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Analysis of Design Challenges and Optimization Measures for High-Rise Buildings

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Abstract. High-rise buildings, serving as core carriers of intensive urban development in modern cities, present particularly complex design challenges due to their vertical scale. Design flaws directly threaten both building safety and durability. This paper systematically analyzes critical issues in the design phase of high-rise buildings from an architectural perspective, focusing on the root causes of inadequate wind and seismic resistance performance. It thoroughly examines the necessity of structural optimization and proposes specific optimization measures, such as refining building form and installing damping and energy dissipation devices, to significantly enhance structural stability. The research demonstrates that scientific design optimization can effectively mitigate wind-induced vibration effects, satisfy seismic design requirements, and provide both theoretical support and practical pathways for the safety and sustainability of high-rise buildings.

Keywords: High-rise buildings; Structural design; Problem analysis; Optimization measures.

1. Introduction

Residential building structural design is a core aspect of engineering project implementation, with its safety and reliability directly determining the building's full lifecycle quality and failure risk threshold. Currently, with accelerated urbanization and increasingly scarce urban residential land, the number of high-rise buildings has surged. This intensifies their structural complexity and the difficulty of design and construction, placing higher demands on the scientific soundness and safety of structural design [1].

However, the increasing complexity and scale of high-rise building structural design also bring numerous challenges. The design process often encounters difficulties in selecting and optimizing structural systems [2], making it hard to accurately predict structural responses under extreme loads (such as strong winds and earthquakes). Simultaneously, inadequate coordination between design schemes and actual construction, coupled with insufficient foresight of potential risks, leads to frequent changes during construction and escalating costs. Furthermore, multi-objective synergy—balancing building function, aesthetics, structural safety, and economic viability—is challenging, necessitating more systematic and refined design optimization methods to resolve conflicts and enhance overall benefits.

This study focuses on the problem analysis and systematic optimization of high-rise building structural design. Its core content includes: in-depth verification of design scheme feasibility and implementation risks, accurate prediction of potential construction issues; aiming to establish more robust design optimization measures to eliminate hidden risks and resolve structural hazards. This research is dedicated to exploring optimal design solutions that balance building quality and economic efficiency. Through meticulous selection of building materials and cost control, it thoroughly verifies the feasibility of design solutions and associated implementation risks, accurately anticipating potential construction problems. The ultimate goal is to establish more comprehensive design optimization measures to eliminate latent risks and address structural deficiencies.

2. Significance and issues of High-Rise Building Structural Optimization

2.1. Significance of High-Rise Building Structural Optimization

2.1.1. Enhancing Safety Performance

For high-rise buildings, optimizing the structural design system is of great significance. A scientific structural design can effectively control costs, achieving significant economic benefits, while also improving building functional attributes and yielding high-performance outcomes [3]. This section analyzes the significance of optimizing residential building structural design from the perspectives of safety and economic benefits.

2.1.2. Achieving Economic Benefits

Through structural optimization, while integrating economic and quality considerations, it is possible to control costs by effectively reducing material consumption. The CITIC Tower project serves as an excellent exemplar of super high-rise engineering, demonstrating good practices. By adopting the equivalent strength principle for reinforcing bars in pile foundations, as illustrated in the table, the use of HRB500 steel bars results in an approximate 21% reduction in steel consumption within the pile foundation scope compared to HRB400 steel bars, amounting to 1115.95 tons. This is estimated to save 480 million RMB in costs. This example clearly demonstrates that optimizing structural materials can effectively control costs and enhance material utilization efficiency, leading to significant economic benefits (Table 1).

Table 1. Reinforcement Bar Arrangement for Pile Foundations

Pile No.	Pile Diameter, mm	Pile length, m	Quntity Units	HRB500 Steel Weight	HRB400 Steel Weight
Foudation Pile P1	1000	40.1	398	1693.47	2144.22
Foudation Pile P2	1200	44.6	403	1935.51	2451.95
Foudation Pile P3	1000	26.1	40	68.09	86.21
Static Load Test Pile TP1	1000	40.1	4	21.24	26.9
Static Load Test Pile TP2	1200	44.6	2	10.5	13.3
Static Load Test Pile TP2a	1200	54.6	3	15.76	19.95
Test Anchor Pile AP1	1000	40.1	22	165.06	208.99
Test Anchor Pile AP2	1200	44.6	12	146.32	185.27
Test Anchor Pile AP2a	1200	54.6	12	135.69	171.81

2.2. The issues of High-Rise Building Structural Optimization

2.2.1. High-Rise Building Design Issues

The design and construction of high-rise buildings are not only reflections of technical prowess but also subject to stringent regulations and guided by future development philosophies. Norms such as the "Code for Seismic Design of Buildings" (GB50011) and "Technical Specification for Concrete Structures of Tall Buildings" (JGJ3) impose strict requirements for special reviews of super-tall buildings [4, 5]. Chinese codes exhibit uniqueness in load combinations and seismic measures; for instance, they consider load effect combinations dominated by vertical seismic action, as well as those dominated by wind loads. Here, we analyze existing problems in high-rise building design from the perspectives of wind resistance and seismic resistance.

2.2.2. Wind Resistance Design Issues

High-rise buildings, due to their relatively low stiffness and long natural vibration periods, are more sensitive to dynamic loads from pulsating wind, making them prone to significant vibrations. As building height surpasses the critical point of 200m, the loads on the structure increase non-linearly—wind loads become the dominant force, escalating according to a height-exponent law. Failure to enhance the wind resistance of high-rise buildings can lead to accelerated fatigue crack propagation, reducing service life and ultimately affecting the overall performance of the high-rise structure. Some buildings have even experienced dynamic instability and structural collapse due to a lack of adequate wind resistance measures.

2.2.3. Seismic Design Issues

High-rise buildings' structural characteristics—extreme height, long natural vibration periods, and relatively low stiffness—present unique challenges during earthquakes. Due to varying intensities of seismic influence across different regions of China, seismic design standards for high-rise buildings also differ regionally. A limitation in the design of some high-rise buildings is the absence of multi-tiered seismic resistance measures, leading to low seismic reliability, which can result in structural collapse and severe damage to non-structural components.

3. Optimization Measures for High-Rise Building Structural Design

3.1. Optimization of Wind and Seismic Resistance Levels

3.1.1. Wind Load Optimization

Wind resistance can be optimized by refining the external form of high-rise buildings to reduce wind resistance. Under a vertical load W, the axial force of a building structure with height H is $N = WH$. Adopting a streamlined building form effectively reduces wind resistance and consequently wind loads. Streamlined designs guide airflow smoothly around the building, minimizing eddies and pressure differentials, thereby reducing wind forces on the structure [6]. The Shanghai Tower in China, for instance, features a unique twisted and tapering profile. This design disrupts the regularity of vortex shedding, successfully reducing wind loads by 24% and significantly improving the building's wind resistance performance [7]. In high-rise building design, enhancing the quality and grade of raw materials can improve the bearing capacity of the foundation's supporting layer. The widespread use of high-strength concrete (HSC) and high-strength steel in high-rise building design allows for smaller structural member sections, thereby gaining more usable space and reducing structural self-weight. Composite materials, like Carbon Fiber Reinforced Polymers (CFRP), exhibit promising application potential in structural reinforcement and specific components due to their lightweight, high-strength, and corrosion-resistant properties [8]. Concurrently, the grade of raw materials such as sand and gravel should be improved, and additional components should be incorporated to enhance the overall structural stability [9], thus boosting wind resistance.

3.1.2. Seismic Resistance Level Optimization

The "Code for Seismic Design of Buildings" explicitly states that China's seismic design standard for residential building structures is "no damage in minor earthquakes, repairable in moderate earthquakes, and no collapse in major earthquakes." Seismic resistance can be optimized through energy dissipation and damping design. The design of energy dissipation and damping devices adopts a combination of Buckling-Restrained Braces (BRBs) and viscous dampers. Arranging BRB components around the core tube can provide substantial damping force even under small displacements. The placement of damping devices fully considers the structural deformation characteristics and stress patterns, achieving an effective increase in structural damping ratio [10]. Modern super high-rise buildings increasingly employ Tuned Mass Dampers (TMDs), such as the massive golden steel sphere at the top of Taipei 101. Furthermore, active and semi-active control systems, like active bracing and viscous dampers, can more intelligently dissipate and absorb vibration energy, enhancing structural performance and seismic resistance [11]. Simultaneously, during the seismic design process, to enhance the seismic effect of buildings, designers should incorporate a dual lateral-force-resisting structural system. In this system, the first line of defense consists of shear walls or seismic walls, and the second line of defense comprises coupling beams. During earthquakes, coupling beams can withstand the impact of initial seismic pulses, thus protecting the building structure [12, 13].

4. Conclusion

This paper first analyzes common problems prevalent in high-rise building design, with particular attention to seismic and wind resistance issues.

(1) Currently, high-rise buildings, due to their low structural stiffness and long natural vibration periods, face dual challenges in terms of wind and seismic resistance: For buildings over 200 meters, a dramatic increase in wind loads can lead to fatigue damage; Seismic design exhibits weaknesses such as a single line of defense and vulnerability of non-structural components.

(2) Subsequently, by analyzing the importance of high-rise buildings in core design concepts, this study discusses solutions for insufficient wind and seismic resistance in high-rise buildings.

(3) Future research can consider integrating streamlined external forms to reduce wind resistance, using high-strength materials to improve stiffness, and incorporating energy dissipation and damping devices combined with a "shear wall + coupling beam" dual-defense system. This will ultimately achieve a dual optimization of safety and economic benefits.

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