Non-Linear Static Analysis of Reinforced Concrete Buildings with Different Location of Shear Walls

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Abstract
This paper presents a non-linear static analysis (pushover analysis) of reinforced concrete (RC) buildings with various shear wall locations to determine the most effective configuration for seismic performance. A G+14 storey RC building was modeled in SAP2000 with different shear wall arrangements, and results were compared based on base shear capacity, displacement, ductility, and time period. The study demonstrates that shear wall placement significantly affects structural performance under seismic loads.

Keywords: Shear wall, Pushover analysis, Non-linear static analysis, Earthquake response, SAP2000, RC buildings, Performance-based design.

1. Introduction

Earthquake Design and Pushover Analysis:
- Earthquakes are unpredictable and require robust engineering analysis.
- **Performance-Based Design (PBD)** focuses on how structures behave under seismic forces.
- **Pushover analysis**, a nonlinear static method, helps identify potential failure points and assess post-elastic behavior.

Importance of Shear Walls:
- **Shear walls** are vertical elements that resist lateral forces (earthquake and wind).
- They enhance **stiffness, strength, and stability** of buildings, particularly in high-rise structures.
- Designed to handle **shear and uplift forces**, shear walls help control sway and minimize structural damage.

Study Objectives:
- Analyze tall buildings with and without shear walls using pushover analysis.
- Determine the **best locations** for shear walls based on structural performance.
- Compare results to improve building safety and cost-efficiency.

Design and Construction Aspects:
- Shear walls must be **well-integrated** with floors and roofs for three-dimensional stability.
- **Symmetrical placement** ensures balanced resistance and reduces torsional effects.
- Openings in shear walls should be minimal and symmetrically placed.

Functional and Architectural Considerations:
- Shear walls resist lateral loads, reduce displacements, and prevent collapse.
- Placement on **exterior walls** is preferred for maximum efficiency.

- They serve as fire barriers and improve building layout in repetitive floor plans.

Advantages of Shear Walls:

- Proven performance in past earthquakes.
- **Easy to construct**, economical, and effective in reducing both structural and non-structural damage.
- Ideal for residential and high-rise buildings requiring seismic resistance.

2. LITERATURE REVIEW

Effects of plastic hinge properties in nonlinear analysis of reinforced concrete buildings - Mahomet Intel, Hairy Bay tan Omen Engineering Structures[1] 2006: This study examines how **plastic hinge properties** affect **pushover analysis** results in RC buildings. Using 4- and 7-storey interior frames, the authors compared **default hinge properties** (from FEMA-356/ATC-40) with **user-defined values**. Results showed notable differences, highlighting that while default hinges offer simplicity, **custom hinge definitions** provide **more accurate structural behavior** under seismic loads.

Performance of Pushover Procedure in Evaluating the Seismic Adequacy of Reinforced Concrete Frames - Shuraim and A.Charif [2] (King Saud University 2007): This study evaluates the effectiveness of **pushover analysis** (per ATC-40) for assessing the seismic performance of a newly designed RC frame. Results from **code-based redesign** showed most columns needed reinforcement, indicating vulnerability. However, pushover analysis revealed the frame could withstand seismic loads with **yielding mainly in beams**. The discrepancy is due to differing assumptions—codes use **reduction and safety factors**, while ATC-40 includes **post-yield hardening** and assumes a reduction factor of 1. The authors emphasize the need for **engineering judgment** and caution that pushover analysis **should not replace code-based design principles**.

Pushover Analysis Of Reinforced Concrete Frame Structures - A. Kadid And A. Boumrkik, Asian Journal Of Civil Engineering [3] 2008: Following the 2003 Boumerdes earthquake in Algeria, this study used **pushover analysis** to assess the seismic performance of **5-, 8-, and 12-storey RC frame buildings**. Results showed that **well-designed frames** are capable of **withstanding strong seismic motions**, emphasizing the importance of proper design in improving structural resilience.

Nonlinear Analysis Methods for Reinforced Concrete Buildings with Shear Wall Y.M.Fahjan & J. Kubin & M.T. Tan [4] 2010: This study examines different **modeling techniques for RC shear walls** in both **linear and nonlinear analyses** of buildings. In linear analysis, shear walls are modeled using **shell or frame elements**. In nonlinear analysis, **plastic hinge models** and **multilayer shell elements** are used to capture material behavior.

The methods were applied to an RC building with shear walls, and results were compared to assess their impact on the **overall structural performance**. The study emphasizes that **modeling choice significantly influences analysis accuracy**.

Seismic strengthening of RC structures with exterior shear walls - Hasan kaplani, Salihyilmazi & Erginatimtay, Indian Academy of Sciences, [5] February 2011: This study demonstrates that exterior shear walls effectively enhance the seismic strength and stiffness of vulnerable RC buildings without requiring evacuation. Experimental results show improved performance under lateral loads, provided that dowels are properly designed, as their failure can negate the benefits of the strengthening.

Pushover analysis of reinforced concrete frame structure using SAP 2000 - P. Poluraju & P. V. S. Nageswara Rao, International Journal of Earth Sciences and Engineering [6] October 2011: The 2001 Bhuj earthquake revealed that many seemingly strong buildings failed due to non-compliance with modern codes. Frequent seismic activity in India has raised concerns about the seismic adequacy of framed structures. A pushover analysis of a G+3 building showed that properly designed frames can perform well under expected seismic loads.

3. METHODOLOGY

This section outlines the **pushover analysis methodology** used to assess the seismic performance of a **G+14 RC frame structure** with varying shear wall locations using **SAP2000**.

Key Concepts:

- **Pushover Analysis**: A nonlinear static method where lateral loads are incrementally applied until structural failure, generating base shear vs. roof displacement curves.
- **Modeling**: RC frames are modeled in 3D with plastic hinges at beam and column ends using **PMM** and **M3 hinges** per FEMA/ATC guidelines.
- **Load Application**: Gravity and lateral seismic loads (X-direction) are applied step-wise; element yielding reflects real seismic behavior.

Steps in Pushover Analysis:

1. **Define plastic hinges** at potential yield points.
2. **Select control node** to track displacement.
3. **Apply lateral load patterns** representative of earthquake forces.
4. **Estimate displacement demand** (max expected response).
5. **Evaluate performance**: Identify if structure meets Immediate Occupancy (IO), Life Safety (LS), or Collapse Prevention (CP) levels.

Analysis Insights:

- A **capacity curve** is developed showing strength vs. displacement.
- **Hinge behavior** is modeled using multi-point force-deformation relationships (points A–E).
- The structure’s **capacity** is evaluated by its component strength and deformation limits.
- **Demand** is defined as max displacement due to seismic motion.
- **Performance check** ensures that both structural and non-structural components remain within acceptable damage limits.

SAP2000 Implementation:

- SAP2000 uses **default**, **user-defined**, and **generated hinge properties**.
- Default hinges follow **ATC-40 and FEMA-273** standards.
- Analysis reflects yielding, degradation, and residual strength of elements.

4. MODELING AND ANALYSIS OF BUILDINGS

A **15-storey RC building** (30m × 25m plan, 3m floor height) was analyzed using **pushover analysis** in SAP2000 to assess seismic performance with various **shear wall configurations**.

For all storeys from **Base to S-14**, the **column and beam sizes** remain consistent:

- **Column Size**: 1000 mm × 1200 mm
- **Beam Size**: 200 mm × 650 mm
- Density of concrete: 25 KN/m3
- Density of brick masonry: 20 KN/m3
- Slab thickness: 180 mm
- Wall thickness: 200 mm

This uniformity simplifies modeling and ensures consistent vertical load-bearing capacity across all floors.

Model Types:

- **Type 1**: No shear wall (basic model).
- **Types 2–6**: Different shear wall placements (e.g., ends, corners, center, middle).

Material & Loading Details:

- Columns: M45 concrete, Beams/Slabs: M25.
- Seismic Zone: II (IS 1893:2002), with R = 3, Importance Factor = 1.
- Loads: Dead, live, floor finish, and earthquake loads applied.

Pushover Setup:

- Default hinges (M3 for beams, PMM for columns) per FEMA/ATC.
- Two push cases analyzed: one with static loads, one with seismic load in X-direction.

This setup enables performance comparison across models, focusing on **lateral load resistance** and **energy absorption capacity** based on shear wall positioning.

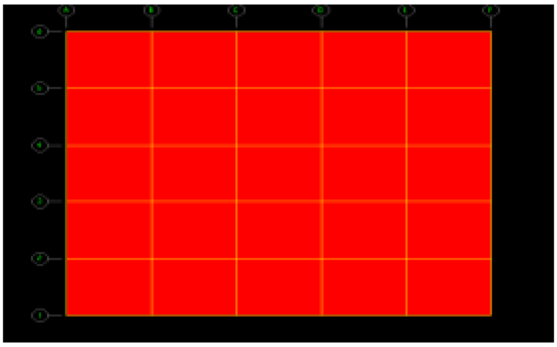

Fig.4.1: Plan of Model 1

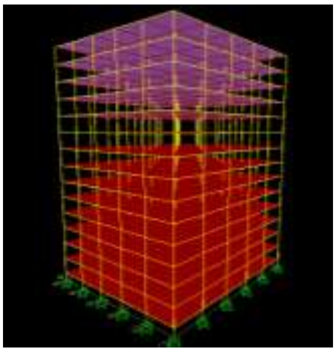

Fig.4.2: 3D View of Model 1

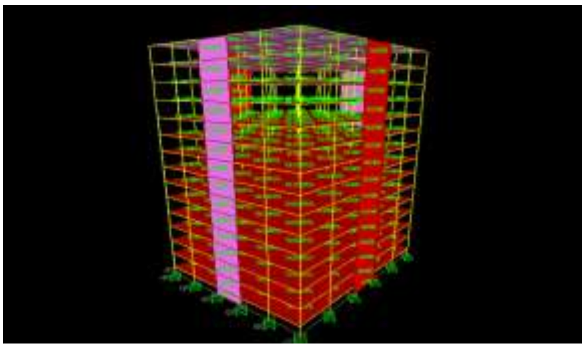

Fig.4.1: End Centers of the Building

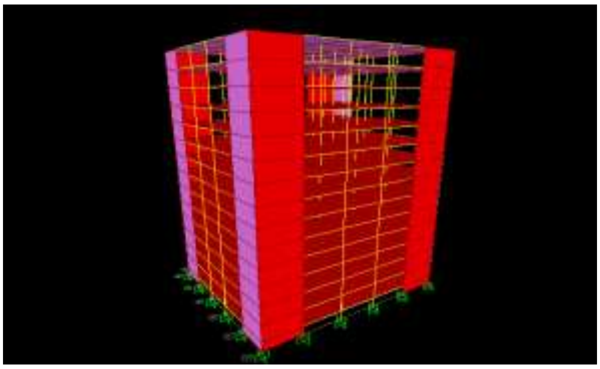

Fig.4.2: End Corner of the Building

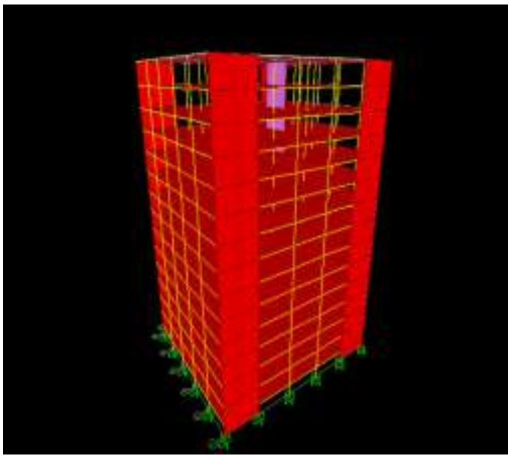

Fig.4.1: Top Ends and Middle of the Building

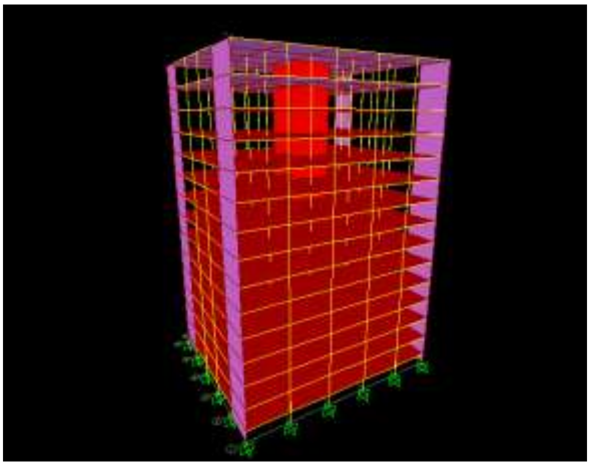

Fig.4.2: shear walls at side ends and middle of the building

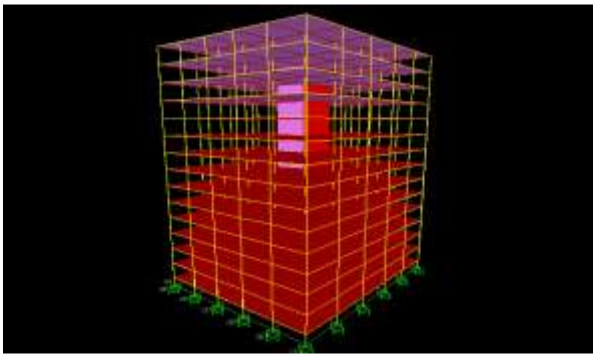

Fig.4.2: 3D View Line Type Shear Walls at Centre of the Building

5. RESULTS AND DISCUSSIONTS

5.1 Pushover Curves

The pushover curves for all six structural models were developed by plotting base shear (Y-axis) against roof displacement (X-axis). These curves provide critical insights into the seismic performance of the buildings under incremental lateral loads.

5.2 Ultimate Base Shear and Ductility

Ductility is a key indicator of a structure's ability to undergo large deformations without failure. It is defined as the ratio of the displacement at failure to the displacement at yield:

Table 5.1: Summary of Ultimate Base Shear and Ductility Ratios

Model Type	Model Description	Ultimate Base Shear (kN)	Displacement at Failure (mm)	Displacement at Yield (mm)	Ductility Ratio (μ)
Type 1	Basic Model	9800	1760	200	8.80
Type 2	Shear Wall Model	33400	765	136	5.63
Type 3	Shear Wall Model	88000	660	184.8	3.57
Type 4	Shear Wall Model	41280	657	175.2	12.25
Type 5	Shear Wall Model	17280	405	145	9.00
Type 6	Shear Wall Model	87000	924	229	4.03

5.3 Capacity Spectrum Analysis

The capacity spectrum method assesses structural performance by comparing demand and capacity curves. Hinges formed sequentially, progressing from initial elastic stages (A–B) to ultimate collapse (Beyond E).

Table 5.2: Capacity Spectrum Performance Summary

Model Type	Performance Point Base Shear (kN)	Displacement (mm)	Performance Level
Type 1	9282.47	237	Immediate Occupancy to Life Safety (IO–LS)
Type 2	14050.19	219	IO–LS
Type 3	25908.34	161	B–IO (Below Immediate Occupancy)
Type 4	17775.89	201	IO–LS
Type 5	11314.10	175	IO–LS
Type 6	23319.03	182	IO–LS

5.4 Displacement Comparison

Displacement analysis shows that **Model Type 1** experienced the **maximum displacement (1.7399 m)**, while **Model Type 5** exhibited the **minimum (0.4104 m)**, attributed to higher stiffness and lower dynam ic response.

Table 5.3: Displacement analysis

Model Type	Displacement (m)
Type 1	1.7399
Type 2	0.7695
Type 3	0.6599
Type 4	0.6615
Type 5	0.4105
Type 6	0.9305

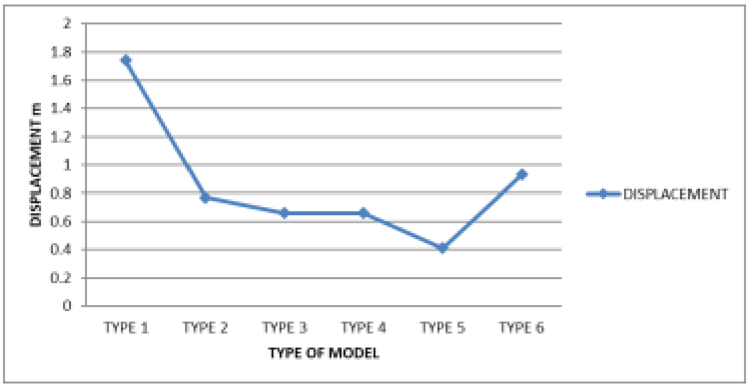

Fig.5.1: Displacement Graph

5.5 Time Period and Frequency Analysis

The natural time period (T) and corresponding frequency (f) were analyzed for all models:

- **Type 1** had the **longest time period (1.515 s)** and **lowest frequency (0.66 Hz)** – indicating greater flexibility and mass.
- **Type 3** had the **shortest time period (1.019 s)** and **highest frequency (0.98 Hz)** – indicating greater stiffness.

Representative Data:

Table 5.3: Time period

Mode	T (Type 1)	T (Type 3)	f (Type 1)	f (Type 3)
1	1.515	1.019	0.659	0.981
2	1.487	1.015	0.672	0.985
3	1.285	0.602	0.778	1.661

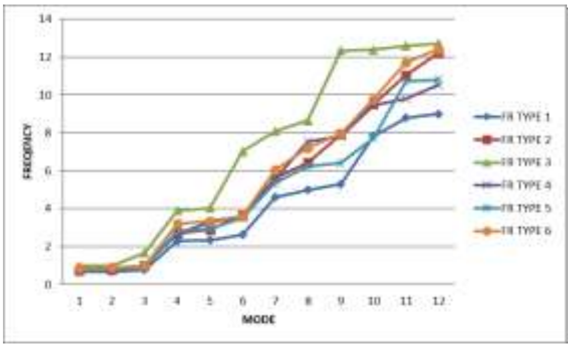

Fig.5.2: Frequency Graph

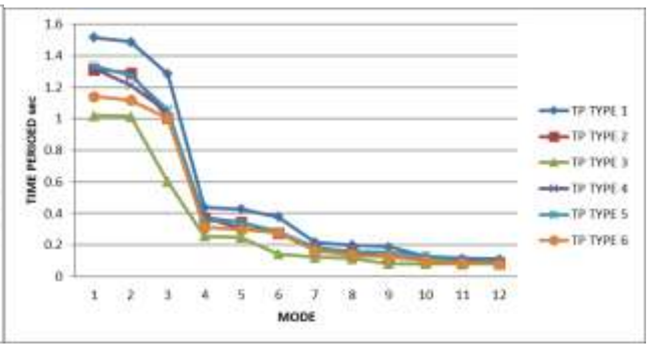

Fig.5.3: Time Period Graph

5.6 Base Reaction (Story Shear)

Story shear is the sum of lateral forces acting above a given story level. Results indicate:

- **Maximum base shear**: Type 1 (178987.5 kN)
- **Minimum base shear**: Type 4 (60103.39 kN)

Table 5.4: Storey shear

Model Type	Story Shear (kN)
Type 1	178987.5
Type 2	74107.22
Type 3	71596.32
Type 4	60103.39
Type 5	69486.5
Type 6	167805

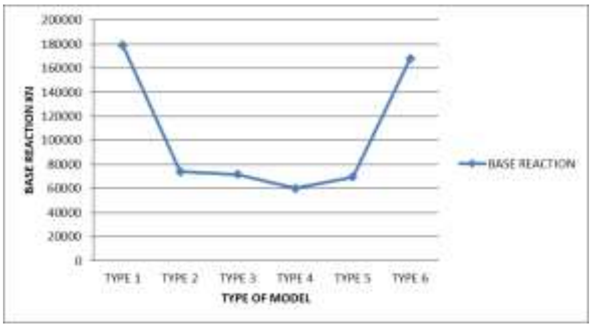

Fig.5.4: Base Reaction Graph

6. CONCLUSIONS AND FUTURE SCOPE OF WORK

6.1 Conclusions

The present study investigates the seismic performance of reinforced concrete buildings by examining the effect of different shear wall locations. The study utilizes **pushover analysis** to evaluate the nonlinear behavior of structures under lateral seismic forces.

The analysis focused on key response parameters, including base shear, displacement, ductility, capacity spectrum, hinge formation, time period, frequency, and base reactions. All models were configured with consistent structural arrangements to isolate the impact of shear wall placement on structural behavior. The key findings are summarized below:

6.1.1 Performance Comparison: Shear Wall Models vs. Basic Model

a) Time Period and Frequency

- **Time Period**: Maximum in **Type 1 (basic model)**, indicating greater flexibility and mass; minimum in **Type 3**, denoting higher stiffness.
- **Frequency**: Inversely related to time period. The maximum frequency is observed in **Type 3**, and the minimum in **Type 1**.
- Conclusion: **Model Type 3** exhibits the most favorable dynamic characteristics in terms of stiffness and seismic responsiveness.

b) Displacement

- **Maximum displacement**: Found in **Type 1 model**.
- **Minimum displacement**: Observed in **Type 5 model**, due to increased structural stiffness and reduced velocity and acceleration responses.
- The reduced displacements suggest that **Type 5 configuration** offers superior stability and human comfort.

c) Base Reaction (Storey Shear)

- **Highest storey shear**: Observed in **Type 1**.
- **Lowest storey shear**: Recorded in **Type 4**.
- The use of shear walls significantly reduces lateral displacements and storey shears, demonstrating their **cost-effectiveness and structural efficiency** in high-rise buildings.
- Proper **positioning and sizing of shear walls** is critical; incorrect placement can lead to uneven force distribution.
- When **adequately dimensioned and correctly located**, shear walls absorb a major portion of lateral seismic forces.

d) Hinges and Structural Performance

- The progression of plastic hinges through Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) stages reflects realistic damage states.
- Column hinges were effectively limited, suggesting that **shear wall models preserve column integrity** better than the basic model.

6.2 Future Scope of Work

While this study demonstrates the advantages of shear wall implementation, future research can expand upon these findings in several ways:

1. **Incorporation of Different Shear Wall Materials**: Investigating alternatives such as **geopolymer concrete**, **steel-plate walls**, or **composite materials** for enhanced sustainability and strength.
2. **Dynamic Time History Analysis**: Employing **real ground motion records** to supplement pushover analysis and validate performance under actual earthquake conditions.
3. **Irregular Building Configurations**: Extending analysis to **plan and vertical irregularities** to better represent real-world structures.
4. **Soil-Structure Interaction (SSI)**: Evaluating the effect of **foundation and subsoil behavior** on the seismic performance of shear wall systems.

5. **Cost-Benefit Analysis**: Assessing the **economic implications** of different shear wall configurations to determine the most **cost-effective seismic design solutions**.
6. **High-Rise and Complex Structures**: Analyzing **tall and mixed-use buildings** with complex load paths and architectural features.

7. References

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