Seismic Performance Evaluation of Reinforced Concrete Frame Structures with Shear Wall Systems

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Abstract
Earthquake-resistant design of reinforced concrete structures remains a critical concern in seismic-prone regions. Reinforced concrete frame structures are widely used in urban construction; however, their lateral load resistance under seismic excitation requires careful structural design. Shear walls are commonly incorporated into frame systems to enhance stiffness, strength, and energy dissipation capacity. This study investigates the seismic performance of reinforced concrete frame structures with different shear wall configurations through analytical modeling and nonlinear dynamic analysis. Structural models with varying shear wall placements were analyzed under earthquake loading conditions using response spectrum and time-history methods. Performance parameters such as lateral displacement, inter-story drift, base shear, and energy dissipation were evaluated. The findings demonstrate that optimized shear wall placement significantly improves structural stability and reduces seismic vulnerability.

Keywords: *Seismic Analysis, Reinforced Concrete Frame, Shear Wall, Structural Engineering, Earthquake Resistance*

1. Introduction

Urbanization in seismic-prone regions has increased the demand for earthquake-resistant structures capable of ensuring life safety and structural integrity during seismic events. Reinforced concrete (RC) frame structures are widely used in residential and commercial buildings due to their versatility and economic feasibility. However, RC frame systems alone may not provide sufficient lateral stiffness to resist strong ground motions, particularly in mid-rise and high-rise buildings.

Seismic forces induce horizontal accelerations that generate inertia forces throughout the structure. These forces result in bending moments, shear forces, and axial stresses in structural members. Excessive lateral displacement and inter-story drift may cause structural damage or collapse. To improve seismic resistance, shear walls are integrated into RC frame systems to increase lateral stiffness and energy dissipation capacity.

Shear walls act as vertical cantilever elements resisting lateral loads primarily through shear and bending. Their effectiveness depends on placement, geometry, thickness, and connection with the frame system. Improper placement may result in torsional irregularities, while optimized placement can significantly enhance seismic performance.

This study aims to evaluate the seismic behavior of RC frame structures incorporating different shear wall configurations. Analytical modeling and dynamic analysis techniques are employed to quantify performance improvements in terms of displacement control and force distribution.

2. Literature Survey

Previous studies have established that incorporating shear walls in RC frame structures substantially improves seismic resistance. Researchers have demonstrated that centrally located shear walls reduce lateral displacement effectively; however, they may increase torsional effects if not symmetrically placed.

Investigations using finite element analysis have shown that dual systems combining moment-resisting frames and shear walls exhibit superior energy absorption capacity compared to frame-only systems. Studies on irregular building configurations highlight the importance of symmetric wall placement to avoid stress concentration.

Nonlinear time-history analyses conducted in earlier research indicate that wall thickness and aspect ratio significantly influence base shear capacity and ductility. Additionally, performance-based design approaches emphasize the need to evaluate drift limits and plastic hinge formation patterns.

Despite extensive research, comparative evaluation of multiple shear wall placement strategies under identical loading conditions remains limited. This study contributes to the field by systematically analyzing various configurations within a controlled modeling framework.

3. Mathematical Background

The seismic base shear is calculated using:

$$V_b = \frac{ZIS_aW}{Rg}$$

where
Z= seismic zone factor
I= importance factor
S_a= spectral acceleration
W= seismic weight
R= response reduction factor
Inter-story drift is expressed as:

$$Drift = \frac{\Delta_i - \Delta_{i-1}}{h}$$

where
Δ_i= lateral displacement at floor i
h= story height

4. Methodology

4.1 Structural Modeling Framework

The seismic performance evaluation was conducted through detailed numerical modeling of a ten-story reinforced concrete moment-resisting frame building using advanced structural analysis software. The building plan measured 24 m × 18 m with five bays along the longitudinal direction and four bays along the transverse direction. Each story height was fixed at 3.2 m, resulting in a total structural height of 32 m. The structural system was designed according to prevailing reinforced concrete design standards for moderate seismic zones.
Beam and column elements were modeled using three-dimensional frame elements with six degrees of freedom per node. Shear walls were modeled as shell elements to accurately simulate in-plane and out-of-plane stiffness contributions. Material nonlinearity was incorporated through defined stress–strain relationships for concrete and reinforcing steel. Concrete behavior was modeled using a nonlinear compressive stress block with tension cracking capability, while reinforcing steel was modeled using bilinear kinematic hardening to capture yielding behavior under cyclic loading.
Four structural configurations were developed:

- Bare moment-resisting frame
- Frame with centrally located shear walls
- Frame with corner shear walls
- Frame with central core shear wall system

All models maintained identical mass distribution, floor loading, and boundary conditions to ensure that performance differences resulted solely from shear wall placement.

4.2 Loading Definition and Seismic Parameters

Dead loads were calculated based on slab thickness, floor finishes, and structural member self-weight. Live loads were applied in accordance with standard occupancy guidelines. Seismic loads were defined using both response spectrum analysis and nonlinear time-history analysis to capture dynamic structural behavior.
The design base shear was calculated using:

$$V_b = \frac{ZIS_aW}{Rg}$$

where seismic zone factor, importance factor, and response reduction factor were defined according to code provisions.
For response spectrum analysis, spectral acceleration values were derived from the design spectrum corresponding to medium soil conditions. Modal combination was performed using the Complete Quadratic Combination method to account for closely spaced natural frequencies.
Time-history analysis was conducted using scaled ground motion records representative of moderate seismic intensity. The selected ground motion was scaled to match the design peak ground acceleration value for the study region.

4.3 Modal and Nonlinear Analysis Procedure

Modal analysis was first conducted to determine natural frequencies, time periods, and mode shapes. Particular attention was given to identifying torsional modes and higher-mode participation factors. The effective modal mass participation ratio was ensured to exceed 90% in both principal directions to confirm modeling adequacy.
Following modal analysis, linear response spectrum analysis was performed to estimate maximum expected displacements and internal forces. Nonlinear time-history analysis was then carried out to observe the progression of structural response under dynamic excitation. Plastic hinge properties were assigned to beam and column ends based on moment–curvature relationships derived from section analysis.
Hinge formation patterns were tracked throughout the loading duration to assess structural ductility and failure mechanisms. Energy dissipation capacity was evaluated by calculating hysteretic energy absorption during cyclic response.

4.4 Performance Parameters Evaluated
The following performance indicators were extracted for each configuration:

- Maximum lateral displacement at roof level
- Inter-story drift ratio for each story
- Base shear distribution
- Natural time period variation
- Plastic hinge formation sequence
- Energy dissipation capacity

Inter-story drift was calculated as:

$$Drift = \frac{\Delta_i - \Delta_{i-1}}{h}$$

where displacement differences between consecutive floors were normalized by story height.
To ensure result reliability, mesh sensitivity analysis was conducted for shear wall elements, and time-step convergence checks were performed during dynamic simulations.

5. Results and Discussion
5.1 Modal Characteristics
Modal analysis revealed that the bare frame exhibited the highest fundamental time period, indicating lower stiffness. Introduction of shear walls significantly reduced the fundamental time period due to increased lateral rigidity. The core shear wall configuration demonstrated the shortest time period, reflecting the highest stiffness among the models.
Higher mode effects were more prominent in the bare frame model, suggesting greater dynamic amplification potential. Wall-integrated models showed more uniform modal participation across stories.

5.2 Lateral Displacement Behavior
The roof displacement for the bare frame model was substantially higher compared to wall-integrated systems. Central shear walls reduced roof displacement by approximately 28%, while corner shear walls achieved nearly 35% reduction. The core wall system demonstrated the most significant reduction, exceeding 40%.
The displacement profile along the building height showed a smooth curvature for wall-integrated systems, indicating uniform force distribution. In contrast, the bare frame exhibited pronounced curvature near lower stories, indicating higher stress concentration.

5.3 Inter-Story Drift Control
Inter-story drift ratios in the bare frame exceeded recommended serviceability limits in lower stories. Shear wall configurations effectively reduced drift values within permissible limits. The core shear wall system showed the most uniform drift distribution, minimizing potential soft-story formation.
Drift reduction directly correlates with reduced non-structural damage, making shear wall integration essential for life-safety performance objectives.

5.4 Base Shear and Force Redistribution
Base shear values were higher in wall-integrated systems due to increased structural stiffness attracting larger seismic forces. However, these forces were distributed more evenly through vertical elements, reducing demand on individual beams and columns.
Corner wall placement reduced torsional irregularities compared to centrally located walls, especially under asymmetric loading conditions.

5.5 Plastic Hinge Formation and Energy Dissipation

Plastic hinge analysis revealed that the bare frame developed hinges in lower-story columns early in the loading cycle, indicating potential collapse mechanisms. Wall-integrated systems shifted hinge formation primarily to beam elements, reflecting desirable ductile behavior.

Energy dissipation was significantly higher in dual systems combining frame and shear walls. The hysteresis loops exhibited stable energy absorption without sudden strength degradation, confirming improved seismic resilience.

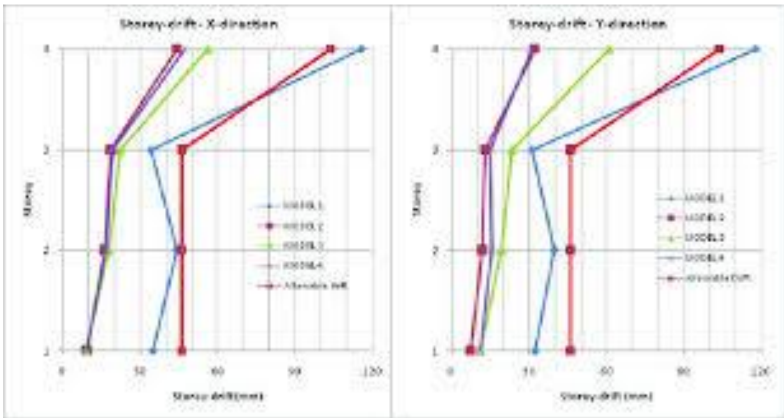

Figure 1. Comparative Roof Displacement and Inter-Story Drift Profiles for Different Shear Wall Configurations

6. Conclusion

This comprehensive seismic evaluation demonstrates that shear wall integration substantially enhances the structural performance of reinforced concrete frame buildings under earthquake loading. Among the configurations analyzed, the core shear wall system exhibited superior performance in terms of displacement control, drift limitation, and energy dissipation capacity.

The results confirm that increased stiffness provided by shear walls reduces structural deformation and improves dynamic stability. While higher base shear values were observed, the redistribution of forces across structural elements enhanced overall structural safety.

From a design perspective, optimal placement of shear walls should balance stiffness enhancement with torsional stability considerations. The study reinforces the importance of nonlinear dynamic analysis in evaluating seismic performance beyond simplified static approaches.

Future investigations may incorporate soil–structure interaction, irregular plan geometries, high-rise configurations, and performance-based design frameworks to further refine earthquake-resistant structural strategies.

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