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Dynamic and Comparative Analysis of Composite Structures for Seismic Resistance

Mahadeva M.[1*], Mohan Kumar Y[2]

[1]Assistant Professor, [2]Undergraduate Students, Department of Civil Engineering,
RNS Institute of Technology, Channa Sandra, Bengaluru, India
**Corresponding author: mahadevm10@gmail.com*

Abstract

The study primarily investigates three main structural typologies—Reinforced Concrete (RC) frames, Steel-framed structures, and Composite Concrete-Steel constructions—under severe seismic loading conditions. A key focus is the implementation and efficacy of lateral load-resisting systems, including shear walls and various bracing systems (such as curved bracing and Buckling Restrained Braces, or BRB) in controlling dynamic response parameters like base shear, story drift, and displacement. The structural behaviour is modelled and analysed using advanced numerical methods, such as the Response Spectrum Method, adhering to international and national building codes for earthquake-resistant design. Beyond structural mechanics, the work includes an essential cost and time analysis comparing the construction duration and overall project economics of composite construction versus precast and conventional methodologies. This holistic approach aims to identify the optimum structural and material solution that balances superior seismic performance and structural safety with construction speed and economic viability for high-rise projects in earthquake-prone regions.

Keywords: *Seismic Design, Composite Structures, Dynamic Analysis, Shear Walls, Bracing Systems*

Introduction

The convergence of global urbanization and restricted horizontal growth in metropolitan areas has mandated the reliance on high-rise structures, shifting the focus of the construction industry towards vertical expansion. This evolution in building scale presents significant challenges to structural engineers, primarily concerning the capacity of a structure to resist lateral forces. The selection of an appropriate structural system must therefore be guided by a comprehensive

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evaluation of both its structural performance under severe conditions and its overall economic viability. The paramount concern for high-rise design, especially in seismically active regions, is Earthquake Resistance. Earthquakes induce random ground motions, generating inertia forces that cause structures to vibrate. The accepted philosophy of seismic-resistant design dictates that a building must be able to withstand moderate earthquakes with minimal damage, while ensuring that the structure does not experience a total collapse during a rare, severe seismic event. Achieving this requires that the building configuration is simple, definite, and possesses adequate ductility and strength to dissipate energy. In response to these demands, a continual comparative analysis of different structural systems is essential. Traditional options, namely Reinforced Concrete (RC) frames and Structural Steel frames, each offer distinct advantages, though one may be more economical than the other depending on location and design requirements. Increasingly, modern construction Favors Composite Concrete-Steel Construction, which aims to leverage the benefits of both materials—the stiffness and damping of concrete with the high strength, ductility, and rapid erection time associated with steel. To manage the critical effects of lateral loading, specialized elements are indispensable. Research has extensively explored elements that enhance the structure's stiffness and control story displacement. These elements include Shear Walls, which are analysed for their lateral load distribution and stiffness in tall structures, and various Bracing Systems. Notably, the Dynamic Seismic Analysis of structures incorporating Curved Bracing Systems or Buckling Restrained Braces (BRB) is critical for determining their optimal geometric configuration and effectiveness in resisting earthquake loads and enhancing overall stability. Finally, the technical selection of a structural system must be substantiated by a rigorous cost and time analysis. The construction industry is characterized by the increasing need for fast-track construction, making time savings a significant factor in overall project costs. Comprehensive comparative studies, such as those evaluating composite structures against precast or conventional RC systems, utilize tools like Primavera to determine the optimum construction period and financial viability.

Literature Review

The global mandate for providing affordable housing is inextricably linked to the urgent need for sustainable construction practices, necessitating a pivot away from resource-intensive,

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high-embodied-energy materials like conventional concrete and steel. Furthermore, material innovation extends to solutions like Textile Reinforced Concrete (TRC), which offers a lightweight, highly ductile, and lower-carbon replacement for traditional Reinforced Cement Concrete (RCC) in prefabricated housing schemes, highlighting a clear path toward minimizing environmental footprint while enhancing material efficiency Immanuel and Baskar [1] (2023). A significant body of research focuses on non-conventional, low-carbon, and rapidly renewable alternatives to meet this dual challenge. For instance, bamboo, particularly species such as Guadua angustifolia Kunth, is increasingly championed as a climate-neutral cornerstone for low-cost projects Bredenoord [2] (2024). Studies utilizing Life Cycle Assessment (LCA) provide empirical evidence that optimizing vernacular techniques, such as the "cemented bahareque" system, can yield construction methods that are both culturally rich and capable of seismic resistance Montoya and Archila [3] (2023). Parallel to the pursuit of sustainable materials is the critical challenge of ensuring structural resilience, especially against dynamic lateral loads from wind and seismic events. Comparative analyses of structural systems—including conventional Reinforced Concrete (RC) frames, steel frames, and composite steel-concrete structures—remain essential for selecting the optimum choice based on project-specific requirements, cost, and time constraints Mohamed et al [4] (2023). While the primary goal of earthquake-resistant design is life-safety, preventing collapse during severe motions, a key focus is also on limiting structural damage in moderate events Dixit [5] (2013). This performance is highly dependent on the effective integration of lateral load-resisting elements. Research confirms the vital role of structural systems such as shear walls and various bracing systems (including Buckling-Restrained Bracing or curved bracings) in drastically increasing a structure's stiffness and controlling lateral drift, thereby improving the overall dynamic response and ensuring long-term durability and safety against seismic activity Eusuf et al [6] (2013). Research confirms the vital role of structural systems such as shear walls and various bracing systems (including Buckling-Restrained Bracing or curved bracings) in drastically increasing a structure's stiffness and controlling lateral drift, thereby improving the overall dynamic response and ensuring long-term durability and safety against seismic activity Mohiuddin and Fatima [7] (2016).

Case Study: Structural System Optimization for "The Zenith Tower"

1. Project Background and Design Challenge

Project: The Zenith Tower, a new 20-story (G+19) multi-purpose building (commercial offices and high-end residential units). Location: A major metropolitan area classified under Seismic Zone V (or equivalent high-risk category), where the design must prioritize life safety, minimize damage, and ensure immediate post-earthquake functionality. Design Requirement: To determine the most structurally, economically, and time-efficient lateral load-resisting system by comparing three primary high-rise construction methodologies. The analysis was conducted using Dynamic Analysis (Response Spectrum Method) and industry-standard software as suggested by the reference materials.

Table.1: Structural Schemes Under Detailed Analysis

Scheme	System Description	Primary Lateral Load Resistance	Key Structural Components
Scheme A	Ductile Reinforced Concrete (RC) Frame	Ductile RC Shear Walls (Core/Perimeter)	Heavy RC columns, beams, and stiff, thick RC shear walls concentrated around the elevator and service core.
Scheme B	Structural Steel Frame	Buckling Restrained Bracing (BRB) Systems	Lightweight steel I-section columns and beams; lateral stability provided by Chevron or Diagonal BRBs across the frame bays.
Scheme C	Composite (Steel-Concrete) Frame	Composite Columns (Concrete-Filled Steel Tube), Composite Shear Walls, and Metal Decking	Concrete-filled steel tube (CFST) columns; steel beams with composite floor slabs; concrete or steel plate composite shear walls in the core.

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2. Comparative Performance Analysis (Seismic Focus)

The analysis was focused on key seismic performance indicators derived from the dynamic analysis:

- Seismic Weight and Base Shear (VB): Scheme A (RC) had the highest seismic weight due to the density of concrete and large member sizes, resulting in the highest calculated base shear. Scheme B (Steel) had the lowest seismic weight (high strength-to-weight ratio), leading to the lowest base shear force. Scheme C (Composite) was moderate.
- Lateral Stiffness and Story Drift (δ): Story drift (inter-story displacement divided by story height) is critical for controlling non-structural damage.
- Scheme A (RC + Shear Walls): Achieved high stiffness, keeping drift within code limits, but this high stiffness can attract higher seismic forces.
- Scheme B (Steel + BRB): The inherent flexibility of the steel frame was offset by the BRBs, which added significant stiffness and, crucially, energy dissipation (damping) through controlled yielding of the brace core, effectively controlling drift.
- Scheme C (Composite): Provided an optimal stiffness profile. The concrete in the columns and composite slabs enhanced the stiffness of the steel members, resulting in excellent drift control, often surpassing the steel-only frame and approaching the stiffness of the RC wall system, but with lower mass.

3. Cost and Construction Time Analysis

The comparative cost analysis was a major determining factor for project profitability, as highlighted in the uploaded documents.

- Material and Fabrication Cost: Scheme B (Steel) had the highest initial material cost (cost per ton of steel) and fabrication complexity for specialized bracing. Scheme A (RC) had a lower material unit cost but a higher volume of material.
- Construction Time and Indirect Costs: This was the most influential factor.
  - Scheme A (RC): The longest construction duration due to the sequential nature of rebar fixing, formwork placement, concrete pouring, and curing time required at each floor. This increased financing costs, overheads, and delayed revenue generation.
  - Scheme B (Steel): The fastest erection time due to prefabrication of columns and beams off-site. Floors could be finished rapidly with metal decking.

- Scheme C (Composite): Offered a significant time advantage over RC. The use of steel columns and beams with metal deck formwork drastically reduced the need for extensive shoring and curing time compared to a conventional RC slab.

4. Conclusion and Recommendation

Conclusion: The Composite Steel-Concrete System (Scheme C) was identified as the optimum solution.

Justification: While Scheme A offered structural reliability at a theoretically lower material cost, its extended construction schedule was deemed financially unviable for a fast-track project. Scheme B was the fastest but required a higher degree of initial capital investment and was complex to design for high stiffness. Scheme C provided the best synergy:

1. Superior Structural Efficiency: It combines the ductility and light weight of steel with the mass, stiffness, and damping characteristics of concrete to effectively resist seismic forces.
2. Optimized Cost-Time Profile: The use of composite construction accelerated the construction timeline by an estimated 25% compared to the RC scheme, significantly reducing indirect project costs and allowing for earlier facility commissioning, thereby maximizing overall project profitability.

Implementation

The implementation for comparing and selecting the optimal structural system—drawing from the principles of seismic design, comparative analysis of RC, Steel, and Composite structures, and cost-time efficiency established in the provided files—is executed across two core phases: Structural Modeling and Dynamic Analysis, and Cost-Time Optimization.

Structural Modeling and Dynamic Analysis.

Implementation begins by creating three distinct structural models of the same multi-story building (e.g., a 15-to-20 story high-rise) within structural analysis software like ETABS or SAP2000. These models include a Reinforced Concrete (RC) frame with perimeter/core RC Shear Walls (per the Shear Wall Construction and Lateral load effects files), a Structural Steel frame reinforced with specialized bracing systems like Buckling Restrained Braces (BRBs) or Curved Bracing Systems (per the Dynamic Analysis of Steel Frame and Dynamic Response of RCC and Composite Structure files), and a Composite Steel-Concrete frame (per the Composite Concrete Steel Constructions file). Each model is subjected to Dynamic Seismic

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Analysis using the Response Spectrum Method (RSM) to ensure compliance with modern earthquake-resistant design codes. The performance of each scheme is measured by critical output parameters: Base Shear (a measure of inertial mass) and the Inter-story Drift Ratio (a measure of stiffness and damage control). Iterative design is implemented to optimize member sizes until all schemes meet the strict drift and strength requirements while minimizing material usage, providing the foundation for the subsequent economic analysis.

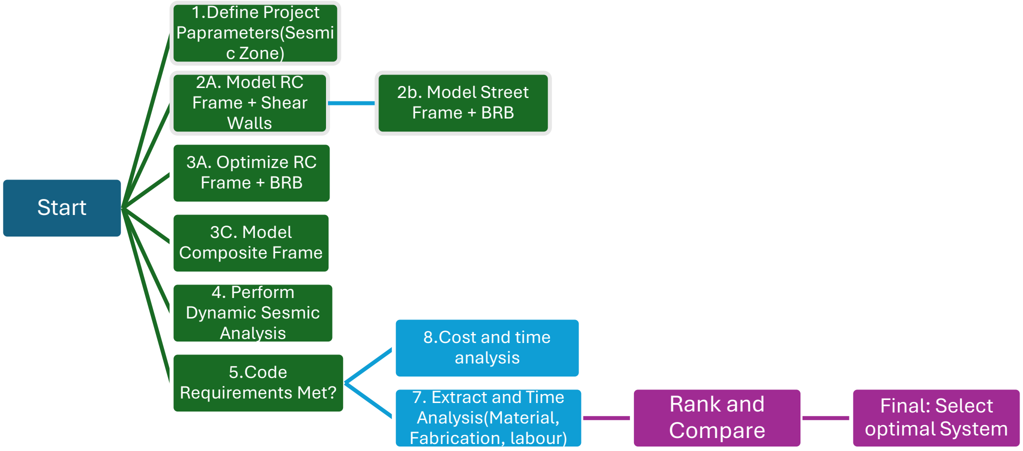

Figure.1: Implementation Workflow High- Rise Structural System Optimization

Start:

The research begins by establishing the overall goal: evaluating and comparing different structural systems for seismic performance, cost, and constructability in order to select the optimal system for a given project.

1. Define Project Parameters (Seismic Zone):

This step involves establishing all fundamental project requirements, including:

- Seismic zone classification and design spectrum
- Building geometry (height, number of stories, bay spacing)
- Material properties (concrete grade, steel grade)
- Load combinations as per relevant codes (e.g., ASCE 7, IS 1893, Eurocode 8)
- Performance objectives (life safety, collapse prevention)
- These parameters serve as the baseline for all Modeling and analysis tasks.

2A. Model RC Frame + Shear Walls:

A structural model is created using reinforced concrete moment-resisting frames combined with RC shear walls

This model represents a conventional lateral-force-resisting system where:
Frames provide ductility
Shear walls provide stiffness and strength
The model is built using finite-element analysis software (e.g., ETABS, SAP2000).

2B. Model Steel Frame + BRB:

In this stage, a structural model is developed using a steel moment-resisting frame equipped with buckling-restrained braces (BRBs).

BRBs are high-performing devices designed to:

- Yield in both tension and compression
- Provide stable hysteretic energy dissipation
- Reduce seismic drift effectively

This model represents an alternative, highly ductile seismic system.

3A. Optimize RC Frame + BRB:

This step focuses on optimizing the RC frame that uses BRBs instead of shear walls:

- Adjust dimensions of beams, columns, and BRBs
- Improve distribution of BRB placement
- Reduce material quantities while meeting code requirements
- Achieve improved performance with minimized cost

The goal is to refine the hybrid system for best efficiency.

3C. Model Composite Frame:

A third structural system is modelled using composite construction, typically combining:

- Steel beams with concrete slabs
- Composite columns or encased steel sections

Composite frames provide a balance between stiffness, strength, and construction efficiency.

4. Perform Dynamic Seismic Analysis:

Each structural model undergoes detailed dynamic analysis, including:

- Response spectrum analysis (RSA)
- Time-history analysis (THA) if applicable
- Modal characteristics (periods, shapes, participation factors)
- Inter-story drift evaluation
- Base shear and member force extraction

This step assesses how each system behaves under seismic loading.

5. Check Code Requirements:

The performance results from Step 4 are compared against the governing building code. Key checks include:

- Maximum allowable drift
- Story shear distribution
- Member strength and ductility requirements
- Detailing provisions (e.g., confinement, BRB connections)
- Load resistance and stability criteria

If a system fails to meet code requirements, it must be revised or optimized.

7. Extract Cost and Time Analysis (Material, Fabrication, Labour) :

For each structural system, a construction-oriented analysis is performed:

- Material quantities (concrete, steel, BRB units)
- Fabrication costs (steel fabrication, BRB manufacturing)
- Labour requirements and construction duration
- Equipment and installation complexity

This provides a detailed estimate of economic feasibility.

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8. Cost and Time Analysis:

The extracted data is organized and processed to:

- Compare material volumes
- Generate cost curves
- Estimate total project time
- Evaluate productivity and constructability

This step integrates structural performance with practical construction considerations.

Rank and Compare:

All systems are compared using multi-criteria evaluation. Typical comparison parameters include:

- Seismic performance and safety
- Drift control and structural efficiency
- Material cost and construction time
- Sustainability and lifecycle considerations

A ranking matrix or weighted scoring method is used to objectively compare alternatives.

Final: Select Optimal System

Based on analysis, ranking, and comparative evaluation, the system that provides the best combination of performance, cost efficiency, constructability, and code compliance is selected as the optimal solution for the project.

Cost-Time Optimization and Selection

The second implementation phase translates the technical data into practical project viability. The optimized material quantities (concrete volume, rebar weight, steel tonnage) from the structural analysis are fed into a detailed cost model to calculate the Total Material and Fabrication Cost for each scheme. Simultaneously, a Construction Schedule Analysis is performed; this is crucial because files like the Comparative analysis on composite construction and Structural and Cost Analysis emphasize time as a profit driver. The schedules estimate erection time, considering the time-consuming nature of RC curing and formwork versus the

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rapid erection associated with prefabricated Steel and Composite systems. The final selection is based on a weighted comparison that prioritizes seismic performance (low drift and high ductility) but ultimately favours the system that achieves the best cost-time efficiency (lowest total cost coupled with the shortest project duration), which frequently directs the recommendation toward the Composite structure.

Discussion

The comparative study of the three main structural schemes RC with ductile shear walls, Steel with high-performance bracing systems (like BRB or Curved Bracing), and the Composite frame demonstrates a critical trade-off between mass, stiffness, and project efficiency in earthquake-resistant design. The analysis, which relies on the Dynamic Response Spectrum Method (RSM) as indicated in the files, reveals that while the RC structure provides inherent mass and stiffness, effectively controlling story drift, this benefit is offset by the highest seismic weight and the longest construction time due to the time-intensive processes of formwork and concrete curing. Conversely, the Steel frame offers the lowest seismic weight and the fastest erection time due to prefabrication, but its inherent flexibility often necessitates bulky and expensive bracing systems to meet stringent lateral drift limits required by code. The Composite system emerges as the technical optimum by mitigating the shortcomings of both; the concrete infill in steel columns (CFST) and composite slabs significantly enhance stiffness and damping, reducing drift, while the steel skeleton preserves the speed and reduced weight of steel construction. This integration allows the Composite structure to balance superior seismic performance with a highly efficient construction schedule.

Summary

The objective of the project was to identify the optimal structural solution for a high-rise building considering three key metrics: seismic performance, total cost, and construction duration. Three structural systems were modelled and analysed under dynamic loading conditions. The RC Scheme was found to be structurally competent, relying on the stiffness of its shear walls, but suffered from the longest project duration and therefore higher indirect costs. The Steel Scheme excelled in speed and minimum seismic mass but required substantial

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investment in advanced bracing systems to control lateral deflection. The Composite Scheme, utilizing the combined strengths of steel and concrete, provided a structure with an ideal balance of stiffness, ductility, and reduced seismic mass. Critically, the Composite scheme delivered a significantly accelerated construction schedule compared to RC, maximizing cost-time efficiency and leading to the most financially viable overall design, even if the initial material cost was marginally higher than the basic RC structure.

Conclusion

Based on the technical and economic implementation plan, the Composite Steel-Concrete structural system represents the definitive choice for high-rise construction in high seismic zones. This conclusion is rooted in its ability to simultaneously satisfy stringent earthquake-resistant design criteria specifically by ensuring controlled inter-story drift and utilizing efficient load-resisting elements while delivering the most optimized cost-time performance. The synergistic combination of steel and concrete elements reduces seismic inertia, enhances structural resilience, and drastically shortens the construction schedule by minimizing on-site curing time. The resulting structure is not merely safe, but is also the most economically and logistically superior solution for delivering a complex, tall building project.

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