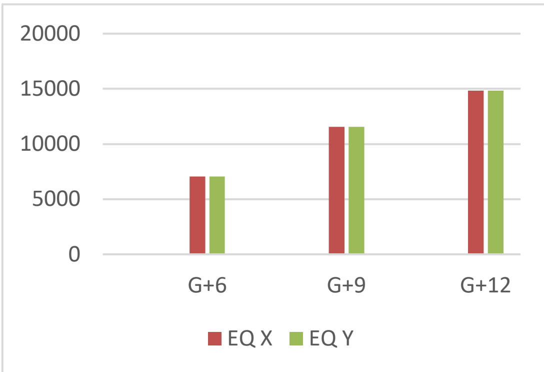


Fig 5: Base shear (EQX and EQY)

As building height increases, stiffness reduces and displacement demand rises, even if base shear capacity increases slightly due to added mass. G+6 buildings are safer and remain closer to Immediate Occupancy (IO) performance. G+9 and G+12 buildings show reduced efficiency of base shear resistance, pushing their performance points towards Life Safety (LS) and Collapse Prevention (CP) levels. For hospitals, where functionality post-earthquake is critical, additional seismic measures (shear walls, dampers, or base isolation) are necessary in taller buildings to control displacement despite high base shear capacity.

Response factor

R Factor	G+6	G+9	G+12
PUSHX	4.45	4.72	4.9
PUSHY	4.46	4.80	4.7

The response reduction factor reflects the capacity of structure to dissipate energy through inelastic behavior. It is a combined effect of over strength, ductility and redundancy represented as:

$$R = R_S \times R_R \times R_u$$

where,

R_S = Over strength factor

R_R = Redundancy factor

R_u = Ductility reduction factor

Code R ≈ Obtained R

The obtained R values are comparable to code-specified values, validating that the modeled buildings provide ductility and overstrength consistent with code assumptions.

Capacity vs Demand curve

Capacity Spectrum (ATC-40 method)

The pushover curve, as per ATC-40 (Applied Technology Council Report 40), is a fundamental output of a pushover analysis, a type of nonlinear static analysis used in performance-based seismic design and assessment of buildings.

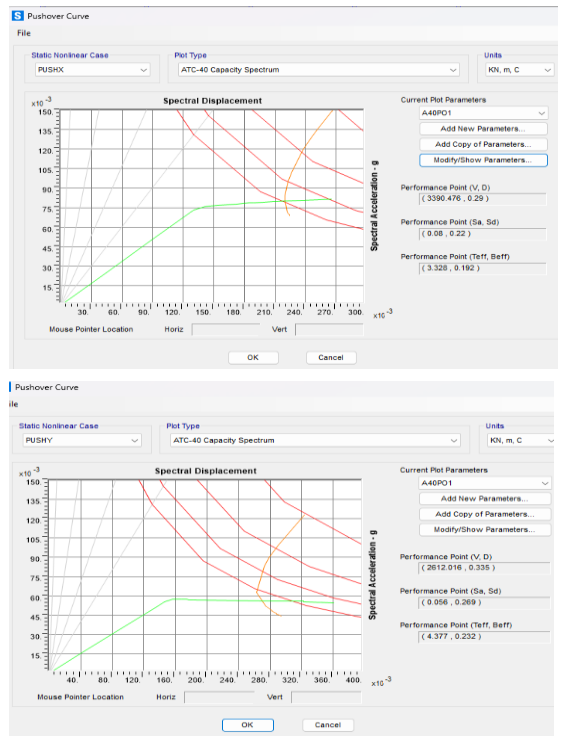
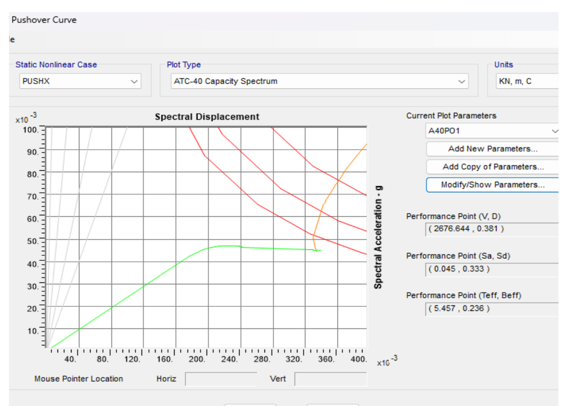


Fig 7: G+6



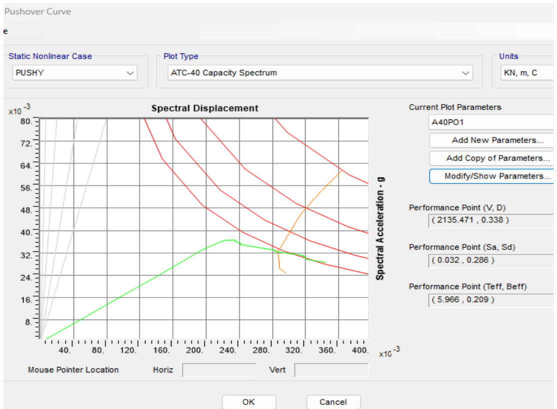
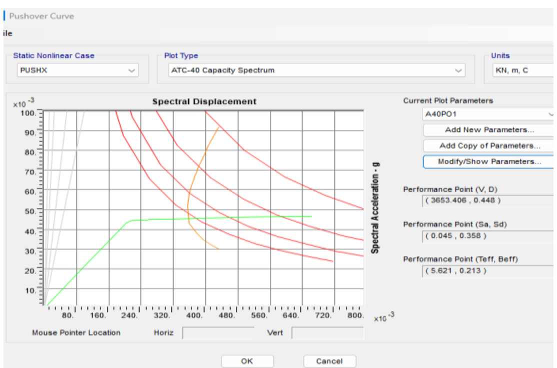


Fig 8: G+9



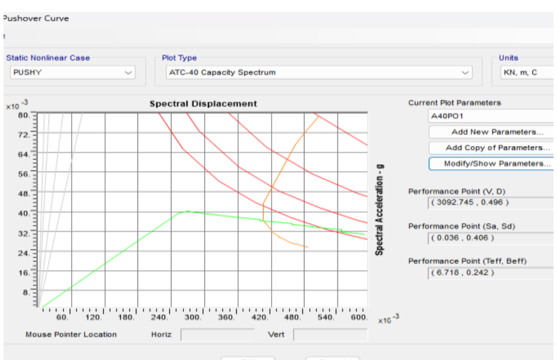


Fig 9: G+12

The pushover curve is converted to Spectral Acceleration (Sa) vs. Spectral Displacement (Sd). It is compared with demand spectra (from seismic hazard).The Performance Point is found: the intersection of capacity and demand.

Hinges Formation

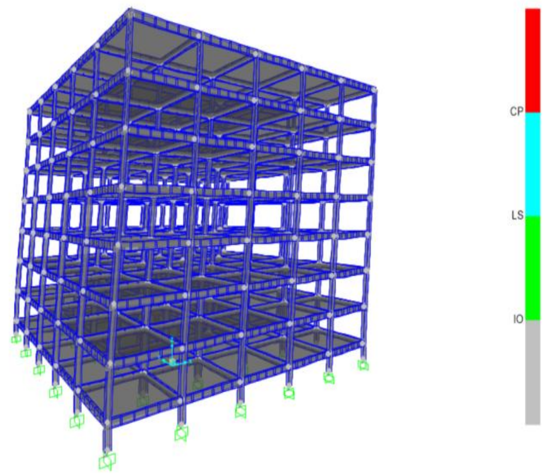


Fig10: G+6 Hinges Formation

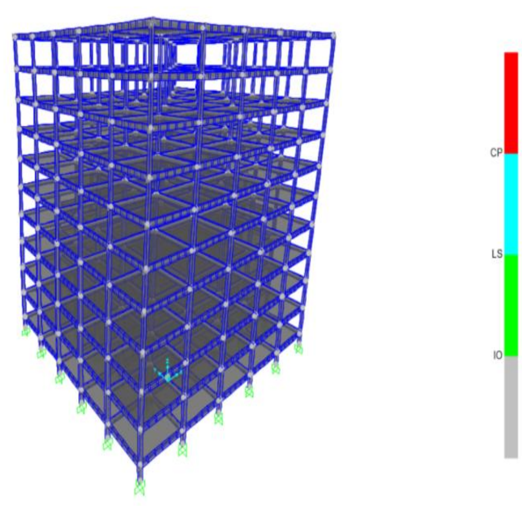


Fig 9: G+9 Hinges Formation

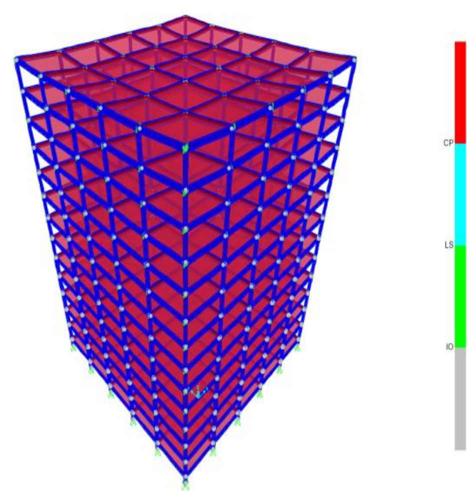


Fig 11: G+12 Hinges Formation

Under the given loading scenario, the structural elements remain within Immediate Occupancy performance level, indicating minimal inelastic deformation and full structural integrity. No significant damage is expected, and the building retains its functionality immediately after the event.
The structure is performing very well. It has minimal damage and no risk of collapse. It's suitable for immediate use post-earthquake. Indicates a safe and resilient design

VII. CONCLUSION

This study examined the impact of vertical expansion on the seismic performance of hospital buildings using nonlinear pushover analysis in SAP2000. By maintaining a uniform floor plan and varying only the number of stories (6, 9, and 12), the influence of height on structural behavior under seismic loads was clearly identified.
The analysis revealed that increasing the number of stories led to a consistent pattern of:
Higher lateral displacement demands, Reduced lateral stiffness and base shear capacity, Earlier formation of plastic hinges - particularly in the lower stories, and Noticeable shifts in performance points.
Despite these trends, all three structural models remained within the Immediate Occupancy (IO) performance level, highlighting their capacity to maintain operational functionality after a design-level seismic event. This level of performance is especially critical for hospital buildings, where continuity of medical services is essential in the aftermath of a disaster.
These findings reinforce the value of Performance-Based Design (PBD) in healthcare infrastructure, enabling engineers to assess and ensure both safety and serviceability. The use of pushover analysis has proven effective not only for identifying potential failure mechanisms but also for informing safer and more resilient design strategies in seismic zones.

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