Analysis of Structural System Selection and Seismic Design for Modern Residential Buildings in China

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Abstract. This article aims to research and review the selection of structural systems and seismic design for modern residential buildings in China. Through a comprehensive analysis of the current research status and practical experience, it explores the application and suitable scenarios of different structural systems in seismic design. The goal of this paper is to provide guidance for architects, engineers, and researchers and promote the development of structural system selection and seismic design for modern residential buildings in China. Conclusions are drawn and future research and practice are discussed through comparison and analysis. This article will discuss the selection of structural systems in building construction, ensuring the quality of construction projects, and guaranteeing the stability and safety of the structures.

Keywords: residential buildings, aseismic structure, seismic design, structural system selection.

1. Introduction

China, as one of the most populous countries in the world, is undergoing rapid urbanization and economic development. Urban construction and residential building projects play a crucial role in this process. With the rapid growth of urban populations and the acceleration of urbanization, higher requirements for the safety and stability of residential buildings have been raised. Especially in regions prone to earthquakes in China, seismic design is one of the most important design requirements that must receive full attention and application to ensure that buildings can withstand earthquakes without damage (small tremors), be repairable in moderate earthquakes, and not collapse in large earthquakes.

In modern urban construction projects, different structural systems have unique advantages and suitable scenarios. Common structural systems such as masonry structures, frame structures, shear wall structures, frame-shear wall structures, and cylindrical structures all have their own characteristics. Their properties and applicability in seismic design vary. By analyzing and comparing these structural systems, a better understanding of their characteristics can be gained, leading to the selection of the most suitable structural system for practical engineering, ensuring that buildings have the best seismic performance in the face of natural disasters such as earthquakes.

2. Requirements and Principles of Structural Design in China

The requirements and principles of structural design in China aim to ensure that buildings have sufficient seismic resistance to protect people's lives and property safety under the influence of earthquakes. According to China's architectural design code, seismic design requirements can be summarized as follows:

Resilience to Small Tremors: The structure should remain stable without damage or severe deformation under small tremors. To achieve this, the building's structure needs to have sufficient stiffness and strength to withstand horizontal forces and vertical loads caused by earthquakes while maintaining structural integrity [1].

Repairability in Moderate Earthquakes: In moderate seismic conditions, the building's structure may experience some degree of damage but should retain a certain residual load-bearing capacity to ensure safe evacuation and emergency repair. Seismic design mandates the careful evaluation of

seismic performance indicators and structural repairability to guarantee the restoration of a structure for service following a moderate earthquake through repair and maintenance.

Non-collapse during major earthquakes: Preventing complete damage or collapse during major earthquakes involves sustaining a building structure in a minimally stable condition. Seismic design necessitates the implementation of safety measures, including appropriate selection of structural systems, utilization of "strong junctions and weak connections", and installation of energy dissipation devices. These measures mitigate building collapses and minimize injuries resulting from earthquakes.

To meet seismic design requirements, China developed a series of building design codes and technical standards. These codes outline the necessary specifications to ensure building safety during seismic activity. These comprise the Code for Seismic Design of Buildings (GB 50011-2010), the Code for Design of Steel Structures (GB 50017-2017), and the Code for Design of Concrete Structures (GB 50010-2010). These codes detail seismic design principles, methods for calculating loads, and parameters for designing structures to guarantee building safety in the event of an earthquake.

The objective of seismic design for Chinese building structures is to embody the "no damage in small earthquakes, repairable in medium earthquakes, and no collapse in large earthquakes" characteristics. Therefore, it is imperative that buildings adhere to the corresponding building codes and standards, employ suitable structural systems and seismic design techniques, and guarantee sufficient stiffness and strength. Adherence to such design codes can significantly enhance the seismic performance of buildings while also creating a secure living and working environment for individuals.

3. Seismic Design Analysis of Residential Building Structural Systems

3.1. Masonry Structural System

3.1.1 Structural Definition

Masonry is a common structural system of traditional residential construction using brick, stone, or similar materials, built according to common local construction rules. It is widely used in Chinese construction and typically involves using bricks as basic components to form load-bearing elements such as walls and columns.

3.1.2 Structural Characteristics

The characteristics of masonry structures include ease of construction, lower cost, and adaptability to different building forms and layout requirements. However, compared to other structural systems, masonry structures have some limitations in terms of seismic performance, requiring special attention to their seismic design requirements and application scenarios.

3.1.3 Seismic Performance Analysis

The seismic properties of masonry structures are mainly reflected in several aspects. First, masonry structures have relatively low yield stages under seismic forces, meaning they have low elastic deformation capacity and are prone to damage. Second, the overall seismic performance of masonry structures heavily depends on the friction and bond strength between bricks, necessitating high requirements for the connection and bonding strength of the structure. In addition, due to the poor tensile performance of masonry structures, cracking and fracture phenomena are common [2]. Therefore, seismic design requirements need to focus on the following aspects: ensuring that masonry structures have sufficient overall rigidity and strength to withstand the horizontal forces of earthquakes, strengthening the connection between masonry walls and other load-bearing components (such as reinforced concrete structural columns and tie beams), and implementing seismic strengthening measures, such as installing reinforced mesh or using strengthening adhesives in masonry walls, to enhance the seismic capacity of masonry structures.

Masonry structures are mainly suitable for small and medium-sized buildings such as houses, villas, and rural houses (Fig.1 Masonry dwellings in Suzhou). For taller buildings or important public structures, masonry structures are not the first choice, and other structural systems such as frame structures or shear wall systems are preferred to provide stronger seismic performance. Seismic design for masonry structures requires attention to their overall rigidity, connection strength, and seismic strengthening measures. Although masonry structures have relatively poor seismic performance, they can meet buildings' seismic design requirements in the right situations through suitable design and construction measures.



Fig. 1 Suzhou Masonry Houses

3.2. Frame Structural System

3.2.1 Structural Definition

Frame construction is a frequently utilized structure in residential buildings that comprises columns and beams responsible for supporting and transmitting loads. Due to its inherent flexibility, frame structures are well-suited for a diverse range of building designs. In frame structures, columns bear vertical loads as beams sustain horizontal loads, bolstering the frame's rigidity.

3.2.2 Structural Characteristics

Frame structures possess excellent vertical load capacity and effectively bear the weight of multi-story floor slabs. The compact footprint taken up by beams and columns in frame structures renders them apt for erecting buildings with commodious and adaptable internal arrangements, an increasingly prevalent design approach in contemporary residential constructions.

3.2.3 Seismic Performance Analysis

The seismic performance of a frame structure depends on its stiffness, strength, and lateral shear capacity. The beam-column structure gives the frame structure good ductility, allowing it to withstand significant deformations while maintaining its design load carrying capacity. To ensure optimal seismic performance, adequate reinforcement must be incorporated in the design and construction of frame structures to resist lateral forces generated by earthquakes.

Common reinforcement measures for frame structures in seismic design include the use of reinforced concrete shear walls, diagonal bracing, and special connection details. The design concept of "strong junctions, weak connections" is incorporated to enhance their lateral stability and ductility. Proper foundation pit design is essential to prevent excessive damage to the structure during seismic events.

Frame structures are appropriate for different kinds of residential buildings, such as medium to high-rise apartment buildings, and certain office buildings. The seismic performance of frame structures differs based on the particular design and construction methods implemented, and correctly planned and constructed frame structures exhibit exceptional seismic performance, leading to their preference for several cutting-edge construction projects in China.

3.3. Shear Wall Structural System

3.3.1 Structural Definition

A shear wall structural system is a lateral load-resisting system that relies on shear walls to resist shear forces, such as those generated by earthquakes or wind. These shear walls, which are typically constructed using reinforced concrete, are strategically placed throughout the building to ensure its structural integrity and strength. The system's effectiveness is predicated on a logical placement of the shear walls during building design.

3.3.2 Structural Characteristics

Shear wall structures possess a high capacity for lateral shear and demonstrate excellent seismic performance. These structures are particularly fitting for the design of high-rise buildings situated in regions with more frequent seismic activity. Shear walls may consist of core walls sited in the center of the building or of walls situated outside the center.

3.3.3 Seismic Performance Analysis

The seismic performance of a shear wall structure relies on the shear wall's shear capacity. Shear walls are created to displace and deform within design safety limits during an earthquake. This action dissipates energy and inhibits excessive lateral drift or sway. As a result, the controlled deformation preserves the building's stability, reducing structural damage to a minimum.

Seismic design of shear wall structures necessitates a meticulous assessment of wall thickness, reinforcement likings within the wall, reinforcement particulars of the shear wall, and the shear wall layout in the building [3]. Adequate detailing of the connections between the shear walls and other structural components like columns and beams is indispensable to guarantee effective load transfer and distribution during an earthquake.

Shear wall structures are frequently utilized in tall buildings, such as high-rise apartments, offices, and some expansive shopping centers. These structures are reliable options in areas at risk of earthquakes due to their remarkable seismic performance and load-bearing capacity. Nonetheless, a suitable design and construction approach is necessary to optimize the seismic performance of shear wall structures.

3.4. Frame-Shear Wall Structural System

3.4.1 Structural Definition

The frame-shear wall structural system merges the benefits of both frame and shear wall structures, incorporating columns and beams of the same frame structure in conjunction with shear walls that primarily offer lateral shear capacity, thus mutually reinforcing each other.

3.4.2 Structural Characteristics

Frame-shear wall construction offers a well-balanced design approach that merges the adaptable and roomy layout of a frame structure with the impressive shear resistance of a shear wall structure. This composite structural system optimizes the utilization of materials and structural elements for enhanced efficacy and resilience in building design.

3.4.3 Seismic Performance Analysis

Shear walls in frame-shear wall structures exhibit greater shear capacity than pure frame structures. The inclusion of shear walls amplifies the building's lateral strength and lessens the permanent deformation and harm caused by earthquakes. Thus, this structural system can efficiently soak up seismic energy, furnishing a secure and steadfast environment for the building's inhabitants.

The careful selection and strategic placement of shear walls within a building is essential for the seismic design of frame-shear wall structures (Fig. 2 Nanjing Jiangbei New District Building). Engineers must consider various factors, such as the location of core and perimeter shear walls and their interaction with frame members [4]. For proper load transfer, it is crucial to enhance the strength

of the connection and decrease it proportionately in the middle of the connection between the framing members and the shear walls.

Frame shear wall structures can be effectively utilized in a broad spectrum of residential and commercial constructions varying from mid to high-rise buildings. Shear wall structures have gained popularity in modern construction projects, particularly in earthquake-prone regions due to their adaptable layout design and exceptional seismic performance.



Fig. 2 Frame-Shear structure building under construction in Nanjing

3.5. Cylindrical Structural System

3.5.1 Structural Definition

Cylindrical structural systems are a distinctive construction method that employs cylindrical members as the main load-bearing structure. These systems can be classified into two types: solid cylinders and hollow cylinders. A solid cylinder is a cylindrical structure made up of solid members, while a hollow cylinder is composed of a reinforced concrete shell that remains empty inside. To achieve maximum load capacity, the correct form of the cylinder should be selected based on the characteristics of the applied loads. This structural system possesses immense strength and stiffness, and its force distribution between members is adequately reasonable. Consequently, it can efficiently transfer and support loads.

3.5.2 Structural Characteristics

The cylindrical structure boasts continuity and integrity, exhibiting robust rigidity and strength that effectively withstands the earthquake's horizontal load. Furthermore, the even distribution of the load between members creates balance, enhancing the stability and seismic performance of the structure. The cylinder structure system displays robust seismic performance and wind resistance, proving highly suitable for constructing ultra-high-rise buildings with spacious floors and large spans. Moreover, the spatial flexibility of the cylinder structure enables adapting to varied building forms and layouts.

3.5.3 Seismic Performance Analysis

The seismic design of the cylinder structure system requires attention to two aspects. Firstly, it is necessary to ensure that the strength, stiffness, and shear capacity of the silo structure satisfy seismic design requirements. This ensures the safety of the structure during seismic activity. Secondly, the construction process and material characteristics of the cylinder structure must be fully considered to guarantee the structure's integrity and durability.

The cylinder structure system finds its primary application in super high-rise buildings, large-span buildings, and special form buildings. It ensures excellent structural stability and significantly helps resist horizontal loads while reducing structural displacement [5]. Moreover, the unique shape of the cylinder structure allows for customizing the shape and layout of the cylinder to meet the design requirements of diverse building projects.

As a housing structure system, the cylinder structure offers good strength, stiffness, excellent seismic performance, and wind resistance. It enhances the building's aesthetic appeal and can meet the design needs of ultra-high-rise and uniquely shaped buildings.

4. Conclusion

From the point of view of seismic performance, the shear wall structural system excels among the common structural systems, effectively reducing structural displacement deformation through the shear capacity provided by the wall. While the frame structural system may have relatively weaker lateral resistance, its seismic performance can be improved through enhanced connections and node design. The cylindrical structural system, due to its overall integrity and continuity, can effectively resist the horizontal loads induced by earthquakes. In contrast, masonry structures are relatively fragile and exhibit weaker seismic performance [6].

From an economic perspective, frame structural systems offer relatively lower construction complexity and cost control, whereas the shear wall structural system may increase construction complexity and costs due to higher wall arrangement and construction requirements. The cylindrical structural system incurs higher construction and material costs but offers superior space utilization in large-span and high-rise buildings.

Regarding space utilization, frame structural systems are more flexible and suitable for various architectural forms and layout requirements. Shear wall structural systems occupy more space with their walls, potentially imposing restrictions on building use and spatial layout. Cylindrical structural systems offer good space utilization and are suitable for super-tall buildings with large spans and multiple floors.

Each structural system has its advantages and limitations, and the choice of an appropriate structural system requires a comprehensive consideration of engineering requirements, seismic demands, cost-effectiveness, space utilization, and other factors. During the design phase, a comprehensive assessment and decision-making process based on specific circumstances are necessary to ensure the safety, cost-effectiveness, and functionality of the building. In future research and practice, there is a need to explore innovative structural system designs continually to enhance seismic resilience, meet the growing urbanization demands, safeguard people's lives and property, and promote the sustainable development of housing construction in China.

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