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Bending-shear performance of column-to-column bolted-flange connections in prefabricated multi-high-rise steel structures

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ABSTRACT

The bolted-flange connection is a new application for mounting rectangular hollow section (RHS) columns in prefabricated multi-high-rise steel structures, which may bear the combination of bending moment and shear under permanent, live, wind loads or earthquake. The performance of the bolted-flange connection used in the structural column is different from that in its popular usage in the pipe because the subjected force is different. To investigate the bearing performance of a bolted-flange connection under the combination of bending moment and shear, this study conducted static tests and finite element analysis (FEA) of 12 column-to-column bolted-flange connections with different flange thicknesses, bolt edge distances, flange edge widths and bolt hole diameters, as well as one column without a connection. The test agreed well with the FEA, which verifies the FEA. The influences of the flange thickness, bolt edge distance, flange edge width and bolt hole diameter on the stiffness and strength of the connections, bolt tension and contact force were studied, and the failure mode and mechanism of the connection were obtained. A significant prying action occurred on the flange contact surface, increased the bolt tension in the tensile region, and caused the bolt shanks to experience tension and bending moment. The flange thickness had a large impact on the prying force, while other factors had less of an effect. Based on the yield line theory, the bearing mechanism of the connection was obtained. The formulas for the yield bearing capacity were proposed and were verified by the test and FEA.

1. Introduction

Prefabricated steel structures can be constructed according to a standardized design, industrial production and on-site assembly, which significantly reduce labour intensity and shorten the construction period. Prefabricated steel structures have become an important type of building in many countries. However, prefabricated steel structures are popular in low-rise buildings and are seldom used in multi-high-rise buildings [1–4]. Broad Sustainable Building Technology Ltd. and the Beijing University of Technology collaboratively proposed and designed a prefabricated high-rise steel structure system called the modular-prefabricated high-rise steel frame structure with diagonal braces [5–8]. Using this structure and technology, a 30-story hotel, a 30-story apartment building and a series of multi-rise buildings were built in Hunan province, China. Additionally, a 26-story office building was built in Shanxi province, a 25-story technology mansion was built in Ningxia province, and an 11-story office building was built in Shandong province (Fig. 1). The columns in these structures were spliced by a bolted-flange connection. Using flanges and other types of connections, the author of the paper proposed a new type of beam-to-column and column-to-column joint for modular prefabricated high-rise steel structures, and a two-story structure was built using this joint [9,10]. The square pipe columns were all connected on-site using bolts instead of welding these structures together, which significantly shortened the construction period. The *Code for Seismic Design of Buildings* [11] requires that the design bearing capacity of the connection be equal to or stronger than that of the columns, and requires that the ultimate bending bearing capacity of the connection be equal to or stronger than the plastic bearing capacity of the columns multiplied by the connecting factor. This requirement is taken reference to the Japanese steel structure code. The strength of the column splice is required according to the structure type in the seismic code of AISC and Eurocode, and it is not required to equal the strength for all the column splice connections [12,13]. The equal-strength connecting for the column splice connection by bolts in GB50011-2010 is too critical. The bolted-flange connections between columns cannot meet the requirement of GB50011-2010, since most of the bolted-flange connections are half-rigid connections. Therefore, columns can only be welded together with equal-strength, otherwise too many bolts are needed, which limits the application of the bolted connections between columns and lengthens the construction period. However, the engineering practice showed that the flange connection could be used in multi-high-rise structures [5–8]. In fact, welded structures are not perfect

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Fig. 1. Modular-prefabricated high-rise steel frame structures with diagonal braces. (a) A 30-story hotel. (b) A 30-story apartment. (c) A 26-story multiple-use building. (d) An 11-story office building. (e) A 25-story technology mansion. (f) A 6-story office building.

with no defect; the welded joints of more than 150 multi-high-rise steel structures were severely damaged during the Northridge earthquake in the US, and 476 steel-structure buildings collapsed or suffered severe damage during the Hanshin earthquake in Japan [14–16]. Brittle fractures formed in the welding-heat-affected zones of the welded square pipe columns during the Hyogo Prefecture earthquake in Japan [17]. During the Hanshin earthquake, 37 steel columns in 21 high-rise residential buildings fractured at the connecting weld seams [18,19]. These cases of severe seismic damage illustrate the problems of welded connections, making bolted connections a better choice. However, a feasible bolted connection between columns has not yet been proposed, and its bearing capacity and seismic performance need further study.

Bolted-flange connections are widely used in pipelines, pressure vessels, carrier rockets, and spacecraft, and the connections mainly bear tension. Researchers have studied the discontinuous and nonlinear changes in the stiffness of flanges under tension and have obtained several relatively mature and reliable results [20,21]. Two typical theoretical methods have been proposed, the T-stub analogy and the yield