Research on Seismic Design Methods for Prefabricated Steel Structures

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Abstract. In recent years, prefabricated structures have developed rapidly. As a subset of prefabricated structures, prefabricated steel structures have received extensive attention. These structures exhibit good performance under earthquake action. The seismic design methods of prefabricated steel structures are studied in this paper. First, it outlines the basic concepts of prefabricated steel structures and discusses their application in contemporary architecture. Then, the seismic design methods of prefabricated steel structures are emphasized deeply, especially for the performance-based seismic designmethod and the key technology in connection design. Finally, the development trend and potential research direction in the field of seismic design of prefabricated steel structures are prospected. The results show that the performance-based seismic design method should be combined with the connection optimization design to ensure the safety, stability and functionality of the structure under earthquake action. This paper aims to provide an effective theoretical reference for the seismic design of prefabricated steel structures.

Keywords: Prefabricated steel structures; Connection design; Seismic design.

1. Introduction

In the domain of contemporary architecture, prefabricated structure has garnered widespread attention due to its efficiency, environmental friendliness, and energy-saving characteristics. The primary advantage of prefabricated structure lies in its abbreviated structure period. As a significant portion of the components is prefabricated in factories, the on-site structure time is substantially reduced, thereby hastening project progress [1]. Furthermore, prefabricated structure ensures the high quality and uniformity of components through factory-based production, mitigating issues arising from environmental fluctuations at structure sites. It also reduces material waste, enhances resource utilization efficiency, and lowers overall structure costs. As a vital component of prefabricated structure, steel structures are renowned for their high strength, lightweight characteristics, rapid structure pace, and commendable seismic performance. These attributes of steel structures have led to their extensive application within prefabricated structure, particularly in large-span buildings, industrial plants, and scenarios requiring swift structure and high flexibility. The integration of steel structures with the rapid structure advantages of prefabricated structure offers a modern, efficient, and sustainable architectural solution [2].

With the acceleration of urbanization and the increase in population density, the seismic performance of buildings has become an important aspect that cannot be ignored in design and construction. Prefabricated steel structures, due to their excellent seismic performance and construction efficiency, are particularly important in construction projects in earthquake-prone areas. The lightweight characteristics and high strength of steel structures enable them to better absorb and dissipate energy under seismic action, reducing structural damage. Furthermore, the prefabricated and modular features of prefabricated steel structures make the structural repair and reconstruction work after an earthquake more rapid and convenient. Therefore, summarizing the seismic design methods for prefabricated steel structures not only helps to enhance the safety and reliability of building structures but also is an important measure to respond to the requirements of sustainable development and to protect the safety of people's lives and property. This paper provides a systematic review of the design philosophy, methods, and practices of seismic design for prefabricated steel structures. It aims to provide references for engineering design and research personnel, in order to promote further development and application of prefabricated steel structures in the field of seismic resistance [3].

2. Overview of Prefabricated Steel Structures

Prefabricated steel structures represent a form of construction that capitalizes on the high strength and lightweight characteristics of steel, while also leveraging the rapid construction advantages of prefabricated building techniques. In this structural system, primary load-bearing components such as beams, columns, and trusses are prefabricated in factories and then transported to the construction site, where they are quickly assembled into a complete structural system using bolt connections, welding, or other mechanical joining methods. Prefabricated steel structures encompass not only traditional steel frame configurations but also composite structures that integrate steel with other materials like concrete and masonry, making them particularly suitable for achieving industrialized building practices and sustainable development [4]. As depicted in Table 1, prefabricated steel structures can be categorized based on their structural systems.

Table 1. Classification and Characteristics of Prefabricated Steel Structural Systems. (Date from: [3, 5]).

No.	Structural System Type	Characteristics	Application Scope
1	Integrated Housing System	Simple structure, easy to disassemble	Temporary housing, offices
2	Modular Structure	Modular buildings that can be constructed rapidly	Social housing or worker dormitories
3	Light Steel Structure System	Suitable for low-rise buildings of 1 to 3 stories	Industrial plants, warehouses, etc.
4	Pure Steel Frame System	Load-bearing frame with beams and columns, good seismic performance, and free internal space division	Multi-story residential buildings
5	Steel Frame-Brace System	Vertical braces added to the steel frame structure to enhance overall stiffness	Multi-story or high-rise buildings
6	Steel Frame-Core Tube System	Composed of cast-in-place concrete structure and external steel frame structure, high lateral stiffness	Newly constructed high-rise and super high-rise buildings
7	Steel Frame-Shear Wall System	Shear walls interspersed within parts of the structure to resist horizontal loads of the building	Multi-story and high-rise structures

3. Seismic Design Methods

The seismic performance objectives for prefabricated steel structures primarily encompass ensuring the safety, stability, and functionality of the structure under seismic actions. Specifically, the goals are to enable the structure to effectively resist the lateral loads induced by earthquakes, preventing severe damage or collapse, and to rapidly regain operational functionality post-earthquake. The design should pursue excellent ductility and energy dissipation capabilities to absorb and disperse seismic energy, thereby reducing damage to both structural and non-structural components [6].

3.1. Performance-based Seismic Design

Performance-based seismic design is an approach that targets the overall performance of building structures under seismic actions. The central concept is to determine the seismic design objectives and methods based on the building's ability to meet all predetermined functional requirements during its service life. Compared to traditional force-based design methods, performance-based seismic design places greater emphasis on the structure's post-earthquake functionality and rapid recovery capabilities. In the field of prefabricated steel structures, this design philosophy is particularly crucial as it pertains to structural safety, construction convenience, and economic viability.

In the context of seismic design for prefabricated steel structures, performance-based design principles demand that the structure achieve anticipated performance targets under seismic actions, such as damage control and post-earthquake recoverability. This principle emphasizes considering the behavior of the structure under various seismic intensities during the design phase, ensuring that the structure maintains its critical functions under the design basis earthquake and avoids collapse under rare seismic events, and can be quickly restored even under extreme conditions. Compared to conventional seismic design methods, performance-based seismic design introduces a multi-objective control approach, which is predictable and offers more options in terms of seismic fortification standards. The concept of "multi-objective control methods" is primarily reflected in user requirements and project investment capabilities, and economic indicators should be considered in the selection among various seismic design schemes. This method requires controlling the amount of economic and property losses while ensuring the safety of people's lives. In the physical quantities used to evaluate the seismic performance status of buildings, in addition to force, displacement, and acceleration, there should also be quantified expressions of energy and degree of damage.

Performance-based seismic design is, in essence, a method that tailors "individualized" multiple seismic performance objectives according to the significance and complexity of a structure. It transforms qualitatively described seismic design goals into quantifiable performance objectives, leveraging the continuously evolving numerical simulation and analysis methods to achieve a performance validation. The implementation of this method is closely intertwined with the advancement of computer technology and numerical simulation techniques.

Taking the requirement for regularity as an example: when employing the static analysis methods from traditional code-based design, the inability to account for the torsional effects of the structure necessitates the use of a series of provisions to limit the degree of structural irregularity. This ensures a uniform distribution of mass, stiffness, and load-bearing capacity along the vertical axis, thereby guaranteeing the structure's seismic resistance. In contrast, when dynamic analysis methods are applied to analyze a three-dimensional model of the structure, the adverse seismic responses caused by irregularities can be accurately reflected in the analysis. A structure designed with such irregularities, when properly engineered, can possess seismic resistance that is not inferior to that of a regular structure.

Therefore, with the advancement in computational capabilities, the application of appropriate computational methods should allow for a moderate relaxation of the overall regularity criteria of the structure, provided that the expected performance objectives are met. This approach reduces the need for excessive empirical measures. Similar concepts are also incorporated in foreign design methodologies. For instance, in Japan, when verifying the seismic performance of a structure using the results of nonlinear time-history analysis, apart from the requirements for durability indicators, other code-based indicators can be waived or reduced depending on the actual circumstances [4].

In terms of analytical methods, since traditional code-based design is typically based on elastic or equivalent elastic analysis, it cannot accurately assess structural performance. Therefore, a series of seismic measures are required to control the yielding mechanism, plastic development, and damage extent of the structure under rare seismic events. This design philosophy can be applied to the conceptual design phase of performance-based design. For rare seismic scenarios that produce significant plastic deformation in the structure, current dynamic elasto-plastic analysis methods can accurately simulate the structure's nonlinear behavior [7].

3.2. Seismic Design of Structural Connections

Prefabricated steel structure connections are critical components for joining structural elements, and their design must meet the requirements for structural safety, construction convenience, and economic efficiency. In seismic design, connections are not only required to ensure adequate strength and stiffness but also to possess good ductility and energy dissipation capabilities to guarantee the safety and stability of the structure under seismic actions. For instance, some studies have shown that by altering parameters at beam-to-column connections, such as increasing the wall thickness of square steel tube columns, the flange thickness of beams, and by adding gusset plates to the square steel tube columns with extended end plates, the load-bearing capacity and initial stiffness of the connections can be significantly improved, thereby enhancing the seismic performance of the structure. These improvements not only strengthen the mechanical properties of the connections but also enhance the overall seismic resistance of the structure [7].

The seismic design of prefabricated steel structures should systematically analyze the relationship between the overall structure and its individual parts, particularly the reliability of connection joints, to ensure effective force transfer and sufficient ductility and energy dissipation capabilities during earthquakes. For example, self-centering connections and damage-controlled connections can absorb and dissipate energy under seismic actions, reducing structural damage and allowing for rapid recovery of building functionality after an earthquake. Connections using shape memory alloy bolts can achieve automatic re-centering through frictional energy dissipation after an earthquake, reducing the amount of repair work needed post-event. Damage-controlled connections, on the other hand, are designed with easily replaceable damage elements, such as incorporating a reduced cross-section in the steel beam as an intended damage zone, which confines plastic deformation caused by strong earthquakes to specific areas. After an earthquake, only the damaged section needs to be replaced to restore building functionality.

Furthermore, the seismic design of prefabricated steel structures must also consider the reliability of connection joints. This means that during the design process, it is essential to fully consider the efficiency of force transfer and the deformation capacity of the connections under seismic actions, ensuring that the connections do not fail catastrophically under extreme loads but instead dissipate seismic energy through plastic deformation. This requires connection designs to have not only sufficient strength and stiffness but also adequate ductility and appropriate yielding mechanisms to achieve the desired seismic performance of the structure [8].

4. Conclusion

This paper provides a comprehensive review of the seismic design methods for prefabricated steel structures, delving into the performance-based seismic design approach and the key technologies in seismic design of connections, leading to the following conclusions:

(a) The application of the performance-based seismic design philosophy in prefabricated steel structures emphasizes the functionality continuity and rapid recovery capability of the structure under seismic actions. This paper summarizes the core concept of this method, which is to determine the seismic design objectives and approaches based on the building's ability to meet all predetermined functional requirements during its service life. Compared to traditional force-based design methods, performance-based seismic design places greater emphasis on the structure's functionality continuity and rapid recovery post-earthquake.

(b) Connections in prefabricated steel structures, as critical components for joining structural elements, are of paramount importance in seismic design. This paper summarizes the various requirements that connection design must meet and highlights the need for connections to possess adequate strength, stiffness, ductility, and energy dissipation capabilities under seismic actions.

(c) While the seismic design methods for prefabricated steel structures have achieved certain progress, there are still some deficiencies and challenges. Firstly, the application of performance-based seismic design methods in practical engineering is not yet widespread and requires further research and practice to verify their effectiveness. Secondly, research on seismic connection design necessitates more experimental and numerical simulation data to support the selection and optimization of design parameters. Additionally, a more in-depth study of the behavior and performance of prefabricated steel structures under varying seismic intensities is required to enhance the accuracy and reliability of design.

References

[1] Gao Rui. Discussion on steel structure construction technology and construction management measures for prefabricated building engineering. Development Guide to Building Materials, 2024, 22(21): 85-87.

[2] Wang Shubo. Research on the development constraints and promotion strategies of prefabricated building in Hangzhou. Zhejiang: Zhejiang University, 2021.

[3] Zhang Mingxin. Research on the historical development of China's introduction of Japanese prefabricated building technology in the 1980s—Taking Beijing as an example. Dalian: Dalian University of Technology, 2021.

[4] Xiang Yang, Luo Yongfeng, Huang Qinglong. Research progress on the seismic performance of prefabricated steel structures. Progress in Steel Building Structures, 2019, 21(03): 1-12.

[5] Kang Lijing. Research on seismic performance of prefabricated concrete-filled steel tubular column base. Changsha: Hunan University, 2022.

[6] Zhan Hong. Research on seismic performance of new precast concrete connection joints. Guangzhou: Guangzhou University, 2023.

[7] Liu Kaiqiang. Overall stability analysis of Multi-story high rise Steel-frames. Chengdu: Southwest Jiaotong University, 2007.

[8] Zhao Chenfu, Bai Yu, Zhong Yixian. Research on seismic performance of a new type assembled steel structure beam – column joint. Sichuan Building Science, 2020, 46(06): 24-28.