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Comprehensive Review on the Structural Performance of Fish-Bellied Steel Waling Systems

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Abstract

As the key force transmission component of deep foundation pit support system, fish-bellied steel purlin is widely used in the field of civil engineering due to its advantages of light weight, high strength, convenient construction and reusability. This paper systematically reviews the research progress of fish-bellied steel purlins in structural static performance (bearing capacity, stability), joint mechanical behavior, dynamic response characteristics, construction process simulation and design methods. The analysis shows that the current research focuses on numerical simulation and scale test, and the research on complex boundary conditions, initial defect sensitivity, real node performance and life-cycle periodic performance is still insufficient. Future research should focus on high-precision numerical model construction, large-scale node test verification, intelligent monitoring technology integration and standardized design guidelines to promote the safe and efficient application of the structural system.

Keywords

Fish-bellied steel purlin ; deep foundation pit support ; structural performance ; stability ; node mechanics ; research progress.

1. Introduction

With the acceleration of urbanization and the development of underground space towards deeper and larger scales, deep foundation pit engineering faces increasingly severe technical challenges. As the core guarantee for foundation pit safety, the performance optimization of retaining structures is crucial. The fish-bellied steel waling (also known as prestressed fish-bellied beam support system) is a planar truss-type retaining structure composed of high-strength steel chord members, web members, tie rods, and braces/angle braces (Figure 1). Compared with traditional concrete or H-beam retaining structures, it offers significant advantages such as lighter self-weight, higher strength, faster construction speed, prestress application capability, reusability, and environmental friendliness, making it particularly suitable for ultra-large span projects, narrow sites, or deep foundation pits requiring strict deformation control. Despite its widespread application, research on its structural performance still lags behind practical demands. Design theories predominantly rely on empirical formulas or simplified calculations, while insufficient understanding of complex stress mechanisms, stability behavior, and actual joint performance constrains the refined development and safety-economic improvement of this technology. This paper aims to review the current status of research on fish-bellied steel waling structure performance, analyze key issues, and explore future research directions, providing references for related theoretical studies and engineering practices.

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2. Characteristics and engineering application of fish belly steel purlin structure

2.1. Geometry and material properties

Geometric adjustability: The string rod is often assembled in sections to adapt to the size of the foundation pit flexibly; the angle of the belly rod can be optimized to balance the force.

Application of high strength materials: The main force members (stringer and web) are generally made of Q345B, Q390B and other high strength steel grades to achieve lightweight.

Introduction of prestress: During construction, axial prestress is applied to the chord rod by jack to effectively control the deformation of the enclosure structure and improve the stiffness of the system.)

2.2. Typical engineering application scenarios

Widely used in subway stations, basement of high-rise buildings, large municipal pipe corridor and other deep foundation pit engineering. Especially suitable for:

Rectangular or irregular foundation pit

Adjacent important buildings (structures) with high requirements for deformation control

Construction site is limited, and the project needs to be installed and disassembled quickly Temporary support structures that need to be used repeatedly

2.3. Structural composition and force transmission mechanism

The core structure of the fish-belly steel cofferdam consists of upper and lower parallel struts (typically box or H-shaped sections), a central inclined web member (steel pipe or section steel), and connecting tie rods[1].By applying prestress at the ends of the struts, the structure forms a self-balancing system that significantly enhances out-of-plane stiffness and overall stability. The load transfer path is clearly defined: earth pressure is transmitted through the retaining piles/walls to the struts, where it is converted into axial force via the web members, ultimately being borne by corner braces or corner supports.

3. Research Status of Structural Performance

3.1. Static load bearing performance and stability

Load bearing study:

Numerical simulation predominates: Extensive studies employ software such as ANSYS and ABAQUS to establish detailed 3D finite element models, analyzing ultimate load-bearing capacities under axial forces, bending moments, and composite loading conditions. Simulations by Zhang et al. (2021) demonstrate that localized buckling of chord members is the primary failure mode, with the width-to-thickness ratio of compressed chord members serving as a key control factor.

Limited experimental verification: Wang et al. (2020) conducted a scaled model test, and the results were well matched with nonlinear numerical analysis, which confirmed the law of local buckling of chord rods before overall instability. However, there is a lack of full-scale test data.

Stability studies:

Out-of-plane instability risk: As slender planar structures, out-of-plane overall instability (bending-torsion instability) is a key concern. Li et al. (2022) conducted systematic research through eigenvalue buckling and nonlinear buckling analysis on the effects of initial geometric defects (such as initial bending of cable members), prestress levels, support spacing, and boundary constraints on overall stability, highlighting that defect sensitivity cannot be overlooked.

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Local stability design: The plate width-to-thickness ratio of the chord (especially under compression) and the local pressure stability of the connection area between the web and the chord should strictly meet the code requirements to prevent the sudden decrease of bearing capacity caused by local buckling.

3.2. Node connection performance

The node (mainly the connection node between the belly rod and the chord rod) is the key part of force transmission, and its performance directly affects the overall safety of the structure[2].

Complex stress state: The node is subjected to the combined action of axial force, shear force and bending moment, which is easy to become a weak link. Chen et al. (2023) revealed the significant stress concentration phenomenon in the core area of the node through refined finite element analysis.

Progress of experimental research: The team of Tongji University (2023) conducted a series of static tests on nodes, and tested the bearing capacity, stiffness and failure mode of different construction forms (welding, bolted connection, node plate reinforcement), which provided valuable basis for node design.

The semi-rigid connection effect: In actual engineering, it is difficult for nodes to achieve ideal rigid or hinged connections. Zhao (2024) study shows that the semi-rigid characteristics of nodes have a significant impact on the overall internal force distribution and deformation of the surrounding purlin, which should be considered in the design analysis.

3.3. Dynamic response and fatigue performance

Dynamic response during construction: The vibration caused by foundation pit excavation, adjacent construction (such as piling), and vehicle load may affect the performance of the perimeter piers. Qian et al. (2021) used time-history analysis to study the dynamic response characteristics of the perimeter piers under construction vibration, and pointed out that resonance risks should be paid attention to[3].

Seismic action: Foundation pits located in seismic zones should consider seismic action. The team of Dalian University of Technology (2022) preliminarily explored the acceleration response, displacement mode and potential failure mechanism of fish-belly beam system under seismic waves through scaled vibration table model test.

Preliminary Study on Fatigue Performance: For perimeter purlins subjected to repeated loads (such as frequent prestress application/release and adjacent traffic vibrations) or long-term use, fatigue issues have begun to attract attention. Central South University (2023) conducted preliminary numerical simulation research based on nonlinear damage accumulation theory, but it lacks experimental data support.

3.4. Construction process simulation and monitoring

Construction process simulation: Key steps such as foundation pit excavation, prestressing tensioning, and support installation significantly influence the internal force state of the surrounding purlin. Numerical simulation techniques (such as those considering contact and geometric nonlinear effects) can accurately simulate the entire construction process, optimizing the tensioning sequence and prestress values [4](Wu, 2020).

Application of real-time monitoring technology: Fiber Bragg Grating (FBG), vibrating string sensor and so on are used to monitor the strain, deformation and prestress loss of key sections of the surrounding purlin, so as to realize informationization of construction process and risk warning (Sun et al., 2022).

3.5. Current situation of design theory and method

Limitations of current methods:

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The multi-purlin is simplified into a continuous beam or simply supported beam on the elastic foundation for calculation, and its truss characteristics, node stiffness and prestress effects are ignored.

The stability design often uses the formula of steel column or plane truss, without considering its unique structure and boundary conditions[5].

Lack of special specifications: There is no special design code or standard for fish-belly steel purlin in China, and the design mainly depends on enterprise experience or reference to general codes such as "Steel Structure Design Standard" (GB 50017), which has problems of applicability.

4. Key Issues and Challenges Facing Current Research

Insufficient refinement model and verification: the simulation accuracy of weld details, initial defects and material nonlinearity of the existing numerical model needs to be improved, and there is a lack of sufficient verification by full scale test[6].

Complex boundary and interaction: the real interaction between the surrounding purlin, the surrounding wall (pile), the support system and the soil (contact, friction and constraint) is complicated, and it is difficult to simulate and simplify.

Deepening requirements of node performance cognition: The real bearing mechanism, failure criterion and fatigue life of nodes under complex stress are not deeply studied, and the reliable design method is missing.

Lack of theoretical system of stability design: there is no systematic study on sensitivity to initial defects, calculation of overall stable bearing capacity in plane, and time-varying stability considering construction process.

Lack of dynamic and long-term performance data: little research has been done on seismic response, fatigue performance, and performance degradation under long-term service[7] (corrosion, prestress relaxation).

Design specification lags behind: it is urgent to formulate special design regulations or standards with strong pertinence and solid theoretical basis to guide engineering practice.

5. Key Issues and Challenges Facing Current Research

Integration of high precision numerical simulation and experimental verification:

Develop high fidelity numerical simulation technology which is integrated with real geometric defects, welding residual stress and material damage model.

Focus on full scale or large scale model test, covering static limit bearing capacity, stability, node performance and typical failure mode, to provide a solid foundation for model verification.

Node performance and new node development:

The mechanical behavior, failure mechanism and fatigue characteristics of various connection nodes under complex load path are studied in depth[8].

Explore new node structures with modularization, assembly and high performance (such as high strength bolted connections and cast steel nodes) to improve construction efficiency and reliability.

Study on complex boundary conditions and soil-structure interaction:

Establish a more accurate synergistic analysis model of purlin-envelope structure-support system-soil.

The influence mechanism of foundation pit excavation sequence and prestress application process on the redistribution of internal force and stability of purlin is studied.

Systematic study of stability and performance:

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The quantitative influence of geometric initial defect, residual stress and load eccentricity on the out-of-plane overall stability is analyzed in depth[9].

Develop practical bearing capacity calculation theory and design method suitable for fish belly type piling.

Dynamic response and full life performance evaluation:

The dynamic response analysis and seismic design method under earthquake motion input are strengthened.

The durability and fatigue performance under environmental erosion (corrosion), long-term loss of prestress, and cyclic load were studied, and the life-cycle performance prediction and evaluation model was established.

Application of intelligent monitoring and digital twin technology:

Advanced technologies such as optical fiber sensing, wireless transmission and BIM are integrated to realize real-time intelligent monitoring and early warning of perimeter stress, deformation and prestress state.

A digital twin model based on monitoring data is constructed for structural condition assessment, predictive maintenance and decision support[10].

Standardization and specification development:

Integrate research results, promote the preparation of "Technical Regulations for Fish-belly steel purlin support" or special design guidelines, standardize material selection, design calculation, structural measures, construction and acceptance requirements.

Green and intelligent design:

Intelligent design software is developed by combining optimization algorithms (such as topology optimization and genetic algorithm) to achieve lightweight structure and optimal performance.

Explore the application potential of higher strength steel and composite materials to further reduce resource consumption.

6. Case Study of Engineering: Application of Shanghai Deep Foundation Pit Project

Project Overview: The foundation pit of Jing 'an Temple Station of Metro Line 14 is 24 meters deep and more than 200 meters long, adjacent to the historical protected building. The drilling and casting pile + fish belly steel purlin support system is adopted.

Key points of enclosure design:

The main string rod adopts box section (mouth 600×300×16×16mm) and material Q390B.

The prestress value is determined by refined finite element analysis (considering step excavation and adjacent building protection requirements), and the horizontal displacement of the retaining pile is effectively controlled within 30mm.

The node is reinforced by welding stiffening rib plate, and the bearing capacity of the node is verified by finite element analysis[11].

The whole process uses fiber Bragg grating sensor to monitor the strain of the key section, and gives real-time feedback to guide the construction adjustment.

Results: The deformation is successfully controlled, the safety of adjacent buildings is guaranteed, and the construction period is shortened by about 15%, which reflects the technical advantages of fish-belly type purlin in complex and harsh environment.

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7. Conclusion

As an efficient and eco-friendly deep foundation pit support system, fish-belly steel cofferpans demonstrate broad application potential. While current research has achieved notable progress in static load-bearing performance simulations, scale-scale tests, stability analysis factors, and construction monitoring, significant challenges remain. Key areas requiring breakthroughs include full-scale verification testing, complex joint performance evaluation, systematic stability theory, dynamic and long-term performance analysis, as well as standardization of technical specifications.

Future research should focus on the deep integration of high-precision models and experimental methods, deepen understanding of key components (especially joints) and system stability mechanisms, enhance studies on dynamic responses and full-life performance, and vigorously promote the application of intelligent monitoring, digital twin technology, and smart design techniques. The ultimate goal is to establish a comprehensive theoretical framework and design methodology, formulate specialized technical standards, provide robust scientific support for the safe, economical, and efficient application of fish-belly steel cofferpans in more complex and large-scale foundation pit engineering, and drive the development of civil engineering temporary support technologies toward greener, smarter, and higher-performance directions.

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