Engineering Structures 147 (2017) 625–638

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Experimental study on interior connections in modular steel buildings

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ARTICLE INFO

Article history:
Received 18 November 2016
Revised 31 May 2017
Accepted 2 June 2017

Keywords:
Inter-module connection
Plug-in device
Beam-to-beam bolted connection
Monotonic test
Quasi-static cyclic test

ABSTRACT

In modular steel buildings, traditional architectures are separated into prefabricated room-sized volumetric units that are manufactured offsite and installed onsite. The connections between the modules are important for load transfer. Conventional inter-module connections mainly use direct plates and connect them using bolts; however, this may prove problematic for the inner connecting regions. A new type of design with beam-to-beam bolted connections is proposed in this paper; this design provides easy working access without being affected by the structural members. The static performance, hysteretic performance, skeleton curves, ductile performance, energy dissipation capacity, and stiffness degradation patterns of the joints are obtained by experiments and finite element analyses. The results showed that because of the construction between two unit joints, gaps would be formed between the upper and bottom columns, and this gap can influence the deformation patterns and distribution of bending loads at each unit joint. The weld quality at the unit joints is critical to ensure overall safety. Stiffeners can effectively increase the stiffness and load bearing capacity, but may reduce ductility performance. The deforming ability of the connection is also closely influenced by the stiffness of the floor beam column joint and ceiling beam column joint and their relative intermediate magnitudes.

1. Introduction

Modular construction involves an assembled structure in which the entire structure or building comprises prefabricated room-sized volumetric units or structural units that are manufactured offsite and installed onsite [1]. The modular units are often fully equipped with the required facilities and transported to the construction site; then they are connected onsite to form a complete and permanent residential or commercial building [2] (Fig. 1(a)). Compared to the conventional construction approaches, the off-site modular construction replaces the slow unproductive site activities by more efficient and faster factory processes. The perceived benefits of off-site manufacture are speed of construction, higher quality, lower cost, less wastage, and higher reliability [3]. Further, the modular steel structures are especially suitable for industrial production [4]. In recent years, off-site modular construction has been receiving increasing attention in high-density urban areas, where the construction practices are often constrained by limited working spaces and high requirements on low disturbance during operations [5]. In general, there are mainly two types of modules: continuous four-side support modules where the vertical loads are transmitted through the walls, and corner-supported modules where the vertical loads are transmitted through the corner and intermediate posts. The structural skeleton of the four-side support module mainly comprises light steel C-sections inside the walls, and is normally used for low-rise modular buildings, while the corner-supported modular form often uses hot rolled steel members that can withstand larger vertical loads in mid-rise or high-rise buildings.

Furthermore, these module forms have the units connected at their corners, so that they can structurally work together to transfer wind loads and to provide an alternative load path in the case of damage to a single module [6]. Lawson introduced the common bolted connection method normally used in the UK, and displayed the application exploration of high-rise modular steel buildings (MSBs) [1,6]. The corner columns or angles in adjacent modular units are normally connected together with single bolted connector plates or side plates [7,8]. Lee [9] later reported a rigid connection between vertically adjacent modules, through an extended bracket end at the lower ceiling beam to ensure fastening of bolts to the upper floor beams. Annan [4,10,11] presented a welded inter-module connection design with the upper and lower modular columns directly welded together, and performed seismic evaluation of the welded corner-supported MSBs. Using a similar method,

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http://dx.doi.org/10.1016/j.engstruct.2017.06.002
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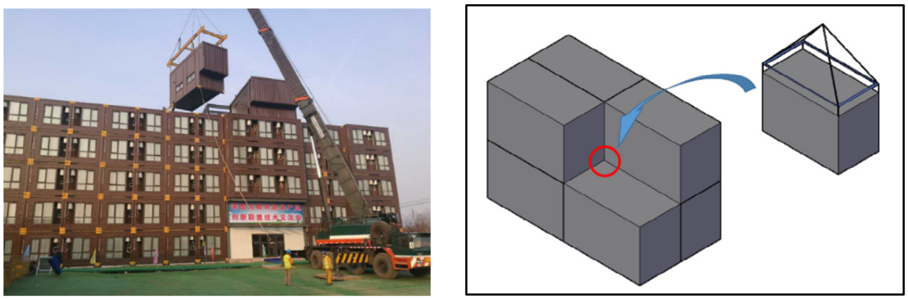

(a) Mid-rise modular residences at Tianjin

(b) Inner connecting locations of modules groups

Fig. 1. Inner connection characteristics of modular construction.

Fathieh [12] also conducted seismic evaluation of MSBs having bolted steel plates as the inter-module connections. However, most of the reports or references cover only the connecting styles or simplification methods, with limited information on the mechanical performance of the inter-module connections.

At present, most of the (MSBs) have a single array arrangement or a simple layout in which most of the inter-module connections would be located in the perimeter region [13,14]. However, for the inner connections, as shown in Fig. 1(b), the fourth module to be placed cannot be easily connected at its base, unless there is enough working access or a special opening. The modular construction features; its convent on-site erection assembly, and a safe and convenient inter-module connection is needed. In the present paper, a new type of inter-module design for the inner connecting regions is proposed. A series of static and cyclic loading tests were performed to understand the load bearing mechanism and seismic behaviour of the structure. The results can provide useful guidance and serve as reference to modular building design in the future.

2. Details of the new interior inter-module connection

Conventional inter-module connections consist of plates and bolts that are welded from outside; they often require certain space to facilitate bolting or welding. As shown in Fig. 2(a), the horizontally arranged modular units are connected through side plates, and the vertical modules are connected with long stay bolts. For perimeter connections, the connecting work can be performed from outside of the building, and hence there would be no requirement of working space and construction gap. However, for the parts in the central region, the inter-module connections may pose difficulties where four modular units are to be joined together. These connections are installed sequentially as each module is placed, but the fourth module to be placed will not have access to the connection, as shown in Fig. 2(a). One possible solution is to create a working opening in the modular column, but this would cause significant weakening of the structural member. Another approach would be to get working access through a service riser or from infill walls. This method also requires a gap between the modular columns and beams to allow the mechanical and electrical facilities pass through, but such a space is normally not allowed in architectural practice.

The construction and assembly method of the proposed inter-module connection is shown in Fig. 2(b). The new MSB has separate vertical and horizontal connecting systems, which comprise cast plug-in devices for horizontal connections and the beam-to-beam high tensile strength bolting system for vertical connections. When the modular buildings are of corner-support type, each inner MSB connection will have four unit joints. All the modular beams and columns are made of cold formed rectangular steel tubes, and the small beams and columns in each unit joint are connected through welding. The connection has a cover plate welded to the upper floor beam, and an intermediate plate and cover plate welded to the bottom ceiling beam to prevent local buckling of the beam plates under the tension forces of the stay bolts. All these manufacturing processes of the modular units can be completed in the factory, and no additional on-site welding is needed.

The cast plug-in unit has four square tube heads on each side of the intermediate connection plate (Fig. 2(b)). During the modular assembly process, the modular column will be inserted in the corresponding head at the plug-in device for alignment. Once the horizontally adjacent modular columns are inserted in place, the modules will be naturally connected together horizontally by the effect of clamping. After the assembly of the modular columns in their correct positions, the long stay bolts will be inserted into the end holes in the beam from the inside of the modular units and fastened to connect the upper floor beam and bottom ceiling beam together. The vertical tension bolts that hold the modules together are hidden behind the base boards in the infill wall; thus, there is no need to create openings that weaken the sections of the structural members, and the gap between the adjacent modules can be small without considering the need for working access.

3. Experimental study

3.1. Description of test specimens and test setup

The connection design was selected from an existing modular office building in Sino-Singapore eco-town in Tianjin Binhai New Area. The office building is a four-story composite modular structure in which the first floor is built with a steel frame structure, and the floors above are constructed using modular units (Fig. 3). The modular units adopted prefabricated concrete slabs in the floor and light weight composite boards for the ceiling, enclosures and partitions of the unit. The floor beams had a comparatively larger section height than the ceiling beams. Although corner-supported modules built and joined with such connections have already been used in practice, the inter-module connections were further modified by using pin connections which cannot transfer moments between the vertically connected unit joints. Therefore, the inter-module connections did not participate effectively in the lateral load resisting system because of the over-conservative designs and lack of knowledge on inter-module connections regarding their actual load transferring behaviours. The aim of the experiments was to study the working mechanism, load bearing mechanism and seismic behaviour of this type of MSB connection in the inner connecting regions. In the actual inner connecting regions, there are four columns and eight beams to be jointed