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Experimental study of an innovative modular steel building connection

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ABSTRACT

In modular steel building (MSB) built by unit-prefabricated on-site assembled construction method, connections are critical parts that can strongly influence the overall structural stability and robustness of the MSB. Previous MSB connections mainly use intermediate connecting plates, which may pose practical difficulties to certain modular arrangements or installations. Thus, this paper proposed an innovative MSB connection design with an intermediate plug-in device and a beam-to-beam bolt system as the horizontal and vertical connections, respectively. This connection design can ensure convenient installation, eliminating on-site welding. Two static uniaxial loading tests and four quasi-static cyclic loading tests were conducted on the T-shaped MSB connection to explore its load transfer capacity and aseismic behavior. Results showed that gaps would form between the upper and the lower columns because of its two-unit-joint structure. This gap can influence the deformation patterns and bending demand distributions in each unit joint. The weld quality in the unit joints was critical to ensure overall safety. Stiffeners can effectively strengthen the stiffness and load-bearing capacity. The deformation capacity of the connection was significantly influenced by the stiffness of floor beam–column joint and ceiling beam–column joint as well as the relative magnitudes between them.

1. Introduction

Modular construction comprises prefabricated room-sized volumetric units constructed in a factory and installed on-site as load-bearing "building blocks" [1]. The discrete modular units usually form a self-supporting structure, and they are generally built in the factory to reach a fully fitted state, complete with floors, lighting, plumbing, and heating, before they are delivered to the site for installation [2]. The assembly-line construction mode in the factory can effectively reduce the time cost and wastage as well as ensure high quality control and construction accuracy. Modular construction is adopted in North America, Japan, and in some parts of Europe [3], mainly for low-rise houses and several high-rise buildings, such as apartment buildings, student residences, and hotels [4].

Modular steel building (MSB) systems differ significantly from traditional on-site counterparts in terms of detailing requirements and construction method [5]. The "unit-prefabricated on-site assembled" construction method have different structural requirements compared with traditional structures, particularly in the design of connections [6,7]. A traditional frame structure generally features a continuous single column to which one or multiple beams are connected with moment connections or joint connections [8]. By contrast, in MSBs, the entire structure has many sub-structures, and each structural unit has its own frame system. In the connecting region, numerous small beams and columns meet together, and this configuration poses new challenges to structural design. In Fig. 1, the corner joint has 2 columns and 4 beams, the side joints have 4 columns and 8 beams, and the inner joint has 8 columns and 16 beams. For this structural system, each modular unit member has to be properly connected to ensure the transfer of lateral loads, axial forces, and bending moments, which are generated from external loads.

MSB connections are structurally important as they can strongly influence the overall structural stability and robustness of MSBs. Annan et al. [5] proposed a horizontally and vertically separated connection, in which the lower and upper modular columns are partially welded to form the vertical connection and the shop-welded angles are field-bolted to the floor beams to form the horizontal connection. Subsequently, they also discussed the effect of direct welding between the strings and the floor beams on the structural design of modular structures [2]. Park et al. [9] introduced a unit connection and an embedded steel column-to-foundation connection for a modular structural system; the unit connection utilizes a cross-shaped plate installed on a column flange and then bolted to the beam web. Fathieh and O. Mercan [10] once performed a seismic evaluation of MSBs. In the evaluation, the inter-modular connections were simulated by adding an additional vertical short column and horizontal beam. Bae et al. [11] optimized the parameters of beam–column joints in a unit modular system

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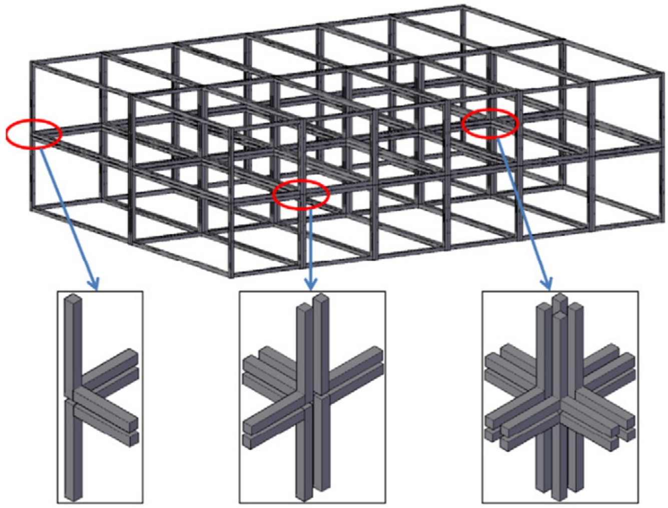

Fig. 1. Connections in modular steel building (MSB).

through basic experiments and theoretical analysis for the development of a high-rise frame unit modular system.

Current MSB connections are horizontal or vertical connecting plates placed at the two ends of module columns of. Access to these connections has to be made externally to the modules, thereby posing practical difficulties for certain module arrangements. This study aims to solve this problem by proposing a new T-shaped beam-to-beam modular connection. Its performance was analyzed through a series of static tests and quasi-static tests. The test results could be used as guide for the design and actual construction of connections for MSBs.

2. Details of the new beam-to-beam MSB connection

The components of the new beam-to-beam MSB connection are presented in Fig. 2. The connection has two effective connecting parts, namely, the plug-in device to transfer the horizontal forces and the long stay-bolt system at the beam ends to tie the upper and lower modular beams together. The modular beams and columns are all made of cold formed rectangular steel tubes, and the small beams and columns are connected by welding. The cover plate is welded to the upper modular floor beam. A bottom plate and an intermediate plate are welded to both flanges of the ceiling beam in the lower module. The cover plates protect the beam tubes from local buckling under the tension forces of the stay bolts. This connection is suitable for a frame module, in which the internal forces are transmitted through the unit corners. The joints inside each modular unit are all welded. The modular frame units are prefabricated in the factory; thus, the welding of the beams and columns and the welding of the cover plate are accomplished in the factory. In addition, the column ends are left open at the end of the modular unit construction.

In this MSB connection, no additional welding process is required at the construction site. Each well-built unit is transported to the work site and lifted to the position above the designed location. The four plug-in devices are placed at the upper ends of the lower modular columns. Subsequently, the lower ends of the upper modular columns are aligned and inserted to the four plug-in devices. The plug-in unit is made of cast steel with two square tubes connected to both sides of an intermediate plate. The outer diameters of the tubes are the same as the inner diameters of the modular columns. The tubes have shrunken ends to facilitate the alignment and provide an allowance for installation error. Then, the upper and lower units are clasped together along the vertical direction. Having no vertical linking mechanism, the plug-in unit itself cannot resist the pull-up force. The long stay-bolt system at the beam ends compensates for this deficiency. In traditional inter-

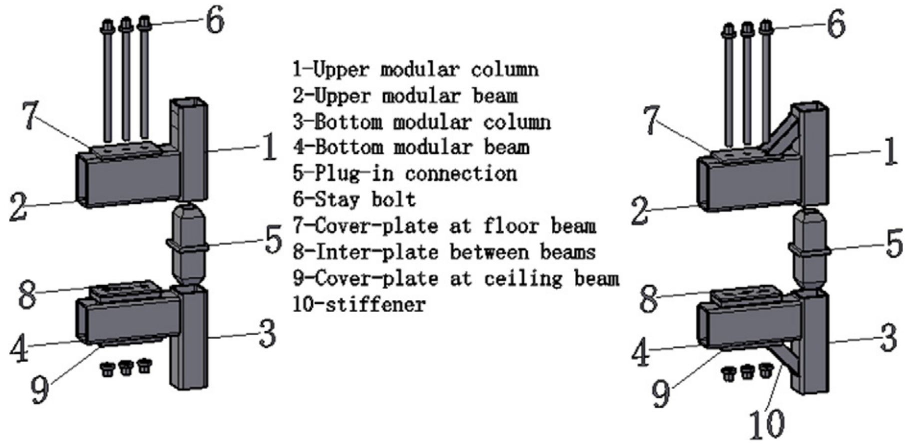

Fig. 2. Two types of beam-to-beam inter-modular connections.

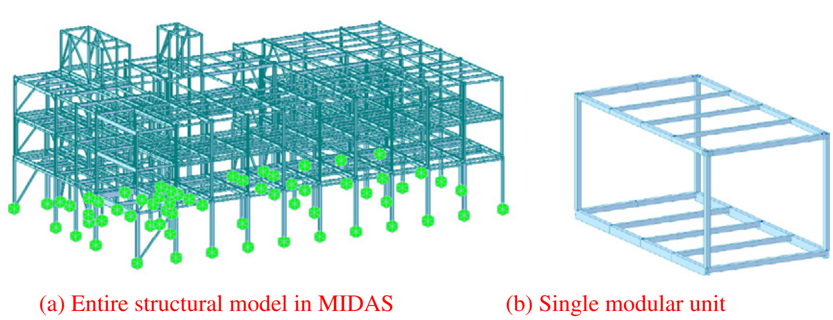

Fig. 3. Structural model and modular unit components of the prototype office building.