Mechanical Performance and Selection Study of High-Rise and Super High-Rise Building Structural Systems

Ziyi Zhao *

School of Civil Engineering, Tianjin University, Tianjin, China

* Corresponding Author Email: 1056011484@qq.com

Abstract. This study focuses on the structural systems of high-rise and super high-rise buildings, with particular emphasis on their mechanical performance and selection. The structural design of high-rise buildings is of paramount importance, requiring safety and stability to be ensured. This paper discusses various structural types, including steel structures, reinforced concrete structures, and their combination structures. Additionally, it analyzes the characteristics and applicability of various vertical load-bearing structures such as frames, shear walls, frame-shear wall systems, cores, and mega-structures, considering their performance under different heights and geographic conditions. Finally, it presents the maximum applicable heights for each structural system, emphasizing the significance of selection in meeting urban demands.

Keywords: High-rise buildings; Frame structures; Shear wall structures; Core structures; Mega-structures; Maximum applicable height.

1. Introduction

The structural design of high-rise buildings is a critical field, demanding the assurance of stability and safety while considering sustainability, efficiency, and flexibility. This paper focuses on the structural systems of high-rise and super high-rise buildings, with particular emphasis on their mechanical performance and selection, providing a solid foundation for design to meet urban demands. Firstly, we will introduce the principles of high-rise building structural design, emphasizing stability and safety. Then, we will discuss various structural types, such as steel structures and reinforced concrete structures, analyzing their advantages and disadvantages. Next, we will delve into various vertical load-bearing structures, including frames, shear walls, frame-shear wall systems, cores, and mega-structures, considering their applicability and performance under different conditions. Finally, we will present the maximum applicable heights for each structural system, offering guidance for engineering decisions.

2. Basic Principles of High-Rise Building Structural Design

The primary objective of high-rise building structural design is to ensure the stability and safety of the structure. This involves understanding the various external loads that the building will be subjected to and effectively resisting these loads. Structural stability is the foremost principle in the design of high-rise buildings, requiring compliance with safety standards and building codes in material and component selection as well as structural system design [1].

3. Structural Selection for High-Rise Buildings

3.1. Types of Structural Systems for High-Rise Buildings

High-rise buildings offer a wide range of structural choices, depending on design requirements, geographical conditions, and building purposes. These choices can be categorized based on material types, including steel structures, reinforced concrete structures, and combinations of steel and reinforced concrete.

3.1.1. Steel Structures

The use of steel structures in high-rise buildings offers several distinctive characteristics and advantages, making it a common choice. Steel possesses excellent strength and rigidity while being relatively lightweight, enabling it to bear significant loads in high-rise constructions, reducing the building's self-weight burden and lowering foundation requirements. The elastic and plastic deformation capacity of steel allows it to absorb and dissipate energy generated by seismic events, providing structural stability and generally exhibiting good seismic performance during earthquakes. Its lightweight nature and strength enable high-rise buildings to incorporate more open designs with larger spans, reducing the number of columns and beams, thus providing more flexible interior space layouts. However, considerations such as corrosion, maintenance, and fire safety need to be addressed when using steel structures [2].

3.1.2. Reinforced Concrete Structures

Concrete structures possess outstanding compressive strength, allowing them to support the vertical loads required by high-rise buildings. Additionally, they typically have longer service lives, withstanding years of use and environmental exposure. Concrete is a non-combustible material, providing excellent fire resistance in case of fires. While concrete structures offer numerous advantages, factors such as the weight of concrete and limited flexibility need to be considered. Furthermore, maintenance and repairs of concrete structures may incur higher costs [3].

3.1.3. Combination of Steel and Reinforced Concrete Structures

By combining the advantages of steel and concrete structures and mitigating their respective shortcomings, it is possible to employ various structural combinations based on specific project requirements. This can include:

(1) Steel-Concrete Composite Method: Embedding steel elements, such as steel profiles or steel pipes, within concrete components creates a steel-concrete composite structure (rigid re-bar). This approach fully utilizes the rigidity and fire resistance of external concrete while utilizing steel to reduce the dimensions of structural elements and enhance seismic performance. Currently, this method is widely applied in engineering. Another approach involves pouring concrete into steel tubes to increase the structural rigidity [4].

(2) Mixed Structural Combinations: In a mixed structural system, a portion of the lateral force-resisting structure utilizes steel, while another part uses reinforced concrete. Typically, reinforced concrete is employed to construct cores or shear walls, while steel is used to create framework beams and columns.

These structural choices should be made based on a careful evaluation of the specific project requirements and design objectives.

3.2. Selection of Vertical Load-Bearing Structural Systems for High-Rise Buildings

3.2.1. Frame Structural System

The frame structural system is a rigid planar structure composed of beams and columns, designed to withstand vertical and horizontal loads of a building. Its characteristics and performance are as follows:

(1)Structural Composition: The frame structural system is comprised of beams and columns, forming a rigid planar structural system. It is responsible for bearing the vertical and lateral actions of the building, and is therefore known as a frame structural system. From a construction perspective, frame structures can be cast as a whole or can be assembled in prefabricated or unitized form.

(2)Advantages and Disadvantages of the Structure: Frame structures have several advantages, including flexible building layout and ease of interior partitioning. Construction is relatively straightforward, and when designed properly, the structure exhibits good plastic deformation capacity. If lightweight infill materials are used for exterior walls, it can reduce the structural self-weight.

However, frame structures also have some disadvantages:

They exhibit relatively low lateral stiffness, leading to weaker resistance to lateral deformation, limiting the building height.

The lateral displacement under horizontal loads is characterized by: Lateral displacement caused by beam-column bending. Lateral displacement caused by axial deformation of columns.

Under horizontal loads, frame structures are subject to moments, shear forces, and axial forces. Under the influence of moments, beam-columns bend, creating inflection points, resulting in overall lateral displacement of the frame (as shown in Figure 1). Beam-columns at the bottom of the frame structure experience greater internal forces, leading to larger inter-story deformations, while those at the top experience smaller inter-story deformations. The overall deformation of the frame structure exhibits shear-type characteristics.

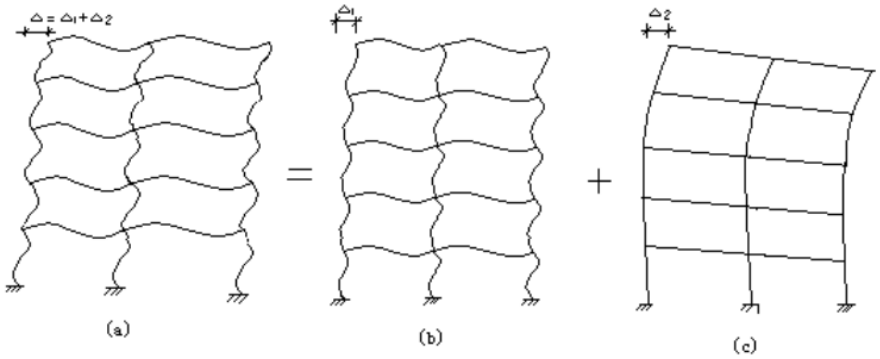


Fig 1. Lateral deformation of frame structure.

3.2.2. Shear Wall Structural System

Shear walls, also known as concrete walls, possess excellent resistance to horizontal loads. In reinforced concrete structures, robust reinforced concrete walls are often employed as the primary components resisting lateral forces, forming shear wall structural systems. In China's"code for seismic design of buildings" (GB50011-2001) [5], this system is referred to as seismic walls and is also commonly known as structural walls.

Displacement Characteristics:

When shear walls have a relatively large height-to-width ratio, they exhibit cantilever wall characteristics, primarily subject to bending. Under horizontal loads, the lateral deformation of shear walls is characterized by bending deformation, with inter-story displacement gradually increasing from the bottom to the top (as shown in Figure 2). To overcome the limitations of shear wall structures, such as small spacing and significant self-weight, developments such as framed shear wall structures (with large open spaces at the base) and skip-level shear wall structures have been introduced.

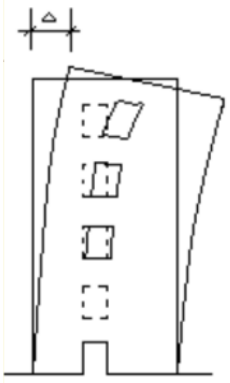


Fig 2. Shear wall deformation.

Small short-leg shear walls perform relatively poorly in bending, shear, and torsion and are, therefore, not suitable for high-rise building structures. Their seismic performance is limited, and their application in earthquake-prone regions is restricted. Hence, in high-rise building structures, shear wall structures consisting entirely of small short-leg shear walls should be avoided.

3.2.3. Frame-Shear Wall (Frame-Core) Structural System

(1) The frame-shear wall structural system is a structural system with dual lateral resistance capabilities. In this structure, some shear walls are incorporated within the frame structure and arranged in the form of a core, known as the frame-core structural system. The core offers significantly improved load-bearing capacity, lateral stiffness, and resistance to torsion compared to a single shear wall. The core can be utilized for purposes such as elevators, stairwells, and vertical pipes.

Lateral Force Resistance in the Frame-Shear Wall Structural System: In this structural system, shear walls possess high stiffness and primarily bear a substantial portion of horizontal shear (typically 80% to 90% of the total horizontal shear), while the frame exhibits lower stiffness, carrying a relatively smaller portion of horizontal shear. The primary role of the frame is to support the majority of vertical loads, providing more usable space.

Combination of Frame and Shear Wall Characteristics: The frame-shear wall structure combines the flexibility and ductility of frame structures with the rigidity and load-bearing capacity of shear wall structures. These characteristics complement each other, jointly resisting horizontal loads. Therefore, this structural system is widely employed in high-rise buildings, with applicable heights comparable to shear wall structures (suitable for constructing buildings with 30 to 40 stories).

3.3. Displacement Characteristics of the Frame-Shear Wall Structure

Under the action of horizontal loads, frame structures exhibit shear-type deformation, while shear walls exhibit bending-type deformation. Due to the interaction of floor slabs and coupling beams, the deformation of the frame and shear walls is coordinated, with lateral (horizontal) displacements equal at the same elevation. At the bottom of the structure, the lateral displacement of the frame is reduced, while at the top, the lateral displacement of the shear wall is reduced, resulting in a lateral displacement curve with a flexural-shear shape. Inter-story displacement is evenly distributed along the building's height, presenting an "S" shape displacement curve, thereby improving the seismic performance of the frame structure and shear wall structure (as shown in Figure 3).

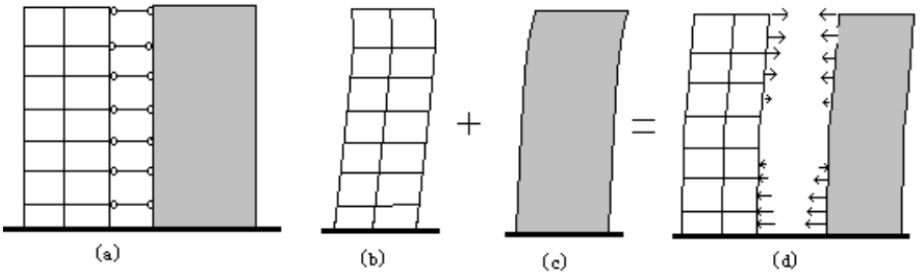


Fig 3. Cooperative operation of frame-shear wall structure under lateral forces.

3.4. Arrangement of the Frame-Shear Wall Structure

Number and Position of Shear Walls: The number and positioning of shear walls have a significant impact on the structure's performance. Increasing the number of shear walls can enhance structural stiffness and reduce lateral deformations. However, with increasing building height, the requirement for the structural lateral resistance parameter $\sum EI$ also increases. Under seismic actions, lateral displacements of the structure are inversely proportional to $\sum EI$. Therefore, increasing the number of shear walls and the bending stiffness $\sum EI$ may increase seismic effects. General experience indicates that a doubling of $\sum EI$ results in a 20% increase in seismic effects. Hence, excessively increasing the number of shear walls may lead to uneconomical design. The appropriate number of shear walls should ensure that inter-story displacements do not exceed the specified limits in the code, while also balancing the shear carried by the frame.

Arrangement of Shear Walls and Frames: In the frame-shear wall structure, shear walls and frames can only resist lateral forces within their respective planes. Therefore, in seismic design, shear walls

should be arranged in both of the structure's principal axis directions to ensure the capacity to resist lateral forces in different directions. This bi-directional arrangement helps improve the overall stability and seismic performance of the structure. The number and position of shear walls should be determined based on the building's specific requirements, height, and geographical conditions to achieve optimal structural performance.

4. Core Structural System

The core structural system is a three-dimensional force system that surrounds the frame or shear walls into a cylindrical shape to effectively resist lateral forces. In high-rise building structures, especially when advanced fortification requirements, large numbers of stories, and great heights need to be met, traditional planar lateral force structures such as frames and shear walls may not meet the structural force requirements. Therefore, the use of core structures has become a common choice.

Core structures comprise several basic forms, including thin-walled cores (solid-core), framed cores (composed of closely spaced columns and deep beams), and truss cores (composed of trusses). These basic core forms can be combined in different ways to create more core structure types, such as framed cores, nested cores, bundled cores (composite cores), and multiple cores. These core structures offer better performance and adaptability in resisting lateral forces for high-rise buildings (as shown in Figure 4).

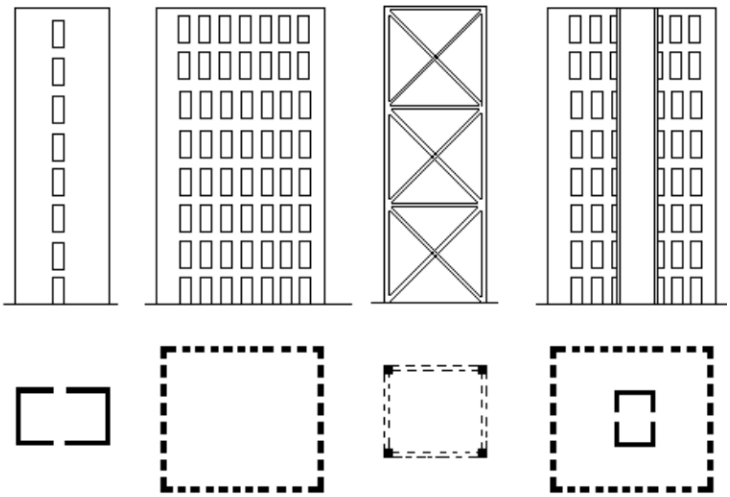


Fig 4. Core structural system types.

4.1. Framed Core Structure

The framed core consists of window openings arranged on the walls of the solid core, surrounded by closely spaced columns and high-stiffness window-sill beams, forming a densely spaced column and deep-beam frame. Unlike traditional frame structures, the framed core is a three-dimensional structure suitable for taller buildings. It can be made of steel, reinforced concrete, or hybrid structures and is often combined with an inner core to form a nested core structure.

4.2. Truss Core Structure

The truss core structure is composed of sparse columns, shallow beams, and diagonal struts, arranged around the building to form the truss core structure. This structure has greater stiffness and is suitable for taller buildings, typically constructed from steel.

4.3. Nested Core Structure

The nested core structure utilizes the outer core as a framed core and then places an inner core in the center. The inner core typically houses service facilities such as stairwells, elevators, and pipes, working together to resist lateral forces, offering good resistance to horizontal shear forces.

4.4. Bundled Core Structure

The bundled core structure refers to multiple cores arranged together to form a bundled structure, working collectively to resist lateral forces. This structural system is suitable for buildings of various plan shapes and configurations.

4.5. Giant Structures

Giant structures typically refer to structures with large column cross-sections. These columns can be arranged around the perimeter or use rectangular or H-shaped solid-section columns, connected with large-span beams or trusses, forming a giant frame structure.

In reinforced concrete giant frame structures, there are two common forms:

(1) Giant frame structures consisting only of primary and secondary frames.

(2) Giant frame-core structure consisting of peripheral primary and secondary frames and a central core. This structure utilizes the core as columns, connecting the cores every few floors with large beams to create a giant frame. Although it still falls under the category of frame structures, the significant size of the beams and column cross-sections gives the giant frame a considerably higher lateral stiffness than conventional frames, making it suitable for taller buildings.

One advantage of giant structures is that, under the premise of a regular layout in the primary giant structures, they allow for changes in architectural layout and spatial arrangements on different floors, creating various architectural plans and spaces, thus achieving the penetration of large openings in the structure (see Figure 5).

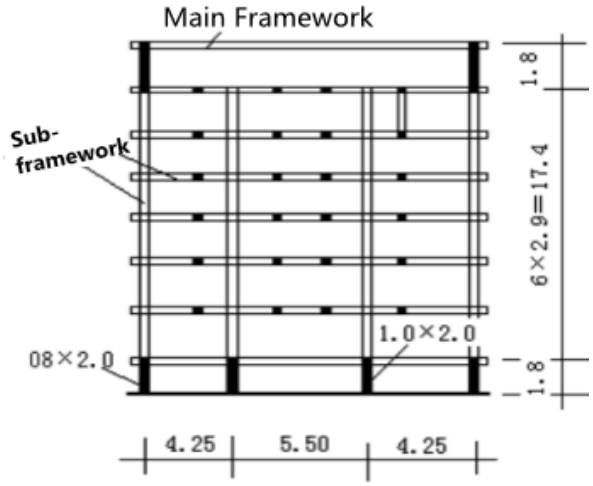


Fig 5. Cross-Section of Giant Structure Sub-frame.

4.6. Maximum Applicable Height of Various Vertical Load-Bearing Structures (i.e., Applicable Height of Lateral Load-Resistant Structural Systems or the Range of Applicability of Structures)

The maximum applicable height depends on multiple factors, including building height, seismic design requirements, and seismic design intensity. These factors are used to determine the most suitable and economical structural system that fully utilizes the structural performance and maximizes the use of building materials. Chinese standards specify the maximum applicable heights for various structural systems. These heights represent the maximum height at which a building can be constructed while complying with national design codes, regulations, and design requirements (see Table 1). Building height is defined as the distance from the outdoor ground to the top of the main roof panel and does not include local protruding roof components, such as water tanks, elevator machine rooms, and framework, among others. If the building height exceeds the specified maximum height, the structural design must incorporate effective reinforcement measures and should be supported by reliable theoretical justification or specialized research and analysis [8].

Table 1. Maximum Heights Applicable to Steel and Concrete Structures.

structural system	Non-seismic design	Seismic hazard level			
		Level 6	Level 7	Level 8	Level 9
Steel frame-concrete core	210	200	160	120	70
Steel-concrete frame-reinforced concrete core	240	220	190	150	70

5. Conclusion

In this study, we conducted an in-depth examination of the structural systems for high-rise and super-tall buildings, with a particular focus on their mechanical performance and selection. We discussed various structural types, including steel structures, reinforced concrete structures, and their combination structures. Each of these structural types has its advantages and limitations, and our research serves as a guide for selecting the appropriate structural type for specific building projects.

Furthermore, we delved into various vertical load-bearing structures, including frame structures, shear wall structures, frame-shear wall structures, cylindrical structures, and giant structures. We examined their range of applicability and performance characteristics to assist engineers in choosing the most suitable structure based on the specific project requirements.

References

[1] “Study on the Mechanical Performance of Super High-rise Building Structural Systems” by Xu Zanyun, Jujiang Construction Group Co., Ltd - 2014

[2] JGJ32010, “Technical Specification for Concrete Structures of High-rise Buildings”[S]

[3] JGJ99-98, “Technical Specification for Steel Structures of High-rise Civil Buildings”[S]

[4] YB9082-2006, “Technical Specification for Steel and Concrete Composite Structures”[S]

[5] GB50011-2010, “Code for Seismic Design of Buildings”[S]

[6] “Development of High-rise and Super High-rise Building Structures in China” by Duan Benshuo, Yang Ke, and Cheng Guangfu, published in “Sichuan Cement”-2018

[7] “Hysteretic Performance Study of Restrained Buckling-Restrained Braced Frame Structures with Irregular Columns”by Qiao Jinli, Ding Dong, Wang Xiaowei, Meng Qiujie, and Ling Xiaoxiao, published in "Industrial Construction”-2018

[8] “Research on the Construction Process and Structural Mechanical Performance of Super High-rise Mixed Structures” by Yang Huijie, Tianjin University - 2018