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Experimental investigations of vertical post-tensioned connection for modular steel structures

Rafaela Sanches[a,*], Oya Mercan[a], Brent Roberts[b]

[a] Department of Civil Engineering, University of Toronto, Toronto, ON M5S 1A4, Canada
[b] Jerol Technologies Inc., Aurora, ON L4G 4B6, Canada

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ABSTRACT

Modular construction is an off-site construction technique. In this method, structural volumetric modular components are produced in a factory and assembled on-site to form a larger, permanent building. Typical vertical connections of modular steel buildings (MSBs) are provided by on-site welding. Welding may interfere with the finishing of the modules and also when several modules are placed together at a given floor level complete access for welding is compromised. As an alternative to on-site welding, the present paper proposes a new vertical post-tensioned (PT) connection for MSBs. This connection is comprised of a post-tensioned threaded rod installed inside hollow structural sections (HSS) columns and a steel box placed between two modules. In order to evaluate the general and the seismic performance of the proposed connection, eight quasi-static cyclic loading tests were performed in T-shaped subassemblies. A combination of three different steel boxes and three initial post-tensioning loads levels were considered. Additionally, two quasi-static cyclic loading tests were performed using standard welded connections. No local buckling was observed in any of the specimens and no welding fractures occurred up to 3% drift demand. Results indicated that in comparison to the welded connection the proposed PT connection have similar lateral stiffness and strain distribution, and a higher cumulative energy dissipation capability. Therefore, the proposed connection has the potential to eliminate on-site welding in the assembly of the modules while providing the lateral resistance required.

1. Introduction

As an alternative to traditional on-site construction, in modular construction volumetric (3-dimensional) modules are pre-fabricated at a factory. They are then transported to the site and assembled together to form a permanent structure. Square hollow structural sections (HSS) and wide flange (W) sections are commonly used for columns and beams of the modules, respectively [1,2]. Due to transportation restrictions, the dimensions of the modules are usually in the range of 3.5–5 m in width, 12–18 m in length, and 3–4 m in height [3]. Modular construction is ideal for buildings with repeatable units which can be modularized more efficiently such as hotels, multifamily dwellings, schools, hospitals, offices, prison and military facilities. Since the modules are generally finished in a factory with a controlled environment, modular construction is known to improve accuracy and quality; and it has the potential to reduce waste material and on-site construction time [4,5].

Although there has been an increased attention to modular steel buildings (MSBs) [6,7], studies addressing their dynamic behavior are relatively recent. Annan et al. [1] performed experiments to analyse a MSB single frame under cyclic loading and compared the results with a regular steel frame. Both frames developed stable and ductile behavior up to high drift levels. In a numerical study, Annan et al. [8] performed nonlinear pushover analyses for MSBs with 2,4 and 6-stories, where a considerable overstrength was observed. More recently, Fathieh and Mercan [2] conducted numerical dynamic analyses for a 4-story MSB and reported a high base shear capacity. This is attributed to the larger number of columns that typically exist in modular structures in comparison to regular steel buildings. All the above-mentioned studies considered typical welded vertical connections. Gunawardena [6] numerically analyzed the seismic behavior of a 10-story MSB with bolted connection and with some modules stiffened by concrete walls. Results showed that column hinge formation is a concern under severe ground motions.

Typically, the vertical intermodular connection is provided by on-site welding. However, once one module is placed next to the other, the access to weld the columns is reduced, which may cause independent rotation between modules and may lead to an undesirable soft-storey

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* Corresponding author at: Department of Civil Engineering, University of Toronto, 35 St. George Street, Toronto, ON M5S 1A4, Canada.
E-mail address: rafaela.sanches@mail.utoronto.ca (R. Sanches).

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response [1]. Alternatives to typical on-site welded connections have been investigated for both modular steel structures and regular steel moment resisting frames (MRFs). Horizontal post-tensioned connection for regular steel MRFs, initially proposed by Ricles et al. [9,10] and further studied by Garlock et al. [11,12], is obtained by post-tensioning the beams to the columns using high strength steel strands. This connection eliminates welding between the beam and the column. It was concluded that the damage in the beams and residual drifts after an earthquake event were reduced. The initial stiffness of the connection was found to be similar to a welded connection. Lin et al. [13] investigated seismic behavior of a new structural system that consists of high strength built up columns and bolted beam-column connections. Cyclic displacement tests were performed in four full-scale specimens. It was concluded that local distortion was avoided in the specimens with stiffened connections, and the column remained elastic. Vertical post-tensioned connection was also proposed to improve structural seismic performance [14]. In this study, the cyclic response of a post-tensioned column base connection of steel frame was investigated through a series of quasi-static tests. The post-tensioned connection was able to withstand high drift levels without damage to the column; it presented a stable hysteretic behavior and negligible residual rotation at the column base connection. More recently, Chen et al. [15] proposed vertical pre-tensioned intermodular connection for MSB with composite columns (steel-concrete). Quasi-static tests were performed in two full-scaled stacked modules to investigate the seismic behavior of the proposed connection. The structure presented adequate load bearing stiffness and ductility. Similarly, monotonic and quasi-static tests were performed in a modular structure subassembly where the HSS columns were vertically connected by a steel plug and long bolts connected floor and ceiling rectangular HSS beams [16,17]. The results indicated that the connection eliminates the need for on-site welding while providing the required lateral capacity and energy dissipation.

The realization of the full potential of the modular construction method requires more efficient and faster assembly techniques and a clear understanding of the behavior of the MSB structure. To address this need, the current paper introduces a new post-tensioned (PT) connection for the vertical intermodular connection of MSBs; and evaluates its seismic behavior and lateral load bearing capacity through a series of quasi-static cycling loading tests. The proposed connection does not require on-site welding and it is suitable for typical HSS steel columns. In Section 2 of this paper, the new PT connection is described. The dimensions of the specimens, test set-up, test matrix and the instrumentation layout are provided in Section 3. Section 4 shows the general behavior of specimens with the welded connection and the ones with the PT connection. The deformation pattern, hysteretic behavior, energy dissipation, lateral stiffness and strain distribution for both welded and PT connections are also described in this section. Finally, the summary and main conclusions are reported in Section 5.

2. Proposed vertical post-tensioned connections for MSB

In order to vertically connect the columns of the bottom and top modules, the proposed connection uses a post-tensioned threaded rod and a steel box as shown in Fig. 1a. The threaded rod goes through the columns full height to establish vertical connectivity between the modules and is anchored against end plates at columns ends. A hollow steel box with sloped sides at the top and at the bottom is inserted and secured inside the typical hollow section column of the lower module half way through its height. Its sloped sides help to guide both the threaded rod through the middle plate of the box and the upper module column as it is lowered during the assembly. The horizontal connectivity of the modules is provided by the steel box that sits over the full height of the two layers of beams at each floor level. Beams are made of W sections and are connected to the columns by off-site welding. Couplers can be used to connect threaded rods to cover longer heights and enable several modules to be tied together. With the proposed connection on-site welding process would not be required to vertically connect the modules and horizontal inter-modular connections are typically bolted (Fig. 1b). The recent work of Lacey et al. [7] provides a state-of-the-art review of modular building structures and other types of connections.

In an earthquake event, the columns may experience a variation in the axial load demand, especially the ones located at the perimeter of the building. Tensile forces that may occur in exterior columns are resisted by the threaded rod and the friction force provided by the contact between the steel box and the inner surface of the HSS column. In order to avoid excessive compression load in the columns, the post-tensioning load should be considered together with the gravity loads in the design process.

3. Experimental study

3.1. Test specimens, test set-up and material properties

The subassemblies tested in this study represent a connection from a MSB previously designed by Fathieh and Mercan [2] (Fig. 2a) with minor adjustments. The thickness of the columns was increased to avoid buckling during the tests, the floor beams and the clearance between floor and ceiling beams were modified to account for the current practices in modular construction. This gap between beams is often required to facilitate easy assembly of the modules (to provide space for the removal of the temporary supports and lifting slings that go underneath the floor beams of the module as its being lifted during the assembly) and allow electrical and mechanical systems to run through the building during its service life [2]. The length of the columns and the beams of the subassemblies were determined based on the inflection points of the MSB (Fig. 2b). Centerline distances of the subassembly are indicated in Fig. 2c as well as the direction of the displacements applied – positive displacement $(+\Delta)$ and negative displacement $(-\Delta)$. Considering the double layer of beams that exist at each floor level, the inflection point for the columns are not exactly at mid-height, thus the bottom column is shorter than the upper column. Dimensions of the modular parts and the steel box are indicated in Fig. 3 and photos of these elements are provided in Fig. 4. Beam-column welded connection was fabricated by the modular construction builder, NRB Inc. who is a collaborator in this project. Fillet welding process was considered, as shown in Fig. 3a and b. The steel box total height is determined such that it covers the height of the two layers of beam at each story level. The floor beam is slightly deeper than the ceiling beam; therefore, the steel box is longer above the middle plate (Fig. 3c).

A general view of the test setup is provided in Fig. 5a. A hydraulic actuator with maximum stroke of ± 127 mm and maximum load capacity of 350 kN was mounted at the top of the upper column. The actuator imposed quasi-static cyclic displacement according to the AISC protocol [18] indicated in Fig. 5b with slow rates varying from 0.35 mm/s to 1.5 mm/s to avoid any dynamic response effects [8]. A constant axial load of 100 kN – which corresponds to 17% of the nominal compressive resistance of the column – was applied in all tests by a hydraulic jack mounted at the base of the bottom column, where a load cell was also installed. This load represents the vertical loads acting in the column of the first floor of the building and it was computed assuming a typical floor system comprised of concrete floor and steel deck ($2.0\,\mathrm{kN/m^2}$) and insulation ($0.25\,\mathrm{kN/m^2}$). Superimposed dead loads for floors, roof, and ceilings are 0.75, 0.32, and $0.7\,\mathrm{kN/m^2}$, respectively. Live load of $1.9\,\mathrm{kN/m^2}$ is considered in every floor and the snow load of $1.1\,\mathrm{kN/m^2}$ is considered for the roof. For the specimens with the proposed PT connection, a 25.4 mm of diameter threaded rod was considered and the initial post-tensioning (PT_0) load varied from 0 kN to 80 kN. The threaded rod was anchored against plates at each end of the column. The PT load was applied as shown in Fig. 6a before the 100 kN constant axial load was applied. A removable support is attached to the top plate and a hydraulic jack is used to apply the PT