Performance Based Analysis and Design of Coupled Shear Wall

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Abstract- **This study investigates the seismic performance of reinforced concrete (RC) buildings with coupled shear walls using a Performance-Based Design (PBD) approach. Coupled shear walls, connected through ductile coupling beams, are an effective lateral load-resisting system for tall buildings as they enhance stiffness, energy dissipation, and overall resilience during earthquakes. The research involves modeling RC buildings of 7, 9, and 11 storey in SAP2000 (v24) and evaluating their seismic behavior under Zone III conditions as per IS 1893:2016. Nonlinear pushover analysis was conducted following FEMA 356 guidelines to assess base shear capacity, roof displacement, plastic hinge development, and performance levels such as Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). The results demonstrate that building height significantly influences structural response, with higher structures showing increased displacement demand but improved ductility. The findings confirm that coupled shear wall systems are highly effective for earthquake-resistant design, aligning well with performance objectives and offering a safer and more reliable alternative to conventional force-based methods.**

Index Terms— **Performance-Based Design (PBD), Coupled Shear Wall, Nonlinear Pushover Analysis, Seismic Performance, RC Buildings, Earthquake Engineering.**

I. INTRODUCTION

Earthquakes are among the most devastating natural disasters, unique in their sudden occurrence and lack of warning. Unlike floods or cyclones, which often provide time for precautionary measures or evacuation, earthquakes strike without notice, leaving people vulnerable and causing large-scale destruction of life and property. Given this unpredictability, the only feasible strategy for mitigating seismic risks is to design buildings that are capable of withstanding earthquake forces. Over the years, earthquake-resistant design concepts have evolved continuously, drawing vital lessons from the damages and failures observed in past

seismic events. Each recorded case of damage has contributed to a better understanding of structural performance, resulting in improved design philosophies and construction practices aimed at protecting building occupants and reducing losses.

In structural engineering, buildings are designed to resist three categories of loads: permanent, semi-permanent, and occasional. Earthquake forces fall into the last category, yet they pose a special challenge due to their dynamic nature. During seismic activity, various parts of a structure undergo differential movement relative to the foundation within a very short time interval. These rapid deformations generate additional internal forces that the structure must resist. The study of structural responses during past earthquakes has made seismic design one of the most dynamic and evolving branches of civil engineering, integrating advances in seismology, material science, and computational methods over the past century.

Traditional seismic design methods, codified in building codes across many countries for more than 70 years, are primarily force-based. In this approach, the design ensures that structures satisfy prescribed force demands. However, one of the major drawbacks of this method is that it does not explicitly consider inelastic structural behavior in terms of either force or deformation. Real earthquake events, such as the Loma Prieta earthquake in 1989 and the Northridge earthquake in 1994, revealed serious limitations of force-based designs. Many structures that met the prevailing code requirements still experienced unacceptable levels of damage, highlighting the inconsistencies between linear analysis assumptions and the actual nonlinear, ductile behavior of materials and systems during seismic events. These shortcomings led to the development of Performance-Based Seismic Design (PBD), a philosophy that shifts the focus from merely resisting forces to ensuring that structures meet predefined performance objectives under varying levels of seismic hazard.

Performance-Based Design is an advanced engineering approach that emphasizes the expected behavior of a structure during and after an earthquake. Instead of relying only on codal provisions, PBD establishes explicit, quantifiable performance goals, such as limits on lateral drift, displacements, or accelerations. These goals are defined based on the expected seismic hazard and the intended function of the building, for example, ensuring that hospitals remain operational even after a moderate earthquake. The design process is iterative, evaluating structural response under multiple hazard scenarios and refining the design until the desired performance is achieved. Typically, three levels of performance are considered: Serviceability, where minor earthquakes cause no damage; Repairability, where moderate earthquakes may lead to damage but it remains repairable; and Safety, where severe earthquakes induce significant inelastic deformations but complete collapse is prevented. Guidelines such as ATC-40 and FEMA 273 provide more detailed criteria for performance objectives, tailored to building owners' requirements.

In addition to design philosophy, structural systems play a critical role in determining seismic performance. Among these, coupled shear walls have emerged as highly effective lateral load-resisting systems, particularly for tall buildings. In this system, two or more shear walls are interconnected by coupling beams. These beams are designed to undergo ductile inelastic behavior, thereby dissipating a significant portion of seismic energy, while the walls provide overall stiffness and strength. The concept is analogous to the "strong-column–weak-beam" philosophy in moment-resisting frames, where controlled energy dissipation prevents catastrophic failures. Coupled shear walls not only reduce deformation demands but also help distribute inelastic deformations more uniformly, both vertically and in plan, thereby enhancing overall seismic resilience.

In the Indian context, where urban growth demands taller and more complex structures, reliance on purely linear design approaches is both uneconomical and insufficient for safety. It is therefore imperative to adopt design philosophies that incorporate post-yield behavior and deformation-based assessments. This research addresses this need by focusing on the integration of performance-based seismic design methodology with coupled shear wall systems, providing insights into their efficiency and suitability for earthquake-resistant construction in India.

II. REVIEW OF LITERATURE

Tande and Karad [1] investigated the inelastic seismic performance of buildings using pushover and nonlinear time-history analysis. Their findings highlighted the ability of PBD approaches to evaluate structural capacity beyond conventional code methods. While the study focused on framed buildings, the nonlinear modeling concepts are directly applicable to coupled shear walls where ductility and hinge mechanisms govern seismic performance.

Cinitha et al. [2] performed performance-based seismic evaluation of RC frames using nonlinear static analysis and FEMA-356 criteria. The study demonstrated how demand–capacity curves could be used to assess performance levels such as Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). Extending this approach to coupled shear walls enables accurate prediction of coupling beam yielding and wall pier ductility, which are central to their energy dissipation mechanism.

The CTBUH guidelines [3] provided a comprehensive framework for performance-based seismic design of tall buildings, emphasizing nonlinear dynamic analysis, drift limits, and collapse prevention. As coupled shear walls are frequently used in high-rise structures, these guidelines are directly relevant to their design, ensuring system-level performance objectives are satisfied under severe seismic demands.

Bhosale [4] evaluated seismic performance of RC framed buildings using a shear failure model. The study stressed the importance of accounting for brittle shear failure in performance assessments. For coupled shear walls, this highlights the need for careful detailing of coupling beams, which are prone to diagonal shear cracking, making shear strength evaluation a critical part of PBD.

McFarlane [5] introduced phenomenological nonlinear modeling techniques for performance-based design of high-rise shear wall buildings. His approach enabled accurate representation of stiffness degradation, pinching, and strength loss in walls. For coupled shear wall systems, this modeling framework is highly beneficial to simulate realistic nonlinear response of wall piers and coupling beams under cyclic seismic loading.

Patil and Kulkarni [6] conducted pushover analysis on framed reinforced concrete shear walls, showing that the presence of shear walls significantly enhanced lateral strength and ductility. Their findings directly support the application of coupled shear walls in seismic zones, where improved displacement control and energy dissipation are vital for tall building safety.

Ravi Kumar et al. [7] studied the seismic vulnerability of RC buildings with shear walls. Their results indicated a remarkable reduction in vulnerability indices when shear walls were incorporated into the structural system. For coupled shear walls, the study provides evidence of how wall integration improves overall building resilience, aligning with the core objectives of performance-based seismic design.

The primary objective of this study is to assess the seismic performance of reinforced concrete (RC) buildings with couple shear wall using a Performance-Based Design (PBD) methodology through nonlinear static pushover analysis. The study emphasizes the effect of building height on structural response and damage progression under earthquake loading conditions.

Specific objectives include:

1. To develop and model multi-story RC buildings with couple shear wall of 7, 9, and 11 storey with identical plan layouts using SAP2000 v24.
2. To design structural members (beams and columns) with M30 concrete and Fe500 steel, incorporating realistic cross-sectional properties.
3. To define and assign nonlinear hinges as per FEMA 356 guidelines to simulate plastic deformation in structural elements.
4. To perform nonlinear pushover analysis in the X direction and evaluate:
   a. Capacity curves (Base Shear vs. Roof Displacement)
   b. Performance point determination using the Capacity Spectrum Method
   c. Performance levels of buildings under seismic loading
   d. Storey drift under earthquake loads

III. METHODOLOGY

This study investigates the seismic performance of reinforced concrete (RC) buildings with coupled shear walls using a Performance-Based Design (PBD) approach. Three building models of seven, nine, and eleven storeys were analyzed to evaluate the influence of height on seismic response.

Model Development

1) Buildings with identical plan dimensions of 36 m × 19.8 m were modeled in SAP2000 (v24).
2) The structural system consists of RC frames integrated with coupled shear walls modeled using the wide-column technique.
3) Materials used include M30 concrete and Fe500 steel. Beam sizes of 300×600 mm and 300×800 mm, and column sizes of 300×1500 mm and 300×4000 mm were adopted.

Loading and Design Parameters

1) Dead loads were applied as per IS 875 (Part 1) and live loads of 3 kN/m² were considered.
2) Seismic loads were assigned according to IS 1893 (Part 1):2016 for Zone III with a medium soil profile, importance factor (I) of 1.0, and response reduction factor (R) of 5.
3) Seismic weight was calculated as dead load plus 25 % of the live load.

Analysis Procedure

1) Initial linear dynamic analysis was performed using the response spectrum method to determine natural periods and mode shapes.
2) Performance-Based Design was then executed for Immediate Occupancy (IO) and Collapse Prevention (CP) levels using nonlinear static

pushover analysis following FEMA 356 guidelines.

3) Nonlinear hinges were assigned to beams and columns to capture inelastic behavior, and lateral loads were applied incrementally in the X direction until target displacement or collapse mechanism was reached.

Evaluation Parameters

1) Key outputs included capacity curves (base shear vs. roof displacement), performance point determination via the Capacity Spectrum Method, storey drift, and plastic hinge formation.
2) Modifiers were applied to represent cracked-section stiffness for accurate estimation of drifts and periods.

This systematic methodology ensures realistic assessment of the seismic behavior of coupled shear wall systems under varying building heights

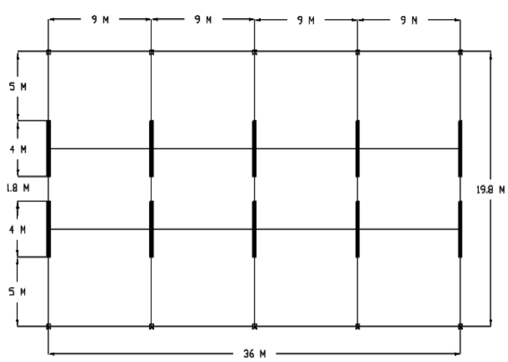

Fig 1: General Plan of The Building

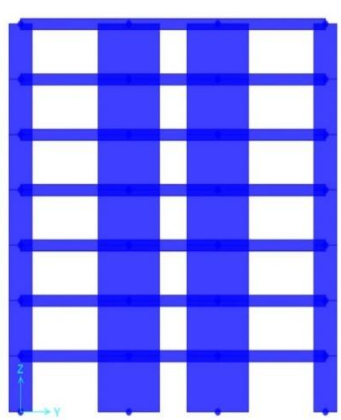

Fig 2: Elevation of 7 storey building in SAP 2000 model

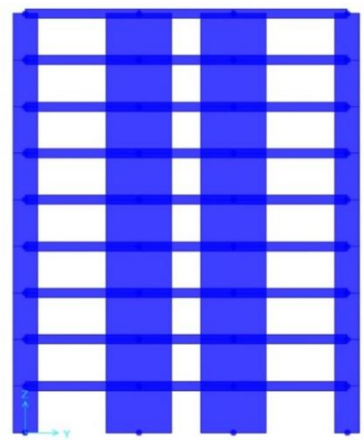

Fig 3: Elevation of 9 storey building in SAP 2000 model

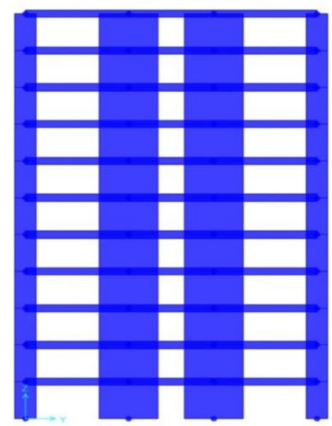

Fig 4: Elevation of 11 storey building in SAP 2000 model

IV. STRUCTURAL MODELING

Description of the Structural Model

1) Structure Type: Reinforced Concrete
2) Usage: Residential Building
3) Plan Geometry: Constant for all models
4) Story Heights Considered: 7, 9, and 11 storey
5) Story Height: Typically, 3.0 m per floor
6) Plan Dimension: 38 m X 19.8 m
7) Load-Resisting System: RC frame
a. (Coupled shear walls)
8) Modelling Software: SAP2000 (v24.0.0)

Material and Section Properties

1) Concrete Grade: M30
2) Steel Grade: Fe500
3) Beam Sizes:
    a. 300 mm × 600 mm
    b. 300 mm × 800 mm
4) Column Sizes:

a. 300 mm × 1500 mm
b. 300 mm × 4000 mm
5) Slab Thickness: 150 mm

Load Considerations
1) Dead Load (DL): Calculated automatically
2) Live Load (LL): 3 kN/m² applied on all floors
3) Seismic Load:
a. As per IS 1893 (Part 1): 2016
b. Seismic Zone: Zone III
c. Importance Factor (I): 1
d. Response Reduction Factor (R): 5
e. Soil Type: Medium
f. Damping Ratio: 5%

Time period calculation

$$T = \frac{0.9\,h}{\sqrt{d}}$$

No. of Storey	Height	Time Period (X Direction)	Time Period (Y Direction)
7 Storey	21m	0.315	0.4247
9 Storey	27m	0.405	0.5461
11 Storey	33m	0.495	0.6675

Modifiers
Modifiers in buildings are adjustment factors applied to structural elements in analysis to represent their actual behavior rather than ideal theoretical stiffness. In reinforced concrete, members lose stiffness due to cracking, creep, and construction imperfections. To account for this, codes like IS 1893 recommend reduced stiffness values (e.g., for beams, columns, and shear walls). Using modifiers ensures realistic load distribution, accurate estimation of drift and natural periods, and reliable seismic performance evaluation of the structure.

Service Stiffness Modifier Values

Elements stiffness modifier	Structural Walls	Retaining Walls	Spandrel beam	Slab	Frames stiffness modifier	Columns		Beam
						Frame	Gravity	
F11	1	1	0.7	0.35	Area	1	1	1
F22	0.9	0.9	0.7	0.35	As2	1	1	1
F12	1	1	0.7	0.35	As3	1	1	1
M11	0.9	0.9	0.7	0.35	T	0.001	0.001	0.001
M22	0.9	0.9	0.7	0.35	I22	0.9	0.1	0.7
M12	0.9	0.9	0.7	0.35	I33	0.9	0.1	0.7
V13	1	1	1	1				
V23	1	1	1	1				

Strength Stiffness Modifier Values

Elements stiffness modifier	Structural Walls	Retaining Walls	Spandrel beam	Slab	Frames stiffness modifier	Columns		Beam
						Frame	Gravity	
F11	1	1	0.35	0.25	Area	1	1	1
F22	0.7	0.7	0.35	0.25	As2	1	1	1
F12	1	1	0.35	0.25	As3	1	1	1
M11	0.7	0.7	0.35	0.1	T	0.001	0.001	0.001
M22	0.7	0.7	0.35	0.1	I22	0.7	0.1	0.35
M12	0.7	0.7	0.35	0.1	I33	0.7	0.1	0.35
V13	1	1	1	1				
V23	1	1	1	1				

Pushover Analysis Setup
1) Analysis Type: Nonlinear Static (Pushover)
2) Load Pattern:
- Lateral loads applied incrementally in X directions
- Distribution pattern: Mode-1 shape or Uniform
3) Hinge Assignment:
- Hinges assigned to beams and columns based on FEMA 356 guidelines
- Default hinge properties used with user-defined locations
4) Control Node: Roof level joint used to monitor displacement
5) Termination Criteria: Based on target displacement or collapse mechanism
6) Performance Evaluation Parameters
7) The following structural performance parameters are extracted and compared across different building heights:
a) Base Shear Capacity
b) Roof Displacement
c) Plastic Hinge Formation
d) Performance Point (using Capacity Spectrum Method)
e) Performance Level (IO, LS, CP)
8) Modelling Assumptions
a) The building is assumed to be symmetric and regular in plan.
b) Rigid diaphragm action is considered at each floor level.
c) Soil-structure interaction is neglected.
d) No torsional irregularity or vertical discontinuities are introduced.
e) Non-structural components are not modelled

V. RESULTS AND DISCUSSION

1) Resultant Base shear vs monitored displacement
Resultant Base Shear vs Monitored Displacement is a concept commonly used in Performance-Based

Seismic Design (PBSD) or nonlinear time-history/pushover analysis to evaluate how a structure behaves under seismic loads. Here's a breakdown:

Resultant Base Shear:

a) Definition: The total horizontal force (shear) at the base of a structure due to seismic action.
b) Unit: kN or kips
c) Source: It is the sum of all lateral forces resisted by the base of the structure.
d) Represents: The seismic demand on the building's foundation.

Monitored Displacement:

a) Definition: The displacement (movement) of a specific point in the structure being monitored during the analysis.
b) Typically Monitored At:
c) Roof level (for global drift)
d) Top of shear walls or cores
e) Critical joints in performance analysis
f) Represents: How much the structure deforms under seismic loads.

Resultant Base Shear vs Monitored Displacement Curve:

This is a nonlinear force-deformation curve used in pushover analysis or time-history analysis.

X-axis: Monitored Displacement (e.g., roof displacement in mm)

Y-axis: Resultant Base Shear (e.g., in kN)

Purpose and Use:

a) To understand structural performance under increasing seismic load.
b) To identify:
1) Elastic range (initial linear part of the curve)
2) Yield point (start of nonlinear behavior)
3) Plastic range (structure undergoing controlled damage)
4) Ultimate capacity/failure point
5) Used in Performance-Based Design to classify building performance levels:
6) Immediate Occupancy
7) Life Safety
8) Collapse Prevention

For 3 models resultant base shear vs monitored displacement graph attached below:

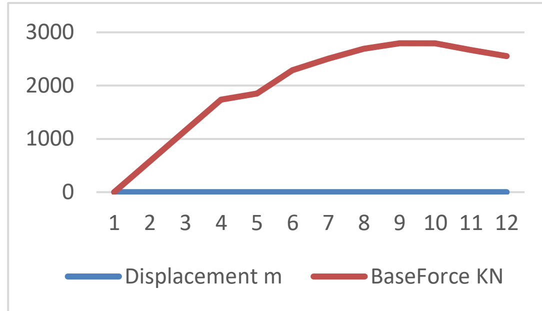

Fig 5: Resultant base shear vs monitored displacement for 7 Storey

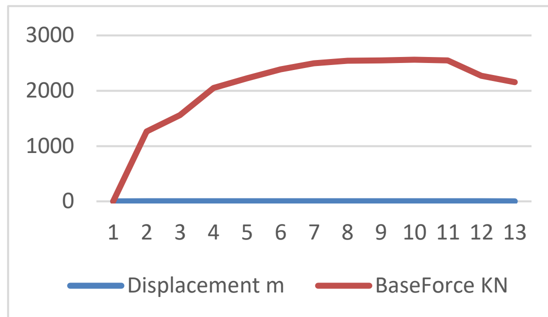

Fig 6: Resultant base shear vs monitored displacement for 9 Storey

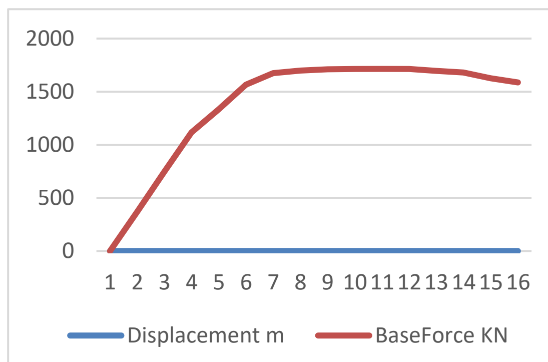

Fig 7: Resultant base shear vs monitored displacement for 11 Storey

ATC-40 Capacity Spectrum-Performance Point

The Performance Point is the point on a structure's pushover curve where the capacity of the structure equals the demand from the earthquake. It represents the expected state of the structure during a design-level earthquake.

Components Involved:

1. Capacity Curve
   a) Obtained from pushover analysis
   b) Represents the base shear vs. displacement behavior of the structure

2. Demand Curve
   a) Represents expected ground motion demand (earthquake intensity)
   b) Based on response spectrum from seismic code or site-specific data

At the Performance Point:
1) The building experiences a certain lateral displacement (monitored at roof or control point)
2) This displacement corresponds to the seismic performance level:
   a) Immediate Occupancy (IO)
   b) Life Safety (LS)
   c) Collapse Prevention (CP)

The base shear at this point is the actual force resisted by the building under that displacement

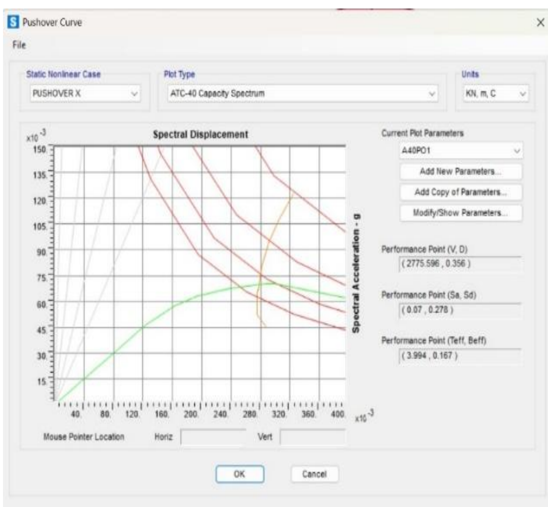

Fig 8: Base shear for 7 Storey

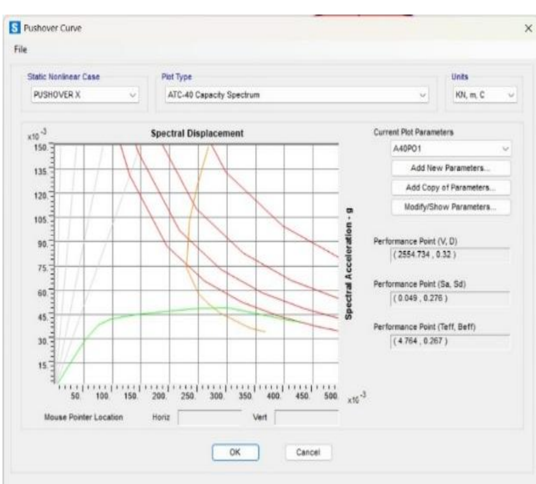

Fig 8: Base shear for 9 Storey

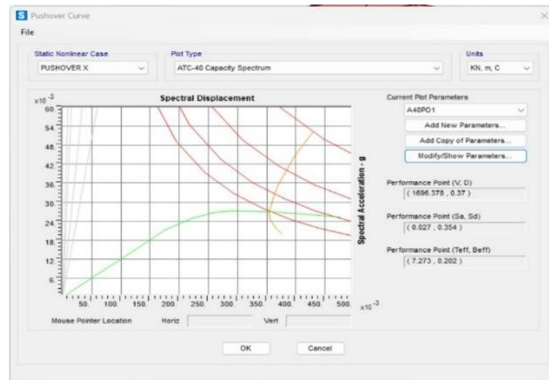

Fig 9: Base shear for 11 Storey

Performance Level

A Performance Level is a qualitative measure that describes the expected condition of a structure after an earthquake. It defines how functional, safe, and repairable the building will be based on the extent of damage to structural and non-structural components.

Purpose:

To ensure that buildings meet specific safety and serviceability goals during and after an earthquake.

Components Considered:
a) Structural elements (columns, beams, shear walls)
b) Non-structural elements (partitions, ceilings, equipment)
c) Building contents
d) Life-safety systems (e.g., fire escape routes)

Applications:
a) Used in Performance-Based Seismic Design (PBSD)
b) Hospitals, emergency centers often designed for Immediate Occupancy
c) Residential buildings may target Life Safety
d) For retrofitting existing buildings to meet a minimum Collapse Prevention level

Table 1: Summary of performance level

Level	Structural Damage	Safety	Function
OP (Operational)	None	Full	No disruption
IO (Immediate Occupancy)	Light	Safe	Minor disruption
LS (Life Safety)	Moderate	Safe	Not functional
CP (Collapse Prevention)	Severe	Barely Safe	Total loss

SAP Model Hinges Result:

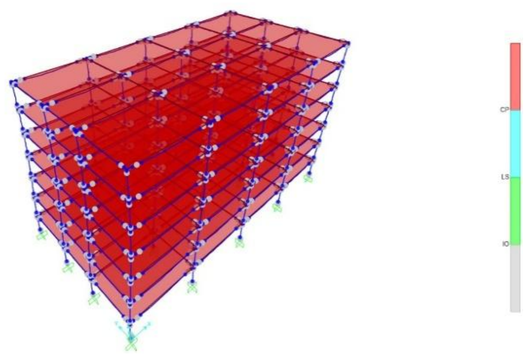

Fig 10: for 7 Storey

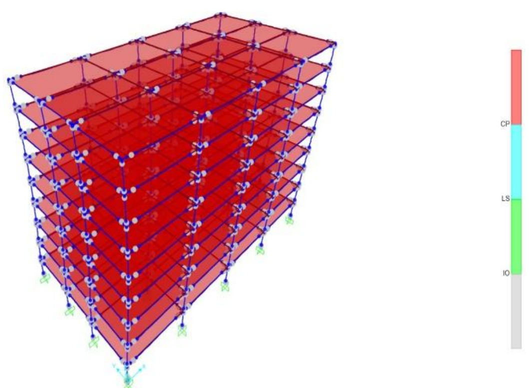

Fig 11: for 9 Storey

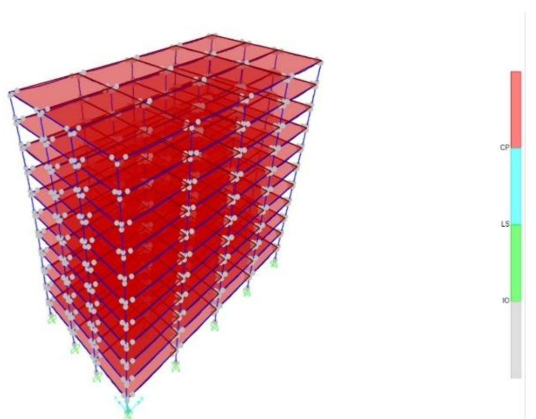

Fig 12: for 9 Storey

<u>Response Factor</u>

The Response Reduction Factor (R) represents a structure's ability to dissipate seismic energy through inelastic behavior. It captures the combined effects of:

a) Over strength (Rs): Reserve strength beyond the design level
b) Redundancy (Rr): Availability of alternate load paths
c) Ductility (Ru): Capacity to undergo inelastic deformation without significant loss of strength.

This relationship can be expressed as:

$$R = Rs \times Rr \times Ru$$

where:

Rs = Over strength factor
Rr = Redundancy factor
Ru = Ductility reduction factor

When the code-specified R value closely matches the calculated R value based on actual structural characteristics, it indicates that:

1) The structure possesses the intended levels of ductility and over strength as assumed by the code
2) The design is aligned with code expectations
3) There is strong agreement between performance-based and code-based design approaches, providing confidence in both design strategies

R value obtained from SAP models:

Storey	R Value
7 Storey	3.6706
9 Storey	5.8782
11 Storey	5.1584

Base Shear

Base Shear is the total lateral force at the base of a structure due to earthquake ground motion. Base shear for 3 models added below:

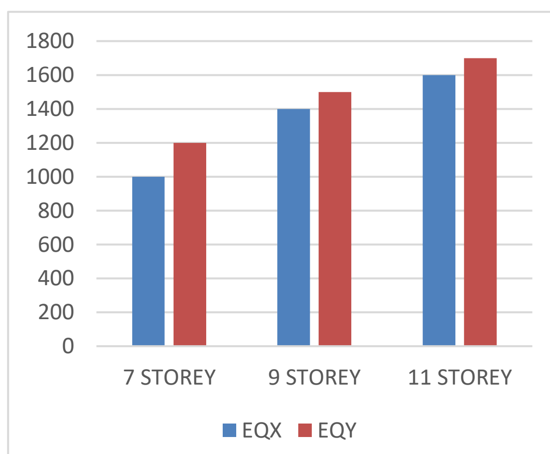

Fig 13: Base shear for 7, 9 and 11Storey

VII. CONCLUSION

Based on the performance-based seismic evaluation of RC buildings with coupled shear walls, the following conclusions are drawn:

- Effectiveness of PBD: Performance-Based Design provides a realistic and comprehensive framework for assessing seismic performance, capturing the true inelastic response of structures beyond conventional force-based methods.
- Coupled Shear Wall Efficiency: Coupled shear walls significantly enhance lateral stiffness, ductility, and energy dissipation, thereby improving the seismic resilience of multi-storey RC buildings.
- Critical Role of Coupling Beams: The behavior of coupling beams governs the overall response of the system. Proper detailing and analytical modeling of diagonally reinforced coupling beams are essential to accurately predict rotations and improve seismic performance.
- Influence of Building Height: Increased building height leads to larger roof displacements and higher ductility demand, yet all models achieved Immediate Occupancy or Life Safety performance levels, demonstrating the robustness of the coupled shear wall system.
- Design Implications: Integrating coupled shear walls within a PBD framework ensures a safe, economical, and dependable design strategy for earthquake-resistant construction, particularly in seismic regions like Zone III of India.

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