Title: **Applying Ancient Structural Principles To a New Prefabricated Steel System**

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Subject: Structural Engineering

Keywords: Prefabrication
Seismic
Steel

Publication Date: 2018

Original Publication: CTBUH Journal, 2018 Issue I

Paper Type:
1. **Book chapter/Part chapter**
2. Journal paper
3. Conference proceeding
4. Unpublished conference paper
5. Magazine article
6. Unpublished

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Abstract

Numerous ancient timber structures located in high seismic zones of China are still standing today, long after experiencing strong earthquakes over hundreds of years. One of the important factors in their longevity is the adoption of the mortise-and-tenon joint as the main connection system. The seismic deformation and sliding friction between the tenons and mortises of timber structures can transfer and absorb seismic energy, such that timber structures exhibit excellent seismic performance. Based on the same concept, the authors propose applying a similar joint within a steel frame structure: a new prefabricated steel structure system that adopts connections similar to those of the mortise-and-tenon joints in timber structures.

Keywords: Mortise-and-Tenon Joint, Seismic Performance, Steel Structure, Prefabrication, Modularization, Bolt/Weld-Less Installation, Structural Steel Adhesive

Introduction

Since the annual steel production of China exceeded 100 million metric tons in 1996, China has been the largest steel producer in the world for the past 20 years. In 2016, the annual steel production was more than one billion metric tons, which accounted for about 50% of overall world steel production. However, the ratio of structural steel (excluding rebar) used in the building industry represents only about 5% to 6% of the total steel production in China, compared with a ratio of 20% to 30% in other developed countries. There exists a great potential for further development (Yue 2016; Zhang & Zhang 2016).

In order to fully capitalize on the advantages of steel buildings, and to upgrade the ratio of structural steel used in the building industry in China, innovation in the methodology, fabrication, and installation technologies of structural systems is required.

To achieve these targets, this paper proposes that mid-rise and high-rise buildings be supported with a new prefabricated steel structure system, with connections similar to mortise-and-tenon joints used in timber structures. The main structural components of this system could be easily and accurately installed on-site, without any bolted or welded connections.

Seismic Performance of Ancient Timber Structures with Mortise-and-Tenon Joints

Origins of the mortise-and-tenon structure

The Hemudu site, in Yuyao, China dates from the Neolithic Age, more than 7,000 years ago. Since archaeological excavation began in 1973, a high number of tenons and mortises have been found at the site (see Figure 1). This indicates that the technology had already been skillfully mastered and widely adopted to build dwellings at that time (Gao, Zhao & Xue 2008).

Seismic performance of existing ancient timber structures in China

The Yingxian Wooden Tower, constructed in 1056, is located in Shanxi province (see Figure 2). The tower, octagonal in plan is 67.3 meters high and has a bottom diameter of 30.3 meters. All the connections of the tower are mortise-and-tenon joints, and there are no iron connectors or nails. It is still intact after having suffered many strong earthquakes, including more than 10 earthquakes with a seismic intensity exceeding 5.0 on the Richter Scale (Gao, Zhao & Xue 2008).

The Nanchan Temple, also located in Shanxi, is the world's oldest wooden structure. The Great Buddha Hall, which is 11.75 meters long and 9.9 meters wide in plan, was constructed in 782 (see Figure 3). During the past 1,200 years, it has endured eight 5.0-plus-intensity earthquakes without sustaining damage (Zhuang & Tang 2009).

The Hall of Supreme Harmony inside the Forbidden City (Palace Museum) of Beijing was first completed in 1420, and then reconstructed after suffering several fires (see Figure 4). The current structure was constructed in 1695. It is 26.9 meters high, 64 meters long, and 37 meters wide. After reconstruction, it survived seven strong earthquakes with a seismic intensity of 6.0 or higher, and whose epicenter was less than 90 kilometers away. During an 8.0-magnitude quake in 1679, no damage occurred, even though the epicenter was only 45 kilometers away (Zhou et al. 2013).

The Yingxian Wooden Tower has been certified as resistant to a 7.0-magnitude quake, and the Nanchan Temple and The Hall of Supreme Harmony are rated to withstand an 8.0-magnitude event. All these timber structures are still standing after suffering several strong earthquakes in the past hundreds of years, and have clearly proven the excellent seismic performance of timber structures, largely on account of the mortise-and-tenon connections used in all three structures. The deformation and frictional sliding between tenons and mortises, combined with the light weight, good ductility, and strong energy dissipation capacity of the system, allowed the buildings to balance, absorb and ultimately dissipate the seismic energy they experienced, and preserved their integrity (Gao, Zhao & Xue 2008; Zhuang & Tang 2009; Zhou et al. 2013).

Recent Applications and Existing Drawbacks of Prefabricated Construction

Prefabrication in construction is a priority of the Chinese government. Li Keqiang, Prime Minister of China, recently called for an increase in prefabricated construction during the State Council Executive Meeting in September 2016. However, most of the completed prefabricated buildings to date are reinforced concrete (RC) structures. There are still very few steel structures, and these are mainly limited to single-story industrial plants and low-rise residential buildings. But there exists a great potential for developing prefabricated steel structures for use in more ambitious buildings.

Prefabricated steel members are generally connected by high-tension bolts or welds, while prefabricated RC members are connected on-site by concrete pouring or cement grouting. On-site assembly of either system is very time-consuming and labor-intensive. These challenges not only affect construction quality, but also increase construction costs, and increase the amount of crane time and the potential for accidents.

Figure 1. Timber structure remnants found at Hemudu site in Yuyao, showing mortise-and-tenon joint connection. Source: China Daily.

Figure 2. Yingxian Wooden Tower, Shanxi province, China. © Gisling (cc by-sa)

Figure 3. Nanchan Temple, Shanxi Province – the Great Buddha Hall. © Zeus1234 (cc by-sa)

Figure 4. The Hall of Supreme Harmony, Forbidden City, Beijing. © Rbs003 (cc by-sa)

> **“The authors believe the proposed prefabricated steel structure system is applicable to tall buildings up to 150 meters; with further improvement, it could be applicable up to 300 meters.”**

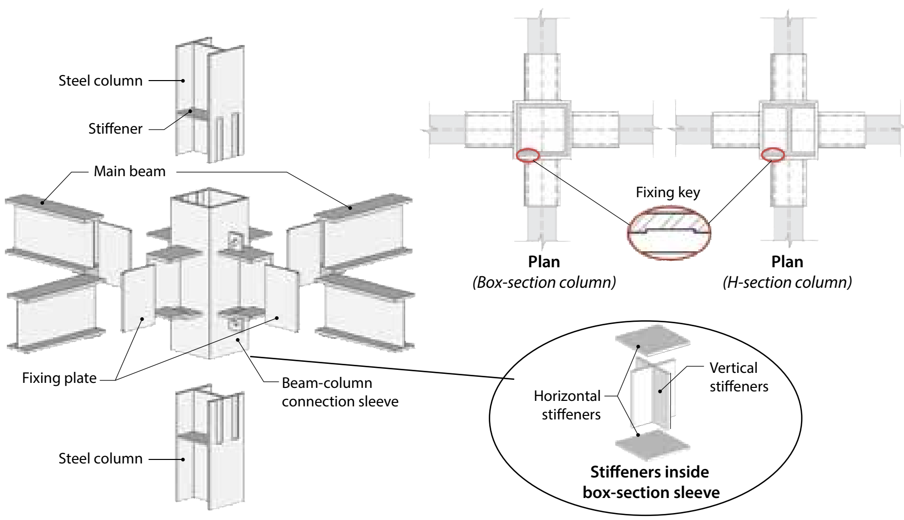

Figure 5. Disassembled components for a beam-column joint.

Adopting the Mortise-and-Tenon Approach for High-Rise Steel Structures

General introduction

The proposed prefabricated steel structure system could easily realize the goal of bolt/weld-less installation on-site. Its main features are described below:

1. Prefabricated special beam-column connection sleeves, patterned after the wooden mortise-and-tenon joint, would be used to connect lower columns, upper columns, and main beams together.
2. Prefabricated special main-secondary beam connection sleeves would be used to connect secondary and main beams, based on the dovetail joint.
3. The sleeves are typically around one meter long and relatively lightweight, with smaller components; in theory, they could be easily and accurately prefabricated in a factory. High-quality mass production is achievable.
4. It could simplify the prefabrication process for primary steel members. Steel columns , main beams, and secondary beams only need to be cut to the designed length, and be fitted with planed grooves at both ends if necessary. Dovetail tenons can be added where necessary.

Beam-Column Connection Sleeve

Figure 5 shows a typical beam-column connection sleeve that could connect the upper column, lower column, and main beams together. Steel gusset plates for fixing the rebar brace with slot holes could be pre-welded at the corners of the sleeve if necessary.

The beam-column connection sleeve consists of a central box-section sleeve, two or more C-section sleeves perpendicular to the sides of the box-section sleeve, and main-beam fixing plates. Inner horizontal stiffeners are pre-welded inside the box-section sleeve. The size of the box-section sleeve and C-section sleeve depends on the size of the connecting columns and main beams. Sunken fixing grooves are provided at the bottom flange of the C-section sleeve to prevent the longitudinal movement of the main beam, and main beam fixing plate would be installed at the open side of the C-section sleeves, to form a box-section sleeve to prevent the transverse movement of the main beam.

Upper and lower column connection

There are two types of column-to-column joints. The first type uses upper and lower columns of the same sectional size. In this case, the dimensions of the upper and lower part of the box-section sleeve are the same (see Figure 6). For the second column-to-column joint, the sectional size of the upper column is smaller than that of the lower column. This type of joint can be derived from the first type.

If the fabrication tolerance is relatively large, or there is a desire to ensure the steel column ends stay firmly locked with the box-section sleeve, a convex shape inside the box-section sleeves, coupled with a groove on the surface of the steel column ends, could be prefabricated to further enhance the interlocking. As an alternative, a structural steel adhesive also could be applied to the contacting surface of the box-section sleeve and steel column end, such that they can stick together firmly. Both methods could effectively enhance the overall seismic resistance and ductility of the connection.

The installation sequence for a beam-column joint is simple and easy. After fixing the lower column, first, place the lower box-section sleeve into the upper end of the lower column, and then install the connecting main beams (a detailed installation sequence is presented in the coming section). Lastly, place the lower end of the upper column into the upper box-section sleeve. The column section could be either a box shape or H-section. If

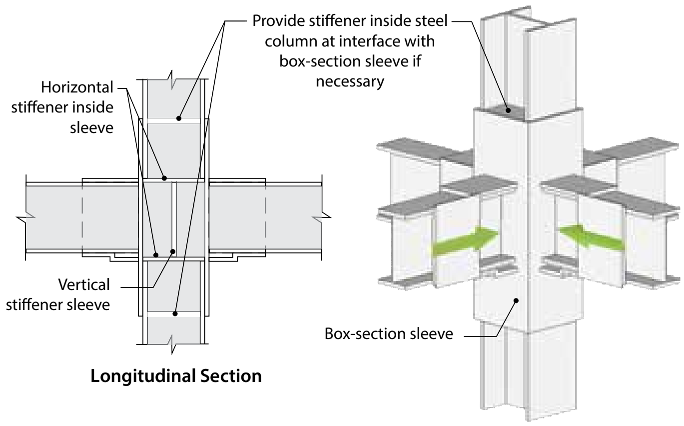

Figure 6. Beam-column joint for identical upper and lower columns.

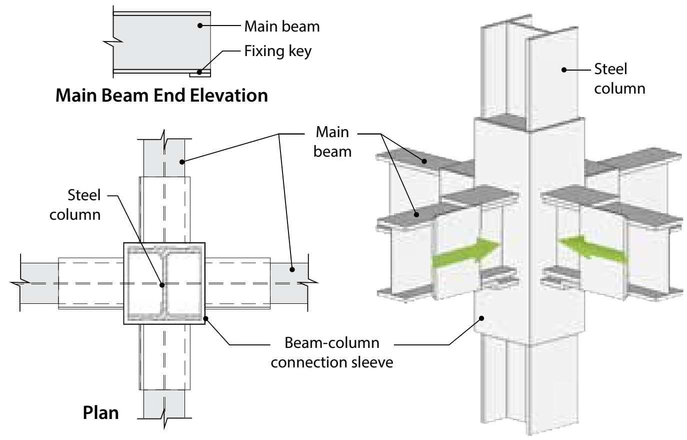

Figure 7. Connection between column and main beams.

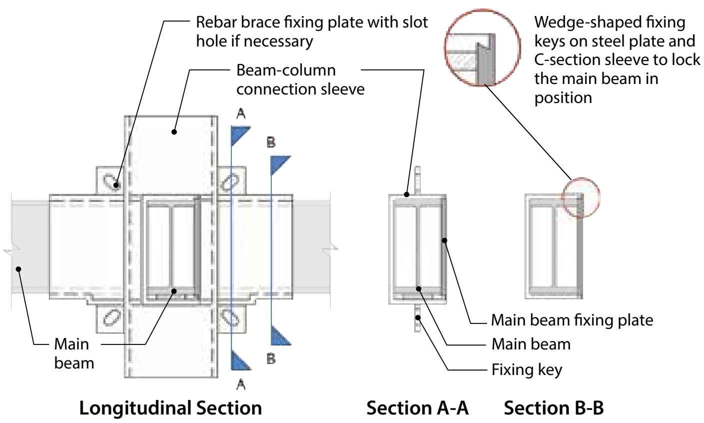

Figure 8. Elevation of the main beam and connection sleeve.

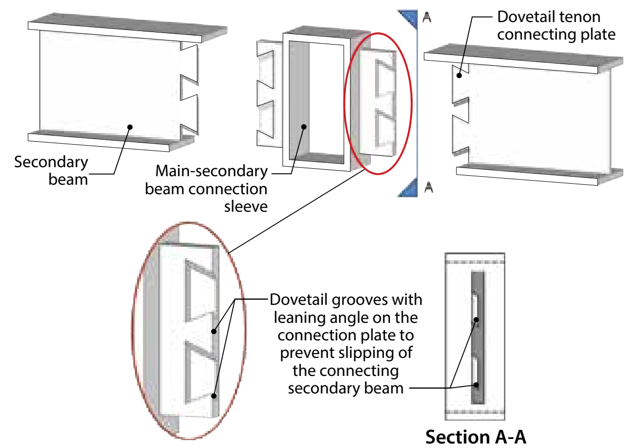

Figure 9. Disassembled components for a main-secondary beam joint using dovetail mortise connecting plate.

necessary, a steel shim plate could be used for fine-tuning the column position.

Column and main beam connections

The main beam could be either an H-section or a box section. Figure 7 demonstrates the connection between the middle column and main beams. The installation sequence for the edge and corner columns is the same.

The installation sequence of a main beam is as follows: first, hoist the main beam to the designated position, and then push both ends of the main beam horizontally into the corresponding C-section beam-column connection sleeves. Finally, insert the main beam fixing plate into the open sides of the C-sections, to form an enclosed box section, and fix the main beam in the correct position. Wedge-shaped fixing keys (see Figure 8) are provided at the open side of top and bottom flanges of the C-section sleeve to prevent lateral movement of the main beam.

When the structure is under seismic or wind loadings, the main beams are also subjected to axial forces. To prevent the main beams' longitudinal movement, fixing grooves are provided at the bottom flange root portion of the C-section sleeves; fixing keys are provided at the end bottom flanges of the main beams. If necessary, a steel shim plate or structural steel adhesive could be used to enhance the overall seismic resistance and ductility of the joint.

Main-secondary beam connection sleeve

There are two types of main-secondary beam connection sleeves. The first one is a dovetail tenon, as shown in Figure 9. This type of main-secondary beam connection sleeve consists of a short central box-section sleeve and dovetail groove, with a leaning-angle connecting plate at one or both sides. The dovetail groove with leaning angles on the connecting plate could prevent both lateral and longitudinal movement of secondary beams. Corresponding dovetail tenons with leaning angles at the ends of the secondary beam are prefabricated, such that they can be interlocked firmly with the connecting plate of the main-secondary beam connection sleeve. Figures 10 and 11 demonstrate the cases in which two secondary beams connect with a main beam and a cantilever beam, respectively.

For the first type of main-secondary beam connection sleeve, the installation sequence is as follows: first, insert the sleeve into the main beam before hoisting. After the main beam is hoisted and installed, adjust the sleeve to the correct position, and then hoist the secondary beam and push its dovetail tenon ends from the side, so that it interlocks

> “The deformation and frictional sliding between tenons and mortises, combined with the light weight, good ductility, and strong energy dissipation capacity of the system, allowed [ancient Chinese] buildings to balance, absorb and ultimately dissipate the seismic energy they experienced, and preserved their integrity.”

firmly with the dovetail mortise connecting plates. If secondary beams are to connect with a cantilever beam, a steel positioning end plate can be pre-welded at the tip of cantilever beam to fix the sleeve. In case of a large fabrication error, structural steel adhesive could be applied to the contacting surface of the connecting plates. To prevent the sleeve from moving, shear studs could be welded at the top flange of the main beam, adjacent to both ends of the sleeve, when installing the steel floor deck.

The second type of main-secondary beam connection sleeve (see Figure 12) consists of a central box-section sleeve and C-section sleeve perpendicular to the box section at

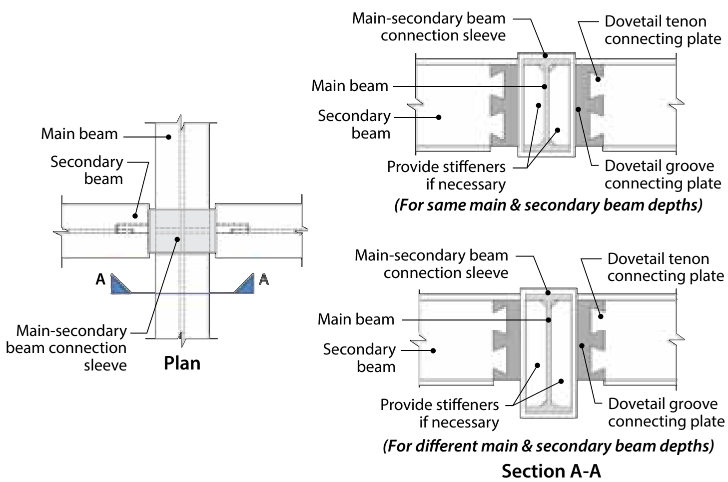

Figure 10. Connection between main beam and secondary beams using dovetail mortise connecting plate.

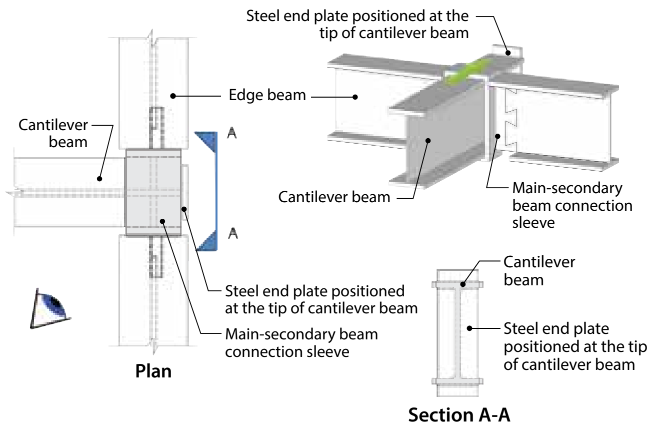

Figure 11. Connection between cantilever beam and secondary beams using dovetail mortise connecting plate.

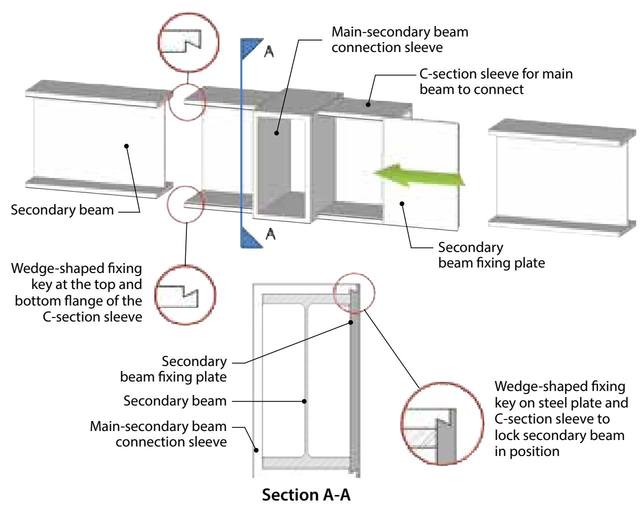

Figure 12. Disassembled components for a main-secondary beam joint using C-section sleeve.

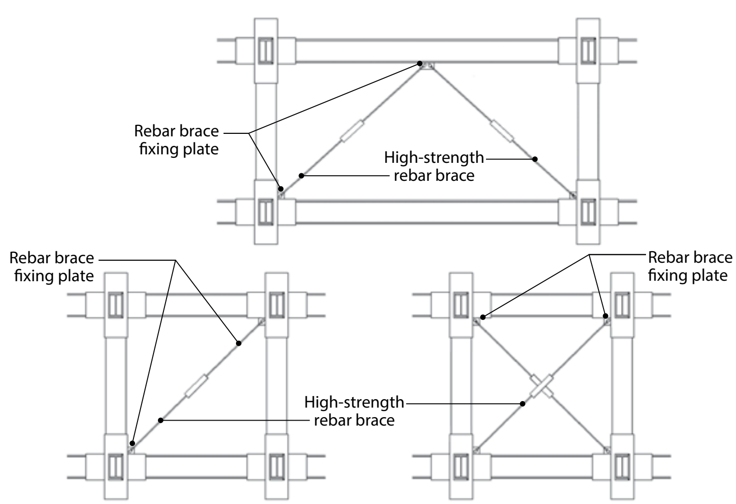

Figure 13. Typical rebar brace application cases.

one or both sides. The installation sequence is similar to those outlined above.

Energy-dissipating rebar brace and connection to the beam-column joint

An energy-dissipating rebar brace consists of two high-strength rebar braces (with yielding strength of 500MPa or more) with a hook at one end and screw threads on the other, with an energy-dissipation coupler in the middle. Both the hook and screw threads of the rebar could be prefabricated in the factory based on design requirements, and the energy-dissipation coupler could consist of a rodded viscous damper or low-yield, high-ductility soft steel.

The installation of the energy dissipation-type rebar brace is as follows: first, place the hooks of the two rebar rods into the slot hole of the rebar brace fixing plates, which are pre-welded at the corners of the beam-column connection sleeve in the factory. Then, lock the other ends of the two rebar rods together by tightening the screws of the energy dissipation coupler. Figure 13 shows some typical applications of the energy-dissipating rebar brace.[1]

Non-structural tie-column connection

When the infill wall of a steel structure is too long, it's necessary to add tie columns to maintain stability. Herein, a simplified bolt/weld-less installation method is proposed for fixing the tie column.

The tie column could be an H-section or channel section. As shown in Figure 14, for H-section tie columns, longitudinal rectangular slots at both ends on the web, parallel and adjacent to its flange, could be prefabricated in the factory. Two vertical fixing keys with a gap (or two closely spaced steel plates) could be pre-welded in the factory at the upper flange of the lower beam, and at the lower flange of the upper beam at the corresponding position. The gap between the two fixing keys should be able to pass through the web of an H-section tie column or the flange of a channel-section tie column, while the thickness of the keys should be able to pass through the rectangular slots of the H-section tie column.

The installation sequence of H-section tie column is shown in the left portion of Figure 15. First, hoist the tie column to the designated position and set it upright. Then, let the top and bottom rectangular slots engage the fixing keys, and push the tie column such that the rectangular slots pass through the fixing keys along the beams' longitudinal direction, until the web of the tie column aligns with the gaps of the fixing keys. Then, push the tie column transversally, such that its web passes through the gaps of the fixing keys, until the tie column rests at the center of the upper and lower beam flanges.

The installation sequence of channel-section tie column is shown in the right portion of Figure 15. First, hoist the tie column to the

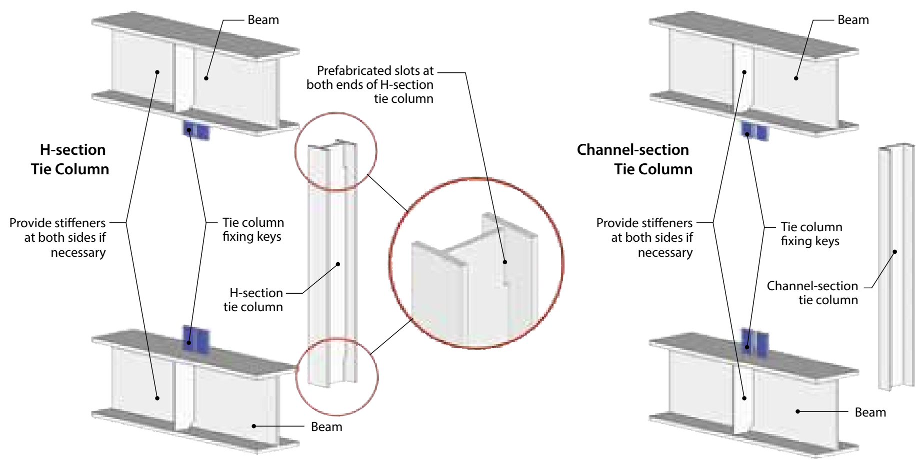

Figure 14. Disassembled components for the connection of tie column.

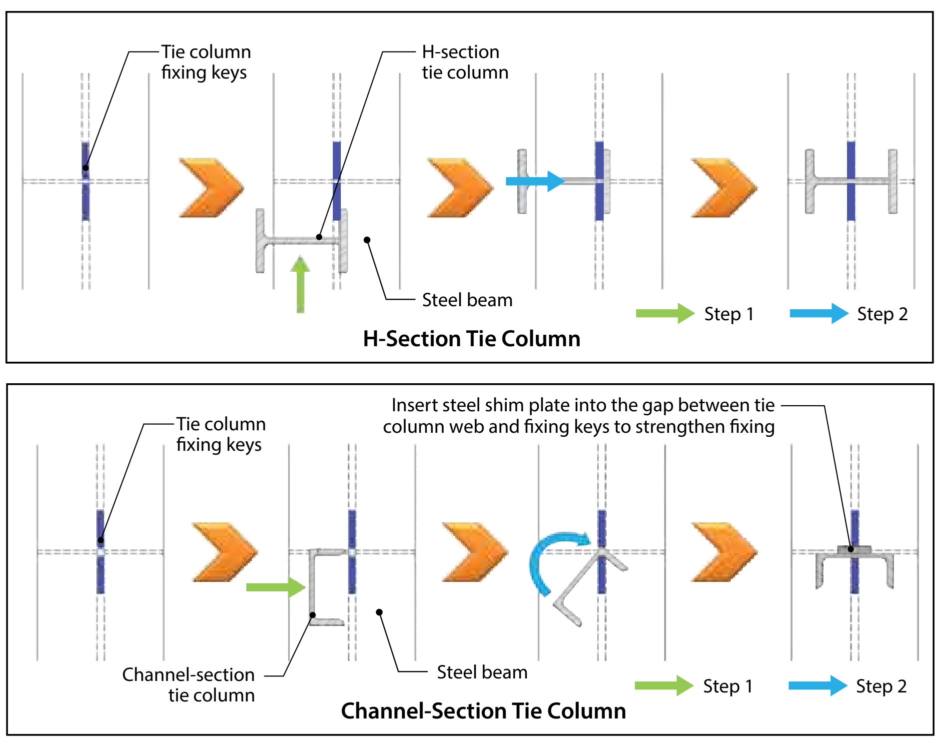

Figure 15. Installation sequence of tie columns.

[1] The column base usually sits on a concrete foundation, so a mortise-and-tenon joint is inadequate here. Conventional details could be adopted.

designated position and set it upright. Then, let the flange of the channel section engage the gaps of the fixing keys, and push the tie column such that its flange passes through the gaps of the fixing keys, until the tie column flange's root portion reaches the aforesaid gaps. Then, further turn the tie column 90 degrees, such that web passes through the aforesaid gaps, until the tie column rests at the center of the upper and lower beam flanges. If necessary, a steel shim plate could be inserted into the gap between the tie column web and fixing keys to form a stronger bond.

Nonstructural tie beam connections

When the infill wall of a steel structure is too high, it's necessary to add a tie beam to keep it stable. Herein, a simplified bolt/weld-less installation method is proposed for fixing the tie beam. The tie beam could either be an H-section or T-section, as shown in Figure 16. For an H-section tie beam, longitudinal rectangular slots at both ends on the web, parallel and adjacent to its lower flange, could be prefabricated in the factory. Two horizontal fixing keys with a gap could be pre-welded in the factory on the corresponding flanges of the two columns, to which the tie beam will be connected. The gap between the two fixing keys should engage the web of the H-section or T-section tie beams, while the thickness of the keys should be sufficient to engage the rectangular slots of the H-section tie beam.

The installation sequence of the H-section tie beam is shown in the left portion of Figure 17. First, hoist the tie beam to the designated position, and then let the rectangular slots on the web at both ends of tie beam engage the horizontal fixing keys. Push the tie beam horizontally to pass through the fixing keys, until its web engages the gaps of the fixing keys. Then, drop the tie beam down, such that its web could pass through the gap until its top flange sits on the fixing keys.

The installation sequence of the T-section tie beam is shown in the right portion of Figure 17. First, hoist the tie beam to the designated position. Then let the web of the tie beam pass through the fixing-key gap, until its top flange sits on the fixing keys.

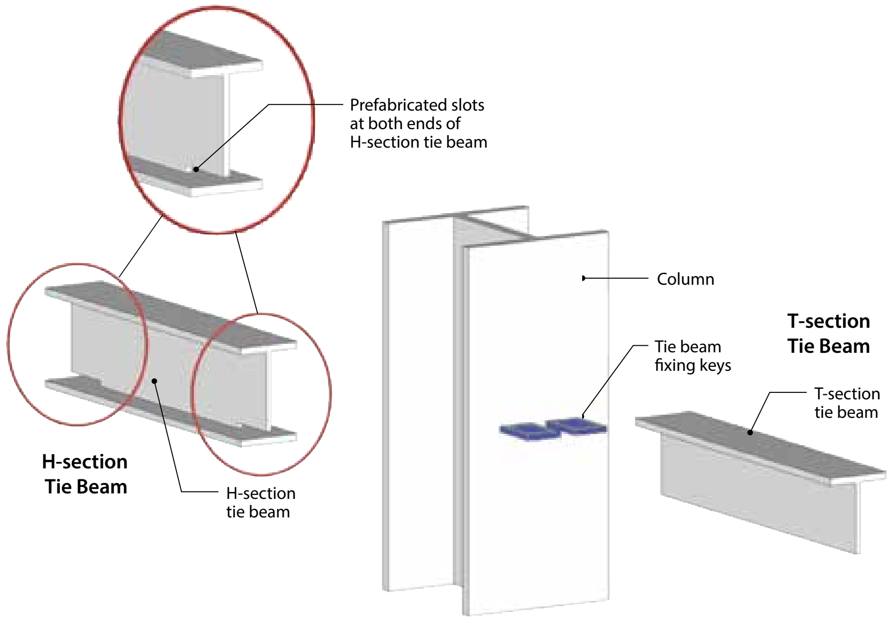

Figure 16. Disassembled components for the connection of tie beam.

Conclusions

Due to recent steel production overcapacity, the Chinese government now pushes the development of prefabricated steel structures in the building industry. For traditional steel structures with bolted and welded connections, both factory prefabrication and on-site installation processes are very complicated, time-consuming, and deliver low-quality product. To overcome the above shortcomings, mortise-and-tenon joints inspired by those used in timber structures could deliver excellent seismic performance, ease of fabrication and assembly, and high-quality product. Through modularized design, industrialized fabrication and simplified installation, high-quality and economical prefabricated steel structures could be delivered, and advance the industrialization of building construction.

Applicability to high-rise structures

It is reasonable to question the applicability of a system designed for low and lightweight timber structures to high-rise steel structures. The authors believe the proposed prefabricated steel structure system is applicable to tall buildings up to 150 meters; with further improvement, it could be applicable up to 300 meters.

The proposed system lacks the shortcomings of timber structures with mortise-tenon connections; because, unlike timber, which suffers weakened joints with mortise-tenon connections, there is no sectional area loss in the joint portion of the proposed system. It would thus comply with the commonly recognized, effective seismic design principle "strong joint, weak members."

Both the strength and ductility of steel are much better than those of timber, meaning that the structural capacity, of the proposed system under vertical and horizontal loadings would be more robust than a timber structure with mortise-tenon connections. Owing to the effects of fixing keys at the bottom of main beam ends, plus the in-situ concrete slab on top of the main and secondary beams, the in-plan horizontal stiffness of the proposed system could preserve its integrity, even under major earthquake and large wind forces. A timber structure with mortise-tenon connections doesn't possess these advantages.

The proposed system could further enhance the advantages of timber mortise-tenon connections, such that the seismic/wind energy dissipation could be realized through the friction and movements between beams and columns and their corresponding connection sleeves. Furthermore, the energy-dissipating rebar brace could absorb and dissipate more seismic energy to protect other main structural members.

In the case of applying this system to tall building up to 300 meters high, where wind pressure might dominate compensatory designs for horizontal displacement and occupant comfort, some further improvement measures for controlling displacement and vibration might be required. For example, a concrete core wall might be needed to increase the overall horizontal stiffness, or a damper system could be used to reduce the horizontal acceleration response.

Limitations and suggested improvements

To improve and practically apply this system, the following issues need to be further explored and studied:

1. More computational and theoretical studies for these new joints and the overall structure system need to be conducted to further improve the joint details.
2. Static/pseudo-dynamic and shaking-table tests for the connection joints and overall structure model should be performed, so as to verify the behaviors of joints and the deformation characteristics, failure scenarios and seismic performance of the overall structure.
3. Relevant codes and standards for design, fabrication, installation and inspection should be established.
4. Fabricators and steel-casting factories would need to comprehensively adopt high-speed, high-precision and intelligent Computer Numerical Control (CNC) machining technology, as well as Building Information Modeling (BIM) technology.
5. A low-cost and high-temperature-resistant structural steel adhesive would need to be developed, so as to avoid the thermal and oxidation decomposition seen in ordinary steel adhesives under fire loads.
6. An efficient and stable 3D printing technology for steel could further improve the prefabrication quality of connection sleeves and produce high-precision complex joints and casting molds. ■

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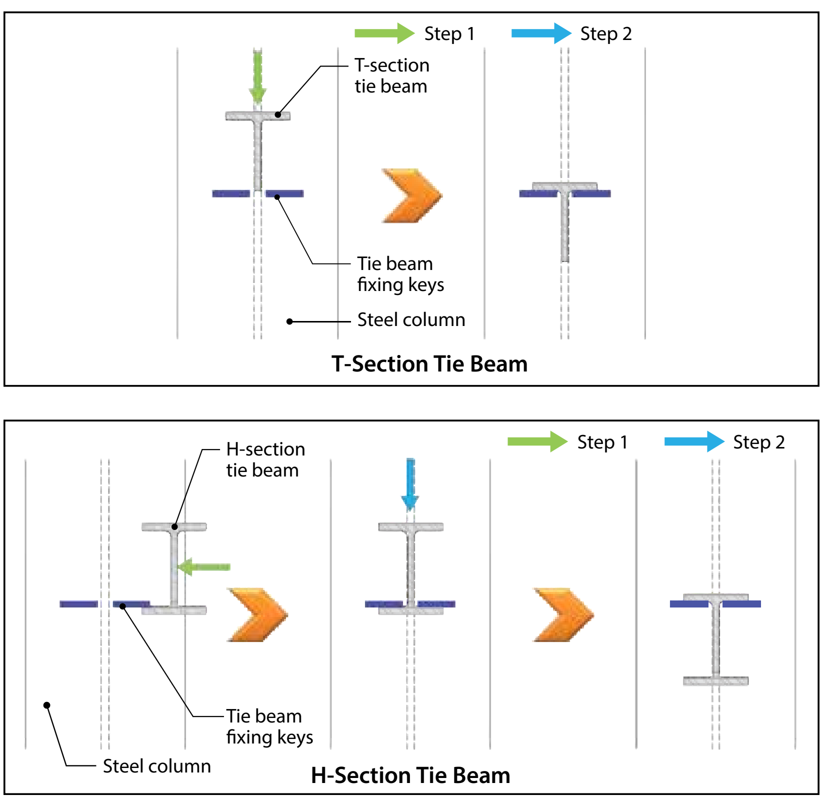

Figure 17. Installation sequence of tie beams.

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