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Shear behaviour of panel zone in through-diaphragm connections to steel tubular columns

Bin Rong[a,b], Shuai Liu[a], Jia-Bao Yan[a,b,*], Ruoyu Zhang[a]

[a] *Department of Civil Engineering, Tianjin University, Tianjin 300072, China*
[b] *Key Laboratory of Coast Civil Structure Safety, Ministry of Education, Tianjin University, Tianjin 300072, China*

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ABSTRACT

This paper experimentally, numerically, and analytically, studied the seismic behaviour of through-diaphragm connections in the steel framed structure. Three through-diaphragm connections between steel tubular column and H-shaped steel beam were tested under cyclic loading to investigate the seismic behaviours of the panel zones. The studied parameters included different configurations of the connections (interior and exterior connections) and thickness of the tube in the panel zone of connections. The failure modes, load-displacement behaviours, ductility and strength degradation of these tested specimens were analysed and discussed. Nonlinear finite element models (FEMs) were developed to simulate the seismic behaviour of these connections. The developed FEMs considered the geometric and material nonlinearities of the connections. The validations of the FE predictions against the test results confirmed the accuracy of the FEM in predicting the seismic behaviour of the connections. With these validated FE models, a subsequent parametric study comprising 15 cases were performed to investigate the influence of thickness of tube web and flange in the panel zone on the shear behaviour of the connections. Finally, the analytical model was also developed to predict the shear resistance of panel zone. The accuracy of this analytical model was validated by the reported test results.

1. Introduction

Concrete-filled steel tubular (CFST) column has been widely used in engineering constructions due to its versatile advantages that include high load carrying capacity, good ductility, easy construction, and reduced cost on construction. As the key elements to transfer the forces in the building, the connections have attracted extensive research interest. There are three representative types of beam-to-CFST columns connections, namely through-diaphragm connection, interior diaphragm connection and outer diaphragm connection. Among these connections, the through-diaphragm connection may be the most popular type [1].

Extensive experimental studies have been conducted on the connections between steel beam and CFST columns. Matsui [2] conducted experiments on the seismic behaviour of connections between wide flange steel beams and CFST columns. Based on the test results, a method for calculating the bending capacity was proposed. Kanatani et al. [3] tested the connections under monotonic and cyclic loading. It was found that the filled concrete can avoid the buckling of the steel tube. Based on the cyclic tests of 10 through-diaphragm connections, Kawaguchi et al. [4] reported two failure modes of the three-dimensional connections, i.e., panel zone failure and column bending failure. Nishiyama et al. [5] also developed an analytical model for the restoring force characteristics of the through-diaphragm and outer diaphragm connections using high strength steel and concrete. Zhou et al. [6] tested six full-size interior diaphragm specimens connected by bolt-welding or welding at the beam end under cyclic loading to investigate the failure mode of this type of connections. It was found that the buckling or fracture of beam flange was the main failure mode in these tests. Fan et al. [7] tested six joints between CFST column and composite beam under bidirectional reversal loads. The failure modes observed in the tests was mainly the bending failure of column tube or beam flange. Rong et al. [8] tested four specimens under static tension load to investigate the flexural resistance of the through-diaphragm connections, Qin et al. [9–11] compared the seismic behaviour of improved type of through-diaphragm connections under cyclic loads. Welding failure and beam failure were the main failure modes of these improved connections with tapered flange. Although extensive experimental studies have been conducted on this connection, most of them focused on the moment transferring mechanism. In addition, most of the previous experimental studies have not investigated the mechanical mechanism of the connections failed in typical shear mode. The information on the shear behaviour of the through-diaphragm

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[*] Corresponding author at: Department of Civil Engineering, Tianjin University, Tianjin 300072, China.
E-mail address: ceeyanj@163.com (J.-B. Yan).

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Table 1
Dimension of specimens, results of test and FEM.

Dimensions	Tube (mm)		Panel Zone (mm)			Beam (mm)				n
	b_c	t_c	t	b	λ_{pz}	b_f	h_b	t_w	t_{bf}	
S-1	250	12	12	250	20.8	250	250	8	14	0.1
S-2	200	12	6	250	33.3	200	250	8	14	0.3
S-3	250	12	6	250	41.7	250	250	8	14	0.2
Results	P_y^t (kN)	P_y^f (kN)		P_u^t (kN)		P_u^f (kN)	P_y^f/P_y^t		P_u^f/P_u^t	
S-1	138.9	141.2		181.0		189.0	1.02		1.04	
S-2	50.3	46.8		65.5		81.8	0.93		1.25	
S-3	107.5	116.4		155.7		168.1	1.08		1.08	
Average	–	–		–		–	1.01		1.12	
COV	–	–		–		–	0.01		0.02	

b_c denotes width of the column tube; t_c, thickness of the column tube; t, thickness of tube in panel zone; b, width of the tube in panel zone; λ, the width-to-thickness ratio of tube web; b_f, width of beam flange; h_b, height of the beam; t_w, thickness of beam web; t_{bf}, thickness of beam flange; n, the axial compressive ratio of the tube column; Cov denotes coefficient of variation.
P_y^t: yielding load of test, P_y^f: yielding load of FEA, P_u^t: ultimate load of test, P_u^f: ultimate load of FEA.

connections is still limited since the shear failure mode (in Ref. [4,5]) is one of the two major failure modes according to several seismic surveys and experiment researches. The other failure mode is plastic hinge in the steel beam (in Ref. [6–11]). However, in recent years, shear failure with local buckling in the panel zone was found in the experimental studies. Pan et al. [12] conducted cyclic loading test on the connection between H-shaped column and beam to evaluating the effect of vertical connecting plates on the panel zone shear behaviour. A typical shear failure with local buckling in the panel zone was observed in their tests. Thus, the same failure mode can occur in the panel zone of tube-column connections. It is still of interest to carry out the experimental studies to obtain the necessary information on the shear behaviour of the through-diaphragm connections to steel tubular column.

Since the shear resistance of the connections is important to the design of the steel frame structures, it is also necessary to analytically investigate the shear behaviour of the through-diaphragm connections. Different analytical models have been developed to predict the shear resistance of the panel zone. The design equations for shear resistance of connections proposed by the Architectural Institution of Japan [13] considered the shear resistance of both the steel tube and the concrete core. Sasaki et al. [14] developed the analytical models for shear resistance of the connections using the “virtual work principle” and specified that the shear resistance of panel zone was contributed by three parts of the panel zone, i.e., the steel tube web, the concrete diagonal strut and the steel frame composed by diaphragm and tube flange. Fukumoto and Morita [15] presented an empirical equation for evaluating the resistance of connections using high strength materials that considered the confinement effect of the tube flange on the concrete. Zhou [6] developed an analytical model for steel frame-shear wall and concrete diagonal short column that considered the shear resistance of panel zone. Qin et al. [11] proposed a theoretical method to evaluate the shear resistance of concrete compression strut in the panel zone of through-diaphragm connections. Kang et al. [16] modified shear resistance-deformation relations of panel zone in the joint through finite element analysis. However, these analytical models were not developed to predict the resistance of the through-diaphragm connections failed in pure shear mode. Furthermore, some existing analytical models still ignored the contribution of the tube flange to the shear resistance of panel zone that may underestimates the shear resistance of the joint. Thus, these limitations compromised the accuracy of these models. Thus, the analytical models to properly predict the shear resistance of the through-diaphragm connections are still necessary.

This paper aims to investigate the shear behaviour of the through-diaphragm connections. This paper firstly carried out quasi-static tests on three through-diaphragm connections under cyclic loading. In the tested specimens, the infilled concrete was eliminated to investigate the shear behaviour of the pure steel panel zone. One connection was constructed in a T-shape to simulate the edge joints in a steel frame structure. Based on the test results, the energy dissipation, plastic deformation capacity, yielding and ultimate resistance of the panel zone were presented and discussed. Finite element (FE) model was developed for the connections and its accuracy was validated against the reported test results. With the developed FE model, parametric studies were also carried out to investigate the contribution of the steel panel zone, including the web and the flange of the steel tube column, to the shear resistance. Finally, an analytical model was developed to evaluate the shear resistance of the panel zone. The accuracy of the analytical model was validated by the reported test results and compared with the FE analysis results.

2. Experimental program

2.1. Specimens design

There are totally three specimens in this test program, i.e., two interior connections and one exterior connection. In order to guarantee the shear yielding of panel zone before yielding of the steel beam, the tube columns in the panel zones of S-2 and S-3 were designed with smaller section size than the rest locations. In this panel zone, both steel and concrete contributed to the shear stiffness and resistance of the beam-to-column connections. In the existing prediction models [15], the shear resistance of panel zone was contributed by steel tube and concrete. They were assumed to behave independently and finally contributed to the overall performance of the connection. In order to investigate the shear behaviour of the pure steel tube, the concrete was removed from the connections. The details of these three specimens are given in Table 1 and Fig. 1.

2.2. Material properties

Cold-formed square steel tube (□250 × 250 × 12 and □200 × 200 × 12) and H-shaped beam (H250 × 250 × 8 × 14 and H250 × 200 × 8 × 14) were used to fabricate the steel tubular columns and beams in the connections, respectively. Steel coupons as shown in Fig. 2 were prepared and corresponding tensile tests were performed accordingly to GB/T228-2010 [17] to obtain the mechanical properties of the steel components in the connections. Table 2 lists the mechanical properties of these steel coupons.