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Seismic performance study on slipping bolted truss-to-column connections in modularized prefabricated steel structures

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ABSTRACT

This study proposed a new-type on-site all-bolted connection that connects a truss to a column and connects a column to a column in modularized prefabricated multi-story and high-rise steel structures. The components in a module are welded together in the factory, and various modules are assembled together quickly using the proposed connection on site. The connection connects a truss to a column through cover plates that extend from the flanges as well as through the vertical connecting plates and the joint flitches. The stiffness of the connection undergoes step-like changes as the load changes. During an earthquake, the cover plates slip relative to the chord members of the truss, dissipating energy. This study conducted tests and finite element analysis on the seismic performance of two specimens of the proposed bolted connection in which slip occurs between the cover plate and chord members, and some seismic performance data associated with the connection, such as hysteretic performance, skeleton curve, ductility, rotational capacity, stiffness degradation and failure mode, are obtained. Some parameters that affect mechanical and seismic properties of the connection were studied, and the slipping rule of the contact surfaces of the bolted connection was obtained. A comparative analysis of the test results for the slipping connection and the non-slipping connection shows that the slipping connection exhibited improved ductility and energy dissipation capacity without significantly reducing the ultimate bearing capacity, and most of the energy was dissipated from the slip. The proposed connection can be used for structures in seismic regions.

1. Introduction

The design and installation of modularized prefabricated multi-story and high-rise steel structure buildings are standardized and modularized. The modules consist of both structural components and equipment and pipelines (e.g., water, heating, and electrical equipment and pipelines), which are preinstalled in the factory. Various modules are quickly assembled with bolts on site, and the pipelines between modules are connected through the interfaces that are reserved in the factory. Modularized prefabricated multi-story and high-rise steel structure buildings have the advantage of rapid construction, less labor intensity and less pollution in comparison with conventional buildings. Further research is necessary to assess the seismic performance of these kinds of structures [1–7]. At present, the prefabricated steel structure is used primarily in low-rise buildings, and the technology for low-rise buildings is relatively mature. There are relatively few applications and studies in multi-story structures, especially in high-rise structures.

To improve installation speed, the truss is connected to a column using only bolts on site. The on-site all-bolted truss-to-column connection can be made into a rigid and semi-rigid connection. The calculation and analysis of rigid connections are simple, so the rigid connections are widely used. However, rigid connections require numerous bolts, increasing the cost. Semi-rigid connections have slightly lower strength but better energy dissipation capacity, require fewer bolts and are more economical relative to rigid connections. Both rigid and semi-rigid connections can be used in multi-story and high-rise buildings in seismic regions [8–9]. Bolted rigid connections can be realized by using bolted T-stub connections. Studies were conducted to investigate the static design methods and seismic performance of some all-bolted T-stub connections [10–12]. Studies are focused mostly on the basic theories and experimental investigations as well as the design and construction methods of some all-bolted connections, bolted-welded connections, and welded connections, including the tree-like connection, the dog-bone-shaped connection, the connection with a cantilever beam, the connection with an opening on the beam web, the bolted connection with long and round bolt holes, the connection reinforced by haunch or ribbed plates, the flange-reinforced connection, and the beam-to-column connection of a cellular frame. The connection

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that is proposed in this paper has never been reported in other literatures [13–21]. The beam-to-column connections in a modularized prefabricated steel structure have a significant impact on the performance of the whole structure. Further studies are necessary to investigate the performance and design methods for beam-to-column connections in these structures. Some results for the connections in prefabricated steel structures have been obtained in recent years. Yu et al. [22–23] conducted FEA on the static and hysteretic performance of a new type of prefabricated rigid beam-to-column connection and investigated the effects of parameters such as number of bolts and width and thickness of the cover plate as well as the length of the cantilever beam on the hysteric performance and failure mode of the connection. Zhang et al. [24] conducted monotonic loading tests on a new type of connection for a square steel tube column to truss, and they analyzed the stiffness, strength and ductility of the connection. Zhang et al. [25] designed three types of Z-type cantilever beam splices for the column-tree connection, which dissipate energy through plastic hinges: a weakened beam splice, a beam splice with a reduced beam and a beam splice with a reduced cantilever beam. The behavior of three types of beam splices for the column–tree connection was investigated and discussed based both on tests and finite element analyses. The results show that the three types of specimens have good ductility performance and plastic rotation capacity. They also proposed simplified computation formulas and seismic design requirements for beam splices. Liu et al. [26] proposed a new type of bolted assembly joint for connecting an H-shaped steel beam to a square HSS column and connecting the HSS columns to each other in a prefabricated high-rise steel structure. Rigid and variable stiffness beam-to-column connections can be obtained by adjusting the number and specifications of the bolts. The connection can be rigid in a weak earthquake, yet the cover plate and beam flange can slip over each other in strong earthquakes, which dissipates energy by slipping. The seismic performance such as hysteretic performance, ductility, and rotation capacity were obtained by finite element analysis and tested. More innovative beam-to-column connections must be proposed for various kinds of prefabricated steel structures.

In this paper, a new type of on-site all-bolted truss-to-column connection that can be used in modularized prefabricated multi-story and high-rise steel structures is proposed. Modules can be assembled together quickly on site by using the proposed connection. The detailed theoretical analysis and tests on a non-slipping connection of this kind were conducted previously, and the simplified equations were proposed [27]. A rigid connection can be obtained with numerous bolts. However, the cost of a rigid connection is high. Compared with the connection in the previous study [27], the number of bolts on the cover plates was reduced, and a semi-rigid connection able to dissipate energy by slipping was constructed. Then, the full-scale model tests were performed. Through comparative analysis of the results from the present and previous study, the seismic performance of the slipping semi-rigid connection was investigated. The finite element analysis was performed to compare with the tests. Then, the model tests and finite element models were verified against each other. Based on the verified finite element models, Liu et al. [28] performed the parameter analysis and static performance studies on six connections with different friction coefficients or sectional sizes of components by FEA to supply for the study in this paper. The FEA results were used to determine the mechanical properties of the connections that were difficult to obtain from the tests such as the changing rule of the bolt tension, the stress distribution of the bolt, the contact force on various contact surfaces, and the pressure on the wall of a bolt hole, as well as the effects of friction coefficients on the performance of the connections. The mechanical model of the connection was established, and the mechanical mechanism of the connection was determined. Furthermore, simplified calculating formulas for the connection under the slip state, the yield state and the ultimate state were proposed, respectively.

The angle truss is widely used in the roofs of lightweight steel structures but is less commonly used in multi-story structures, and seldom used in high-rise structures because the load-carrying states and requirements are quite different among these structures. The truss is usually used in the roofs of lightweight steel structures, where the truss is hinged to the column and could not resist the bending moment, but the truss to column has a normally rigid or semi-rigid connection to resist the bending moment in multi-rise structures, and a plastic hinge is expected to occur on the truss in a large earthquake to dissipate energy. Goel and Itani [29] designed a four-story steel structure with angle trusses as early as 1994, and the hysteretic performance of single beams under low cyclic loading was investigated. Because the truss had excessively slender web members, no out-of-plane constraints and some connecting problems between members, the web members prematurely lost stability, which resulted in relatively poor seismic performance. Basha and Goel [30] improved the steel structure that was designed by Goel with X-diagonal web members, and the improved steel structure exhibited relatively good energy dissipation capacity. Some researchers set special energy dissipation devices on the truss of structures, and the modified structures exhibited good seismic performance. For example, a 9-floor structure that was equipped with energy dissipation devices on its trusses exhibited good seismic performance [31–34]. However, these methods are complex and slightly costly, and make construction difficult. In the proposed on-site all-bolted connection, the web angles are extended to connect with both legs of double angles of the chord and are welded to both legs. Moreover, the connections between web angles and chord angles are strengthened by subplates, instead of being connected with a gusset plate as they are in lightweight steel structures. The improved connections between web angles and chord angles could resist an in-plane and out-of-plane bending moment, increasing the stability bearing capacity of the web and chord angles. We also improved the structure by adjusting the cross-section size and the length of the chords and web members to avoid elastic instability. These improvements are relatively cheap and easier.

2. Composition and engineering application of the structural system and connection

A new modularized prefabricated high-rise structure composed of angle trusses and rectangular HSS columns was proposed [35]. This structure primarily comprises modules of prefabricated truss mainboards and prefabricated flange columns. The prefabricated truss mainboard includes angle trusses, column bases, and a floor slab. The trusses and column bases are welded together in the factory, and the floor slab, which is made of reinforced concrete, is cast in the factory and connected to the truss by studs. The prefabricated truss mainboard modules are spliced together on site via the single-angle truss at the edge of the module and with truss-to-column connections. Prefabricated flange columns are made of rectangular HSS columns and flanges with cover plates, and they are connected to the column bases in the mainboards through their flanges.

The FEA and experimental research on the welded truss-to-column connections in a module [35], the bolted-welded truss-to-column connections for connecting two adjacent modules on site [36], and the all-bolted rigid truss-to-column connections for connecting two adjacent modules on site [27] in the modularized prefabricated steel structure were performed. As shown in Fig. 1 (a), one flange with a cover plate was welded onto the end of the column to form the flange column in the factory. Vertical connecting plate 1, a short column and two flanges were welded together to form the column base in the factory. Two single-angle trusses, vertical connecting plate 2, and subplates were welded together to form a double-angle truss in the factory. As shown in Fig. 1(b), the all-bolted connection consisted of a column base, two flange columns with a cover plate, a truss, and two joint flitches. The upper and lower flange columns were connected to the column base through flanges with bolts, the chord members of the truss were connected to the cover plates using high-strength bolts, and the vertical