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Performance Analysis and Optimization Path of Connection Nodes in Prefabricated Building Structures

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Abstract: As one of the core technologies for force transmission and deformation coordination in prefabricated building structures, the performance of connection nodes directly determines the overall safety, stability, and durability of the structure. With the current changes in prefabricated building structures, the performance of traditional connection nodes has gradually exposed many problems. Based on this, this paper analyzes the performance and significance of connection nodes in prefabricated building structures and explores their optimization paths, aiming to provide theoretical support for the efficient construction and high-quality development of prefabricated buildings.

Keywords: Connection nodes; Performance; Prefabricated buildings; Industrialization; Construction

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1. Introduction

Guided by the development strategies of green buildings and new building industrialization, prefabricated buildings have become the core direction for promoting the transformation and upgrading of the construction industry due to their significant advantages such as energy conservation and emission reduction, efficient construction, and controllable quality. The overall performance of prefabricated building structures is highly dependent on the connection nodes between components. They can not only ensure the strength and stability of the connection parts, improve the safety of the entire prefabricated building structure but also optimize disaster resistance performance such as seismic and wind resistance. In extreme weather or natural disasters such as earthquakes, the building can maintain structural integrity and protect people's lives and property safety [1]. Against this background, systematically conducting research on the performance analysis and optimization of connection nodes, accurately revealing the force mechanism and failure law of nodes, and constructing a scientific and effective optimization system have become an urgent demand for industry development.

2. Performance analysis of connection nodes in prefabricated building structures

2.1. Mechanical performance

The force situation of connection nodes in prefabricated building structures is relatively complex. Connection nodes occupy an important position in the prefabricated building system, undertaking the important functions of connecting load-bearing parts, transmitting forces, and ensuring structural stability. From this perspective, the quality of mechanical performance directly affects the stability and safety of the entire prefabricated building system [2]. At the same time, since connection nodes play the role of connecting different components, to ensure the smooth transmission of forces between components, it is necessary to realize the reasonable distribution and conversion of various loads such as axial force, shear force, and bending moment between components through a reasonable force transmission path, and ensure the requirements of structural stability. Bearing capacity, as the main quantitative standard of the mechanical performance of connection nodes, mainly considers the influence of the node itself and various related parameters on the bearing capacity level during this process, focusing on the ultimate bearing capacity of the node and the bearing capacity under the serviceability limit state, so as to understand the critical failure state of the node under overload conditions and the total load it can bear. In addition, an ideal connection node should also have a certain elastic-plastic deformation capacity, which can not only meet the changes in displacement requirements during the structural work but also have a certain plastic deformation capacity to reduce energy, so that the structure will not suffer sudden damage under extreme loads.

2.2. Seismic performance

As the connection hub between components, connection nodes need to bear alternating stresses caused by cyclic loads, and their seismic performance directly determines the overall seismic resilience of the structure. On the one hand, energy dissipation capacity is the core indicator of the seismic performance of connection nodes, referring to the ability of the node to dissipate seismic energy through plastic deformation, frictional sliding, and other methods under cyclic loads. The stronger the energy dissipation capacity of the node, the more significant the seismic protection effect on the overall structure, which can effectively reduce the transmission of seismic energy to the main structure and reduce the risk of component damage [3]. On the other hand, ductility refers to the ability of the node to produce plastic deformation without losing bearing capacity. Good ductility can enable the node to produce large plastic deformation under earthquake action to dissipate energy, avoid sudden brittle failure, and provide a buffer space for structural seismic resistance.

2.3. Durability performance

Compared with the main structural components, connection nodes are more susceptible to erosion by external environmental factors due to their complex structure and numerous splicing interfaces and gaps, and their durability degradation rate is usually faster. Once the node is damaged due to insufficient durability, it will directly lead to a decline in the overall performance of the structure and even trigger safety accidents [4]. Therefore, it is necessary to consider the comprehensive effect of environmental factors and the node's own characteristics from the perspective of long-term service to understand the performance change mechanism. Due to the influence of external factors, the durability of nodes is easily affected by temperature and humidity changes, acid-base salt erosion, freeze-thaw cycles, and carbonation, leading to cracking of splicing interfaces, aging and failure of sealing materials, thereby damaging the watertightness and airtightness of nodes and creating conditions for the intrusion of other erosion factors.

In addition, it is necessary to focus on the impact of node structural details on durability. Structural details such as the splicing method of nodes, sealing treatment, and the quality of anti-corrosion coatings directly determine the erosion resistance of nodes. For example, insufficient selection and construction quality of sealing materials will lead to the failure of node gap sealing and exacerbate the intrusion of environmental media. According to the influencing factors of node durability, the degradation law and key influencing factors of nodes in long-term service environments can be clarified, providing a theoretical basis for the optimal design of node durability, the formulation of protective measures, and long-term maintenance, and ensuring the safety of prefabricated building structures during long-term service [5].

3. Significance of performance optimization of connection nodes in prefabricated building structures

3.1. Improve the safety of prefabricated building structures

As a modern building technology, the core of prefabricated buildings lies in decomposing the building structure into prefabricated components, which are standardized produced in factories and then transported to the construction site for rapid assembly, which extremely tests the safety of the prefabricated structure. Node performance optimization can accurately improve the mechanical performance and disaster resistance of nodes, ensuring that the building has sufficient bearing redundancy and deformation coordination capacity under static loads, earthquakes, strong winds, and other loads, effectively reducing the risk of stress concentration, avoiding premature node damage, and ensuring the overall stability of the structure under various load conditions [6]. At the same time, with the help of structural sealing design, improving material adaptability, and strengthening anti-corrosion and seismic measures, the intrusion path of environmental erosion media can be effectively blocked, the material degradation rate can be reduced, the service life of nodes can be prolonged, and thus the safety of the building throughout its life cycle can be guaranteed.

3.2. Promote green buildings and energy conservation and emission reduction

Compared with traditional cast-in-place buildings, prefabricated buildings have significant advantages in energy conservation and emission reduction during production, transportation, and assembly. Optimizing the performance of connection nodes can further optimize the production process of components, reduce material usage, and improve material utilization rate. Specifically, with the help of optimized structural design, the standardization and intensification of connection processes can be realized, the amount of on-site wet work can be reduced, and the dependence on large construction machinery can be reduced [7]. Optimized nodes often have better construction adaptability, which can improve component installation accuracy and connection efficiency, reduce rework and material waste during construction, and reduce carbon emissions during the construction phase. In addition, nodes have better durability and stability, which can reduce the sealing failure of the enclosure structure and the decline in thermal insulation performance caused by the degradation of node performance, avoid additional energy consumption and material waste caused by later maintenance and reinforcement, and ensure the energy-saving benefits of the building during long-term operation.

3.3. Promote the standardized and normalized development of the prefabricated building industry

With the improvement of standardization, the promotion and application of prefabricated buildings will be more extensive, which helps to form economies of scale and promote the transformation and upgrading of the entire construction industry. Research on node performance optimization can systematically sort out the performance influencing factors, force mechanism, and failure law of different types of nodes, establish a scientific node performance evaluation index system and design theory system, help clarify the design requirements, material selection standards, construction process parameters, and quality control points of nodes in different application scenarios, and fill the technical gaps in the industry in terms of refined node design and accurate performance evaluation, thereby forming a technical system covering the entire process of node design, construction, acceptance, and maintenance [8]. At the same time, optimizing node performance can promote the formation of standardized methods for node performance testing and evaluation, improve the scientificity and accuracy of node performance evaluation, and provide reliable technical means for engineering quality supervision.

4. Optimization path of connection nodes in prefabricated building structures

4.1. Select suitable building materials to improve the performance of connection nodes

Materials are the foundation for improving the performance of connection nodes in prefabricated buildings. Currently, to better ensure the stability of prefabricated building structures, it is necessary to solve the problems of single material selection, mismatched performance, and fast degradation rate of traditional nodes, focus on the performance complementarity and synergistic efficiency between multiple materials, and realize the overall improvement of node performance. In terms of material selection, it is necessary to reasonably select the concrete strength grade according to the force strength requirements and deformation needs of the node, balance strength and ductility, and avoid brittle failure of the node caused by high-strength concrete [9]. For example, the performance of concrete can be modified by adding fibers, mineral admixtures, etc., to improve its tensile strength, crack resistance, and wear resistance.

From the perspective of material performance, the performance parameters of different materials inside the node need to be accurately matched, such as concrete, steel bars, connectors, and sealing materials, to avoid interface failure or stress concentration caused by excessive differences in material performance. On the one hand, it is necessary to ensure that the thermal expansion coefficients of different materials are similar to reduce interface stress and cracks caused by temperature changes; on the other hand, it is necessary to realize the gradient transition of material stiffness and strength to avoid poor load transmission caused by sudden changes in material performance [10]. From the perspective of material environmental adaptability, it is necessary to select materials with targeted anti-degradation performance. In corrosive environments, corrosion-resistant materials such as corrosion-resistant concrete and stainless-steel connectors should be preferred, and high-performance anti-corrosion coatings and sealing materials should be used to build a multi-layer anti-corrosion system. In freeze-thaw environments, concrete materials with strong frost resistance should be selected, and the pore structure of concrete should be optimized to reduce the damage of freeze-thaw cycles to materials [11].

4.2. Improve construction quality control to ensure the practical effect of node performance

The improvement of the quality of connection nodes in prefabricated buildings is closely related to the safety and stability of the final structure, which involves three aspects: engineering technology, operators, and operating standards. First, the professional skills of construction personnel determine the quality of connection nodes. Therefore, when formulating skill training plans, it is necessary to combine the key links and special processes of node construction to improve the technical level and quality awareness of construction personnel. For high-precision connection, complex grouting and other links, it is necessary to ensure that construction personnel have certain qualifications and practical operation capabilities. In addition, special technical training should be organized regularly to make construction personnel familiar with the operation steps of grouting technology, prefabricated component positioning and hoisting, connector fastening, etc., to ensure the quality of node connection and the safety of the entire structure [12].

Second, the introduction of intelligent monitoring equipment provides technical support for connection quality control. It is necessary to calibrate and debug key equipment such as measuring instruments, grouting equipment, and fastening tools in advance to ensure that they achieve a precise and stable performance state, preventing and eliminating deviations in construction effects caused by improper equipment use; at the same time, it is necessary to establish an automatic early warning prompt function and an alarm feedback system to timely detect changes in grouting pressure, flow rate, and grout temperature, providing clear and clear data for operators to help them adjust construction parameters and operation processes in a timely manner [13]. In addition, it is necessary to introduce positioning instruments such as total stations and 3D scanners to conduct comprehensive inspections on important materials such as concrete, steel bars, connectors, and sealing materials, ensuring the quality of node construction from the material level; finally, establish a key process quality control point system. For core links affecting node performance such as component positioning, interface treatment, connection fastening, and grouting density, clarify quality control points, operation processes, and allowable deviation ranges to achieve precise control of the construction process.

4.3. Promote refined design of node structures to optimize the overall performance of nodes

As the basic carrier for the realization of node performance, structural design optimization needs to be based on the mechanical essence and service requirements of nodes, realizing the transformation from empirical design to precise design, and promoting the high alignment between node performance and the overall structural design goals. First, guided by the force characteristics of nodes, systematically analyze load types such as axial force, shear force, and bending moment, clarify the core path and auxiliary path of load transmission, and avoid the occurrence of force transmission blind areas or superposition phenomena [14]. At the same time, it is necessary to strengthen the redundant design of the force transmission path, build a backup force transmission mechanism outside the core force transmission path, improve the force transmission reliability of the node under extreme loads, and avoid the overall damage of the node caused by the failure of a single force transmission path.

Second, aiming at the problems of weak interface bonding, insufficient sealing performance, and poor seismic resilience of traditional nodes, it is necessary to refine structural details from multiple dimensions. For example, in terms of interface treatment, the roughness design of the connection surface of prefabricated components can be optimized, interface shear keys or concave-convex groove structures can be added to strengthen the bonding performance and anti-slip ability of the interface between new and old materials, thereby ensuring the coordinated force transmission of the interface [15]. Third, the refined design strategy of connection nodes in prefabricated buildings is reflected in multi-dimensional precise calculation and simulation analysis. A calculation model can be established to targetedly verify and detect the behavior of connection nodes under static loads, dynamic loads, and long-term loads, clarify the weak links of prefabricated building structures, and thus accurately adjust key design parameters, building material dosage, and the diameter and distribution form of steel bars to ensure the smoothness of the force transmission path and the stability of the structure.

5. Conclusion

In summary, with the continuous improvement of social requirements for building speed, quality, and environmental protection, prefabricated buildings are gradually becoming the mainstream of the construction market due to their fast, efficient, and environmentally friendly characteristics. By selecting suitable building materials, improving construction quality control, and promoting refined design of node structures, the performance and quality of prefabricated buildings can be improved, their competitiveness in the market can be enhanced, new competitive advantages can be brought to construction enterprises, the market demand for high-quality buildings can be met, and thus stand out in the fierce market competition.

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