Journal of Constructional Steel Research 93 (2014) 32–43

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Experimental seismic behavior of through-diaphragm connections to concrete-filled rectangular steel tubular columns

Ying Qin [a,b], Zhihua Chen [a,*], Qiangyue Yang [c], Kuijie Shang [d]

[a] Department of Civil Engineering, Tianjin University, Tianjin, China
[b] Department of Civil Engineering, Johns Hopkins University, Baltimore, MD, USA
[c] Zhejiang Hangxiao Steel Structure Co. Ltd., Zhejiang, China
[d] Architecture Design Co. Ltd of Tadi, Tianjin, China

ARTICLE INFO

Article history:
Received 28 May 2013
Accepted 19 October 2013
Available online 30 November 2013

Keywords:
Through-diaphragm connections
Concrete-filled rectangular steel tubular column
Cyclic loading
Seismic performance
Experimental behavior

ABSTRACT

In this paper, four full-scale specimens of existing and proposed through-diaphragm connections to concrete-filled rectangular steel tubular columns were tested under cyclic lateral load. The variables in the experiments include the geometry of the through-diaphragm, the configuration of the weld access hole, horizontal stiffeners, and the methods of connecting beam webs to columns. Three failure modes were observed in the test. The strength, stiffness, ductility and energy dissipation capacity were evaluated at different load cycles. It is found that the moment-rotation hysteresis curves are all stable and plentiful and exhibit no obvious strength deterioration or stiffness degradation. The energy dissipation capacity of the proposed through-diaphragm connections are significantly improved when compared to the existing one. Although fabricated in poor condition with an extremely low temperature, the proposed connections could obtain more than 0.1 rad of the inelastic rotation capacity. This indicates that the proposed through-diaphragm connections show good seismic behavior and could be applied to composite ordinary moment frames.

1. Introduction

Fully-rigid/fully-welded open beam-to-tubular column connections have been widely studied by many researchers such as Cao et al. [1], Kosteski et al. [2,3], Kurobane et al. [4,5], and Málaga-Chuquitaype et al. [6]. The suitable design guidance is available as well [5]. Eurocode 3 Part 1.8 [7] proposed rules for evaluating the performance of fully welded tubular joints but lacks information on their concrete-filled tubular counterparts. Meanwhile, Eurocode 4 Part 1.1 Section 8 [8] only presented basic design methods for composite joints. From many researchers' studies, tubular steel columns offer architectural and structural advantages over open members, particularly in terms of their strength-to-weight ratio, minor axis resistance, torsional stiffness and aesthetic appearance. Nevertheless, from the practical point of view it is meaningful to utilize concrete-filled tubular column systems as well.

Although concrete-filled hollow sections are much heavier than the corresponding unfilled sections, the significant increase in overall stiffness, improved fire resistance and better connection response have made them increasing attractive. Some other advantages of in-filled concrete include: (1) the concrete prevents local buckling of the steel tube wall; (2) the bearing capacity of concrete-filled tubular columns is superior to that of steel tubular columns and concrete columns. Therefore, structures with concrete filled tubular columns are increasingly used in civil engineering projects such as bridges, high-rise buildings, underwater structures and so on [9–13].

Three conventional connections are currently used for concrete-filled rectangular steel tubular (CFRST) column moment resisting frame (MRF) systems in some Asian countries such as China, Japan, and Korea [14]. As shown in Fig. 1, each employs an internal diaphragm, an external diaphragm, or a through-diaphragm.

Since the 1994 Northridge and 1995 Kobe earthquake, a large amount of research has been conducted on the performance of CFRST connections. Researchers have extensively investigated the force transfer mechanism [15], elasto-plastic behavior of connections [16,17], the load-carrying capacities [18–23], and the load-deformation relationship models [24]. Additionally, they have looked at the significance of weld defect [25], the effect of types of weld tabs and welding procedure, as well as welding heat and loading pattern on connection performance, the material properties of steel and weld metal [26], the geometry of weld access hole and other weld details [27], the elimination of weld access hole [28], the prediction and assessment of the brittle fracture [29–31]. The improvement of the existing connections by using additional fittings to strengthen the interface of the beam to column flange or reducing the beam section in the potential plastic hinge region to protect the complete joint penetration (CJP) and the heat affected zone (HAZ) of the beam flanges [32–38] represent other areas of interest. Various connection alternatives have been proposed and explored by researchers, such as the use of blind bolt [39,40], combined channel angle connections [6], through-bolt connections [41], and passing the

* Corresponding author at: School of Civil Engineering, Tianjin University, Weijin Road No. 92, Nankai District, Tianjin, 300072, China. Tel.: + 86 022 27403736; fax: + 86 022 27409933.
E-mail address: zhchen@tju.edu.cn (Z. Chen).

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http://dx.doi.org/10.1016/j.jcsr.2013.10.020

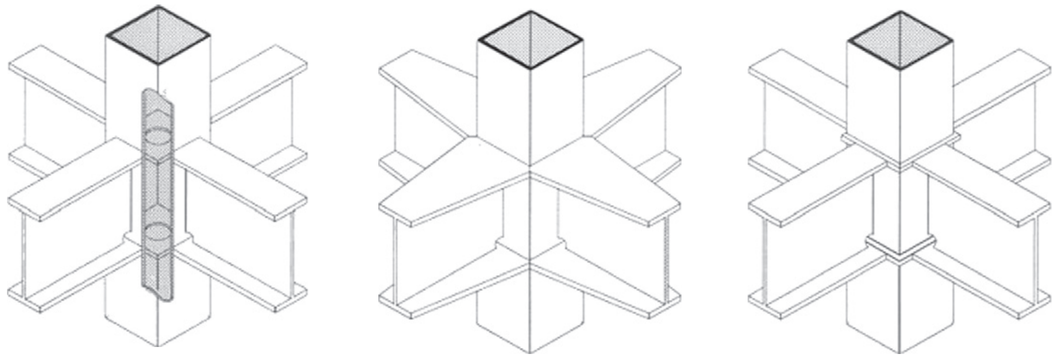

Fig. 1. Conventional details of connections to CFRST columns (a) Internal diaphragm (b) External diaphragm (c) Through diaphragm.

beam completely through the column [42]. Several state-of-the-art reports and papers also presented a large number of research results on CFRST connections [43–46].

As a part of investigations on the seismic behavior of CFRST connections, this paper focuses on the experimental performance of the existing and proposed through-diaphragm connections to CFRST columns in an effort to move the beam plastic hinges away from the column face.

The work described in this paper attempts to investigate the effect of various parameters on the performance of the proposed through-diaphragm connections subjected to cyclic loading. The parameters include the geometry of the through-diaphragm, the configuration of the weld access hole, the horizontal stiffeners and the methods of connecting beam webs to tube columns. Based on the experimental results, the cyclic characteristics of the through-diaphragm connections are presented and discussed in terms of failure mode, strength, stiffness, ductility, deformation, and energy dissipation capacity.

2. Experimental program

2.1. Specimen design

The test specimens were constructed in a tee shape to simulate the external connection of a steel MRF with a height of 4.2 m and a width of 7.2 m, assuming that the deflection points of the columns and beams occur at the mid-points subjected to the cyclic lateral loading. It was not feasible to fabricate specimens in a cruciform shape to analyze the internal connection of the frame due to the limitations of cost and laboratory testing area. Four full-scale beam-to-column connections were tested under quasi-static cyclic loading to study the seismic behavior of the existing and proposed through-diaphragm connections to CFRST columns.

The geometric detail of the connections as well as the beam and column sizes is provided in Fig. 2. Except for the different connection configurations in each specimen, the columns and the steel beams for the four specimens were all identical. Previous experimental work and practical application with through-diaphragm connections utilized traditional cold-formed steel tubes [14], while in this study, the CFRST columns $700 \times 500 \times 30 \times 35$ mm in size were made of four steel plates vertically seamed by CJP welds. This is believed to enhance the versatility and practicality of this type of connection due to the wider range and larger size available in tubular sections. Meanwhile, the beams were H-shaped steel sections of a cross-section $700 \times 300 \times 13 \times 24$ mm for all test specimens. The end of each steel beam opposite to the connection side had a 300 mm (width) by 740 mm (height) end-plate. Three vertical plates, parallel to each other, were attached to the end-plate by CJP welds, in order to connect the rigid bar to the beam. The through-diaphragms, with a thickness 2 mm larger than that of beam flange, penetrated the columns and were welded to the tubes. The purpose of this detail was to provide sufficient capacity and stiffness of the connection. A concrete-pouring hole with a diameter of 250 mm was prepared at the center of each diaphragm for concrete-filling. Four small holes with a diameter of 25 mm were also located near each corner of the column. The high-strength bolts used in the tests were Grade 10.9 M24. Namely, the exterior diameter of the bolts was 24 mm and the ultimate strength of the bolts was assumed to be 1000 N/mm^2. The ratio of the yielding strength to the ultimate strength of the bolts was 0.9. The high-strength bolts were initially tightened with a spanner and then with a torque wrench in accordance with the specified torque values following the Chinese Code for Acceptance of Construction Quality of Steel Structures GB50205-2001 [47]. The temporary bolts were M20 with a diameter of 20 mm. They were used in the fabrication process of the specimens when connecting the beams to the columns.

The Specimen JD-1 detail was the same as that of the existing through-diaphragm connection. The diaphragm extended the column face for a length of 100 mm. The beam flanges were connected to the through-diaphragms by CJP welds on site. The beam web was bolted to the column through the shear tab, while the other three specimens had beam webs fillet-welded around their perimeters to the shear tabs. The shear tab and the column were connected by CJP welds, as shown in Fig. 2(a).

Specimen JD-2 had a tapered diaphragm connection detail as shown in Fig. 2(b). This was designed to transfer the tension force from the beam flange to the sides of the steel tube and provide a more gradual transition in the geometry of the connection region.

Specimen 3 had two triangular plates groove-welded to the beam flange to form the tapered flange at the beam end as shown in Fig. 2(c) in order to move the plastic hinge away from the column face.

Specimen JD-4 was identical to Specimen JD-3 except that the former's tapered plates were 330 mm shorter, as shown in Fig. 2(d). The purpose is to examine the effect of the length of horizontal stiffeners.

The weld access hole shown in Fig. 3(a) was used for specimen JD-1 and JD-2, while that in Fig. 3(b) was used for specimen JD-3 and JD-4. The geometry of these two types of weld access holes, referred to as the modified weld access hole 1 and modified weld access hole 2, were designed according to the results from the finite element analysis. They were variations of the recommended geometry in AISC (2005) [48]. The primary characteristics of each specimen are presented in Table 1.

2.2. Material properties

The rectangular hollow steel tubes were manufactured from mild steel sheets with four plates being cut from the sheet, tack-welded