

A Review of Research on Structural Performance of Fish-bellied Prestressed Steel Purlins

Jiayu Yang¹, Xueyuan Guo²

¹ School of Civil Engineering and Architecture, North China University of Science and Technology, Tangshan 063210, Hebei, China

² School of Civil Engineering and Architecture, North China University of Science and Technology, Tangshan 063210, Hebei, China

Abstract: With the acceleration of urbanization, the number of deep foundation pit projects is increasing, and the limitations of traditional internal support systems in large-span and complex environments are gradually highlighted. As a new type of foundation pit internal support structure, fish-bellied prestressed steel purlin combines the concept of prestressed technology and string structure. It has significant advantages such as large span, large space, high stiffness and reusability, and has been more and more widely used in foundation pit engineering. In this paper, the structural composition and working principle of fish-bellied prestressed steel purlin are systematically reviewed. The research progress of its structural performance is reviewed from the aspects of stiffness characteristics, stress deformation, stability and deformation control. The influence of prestress level, geometric parameters, material properties and construction technology on its performance is analyzed. Typical engineering application cases and effects are summarized. In view of the problems of simplified theoretical models, lack of long-term performance data and weak seismic research in current research, the future research directions of multi-scale numerical simulation, intelligent monitoring and control, and application of new materials are prospected, in order to provide reference for the further development and engineering application of this technology.

Keywords: Foundation Pit Engineering, Fish-Bellied Steel Purlin, Prestressing, Structural Performance, Stiffness.

1. Introduction

In recent years, with the large-scale development of urban underground space, deep foundation pit engineering presents the development trend of 'deep, large and near'. Although the traditional reinforced concrete internal support system has the advantages of high stiffness and high safety, there are some problems such as long construction period, difficulty in dismantling support and serious environmental pollution. The construction of ordinary steel support system is convenient, but the stiffness is low, and the deformation control ability under complex working conditions is difficult to meet the requirements. In this context, the fish-bellied prestressed steel purlin, as a new type of support form that integrates prestressed technology with the concept of string structure, has gradually become a hot spot of research and application.

The fish-bellied prestressed steel purlin (also known as prestressed fish-bellied beam steel support, IPS method) applies prestress to the lower chord steel strand of the fish-bellied beam, so that the upper chord steel beam has an anti-arch effect, forming a self-balancing system in which the upper chord rigid member and the lower chord flexible cable work together. The system combines the high stiffness of rigid support and the controllability of flexible cable, which can provide efficient support capacity in super-large span foundation pit. In-depth study of the structural performance of fish-bellied prestressed steel purlins is of great theoretical and engineering significance for optimizing the design of foundation pit support, improving engineering safety and promoting the development of green construction technology.

2. Structure Composition and Working Principle

2.1. Structural Composition

Fish-bellied prestressed steel purlin is mainly composed of

the following parts :

(1) Upper chord beam : H-shaped steel or box section is usually used as the main flexural member to bear the bending moment and axial force ;

(2) The lower chord steel strand : the high strength and low relaxation steel strand is adopted, and the prestressing force is generated by tensioning to provide the tensile stiffness for the system ;

(3) web member system : including straight web member and inclined web member, connecting the upper chord beam and the lower chord steel strand, transmitting load and maintaining the geometric shape of the system ;

(4) Anchorage system : including anchorage, tensioning equipment, etc., for the application and maintenance of prestress ;

(5) Connection node : The support system is connected to the retaining pile (or underground continuous wall) to ensure the effective transmission of load.

2.2. Principle of Operation

The working mechanism of fish-bellied prestressed steel purlin can be summarized as 'prestressed active control + rigid-flexible cooperative force' :

Prestress application stage : through the tension of the lower chord steel strand, the upper chord beam produces an upward inverted arch, and the initial prestress field is established in the system. At this time, the upper chord beam is bent, the steel strand is pulled, and the web member is subjected to axial force[1].

Foundation pit excavation stage : With the excavation of the earth, the lateral earth pressure acts on the retaining[2] structure and is transmitted to the support system through the purlin. The anti-arch effect caused by prestress can offset the deformation caused by partial earth pressure. The upper chord beam and the lower chord steel strand work together to resist bending moment and tension, forming the working mode of "

prestressed control beam deformation with cable."

Deformation control stage : the prestress level can be adjusted by secondary tension of steel strand, and the support stiffness attenuation caused by soil creep and load change can be compensated in real time, so as to realize the dynamic control of foundation pit deformation.

Different from the traditional support relying on large stiffness to passively resist soil pressure, the fish-bellied prestressed steel purlin stimulates the passive soil pressure outside the pit by actively applying prestress, and can obtain smaller foundation pit deformation under the same support stiffness.

3. Structural Performance Research

3.1. Stiffness Characteristic

Stiffness is the core index to evaluate[3] the structural performance of fish-bellied prestressed steel purlin. The fish-bellied beam is simplified as a structural beam fixed at both ends. The deformation under load is solved by displacement method and MATLAB program. The concept of 'equivalent bending stiffness' is introduced. The fish-bellied beam is regarded as a 'strengthened beam' of steel purlin under the combined action of straight web member and steel strand, and the calculation formula of stiffness is derived. The research shows that the load deformation curve of the fish-bellied beam under uniform load is a quartic parabola.

Regarding the influencing factors of stiffness, the study found that the fish-bellied curve model, the number of steel strands, the angle of the end and the span all have a significant impact on the stiffness of the fish-bellied beam. The comprehensive[4] stiffness of the assembled prestressed fish-bellied steel support system can be determined according to the results of structural analysis. The study also pointed out that the focus of foundation pit support has changed from 'strength control' to 'stiffness control'.

3.2. Force and Deformation Characteristic

The stress and deformation characteristics of fish-bellied prestressed steel purlin is another important aspect of its structural performance research. Some scholars have simplified the fish-bellied beam structure into a statically indeterminate beam string structure, and deduced the analytical solution of the force deformation based on reasonable assumptions. In terms of load transfer path, the lateral earth pressure is transmitted step by step through the retaining pile → purlin → connection node → upper chord beam → web member → lower chord steel strand → anchorage system → foundation. The prestress is superimposed[5] as the initial internal force and the load internal force to form a complex stress state.

In terms of the relationship between prestress value and structural performance, reasonable prestress can effectively reduce the mid-span bending moment of the upper chord beam and control the structural deformation. Prestressing should follow the principle of 'partition, classification and circulation'. The increase of the axial force of the inner support caused by the prestressing force is usually several times the increase of the axial force caused by the excavation of the foundation pit soil, which is worthy of design attention.

3.3. Stability

Stability is the key to ensure the safety of fish-bellied prestressed steel purlin. For the super long brace, the design

needs to meet the requirements of strength, stability and so on. In terms of collapse resistance, some scholars have carried out the redundancy study of steel support of prestressed fish-bellied foundation pit by using the 'dismantling component method'. It is found that the redundancy of each member of the second layer support is smaller than that of the first layer support, and more attention should be paid to the monitoring of steel strand and support axial force during construction.

3.4. Deformation Control Performance

The deformation control effect of the fish-bellied prestressed steel purlin is its core advantage over the traditional support. The concept of 'hidden negative displacement' is proposed in related research, and the calculation formula of lateral displacement of retaining structure under this support is derived on the basis of p-y curve. The research shows that the prestressed fish-bellied beam steel support is better than the concrete support to control the lateral displacement of the retaining structure. By applying prestress to stimulate the passive earth pressure outside the pit, the horizontal displacement of the foundation pit can be effectively controlled[6].

4. Analysis of Influencing Factors

4.1. Prestress Level

The prestressing level is the most critical factor affecting the structural performance of fish-bellied prestressed steel purlins. Prestressing should follow the principle of 'partition, classification and circulation'. The reasonable prestress[7] level should be comprehensively determined according to the magnitude of earth pressure, support span and deformation control requirements. The research shows that the increase of the axial force of the support caused by the prestressing force is significantly greater than that caused by the excavation of the foundation pit. During the construction process, the deformation of the foundation pit should be controlled by timely tensioning of the steel strand and adjusting the pre-axial force of the support.

4.2. Geometric Parameter

The influence of geometric parameters on structural performance is mainly reflected in two aspects : span and rise-span ratio[8]. When the span increases, the deflection and bending moment of the structure increase significantly. Bi et al. studied the influence of fish belly curve model and end angle on the stiffness of fish belly beam. At present, the plane layout of the fish belly beam mainly relies on experience, and a complete and reasonable plane layout method has not yet been formed.

4.3. Material Properties and Construction Technology

The use of high-strength steel (such as Q355 B) in the upper chord beam can improve the section stiffness and reduce the size of the component [9]; lower chord steel strand should adopt low relaxation steel strand to reduce prestress loss. In terms of construction technology, tension sequence and prestress loss control have an important impact on structural performance. The grading tension can reduce the initial deformation of the system. The tension height of the diameter of the steel strand also has a significant effect on the displacement of the foundation pit.

5. Engineering Application

The fish-bellied prestressed steel purlin has been applied in many deep foundation pit projects across the country. The deep foundation pit project of a building in Xuzhou adopts the prestressed fish-bellied steel support system[10]. The foundation pit has been constructed for 10.5 months. It has experienced many heavy rains and severe cold and heat, and the monitoring results are always within the controllable range. Through the layout of monitoring points in the deep foundation pit project of Xi'an Cultural Tourism Center, the axial force of internal support, surface settlement and horizontal deformation law of supporting piles during the construction of foundation pit are obtained. The surface settlement caused by foundation pit excavation does not exceed 20 mm. The application of large-scale prefabricated prestressed fish-bellied beam steel support system in a soft soil area in Shanghai shows that the system has the advantages of fast construction, controllable deformation and large excavation space. The practice of a deep foundation pit in Wuhan also verifies the good control effect of the prestressed fish-bellied beam[11] steel support system on the overall deformation of the foundation pit.

In terms of technical standardization, Shaanxi Province has issued DBJ61 / T 191-2021 ' Technical specification for assembled prestressed fish-bellied beam composite steel support ', which provides a basis for the standardized application of this technology.

6. Existing Problems and Prospects

6.1. Shortcomings of Current Research

Although fish-bellied prestressed steel purlins have been widely used in engineering, there are still the following deficiencies in related research[12]:

(1) Simplification of theoretical model : The existing theoretical models mostly simplify the support system as a plane structure, and fail to fully consider the three-dimensional spatial effect and soil-structure interaction ;

(2) Lack of long-term performance research : There are few studies on long-term performance such as prestress loss law and material aging, and lack of long-term monitoring data support ;

(3) The construction control is difficult : the pre-stressed tension accuracy is high, and the on-site construction is prone to problems such as uneven tension and mismatch of joint stiffness [13];

(4) Weakness in seismic research : There are few application cases in seismic areas, and there is a lack of systematic research on seismic mechanism and design methods.

6.2. Future Research Direction

(1) Multi-scale numerical simulation: A multi-scale model considering soil nonlinearity, joint flexibility and construction process is established by combining finite element method and discrete element method[14].

(2) Intelligent monitoring and control : introducing optical fiber sensing and BIM technology to realize real-time monitoring and automatic compensation of prestress ;

(3) Application of new materials : explore new materials such as high-strength composite cables and self-prestressed concrete to further improve the performance and durability of the system ;

(4) Seismic design method : carry out model test and numerical analysis under earthquake action, and establish a design method suitable for seismic zone.

(5) Standardization and normalization : improve the design, construction and acceptance criteria, and promote the wide application of technology.

7. Conclusion

As a new type of foundation pit internal support system integrating prestressed technology and string structure concept, the fish-bellied prestressed steel purlin shows significant technical advantages in foundation pit engineering. In this paper, through the systematic combing of its structural performance, the following conclusions are drawn :

(1) The fish-bellied prestressed steel purlin can effectively reduce the bending moment and deformation of the support system through the mechanism of 'prestressed active control + rigid-flexible synergistic force ' ;

(2) Stiffness characteristics, force deformation characteristics, stability and deformation control performance are the core indicators to evaluate the performance of the system structure. The introduction of ' equivalent bending stiffness ' provides an effective way for stiffness analysis.

(3) The prestress level, geometric parameters, material properties and construction technology are the key factors affecting the structural performance.

(4) The engineering application shows that the system can effectively control the deformation of foundation pit, shorten the construction period and reduce the cost.

(5) In the future, it is necessary to conduct in-depth research on theoretical models, long-term performance, construction control and seismic design to promote the further development and engineering application of this technology.

References

- [1] Feng, T., Liu, L., Tong, T., et al. (2017). Numerical study on lateral wall displacement of deep excavation supported by IPS earth retention system. *Underground Space*, 2(4).
- [2] Kim, N. K., Park, J. S., Han, M. Y., et al. (2004). Development of innovative prestressed support earth retention system. *Journal of the Korean Geotechnical Society*, 20(2), 107–113.
- [3] Roboski, G. (2004). Behavior of braced excavations. *Journal of Geotechnical and Geoenvironmental Engineering*, 130(12), 1215–1224.
- [4] Park, J., Joo, Y., & Kim, N. (2009). New earth retention system with prestressed wales in an urban excavation. *Journal of Geotechnical and Geoenvironmental Engineering*, 135(11).
- [5] Liang, Z. R., Huang, K. Y., Wei, X., et al. (2023). Application of two fish-bellied steel supports in synchronous construction of adjacent deep and large foundation pits in soft soil areas. *Building Structure*, 53(S1). (in Chinese)
- [6] Sun, W. W., Feng, J., & Gu, L. N. (2022). Collapse resistance analysis of prestressed fish-bellied foundation pit steel supports. *Chinese Journal of Underground Space and Engineering*, 18(3). (in Chinese)
- [7] Lu, X. J., Mi, R. J., & Wang, T. P. (2023). Application of prestressed fish-bellied steel support system in deep foundation pits. *Building Construction*, 45(8), 1524–1527, 1535. (in Chinese)
- [8] Zhuang, S. C., Zhang, J. L., Zhang, C. H., et al. (2021). Study on stiffness of prefabricated prestressed fish-bellied steel support system. *China Civil Engineering Journal*, 54(4). (in Chinese)

- [9] Su, Y. J. (2019). Stability analysis of ultra-long opposite supports in prestressed fish-bellied foundation pit steel support system. *Building Structure*, 49(S1). (in Chinese)
- [10] Liu, J. (2018). Application of prestressed fish-bellied steel supports in optimization design of deep foundation pit support schemes. *Building Structure*, 48(9). (in Chinese)
- [11] Han, Q., Wang, L., & Xu, J. (2017). Test and numerical simulation of large angle wedge type of anchorage using transverse enhanced CFRP tendons for beam string structure. *Construction and Building Materials*, 144, 225–237.
- [12] Zhao, X., Yan, S., Xu, Z., et al. (2015). Research and application of beam string structures. *Structural Engineering International*, 25(1), 26–33.
- [13] Ferraioli, M., Lavino, A., & Mandara, A. (2022). Progressive collapse assessment and retrofit of a multistory steel braced office building. *International Journal of Steel Structures*, 22(4), 1086–1107.
- [14] Zhang, W., Goh, A. T. C., & Xuan, F. (2015). A simple prediction model for wall deflection caused by braced excavation in clays. *Computers and Geotechnics*, 63, 67–72.