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Experimental and numerical analysis of blind bolted moment joints to CFTST columns

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ABSTRACT

Experiments and numerical analysis were conducted to investigate the mechanical behavior of the blind bolted end plate joints to concrete-filled thin-walled steel tubular (CFTST) columns. Four blind bolted end plate joints to CFTST columns subjected to the monotonic loading were tested. Then, finite element analysis (FEA) modeling of the tested specimens was developed, and the results obtained from FEA modeling were verified against those from the test results. Parametric studies were conducted to investigate the influence of end plate thickness, axial load level, steel ratio and slenderness ratio etc. on moment-rotation curves of composite joints. Some methods of effective provisions were proposed and discussed in order to enhance the connection behavior. The test and numerical analysis results indicated that the typed joints to CFTST columns behaved in a semi-rigid and partial strength manner. The proposed innovative blind bolted joint using reliable and effective solutions could be applied in the mid- and low-rise buildings.

1. Introduction

Concrete-filled thin-walled steel tubular (CFTST) columns consisting of very thin steel tubes and concrete were developed based on the traditional concrete-filled steel tubular (CFST) columns [1,2]. The CFTST columns widely used in modern structural application could provide confinement, economic price and better mechanical behavior and eliminate the use of formwork during construction. Due to the merits of both thin walled steel structures and reinforced concrete structures, there has been a growing research interest. Some experimental investigations have been performed on the static, seismic and fire behavior of CFTST columns in recent decades such as Petrus et al. [3], Xu et al. [4], An et al. [5], Xu et al. [6], Liu et al. [7], Tao et al. [8,9], Zhang et al. [10]. The experimental results revealed that the CFTST columns exhibited better strength, stiffness and ductility.

Presently, there have been several attempts to investigate performance of CFTST columns using finite software. Liu et al. [11] reported a nonlinear elastic-plastic finite element model using OpenSees software to investigate the seismic behavior of CFTST arches. Tao et al. [12] had conducted a series of nonlinear analysis and design of CFTST columns under axial compression. Goto et al. [13] elucidated the numerical results of the behavior of stiffened rectangular CFTST columns and prevented the premature failure resulting from metal fracture.

Some scholars have started to pay attention to explore the performance of steel beam to CFTST column joints, such as Hasham et al. [14], Xu et al. [15] and Patel et al. [16]. However, most of them focus on beam-to-column rigid connections but scare concern with semi-rigid joints. To overcome the inconvenience of extensive welding and the required high tolerance, there has been a growing concern in the blind bolted connections. Some studies on the behavior of T-stub connections to RHS and CFST columns using one-side fasteners were explored by Goldsworthy et al. [17] and Yao et al. [18]. Other main studies were conducted on the behavior of RHS and CFST column joints with various blind bolts, such as France et al. [19]. Test results and design recommendations were also given by Yeomans [20–22] and Packer and Henderson [23]. Wang et al. [24,25] had firstly reported a novel blind bolted connection between steel beam and CFTST columns. The test specimens were designed and fabricated by Wang et al. [24,25] to study the static or seismic behavior of blind bolted connections to CFTST columns under axially compressive load on the top of the columns and static or cyclic loads on the beam tip, respectively. These test results showed that the proposed steel beam to CFTST column connections exhibited favorable strength and stiffness and were a reliable and effective solution for modern structures. Experimental results also indicated that CFTST column joints were different with RHS column joints in forced mechanism tested by Yao et al. [26] and Lee et al. [27–29] in considering the anchoring action of blind bolts.

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Nomenclature

A_c	Cross-sectional area of the concrete core
A_s	Cross-sectional area of the steel tube
B	Width of square steel tube
b_{fb}	Beam flange width
CFTST	Concrete-filled thin-walled steel tube
CFST	Concrete-filled steel tube
d_b	Bolt diameter
E	Young's modulus of steel
E_c	Young's modulus of concrete
E_s	Modulus of elasticity of steel
EI_b	Flexural rigidity for the beam
FEA	Finite element analysis
f_c	Cylinder strength of the concrete
f_{cu}	Concrete strength
f_{ck}	Characteristic strength of the concrete
f_y	Yield strength of the steel
H	Column Height
h_b	Beam section height
h_{jc}	Height of column wall thickening
i	Beam to column linear stiffness ratio
i_b	Linear stiffness of steel beam
i_c	Linear stiffness of CFTST column
k_m	Beam to column yield strength ratio
L	Beam Length
l_{cb}	Bolt anchorage length
M	Connection moment
M_{bp}	Design plastic moment resistance of the beam
M_{by}	Analytical sectional yielding bending capacity of steel beam
M_{cy}	Analytical sectional yielding bending capacity of CFTST column
M_u	Ultimate moment of the connection
M_m	Maximum moment of the connection
m	Dimensionless connection moment
N	Axial load applied to the CFTST column
N_u	Ultimate axial load applied to the CFTST column
n	Axial load level, n=N/N_u
P_o	The normal pretension forces of bolt
p_b	Bolt pretension force
SCC	Self-consolidating concrete
$S_{j,\,ini}$	Initial stiffness of connection
t_{ep}	End plate thickness
t_{fb}	Beam flange thickness
t_{jc}	Thickness of column wall thickening
t_p	End plate thickness
t_{wb}	Beam web thickness
α	Steel ratio
α_o	Bolt anchorage length ratio
λ	Slenderness ratio
ξ	Confinement factor
θ	Dimensionless connection rotation
θ_r.	Connection rotation

Up until now, there has been a few of theoretical research studies on the behavior of steel beam to CFTST columns joints by developing an accurate FEA model. Sixty-one parametric studies on beam-column joints were carried out using the verified finite element model by Chen et al. [30]. Patel et al. [31] had presented a new multiscale numerical model for simulating the structural performance of biaxially loaded high-strength thin walled rectangular CFST slender beam-columns. However, scant numerical analysis was studied to blind bolted moment connections for CFTST columns.

The research contents in this paper were significantly different with the Refs. [17,18] which focused on behavior of the tensile components, but the main objective of this study was to investigate the structural behavior of blind bolted flush or extended end plate joints to CFTST columns under static load by experimental and theoretical studies. In this paper, finite element analysis (FEA) models were verified by tested results obtained from Ref. [24]. The finite element program ABAQUS was employed in the analysis, in considering the concrete confinement effects, local buckling and interface between concrete core and steel tube. Extensive parametric studies were conducted to investigate the influence of axial load level, steel ratio, column slenderness ratio, and bolt pretension force etc. on the structural behavior of the typed joints. Based on the experimental and numerical studies, the feasibility of connecting an end plate to the steel beam using an alternative method to improve the joint behavior has been explored.

2. Experimental program

2.1. Test specimen description

Four blind bolted end plate connections to square CFTST columns subjected to static load were tested to explore the effects of the steel tube thickness and the end plate type. The relevant design details of the test specimens are clearly shown in Fig. 1 and Table 1. All specimens used the H-shaped steel beam section size of HN300×150×6×10 mm and end plate of 12 mm thickness. The steel beams and columns are assembled by means of end plate connections with blind bolts at the first, as illustrated in Fig. 2. All the bolts for the connections are tightened by a torque wrench with designed torque value, so as to ensure consistency. And then the self-consolidating concrete (SCC) mix was filled in the square CFTST columns.

2.2. Material properties

Table 2 summarizes the results of the material tests of the steel used in the test specimens. The blind bolts are Grade 10.9 M20, namely that exterior diameter of the bolts is 20 mm and the ultimate strength of the bolts is 1000 N/mm^2. The ratio of the yielding strength and the ultimate strength of the bolts is 0.9. These were tightened to 442 N m torque following the specifications GB50017 [32]. The blind bolts were welded with 20 mm diameter 50 mm length high strength reinforcing bars of grade 335 N/mm^2 to discuss the effect of anchorage length ratio, as shown in Fig. 3.

The size of the concrete cubes was 150 mm×150 mm×150 mm in the test of cube compressive strength and 100 mm×100 mm×300 mm for the modulus of elasticity. The three group tests have been undertaken and each group of tests had three specimens of concrete cube. The compressive strength of the concrete was determined by the standard cylinder compression tests. The compressive cube strength (f_{cu}) of the self-consolidating concrete (SCC) was found to be 44.34 N/mm^2 at day 28. On the day of testing, the compressive strength from the cube samples was 48.27 N/mm^2 and the modulus of elasticity was 33,521 N/mm^2.

2.3. Test setup and loading program

It can be found from Fig. 4 that the test setup with hydraulic actuator of 500 kN capacity was utilized to add the monotonic load to the beam end in the vertical direction. The axial load level (n) in the specimens was selected as 0.4, which generally reflected the real axial level of the CFTST columns in a practical building structural system. The axial load level (n) in this paper is equal to:

$$n = N/N_u \tag{1}$$