

Research on the Connection of Modular Steel Construction

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Abstract. With the development of the construction industry, the market is increasingly pursuing efficient and energy-saving building models. Modular steel building is one of the main forms and has become an important development trend of future architecture. In the design and construction of modular steel buildings, the connection between modules is one of the most critical links. The research of the connection of modular steel building is mainly embodied in the connection structure, force transfer mechanism and experimental testing. In this paper, according to the structural differences, the connection of modular steel buildings is divided into bolt connection, self-locking connection and prestressed connection, and each connection form is explained and analyzed in detail. The results show that although the current modular steel building has carried out various innovations in the structure of connections, some methods are still lacking of practical engineering verification. Future studies are necessary to test their ease of installation and reasonableness of force transfer.

Keywords: Structural Engineering; Steel Structure; Module Construction; Connection.

1. Introduction

Due to relatively low labor costs in some countries, traditional construction methods using on-site poured structures and brick walls are still widely employed. However, the inefficiency of these construction methods has become a barrier to economic growth in the construction industry, and with the continuous rise in labor costs, their financial advantages are gradually diminishing [1].

Modular construction is a method that can overcome this issue. Modular construction provides several advantages over conventional construction processes, including faster and safer manufacturing, better predictability of completion time, superior quality, fewer workers on site, reduced resource wastage, and a more environmentally friendly solution [2]. This construction method can lower costs when building high-rise structures, which is a promising solution to the challenge of providing affordable residential housing for various population groups in densely populated urban areas [3]. For example, since 2014, the Singaporean government has mandated the use of modular construction for certain residential buildings. These projects have proven to save an estimated 60% of construction time and 40% of labor resources compared to traditional construction methods [1].

Modular construction can effectively address the need for rapid construction of temporary structures in exceptional circumstances. For instance, in 2022, China successfully constructed the Huoshenshan Hospital, covering an area of over 30,000 square meters, within just ten days as part of its response to the COVID-19 pandemic. This advanced construction technology played a crucial role in providing timely medical facilities, thus saving invaluable time for countless patients [4]. The design of connection plays a pivotal role in modular construction, as the reliability of these connections directly determines the overall structural performance. To achieve optimal results, connection designs must not only ensure structural integrity but also facilitate efficient construction processes. Furthermore, they should seamlessly integrate with the interior finishes and functional requirements of the modules, thereby supporting both structural and operational objectives [5].

This paper presents an overview of the current research on connection in steel modular construction, highlighting existing shortcomings. It also provides an outlook on future research directions in this field, aiming to offer valuable insights for the design and engineering applications of such structures.

2. Bolt Connection

To enhance efficiency, cost-effectiveness, and flexibility in installation, bolted connections are the most used method in practical engineering applications. Since the mechanical properties of each module have been confirmed, the focus of the connection between modules lies in how the modules are joined together. For the connections between modular buildings, they can primarily be classified into column-column connections and beam-beam connections.

From a mechanical perspective, beam-beam connections may lead to errors in the mechanical model assumptions during the design phase, potentially misjudging the effective length of the columns, which could compromise the safety of the final design. Although adding bolts for constraints may enhance the mechanical performance of the columns, this increases the number of bolts required, which in turn affects construction efficiency. Furthermore, the presence of more bolt holes increases the tolerance, negatively impacting the lateral stability of the building. Additionally, due to the requirements for internal wall surfaces, the existence of these bolt holes is undesirable [1]. Therefore, more attention is focused on column-to-column connections. Based on the position of the column, connections can be categorized into corner connections, external connections, and internal connections. Different connections have varying connection details between modules, resulting in distinct structural performance and loading conditions. Furthermore, it is essential to ensure that the location of the connection is as far as possible outside the module, in order to avoid affecting the interior of the already integrated modular building [1].

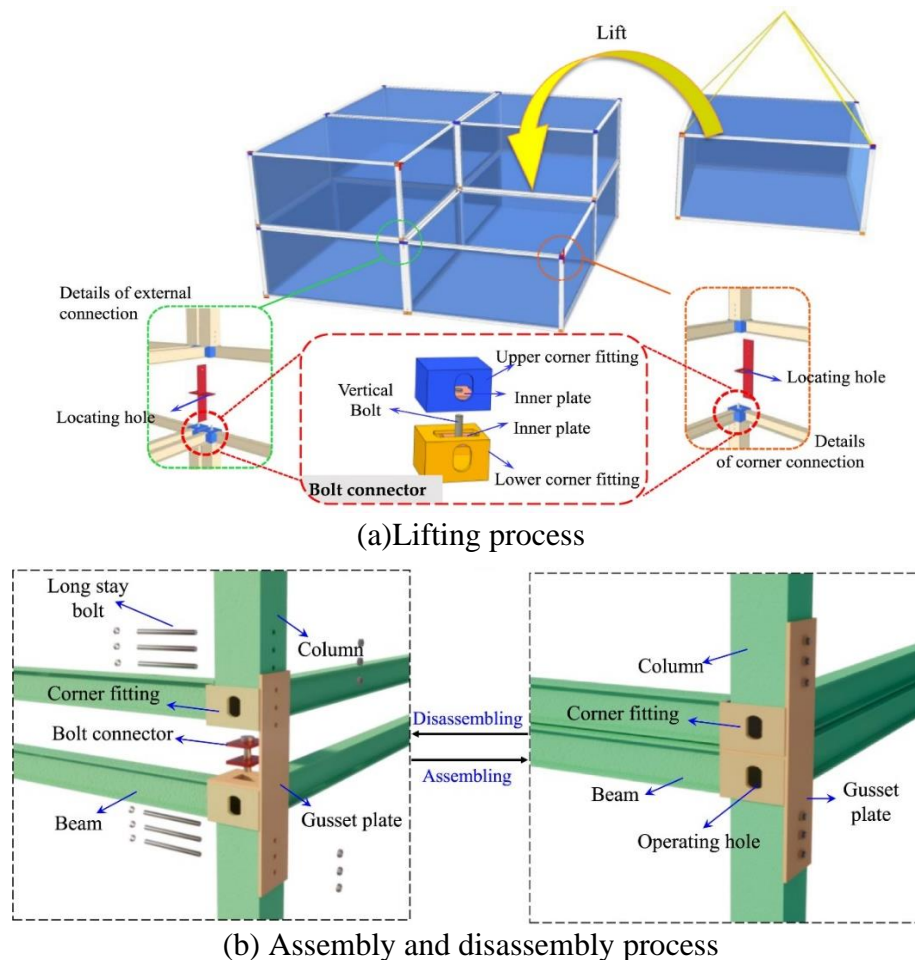


Fig 1. Details of the fully prefabricated liftable connection [6].

Lawson et al. proposed a typical single-bolt connection, which involves creating construction holes at the ends of the upper and lower columns and connecting them using high-strength bolts [7]. The advantage of this method is that the connection can be arranged on the exterior of the modular building, without affecting the construction process. However, the disadvantage is that the presence

of the holes leads to a reduction in the stiffness of the column ends. Moreover, this method is not suitable for internal connections. Deng et al., building on Lawson et al.'s work, designed the fully prefabricated liftable connection, as shown in Fig. 1 [6]. This design adds a corner fitting at the end of the column, with holes at the end, allowing it to be directly lifted and installed during construction. Large holes are also provided on the side for securing the connection. However, this design also cannot be installed on internal connections. Similar designs have also been proposed by Shi et al [8].

For internal connections, most bolted connections consider beam-to-beam connections, including the cruciform plate bolted connection design by Park et al. Deng et al. designed a cruciform plate bolted connection with a tenon-and-mortise mechanism. However, due to its relatively weak capacity to transfer horizontal forces, as well as the issues mentioned earlier, this type of connection is not considered an ideal choice [9].

For traditional steel structure, the most common connecting method is welding. However, for welded connections, since they require on-site operations, they do not align well with the concept of rapid construction in modular buildings. Therefore, most connections are made by combining welding with bolted connections. Annan et al. [10] proposed a full-welded connection between modules with inclined braces. This connection directly welds the upper and lower modules together through a column cover plate, resulting in improved mechanical performance. Deng et al. [11] proposed a hybrid connection method combining bolts and welding, as shown in Fig. 2. High-strength bolts are used to connect the columns to the base plate, and the base plate is welded to the column, thereby enhancing the stiffness of the column ends.

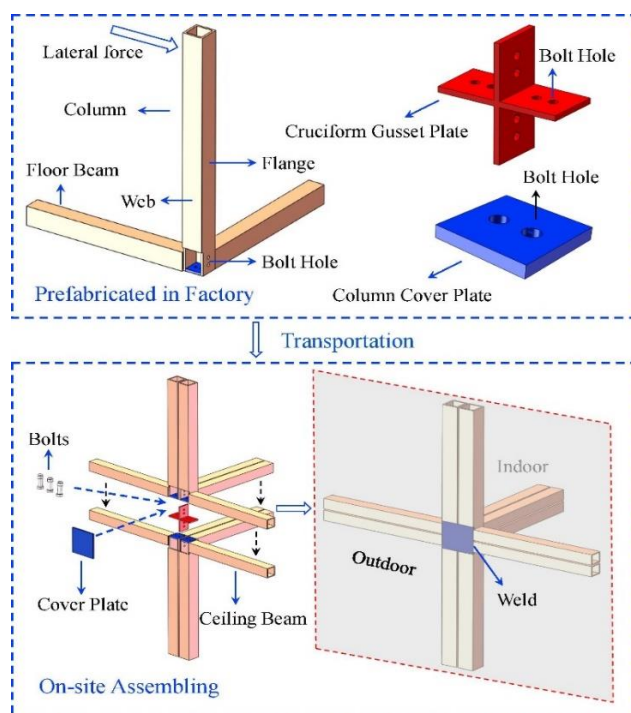


Fig 2. Conceiving of the innovative connection [11].

3. Self-locking Connection

Self-locking connections are an innovative type of connection, primarily used in situations where installation space is limited and high installation efficiency is required. Many scholars have conducted innovative research on self-locking connection joints in recent years.

Dai et al. innovated a self-locking connection method, where the stud at the lower column end is inserted into the threaded hole of the upper column with matching threads to form the connection, as shown in Fig. 3 [12]. Seismic tests revealed that the failure of the beam-column connection occurred before the column-column connection, meeting the "strong-column-weak-beam" requirement. However, alignment during installation can be challenging.

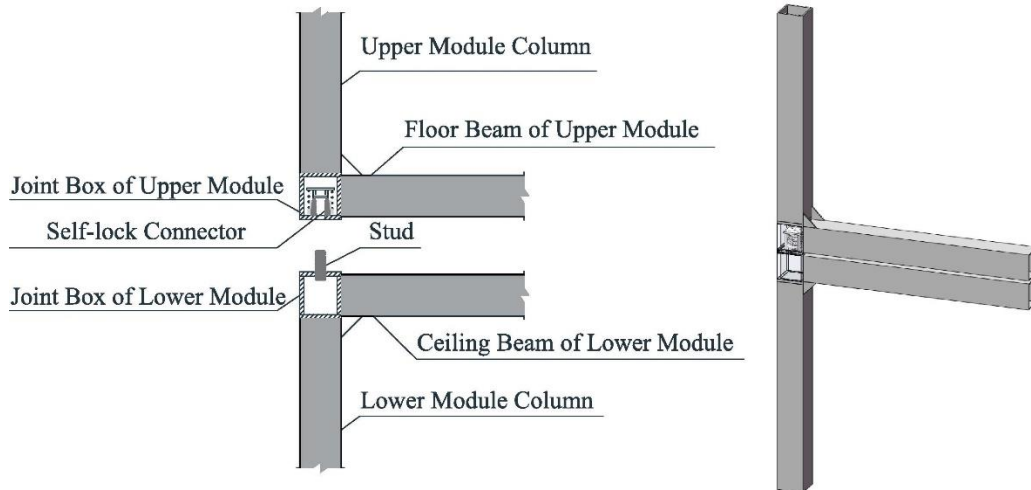


Fig 3. Plug-in self-lock joint [12].

Chen et al. proposed a connection method using locktabs with springs at the lower column end [13]. The columns of the upper module are inserted into the lower module's column, and a gusset plate is placed between the columns to enhance the overall integrity, as shown in Fig. 4. The shape of the gusset plate varies depending on the column position. Under horizontal loading, the joint connection remains stronger than the beam-column connection.

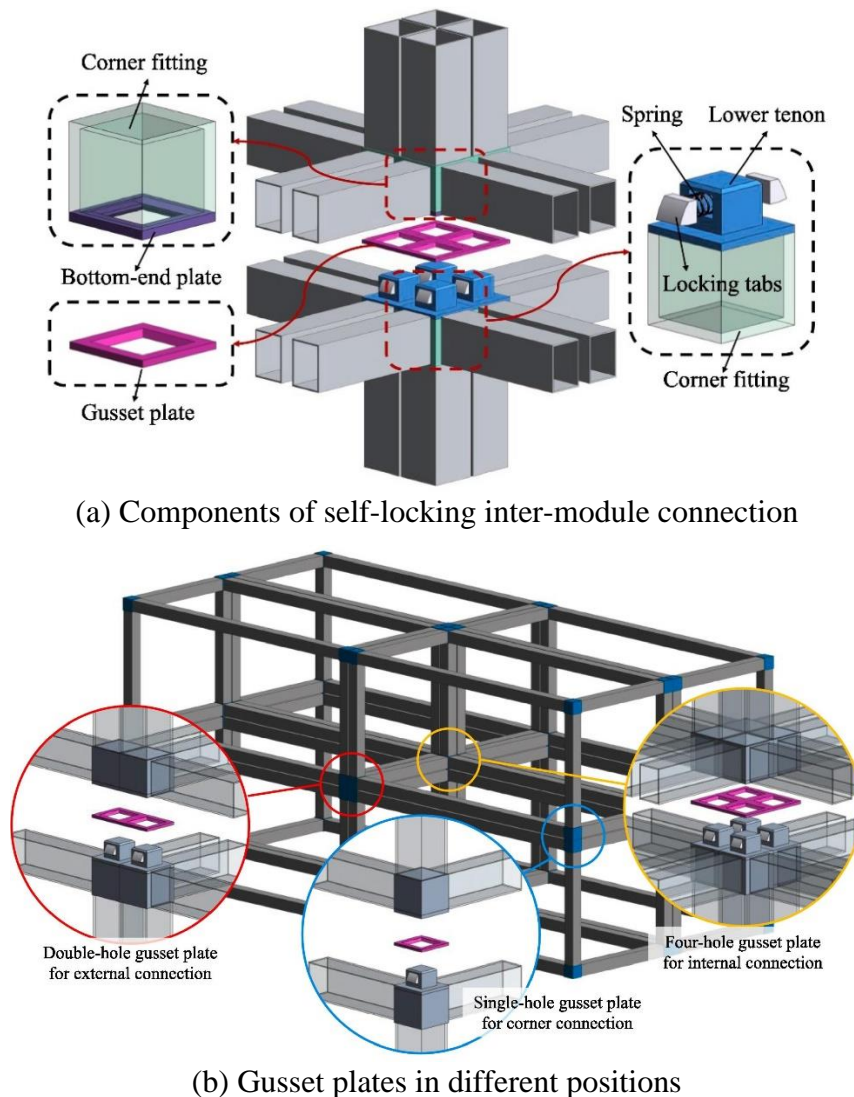


Fig 4. Details of self-locking inter-module connection [13].

There have been many innovations in self-locking connections, with the advantage of not affecting the interior decoration of the modules. At the same time, the strength of these connections is ensured. However, their actual performance in real-world engineering projects still needs further validation.

4. Prestressed Connection

Restressed connections are achieved by placing several tensioned steel bars or cables from the foundation to the top of the building at the corner columns. This method enables the building to better resist external tensile forces during loading, thereby enhancing the overall integrity of the structure. Chen et al. designed a restressed connection method suitable for high-rise buildings [14]. In this design, concrete is poured into the corner columns, and for each floor, two steel bars are placed along each of the four sides of the corner column. Fig. 5 shows its detail. Shear blocks are also provided to resist shear forces. In the seismic tests, the inter-story inclinations were all within the limits for small and medium earthquake levels specified in the design code. However, the construction complexity was greatly increased.

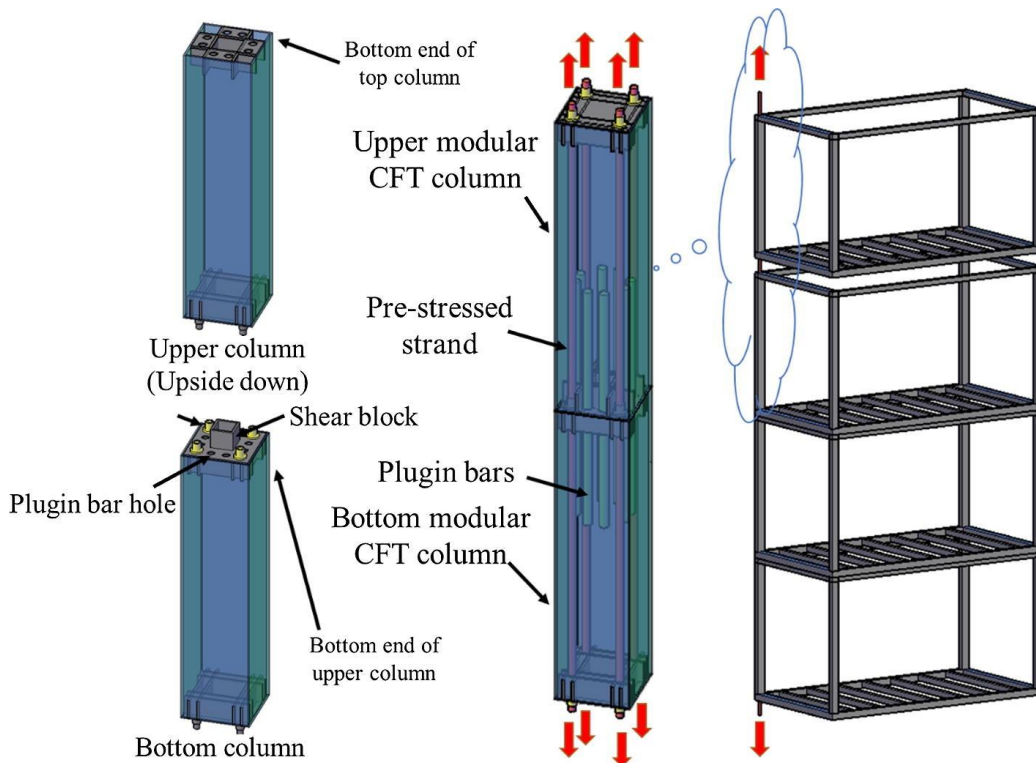


Fig 5. Construction detail of pretension connection [14].

5. Conclusion

This paper reviews the various connection forms of steel structure module connections and analyzes their advantages and disadvantages. From the review, it is evident that bolted connections are currently the most used type. However, due to the lack of column-to-column connections in internal connections, the number of bolts required for bolted connections is higher compared to other connection types to meet the strength requirements of the columns. Additionally, welding connections involve significant on-site construction work, making them less suitable for modular construction. Self-locking and prestressed connections are new types of connections, which have been validated through mechanical experiments to meet the requirements, but their performance still needs to be verified in actual engineering projects. Overall, the development of modular building connection connections continues to focus on reducing construction effort while ensuring strength.

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