Application of Modular Construction in Non-modular Design Civil Steel Structure Buildings

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Abstract. With the demand for carbon neutrality, adopting a high assembly rate in modular buildings has become the development trend in China's civil buildings. This paper analyzes non-modular design examples in civil steel structure buildings, summarizing the principles of modular decomposition and temporary support system design. The wheel-buckle scaffold system, independent support system, and foldable steel structure support system were selected for finite element simulation. The simulation results indicate that an independent support system should be chosen for high load-bearing capacity and rigidity requirements scenarios. A lifting analysis is also conducted for a decomposed module in the case study. Combining modular decomposition, temporary support systems, and lifting point selection methods, an application framework is further proposed. This framework will contribute to achieving modular construction in non-modular design civil steel structure buildings and promote the development of prefabricated construction.

Keywords: Modular construction; Civil building; Modular decomposition; Temporary support; Hoisting construction

1 INTRODUCTION

Driven by national policies and industry demands, China's prefabricated steel structure construction has rapidly advanced from the 1.0 to the 2.0 era [1]. Building upon traditional steel structure forms, a new improved architectural system has been developed, including modular construction systems and industrialized residential construction systems [2]. Generalova et al. analyzed advanced modular construction experiences worldwide and demonstrated their feasibility [3]. Over the past decade, some researchers have applied modular structures to steel construction. 2010 Junming adopted modular construction methods in the first KR molten iron pretreatment project at Laigang [4]. Feng et al. utilized modular construction for the main structural steel frame in

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constructing the 2019 JUMBO petrochemical project in the United States [5]. These studies and practices indicate that modular construction can accelerate progress, reduce costs, and represent an essential direction for developing civil steel structure buildings. In recent years, many scholars have researched modular construction for civil buildings. Liew et al. researched the design and construction of modular structures in high-rise buildings [6]. Deng et al. researched modular connections [7]. Wang et al. studied the modular design of structures [8]. However, current research primarily focuses on the structural aspects of modular design, and there has been limited in-depth exploration into how non-modular designed buildings can achieve modular construction. For non-modular designed buildings, their structural characteristics often do not fully align with the adaptability of modular construction. It is worth mentioning that civil buildings, as a building type with a significant market share, would undoubtedly undergo a revolutionary transformation if modular construction is successfully implemented. This helps drive the transition of civil building construction from traditional labor-intensive methods to technology-intensive approaches and enhances the industry's overall competitiveness.

In this paper, we take the standard floor of Building 12 in the Lantai Apple Gar-den renovation project as an example. It was divided into six modules, with a focus on Module One. Three commonly used temporary support systems suitable for lightweight steel structures were selected. Stress analysis of these three temporary support systems was using SAP2000. A finite element simulation was performed to determine the optimal lifting points for Module One and achieve a complete modular construction process. Finally, an application framework was proposed for modular construction of non-modular design civil steel structure buildings.

2 MODULAR DECOMPOSITION OF STEEL STRUCTURE

We take the standard floor of Building 12 of the Lantai Apple Orchard shantytown renovation project as an example. We have summarized the following modular decomposition principles: (1) Reasonable load distribution: The modular decomposition of steel structural modules should ensure reasonable load distribution, and adequate load transmission. (2) Transportation conditions: Taking into account the dimensions and weight of the components, it is necessary to meet the restrictions of transportation routes, bridges, and tunnels. (3) Lifting capacity: Considering the lifting capacity of on-site lifting equipment, the weight and dimensions of the steel structural modules should be reasonably divided. Fig 1 shows the modular decomposition scheme of the standard floor in the project, which is divided into six modules in total. Module One was selected as the object of further research in the subsequent design of temporary support systems and lifting studies.

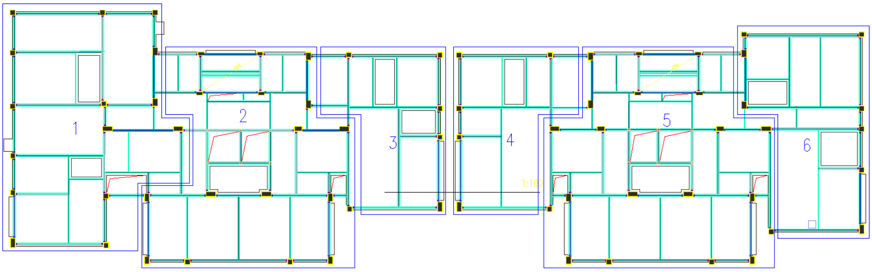

Fig. 1. Modular decomposition scheme for standard layer

3 TEMPORARY SUPPORT SYSTEM FOR MODULAR CONSTRUCTION

Based on the characteristics of lightweight and small spans in civil steel structure buildings, we have chosen the following three support systems:

(1)Wheel-buckle scaffold system.

The wheel buckle bracket system's load-bearing performance is numerically simulated using the SAP2000 frame element. In the wheel-buckle scaffold system model, frame elements were used for the horizontal beams and vertical columns, and the connections between the longitudinal and transoms were simulated using end releases. We calculated the maximum stress of the vertical columns as 210 MPa, with a maximum vertical deformation of 2.8 mm. The deflection requirements refer to the "Code for Design of Steel Structures" (GB 50017-2017). Fig 2 shows the vertical maximum deformation diagram of the first three buckling modes of the structure, and the first three buckling coefficients of the wheel-buckle scaffold are all around 5.

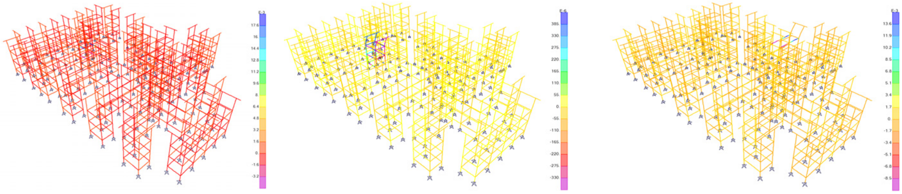

Fig. 2. Vertical deformation diagram of the wheel-buckle scaffold system

(2)Independent support system.

The load-bearing performance of an independent support system is numerically simulated using the SAP2000 frame element. The maximum stress in the independent support system is calculated to be 114 MPa, and the maximum vertical deformation is 2.34 mm, meeting the deflection requirements. Fig 3 displays the vertical deformation diagram of the first three buckling modes in the independent support system, with buckling factors around 1.1.

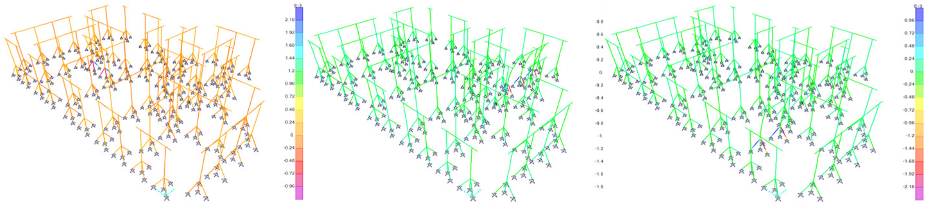

Fig. 3. Vertical deformation diagram of the independent support system

(3)Foldable steel structure support system.

The structural properties of the foldable steel structure support system are numerically simulated using the frame element of SAP2000. The maximum stress obtained was 120 MPa, with a maximum vertical deformation of 2.86 mm, meeting the deflection requirements. Fig 4 shows the vertical maximum deformation diagram of the first three buckling modes of the lightweight steel bracing system, and the bracing system will experience buckling at approximately 29 times the normal service load.

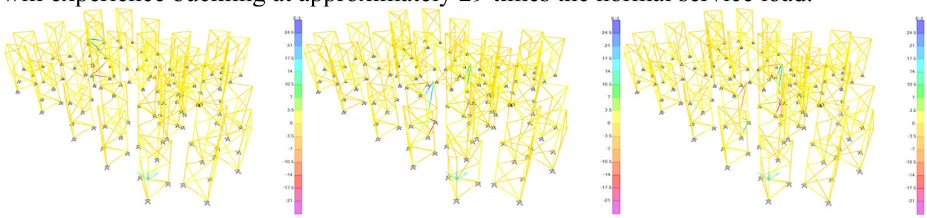

Fig. 4. Vertical deformation diagram of the foldable steel structure support system

4 MODULAR LIFTING OF STEEL STRUCTURE

The selection and distribution of lifting points must ensure that the structure, after being lifted, undergoes axial relative deformation equal to or close to zero under self-weight. We use SAP2000 to preliminary calculate the optimal lifting point height for Module One (Fig 5). The beam-column structure is modeled using frame elements, and the lifting cables are simulated using cable elements. When defining load cases, we mainly consider the self-weight load of the structure and the impact load during lifting, with the magnitude of the impact load considered 30% of the self-weight. Through calculations using various lifting schemes, we have determined the position that results in the most minor deformation and stress on the structure.

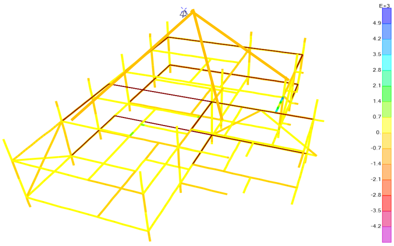

Fig. 5. SAP2000 simulation diagram

Based on the research process, we propose a framework for applying modular steel structure construction in civil buildings. The framework is shown in Fig 6.

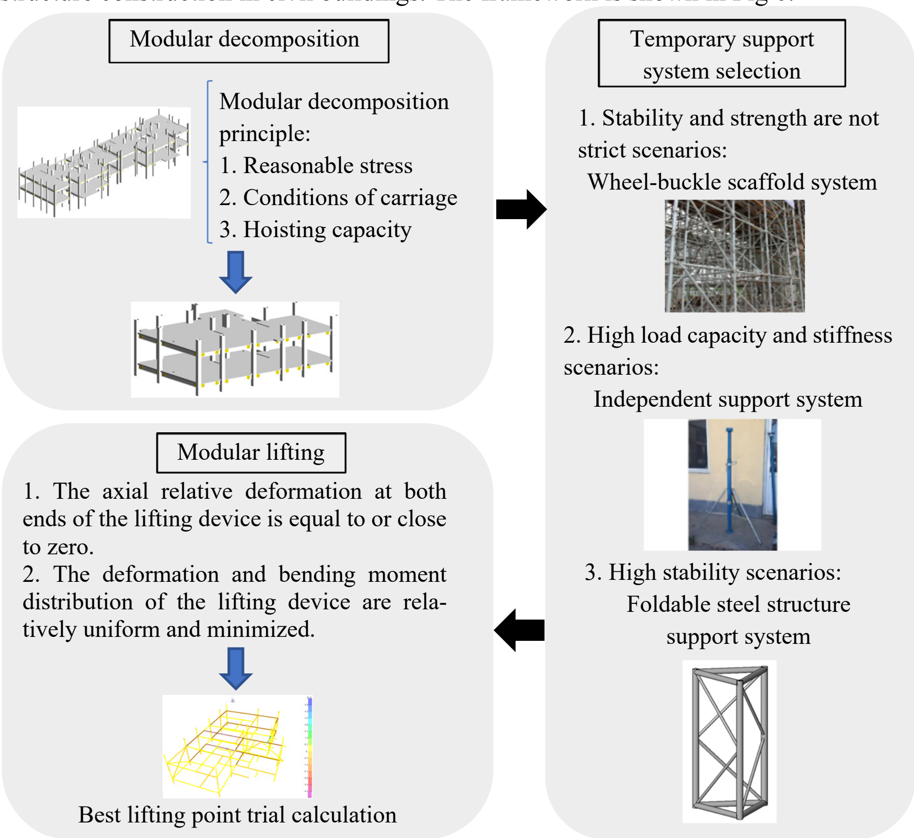

Fig. 6. Civil building steel structure modular construction framework

5 CONCLUSION

This paper analyzes the modular construction of civil buildings with non-modular design, and the specific conclusions obtained are as follows:

1. Due to civil buildings' design complexity and lightweight nature, each project needs to achieve modular construction based on its structural characteristics.

2. Selecting an appropriate temporary support system ensures project safety and stability. The independent frame support system suits scenarios with high load-bearing capacity and stiffness requirements. In contrast, the folding lightweight steel support system suits scenarios with high stability requirements.

3. When carrying out modular lifting, it is necessary to select a reasonable lifting scheme through actual working conditions and perform calculations to ensure the safety of the lifting process.

In addition, our research has certain limitations. Our primary focus is on studying civil buildings that utilize steel frame cores. Further research is needed for civil buildings that employ other structural types. This will help drive the development of modular construction technology more effectively and contribute more to innovation and progress in the construction industry.

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