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Monotonic and cyclic response of bolted connections with welded cover plate for modular steel construction

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ABSTRACT

Attributable to the superiority in construction speed and quality, modular steel constructions (MSCs) have been increasingly used for mid-to-high rise buildings with repetitive units. An architecturally pleasing bolted connection with welded cover plate was proposed in this paper to settle the current research limit. Tests on seven full-scaled tee-shape connections made of hollow structural section (HSS) members were conducted under monotonic and cyclic load. The results indicated that all the specimens under monotonic load were capable of developing the full plastic strength of the twin-beams. The twin-beams were found to have individual bending behavior. The current seismic design code GB 50011-2010 and AISC 341-10 were used to evaluate the seismic performance and verify the applicability for seismic design of the proposed connection, demonstrating the satisfactory deformation capacity and ductility. Furthermore, EC3 Part 1–8 was adopted to evaluate the stiffness characteristic of the proposed connection, indicating that the proposed connection can be classified as "semi-rigid" connection. In addition, the design consideration was recommended to predict the bending capacity of the proposed connection. The presented research work will provide useful references for expanding the application of MSCs.

1. Introduction

With growing environmental pollution, increasing cost and shortage of skilled labour, there is an increasing trend across the construction industry to focus on modular construction. The idea of modularized production of constructions results in controlled factory environment to ease pressure on the industry as well as shortened project period, improved quality and potential advantage on recycle. The promising method of construction has been extensively adopted for hotels, apartment, student accommodations, hospitals and other similar buildings with repetitive units thanks to its significant technical highlights [1–3]. Taking Fig. 1(a) as an example, each room is designed as a standard module, which is pre-fabricated in the factory by line production. The room-sized module unit is completed with floor, ceiling and walls to provide thermal, sound and fire performance, as shown in Fig. 1(b). When the modules are transported to the construction site, the construction team can carry out module erection and connection quickly. In this way, a brand-new construction with full internal finish can be handed over and put into use as soon as possible, creating value much higher than that of traditional on-site buildings for its investor.

Previous case studies conducted by Lawson et al. [1] and Kim et al. [4] have verified the applicability and construction feasibility of modular steel constructions (MSCs) to be applied to a wide range of building forms. Giriunas et al. [5] introduced the development of MSCs using shipping containers and their overall mechanical properties. Park and Ock [6] presented a 12-story residential building using modular in-fill method. Despite the extensive use, it could be easily found that the current application of MSCs are mainly limited to non-seismic regions. This is partially due to the insufficient studies on the seismic performance of connection for MSCs, which is crucial to guarantee the structural stability and desired lateral resistance.

Lawson et al. proposed a typical connection for MSCs widely used in UK [1]. The modular units are connected using a connection plate and a high-strength bolt. An access hole is necessary for erection of the bolt, which will cause cross-sectional loss of the column and is unfavorable for "strong column-weak beam" seismic design concept. The connection developed for shipping containers is also well accepted for MSCs in practice owing to the convenience for assembly [7,8]. The connection devices lock the module units together by attaching through the top or bottom openings on the corner fitting by twist locks and bolts.

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(a) Construction process (b) Internal finish

Fig. 1. Instances of modular construction.

However, its structural characteristics remain unknown and further modification may need to be explored to accommodate to structural application. In addition, these two connections are pinned connection and disadvantageous to form a moment-resisting frame for seismic application.

Currently, several scholars have contributed great efforts to develop potential rigid connections for MSCs and various types of connections have been suggested. Park et al. [9] introduced a bolted connection with the adjacent module units bolted to the cruciform gusset plate directly. Deng et al. [10] proposed an innovative connection using socket-shaped tenons and cruciform gusset plate to connect the module units. Chen et al. [11] proposed a beam-to-beam bolted connection using plug-in device and long stay bolts to connect the module units. These connections connect the upper module and lower module by bolting the ceiling beam of the lower module and the floor beam of the upper module without connecting the columns, leading to indirect uplift load transferring path when MSCs suffer from lateral load, as can be observed from the tests conducted by Chen et al. [11]. Furthermore, they are inadequate to go well with the internal finish due to the existence of the floor and walls served as building function. Accordingly, they are basically suitable for structural component of the module, which goes against the original intention of MSCs to some extent. The more prevalent use of MSCs has been limited due to a lack of connection that can serve as a moment-resisting frame with the ability to co-operate with building function.

In this paper, an architecturally pleasing bolted connection with welded cover plate was proposed for MSCs to make up the aforementioned disadvantage and expand its potential application. A series of full-scaled monotonic and cyclic tests were performed to provide a comprehensive understanding of its load-transferring mechanism, load bearing mechanism and seismic performance. Various configurations of the joint zone were considered in the test specimens. The static and hysteretic behavior in terms of failure mode, strength and stiffness characteristic, deformation capacity, ductility, energy dissipation capacity were evaluated carefully. The presented study provides a practical connection and important guidance for MSCs in the further applications.

2. Details of the innovative connection

Fig. 2 presents the details of the proposed connection and the assembly process. All the structural members including columns, floor beams and ceiling beams are made of hollow structural sections (HSS) attributable to their excellent compression, torsion, bending behavior and high strength-to-weight ratio [12]. The beam width-column width ratio (β) is 1.0 so that a matched connection is constructed, providing the opportunity to obtain smooth building elevation and satisfactory seismic performance [13,14]. The floor beam and ceiling beam are welded to the column using complete joint penetration (CJP) groove weld. It may be combined with other lateral-force resisting systems

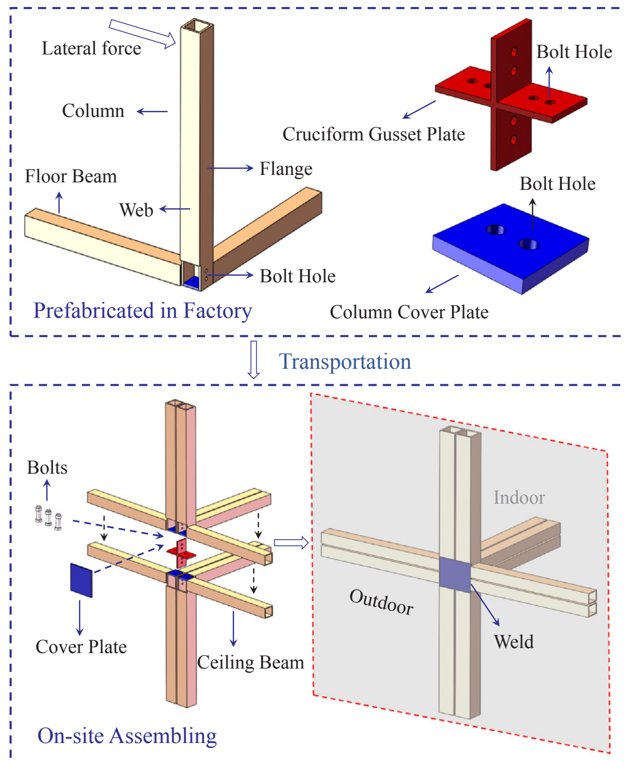

Fig. 2. Conceiving of the innovative connection.

(such as steel plate shear walls) for high-rise MSCs. After the completion of steel framework, the modules are then completed with floor, ceiling and walls. To this end, the connecting process is intended to be performed from outside of the building to integrate with building function.

The proposed connection is adequate to meet these requirements. As shown in Fig. 2, the implementation of the connection can be divided into two phases:

(a) Prefabrication in the factory: The outward column web is partially cut and a cover plate is welded to the bottom of the column. Bolt holes are drilled into the column cover plate and the outward column flange. In addition, cruciform gusset plates are prepared with matched bolt holes.
(b) On-site assembling: The cruciform gusset plate is inserted into the gap between the two lower modules firstly, and then the two upper modules are lifted on and the four modules are bolted horizontally and vertically from outside. Finally, a cover plate is welded to replace the cut portions of the columns.