

Original Paper

Research on Optimization of Large Span and Large Cantilever Steel Frame Structures

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Abstract

This paper takes the design optimization of a large cantilevered steel frame and a large-span steel frame structure at a school in Jinan as an engineering case, and conducts an in-depth comparison of the significant differences in structural systems, member cross-sections, and steel consumption before and after optimization. Due to the lack of steel structure design experience among the designers, concrete design thinking was improperly applied to the design of large cantilevered and large-span steel structures, resulting in seriously unreasonable structural layout. Although the reinforced concrete frame and steel frame structural systems have similarities in simplified member modeling and force transmission paths, there are significant differences in aspects including beam-slab interaction, joint connection methods, torsional resistance, and seismic performance. For large-span steel frame structures, taking the steel structure roof of a 20-meter-span school auditorium as an example, this study compares and analyzes two schemes: arranging secondary beams along the large-span direction and arranging secondary beams perpendicular to the large-span direction, and draws the conclusion that the scheme with secondary beams arranged perpendicular to the large-span direction can reduce steel consumption by more than 50%. For large cantilevered steel frame structures, taking the 3-meter cantilevered external corridor of the school as an example, through comparative analysis of two schemes: the joint cantilevering of primary and secondary beams and the cantilevering of only primary beams, it is found that the scheme with only primary beams cantilevering can save approximately 30% of steel consumption. The biggest problem of the original scheme lies in its failure to fully leverage the core advantage of low self-weight of steel structures. This case clearly demonstrates that in the design of large cantilevered and large-span steel structures, structural layout scheme is the key factor determining structural efficiency and economic performance. Adhering to the design concept of "light roof, high-performance members" is the fundamental approach to achieve an integrated structural solution that is safe, economical, and reasonable.

Keywords

Large-span steel structure, Large-cantilever steel structure, Design optimization, Structural layout, Load transfer path, Steel consumption, Concrete thinking

1. Introduction

With the rapid development of China's construction industry, steel structures have been widely applied in large-span public buildings including stadiums, convention and exhibition centers, and school auditoriums owing to their prominent advantages such as high strength, light self-weight, excellent plasticity and toughness, and fast construction speed. Compared with traditional reinforced concrete structures, the "lightweight" characteristic of steel structures constitutes their core competitiveness. This advantage is not only inherent to the material itself, but should also be integrated into the design concept of the entire structural system. However, in engineering practice, many designers who have transitioned from traditional concrete design often unconsciously adopt "concrete thinking" in steel structure design, that is, they directly apply the design logic of reinforced concrete frames to steel structures, including excessively conservative load value, uniformly spaced secondary beams, and ambiguous handling of joint stiffness. This mode of thinking ignores the fundamental differences between steel and concrete in mechanical behavior, connection construction, and system efficiency, which easily leads to unreasonable structural layout, roundabout force transmission paths, and bulky joint design, ultimately resulting in a sharp increase in steel consumption and completely negating the core advantages of steel structures.

A school project in Jinan simultaneously incorporates a 20 m-span roof and a 3 m-cantilevered external corridor, whose original design is a typical product of the "concrete thinking". In the optimization design, targeting the two types of problems involving large span and large cantilever, we carried out subversive adjustments starting from the top-level design of structural layout schemes, and achieved a remarkable benefit of 30%-50% reduction in steel consumption. This paper aims to systematically elaborate the methodology for optimization design of steel structures through these two contrasting cases, reveal the mechanical essence behind unreasonable layout, and provide practical references for getting out of the misunderstanding of "concrete thinking" and giving full play to the real efficacy of steel structures. Meanwhile, as two major architectural structural systems, steel frame structures and concrete frame structures each have their own advantages and disadvantages in practical engineering. An in-depth understanding of their similarities and differences is of great significance for rationally selecting structural forms and optimizing design schemes.

2. Diagnosis of Problems in Original Design: Typical Symptoms of "Concrete Thinking"

2.1 Root Causes of Confusion in Structural Systems

In the design of concrete frames, cast-in-place slabs are commonly adopted for floors and roofs, which feature extremely large in-plane stiffness and can effectively coordinate the deformation and force

distribution of all beams. The layout of secondary beams is relatively flexible, and its influence on the overall stress is less sensitive than that in steel structures. Although joints are regarded as rigid connections, their construction implementation and actual stiffness are completely different from those of steel structures. Designers have introduced this habit of "heavy slab + uniformly distributed secondary beams + conceptual rigid connection" into steel structure design.

2.2 Problems with the Original Scheme of Large-span Gymnasium

To reduce the load-bearing area of the longitudinal main girder, the original scheme densely arranged steel secondary beams along the 20 m-span direction (longitudinal direction), dividing the slab into small-span one-way slabs. The structural layout is shown in Figure 2.2.

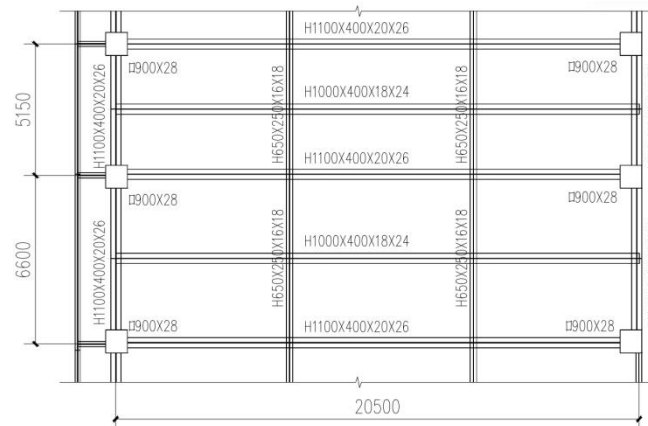


Figure 2.2 Pre-optimization Scheme of Large-span Roof

This scheme has the following deficiencies:

2.2.1 Inefficient force transmission path: Loads are transmitted from the slab to the longitudinal secondary beams, and then to the transverse main beams, resulting in dense concentrated forces acting on the transverse main beams, complex distribution of bending moment and shear force, and thus requiring large cross-sections.

2.2.2 Failure to exploit the material advantages of steel structures: Longitudinal main beams are the key load-bearing components for spanning the design span, but dense longitudinal secondary beams transfer loads to the transverse main beams. Since the secondary beams are hinged at both ends, the advantage of high bearing capacity of steel structures is not fully utilized, leading to low material utilization efficiency.

2.2.3 Vicious circle of structural self-weight: Dense secondary beams lead to excessive structural self-weight, which causes a sharp increase in the seismic action borne by the main structure. This forces the cross-sections of the transverse main beams (H1100 * 400 * 20 * 26) and frame columns (square steel tube 900 * 900 * 28) to become extremely large, resulting in a further increase in structural stiffness, which in turn leads to a vicious circle of additional increase in seismic action.

2.3 Deficiencies in the Original Scheme of Large Cantilevered Corridor

In the original scheme, the cantilevered corridor has a length of approximately 3 m. Following the conventional design mindset used for concrete structures, a co-cantilever scheme of "transverse main beams + transverse cantilevered secondary beams perpendicular to the longitudinal main beams" was adopted to reduce the load on the cantilevered main beams. The structural layout is shown in Figure 2.3.

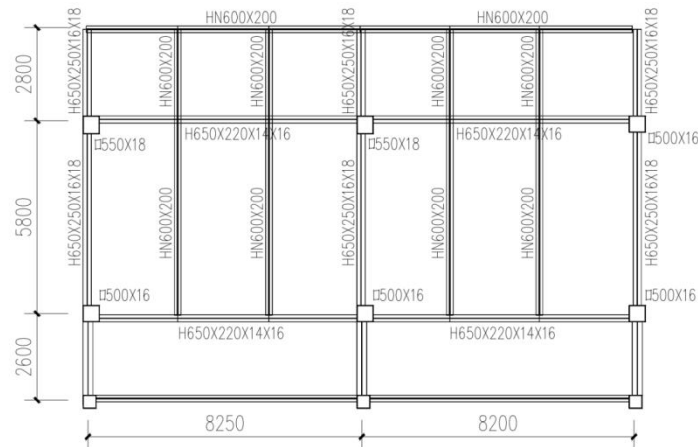


Figure 2.3 Pre-Optimization Scheme for the Cantilevered Corridor

This scheme presents the following issues:

2.3.1 Excessively Long Cantilevered Load Transfer Path: The load is transferred from the slab to the cantilevered secondary beams. These secondary beams then transfer concentrated bending moments and shear forces to the primary beam. Consequently, the primary beam is subjected not only to vertical bending but also to significant torsion, resulting in complex stress conditions.

2.3.2 Sharply Increased Demand for Torsional Resistance: To resist the torsional moments, the primary beam requires high torsional stiffness and load-bearing capacity. This typically necessitates the use of closed sections (such as box girders) or significantly enlarged open sections, both of which are highly material-intensive.

2.3.3 Complex Joint Detailing: The connections between the cantilevered secondary beams and the primary beam must transfer bending moments, requiring moment-resistant (rigid) connections. This leads to demanding requirements for the design, fabrication, and welding of these joints.

3. Optimization Strategies and Scheme Comparison: Returning to Steel Structure Logic

The core of the optimization lies in breaking free from the concrete mindset and reshaping an efficient load transfer path based on the characteristics of steel structures.

3.1 Structural Optimization of the Large-Span Covered Sports Court: A Revolution in Secondary Beam Orientation

Key Optimization Point: Accurately calculate the roof load. Crucially, completely change the orientation of the secondary beams—eliminate those along the large-span direction and instead arrange them perpendicular to the 20-meter main span direction. **The optimized structural scheme is shown in Figure 3.1.**

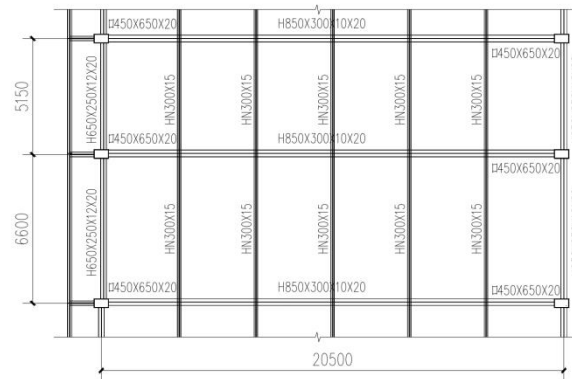


Figure 3.1 Optimized Scheme for Large-span Roof

Optimized Scheme (longitudinal secondary beams eliminated): Small-sized steel secondary beams (purlins) are directly laid on the main beams, and the load of lightweight roof panels acts directly on the main beams in the form of uniform load via the secondary beams. The main beams bear straightforward uniform load, with a smooth parabolic bending moment diagram and clear force distribution.

Optimization Results: After optimization, the force transmission path is simplified as "slab → secondary beam → longitudinal main beam → frame column", eliminating the inefficient force transmission link of "slab → longitudinal secondary beam → transverse main beam → frame column". The main beams change from bearing complex concentrated forces to bearing efficient uniform forces, allowing full utilization of material strength. While eliminating longitudinal secondary beams, the cross-section of longitudinal main beams is optimized from $H1100 \times 400 \times 20 \times 26$ to $H850 \times 300 \times 10 \times 20$, the cross-section of transverse main beams is optimized from $H1100 \times 400 \times 20 \times 26$ to $H650 \times 250 \times 12 \times 20$, and the column cross-section is optimized from 900×28 (square steel tube) to $450 \times 650 \times 20$ (rectangular steel tube), with steel consumption reduced by more than 50%. **Design enlightenment:** For large-span steel frames, the span of secondary members (purlins and secondary beams) should be reduced, and the force-bearing mode of main members should be simplified. Arranging secondary beams (purlins) perpendicular to the large-span direction is the optimal layout to achieve direct and uniform load transfer to main beams.

Design Implication: For large-span steel frames, the span of secondary members (purlins, secondary beams) should be small, and the load-bearing mode of primary members should be simple. Arranging secondary beams (purlins) perpendicular to the large-span direction is the optimal layout for achieving direct and uniform load transfer to the primary beams.

3.2 Optimization of Large Cantilevered External Corridor

Key Optimization Points for Simplification of the Cantilever System: The independent cantilever secondary beams are eliminated, and the layout scheme of "only primary beams are cantilevered, and secondary beams are arranged only in non-cantilevered spans" is adopted. The optimized structural scheme is shown in Figure 3.2.

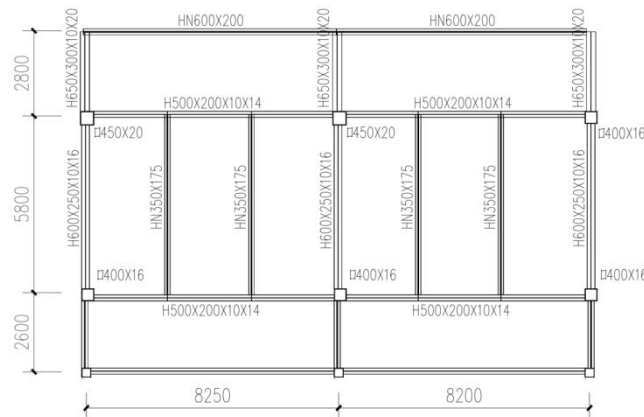


Figure 3.2 Optimized Scheme of the Cantilevered Outer Corridor

Optimized Scheme (only main beam cantilevering): The load on the cantilevered part is directly transferred to the cantilevered main beam through the slab (or a light slab with a small number of secondary purlins). The main beam bears the uniform load at the cantilevered end, acting only as a flexural member with no or negligible torque. The elimination of cantilevered secondary beams also eliminates complex flexural-resistant joints.

Optimization Results: After optimization, the torque acting on the main beam is completely eliminated, restoring the main beam to a clear stress state of pure bending or compression-bending. The section of the main beam can be efficiently designed for bending (e.g., adopting a tall H-shaped steel section), eliminating the extra material cost required for torque resistance. Joints are also simplified to hinged connections or simple rigid connections. After eliminating the cantilevered secondary beam, the section of the cantilevered main beam is adjusted from H650*250*16*18 to H650*300*10*20, the section of the longitudinal main beam is optimized from H650*220*14*16 to H500 * 200 * 10 * 20, the secondary beam section is optimized from HN600*200 to HN350*175, and the column section is optimized from 550*18 (square steel tube) to 400 * 16 (square steel tube), resulting in a steel consumption reduction of more than 20%.

Design Implication: For cantilevered structures, the force transmission path should be as direct as possible to avoid torsion in members. "Direct cantilevering via main beams" is the most concise and efficient structural system. When the cantilever width is relatively large, clearer force transmission methods such as cable-staying and bracket setting should be considered instead of relying on secondary beam cantilevering.

4. From Phenomenon to Essence: Reunderstanding of Structural Differences Between Steel and Concrete Structures

4.1 Similarity in Fundamental Principles

Steel frame structures and concrete frame structures exhibit remarkable similarity in the fundamental principles of structural analysis:

4.1.1 Simplified Member Model

Both structural systems can be simplified into member systems for analysis. Beams and columns, as primary load-bearing components, are connected via joints to form a spatial frame system.

4.1.2 Clear Force Transmission Path

The load transmission path is well-defined: vertical loads are transferred through the floor slab to secondary beams, main beams and columns, and ultimately transmitted to the foundation; horizontal loads are transferred to the lateral force-resisting system through the in-plane stiffness of the floor slab.

4.1.3 Basic Design Principles

Both types of structures are required to meet the requirements of ultimate limit state of bearing capacity and serviceability limit state, and comply with the seismic design principle of "strong columns and weak beams, strong joints and weak components".

4.2 Materials and Differences in Seismic Performance

The optimization presented in this case study essentially corrects design errors induced by neglecting the essential differences between steel structures and concrete structures. These differences are summarized as follows:

4.2.1 Differences in Material Performance

Concrete features superior durability and low maintenance requirements under normal service conditions. It can isolate corrosive media in humid and corrosive environments to protect reinforcing steel bars from corrosion. However, concrete structures have relatively high self-weight. In large-span and large-cantilever structures, the advantages of steel, including high strength and low component self-weight, can be fully exploited.

4.2.2 Synergistic effect of beam and slab

In concrete structures, the cast-in-place slab and the beam work together to form a T-beam or L-shaped section, which provides a large stiffness contribution and exhibits significant beam-slab synergistic effect. This configuration makes the load distribution more uniform and improves the structural integrity. For steel structures, the synergistic effect between the medium steel beam and the roof slab is weak: the roof slab mainly bears vertical loads instead of acting as the flange of the beam, so its contribution shall not be overestimated in design.

4.2.3 Joint Connection Mode and Stiffness

Concrete joints are generally cast-in-place, characterized by high stiffness but strong nonlinearity. Steel joints are connected by welding or bolts, and their stiffness (hinged, semi-rigid, rigid) can be precisely designed to match the calculation model. The connection between secondary beams and main beams

generally adopts hinged joints to simplify the configuration and facilitate construction. Rigid connection is only adopted when bending moment needs to be transmitted, but special structural measures are required. In the original scheme, the assumptions for complex joints may be inconsistent with the actual situation.

4.2.4 Torsion Resistance Capacity

Owing to the cooperative work with the floor slab, concrete beams have strong torsion resistance capacity, and the joints between secondary beams and main beams are generally rigid joints. Open-section steel beams (such as H-section steel) have extremely poor torsion resistance capacity, and torsion shall be strictly avoided in design. This is a key difference from concrete structure design.

4.2.5 Seismic Performance

The generally recommended damping ratio for concrete structures is 0.05; for steel frame structures, a damping ratio of 0.02 can be adopted for structures with more than 12 floors, and 0.035 can be adopted for structures with no more than 12 floors. A smaller damping ratio corresponds to a larger seismic influence coefficient. Under the same natural vibration period and equivalent total gravity load, the seismic action of steel frames is theoretically larger than that of concrete frames. A bulky steel structure designed under the design logic of concrete structures is not only uneconomical, but also leads to unreasonable design due to increased seismic force. After optimization, the self-weight of the structure is significantly reduced, and the seismic action is also significantly reduced, which is more conducive to seismic resistance.

5. Conclusions and Inspirations

The optimization practice of the large-span and large-cantilever steel structure of a school in Jinan has brought the following direct and indirect benefits to the project:

Steel cost saving: The steel consumption is reduced by approximately 30%. The smaller and lighter members lower the difficulty and cost of fabrication, transportation and hoisting, and shorten the construction period.

Foundation cost saving: Due to the reduction in structural self-weight, the load transmitted to the foundation is greatly decreased, which reduces the number of precast square piles by about 20%. The size and reinforcement of pile caps are correspondingly reduced, thus saving concrete and steel reinforcement.

Installation cost saving: The number of steel structure joints is reduced, and the rigid joints of primary and secondary beams are eliminated, which greatly reduces the construction difficulty of joints.

Improved structural safety: The reduction of structural self-weight lowers the seismic action, and increases the seismic safety margin of the structure; smaller member sections can often release more usable space for buildings.

Through the optimization analysis of this structural design, important conclusions at two levels are drawn:

Technical level: In large-span steel frames, arranging secondary beams perpendicular to the span direction is the most economical layout; in large-cantilever steel frames, primary beams shall be preferred for direct cantilevering, so as to avoid torsional effect on primary beams caused by cantilevered secondary beams. This conclusion is determined by the characteristics of steel structure members that they have high bending efficiency but low torsion resistance.

Conceptual design level: Structural layout scheme is the primary factor determining the economy of steel structures, and its importance is even greater than that of member section optimization. Excellent steel structure design starts with careful conception of force transmission paths at the conceptual design stage. Designers must completely get rid of the constraint of "concrete thinking" and not simply transplant the layout habits of concrete structures. An independent design logic based on the material properties, connection characteristics and mechanical properties of steel structures should be established.

The success of this optimized design is ultimately attributed to the adherence to the concept of "light roof, efficient members". Lightweight roof reduces the load from the source; the term "efficient members" does not refer to oversized sections, but enables each member to work on a clear and efficient force transmission path through reasonable structural layout, so that the material strength can be fully utilized, thereby achieving a safe, economical and reasonable overall structure. This concept should be taken as the basic criterion for all steel structure designers.

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