Engineering Structures 151 (2017) 68–84

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Experimental investigation of special-shaped concrete-filled steel tubular column to steel beam connections under cyclic loading

Jingchen Liu [b], Yuanlong Yang [a,c,*], Jiepeng Liu [a,c], Xuhong Zhou [a,c]

[a] Key Laboratory of New Technology for Construction of Cities in Mountain Area (Chongqing University), Ministry of Education, Chongqing 400045, China
[b] CNNC China Nuclear Power Engineering Co., Ltd., Beijing 100840, China
[c] School of Civil Engineering, Chongqing University, Chongqing 400045, China

ARTICLE INFO

Article history:
Received 15 February 2017
Revised 16 June 2017
Accepted 8 July 2017

Keywords:
Special-shaped column
Concrete-filled steel tubular column
Connection
Exterior diaphragm
Pseudo static experiment
Inter-story drift
Joint shear resistance

ABSTRACT

This paper presents experimental investigation and numerical investigation on seismic behavior of special-shaped concrete-filled steel tubular (CFST) column to steel beam joints. Exterior diaphragm and vertical rib are respectively introduced as joint stiffeners. A pseudo static experiment was conducted to investigate load transmission mechanism, failure mode and seismic performance index based on load-deformation curves and strain curves. The seismic behavior of the two kinds of joints were compared and evaluated. The classification of the joints by stiffness is conducted according to Eurocode. Inter-story drift of the specimens was calculated with data from laboratory apparatus and verified with test results. A design formula of joint shear resistance based on internal load transmission was proposed for engineering application. A finite element model of special-shaped CFST to steel beam connections was established as a supplement to analyze load transmission mechanism.

1. Introduction

The frame structure with special-shaped concrete-filled steel tubular columns (CFST columns) is an improved architectural approach compared to traditional frame structure with rectangular columns. Larger efficiency of indoor room and convenience of furniture placement are guaranteed by smooth joints of special-shaped column and connected in-filled wall. Moreover, it has preferable seismic behavior for a wider range of seismic zones [1].

However, there is no existent design standard for special-shaped CFST column structures. China national design standard are issued only for special-shaped RC columns. As the most commonly used special-shaped column, static behaviors of special-shaped RC short columns under concentric compressive load or biaxial eccentric compressive load drew much attention, which promoted the propose of interaction curves of M-N resistances for practice [2–7]. To adapt to development of real estate industry, Chinese researchers [8–10] has carried out extensive study to concentrate on their seismic behaviors in frame structures or frame-shear wall structures.

But the special-shaped RC columns have strict limitations in seismic design. The Chinese codes JGJ 149-2006 [11] and GB 50010-2010 [12] provide significant comparison in maximum building height between frame structure with special-shaped columns and that with rectangular columns in Table 1.

Special-shaped CFST columns, as an improvement on seismic behavior, are introduced into the academic research. The stiffeners, including plate rib, pulled binding bar et al., are suggested to be welded in the specimens to postpone local buckling of special-shaped tubes. Shen et al. [13] have reinforced L-shaped CFST columns by introducing plate ribs, which is the most commonly suggested in square or circular CFST columns. The flexural stiffness of steel plate is enlarged by plate ribs. Shen et al. [14] also have conducted experimental investigation in seismic behavior of special-shaped CFST columns (with plate ribs) in frame structures. Another theoretical and experimental researches [15–17] have been conducted to investigate pulled binding bars in T-shaped and L-shaped CFST columns under static load. Besides, some special-shaped columns including latticed concrete filled steel tubes were experimented and investigated under axial load and cyclically varying flexural loads [18]. These above kinds of columns worked integrally and their seismic behaviors were good enough. Based on above research, the special-shaped CFST column is a new type of composite structural member with good prospect.

* Corresponding author at: Key Laboratory of New Technology for Construction of Cities in Mountain Area (Chongqing University), Ministry of Education, Chongqing 400045, China.
E-mail address: yangyuanlong@cqu.edu.cn (Y. Yang).

http://dx.doi.org/10.1016/j.engstruct.2017.07.021
0141-0296/© 2017 Published by Elsevier Ltd.

Table 1
Maximum building height of special-shaped and rectangular columns in frame structures.

Section	Non-seismatic design	Seismic design					
		6-degree	7-degree		8-degree		9-degree
		0.05 g	0.1 g	0.15 g	0.2 g	0.3 g	0.4 g
Special shape	24 m	24 m	21 m	18 m	12 m	–	–
Rectangular shape	70 m	60 m	55 m	55 m	45 m	45 m	25 m

However, the column-beam connection tends to be critical damaged component in the special-shaped column frame structure, for its irregularity of column cross section reduces stiffness and resistance of the joint to a certain extent. Therefore, simple and high-efficient connections of special-shaped CFST column and steel beam are urgently called for in engineering application. A small number of experiments were conducted to research on connections of special-shaped CFST column and steel beam by experts and scholars. Liu et al. [19] proposed special-shaped CFST column to steel beam connections with extended end-plate or with top and bottom steel angles connected to beam flanges. A pseudo-static experiment of these specimens demonstrated these two kinds of joints can be classified as semi-rigid joints. Another research conducted by Wan et al. [20] focused on special-shaped CFST column to steel beam connections with exterior diaphragm. The weak joint and strong joint, differentiated by adjusting beam dimensions, were researched to investigate their failure mode and seismic behavior. Experimental results suggested that sufficient bearing capacity, ductility and energy dissipation of beam to column connections can be expected in engineering application.

As a supplement of research on connections of special-shaped CFST column and steel beam, the square CFST column to steel beam joints, which have similar mechanical behavior to that of special-shaped CFST to steel beam joints, provide some research directions for the research in this paper. Prion and McLellan [21] proposed a connection including beam end-plates and through-column bolts, and the connection showed good behavior. Chung et al. [22] and Wu et al. [23,24] also published that acceptable performance is guaranteed with appropriate design of bolted connections. Ricles et al. [25] carried out experimental research on seismic behavior of square CFST column to steel beam connections with interior diaphragm. The weak panel zone specimens were investigated to possess good seismic behaviors with sufficient cyclic strength. Nishiyama et al. [26] proposed a shear strength formula of panel zone for joints with interior diaphragm or exterior diaphragm based on previous experiment. Besides, an analytical model for restoring force characteristics of shear panel was also proposed in order to reproduce the experimental results with good accuracy. Hawileh et al. proposed a nonlinear finite element analysis and modeling of a precast hybrid beam-column connection subjected to cyclic loads [27] and furtherly conducted a non-dimensional design procedures for precast concrete hybrid frames [28]. Research results showed that good seismic behavior can be expected for this kind of connections and frames.

In this paper, seismic behavior of special-shaped CFST column to steel beam connections with exterior diaphragms or vertical ribs was experimentally and numerically researched, based on the previous research on seismic behavior of special CFST columns [29–31]. A pseudo static experiment was conducted on specimens consisted of special-shaped CFST column, steel beam and joint panel zone. The beam and column extended to another end at contra-flexure point. A constant axial load and subsequent horizontal cyclic loads were applied on top of the column. During the experiment, yielding or local buckling of steel beam and shear failure of joint panel zone were observed and analyzed. Load-displacement curves (hysteretic or monotonous) of the column, beam and joint panel zone were drawn to investigate stiffness, resistance, ductility and energy dissipation of specimens. With the curves, joints of specimens were then classified by stiffness according to European3: Design of steel structures-Part 1-8: Design of joints [32]. To calculate accurate deformation of frame structure, three types of deformation: elastic flexural deformation of beam and column, plastic hinge deformation of beam and shear deformation of joint panel zone were respectively monitored during experiment. A finite element analysis with software ABAQUS, verified by experimental data, was further conducted to investigate load transmitting mechanism. On the basis of load transmitting mechanism, simplified design formulae of joint shear resistance were proposed for engineering application.

2. Experimental design

2.1. Details of specimens

The key parameter investigated in this experiment is type of connections between steel beam and special-shaped CFST column: exterior diaphragm and vertical rib. The specimens include three center cross-shaped CFST column to steel beam connections (J1, J2 and J3) and one side T-shaped CFST column to steel beam connection J4.

Fig. 1 shows configuration and dimensions of half-scale special-shaped CFST column to steel beam connection specimens. Fig. 2 illustrates cross-sectional configuration and dimension of special-shaped CFST columns and welding position of connection stiffeners. The beam and column of specimens extend from joint panel zone to contra-flexure points which are approximately assumed to be mid-points of beam and column. Therefore, the lengths of beam and column in the experiment are respectively 1300 mm and 725 mm according to actual engineering dimensions.

The vertical rib, on one hand, is perpendicularly welded with edges of beam flange, and on the other hand welded with the steel plates and concave corners, guaranteeing that tension force (or a portion of compression force) was transferred from beam flange to steel tube. Tensile bar stiffeners, to prevent or postpone local buckling of steel tube with vertical spacing of 100 mm, are employed to be welded on the concave corner and on the steel plate with large width-to-thickness ratio.

Fig. 3 exhibits steel beam, exterior diaphragm and vertical rib. Rolled I-shaped steel is employed as steel beam with section 200 mm×100 mm×4.44 mm×7.37 mm. To effectively transfer internal force of beam, the thicknesses of exterior diaphragm and vertical rib are the same with that of beam flange. The axial compression ratio of columns in the experiment is 0.5. The corresponding axial compressive load is 1342 kN.

2.2. Material properties

According to the Chinese National standard – metallic materials-tensile testing at ambient temperature (GB/T228-2002), mechanical properties of steel plate and reinforcement bar were tested. The yield strength f_y of beam flange (thickness