ARTICLE IN PRESS

Engineering Structures xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Engineering Structures

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

Seismic performance of a new through rib stiffener beam connection to concrete-filled steel tubular columns: An experimental study

Mahdi Zeinizadeh Jeddi, N.H. Ramli Sulong *, M.M. Arabnejad Khanouki

Department of Civil Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

ARTICLE INFO

Article history:
Received 15 March 2016
Revised 17 October 2016
Accepted 18 October 2016
Available online xxxx

Keywords:
Beam to concrete-filled tubular (CFT) column connection
Through-rib stiffener
Cyclic loading
Seismic performance
Ductility
Energy dissipation

ABSTRACT

This paper proposes a new moment-resisting connection known as a through rib stiffener beam connection, which is directly passed through a pre-slotted circular column with concrete infill. Four half-scale cruciform specimens with orthogonal beams were tested under cyclic loading. The failure modes, hysteretic performance, rotation capacity, strength and stiffness degradation, ductility, and energy dissipation of the connections were analysed. The effect of different parameters, such as through rib stiffener and beam section size, on the connection performance was investigated. The experimental results indicated that the new through rib stiffener beam connected with circular columns exhibited a large hysteretic enclosed area, good ductility, and excellent energy dissipation. The results proved that the proposed connection satisfies the seismic provisions and ductility design requirements for it to be utilized as moment-resisting frames in a seismically active area.

1. Introduction

A concrete-filled tubular (CFT) column has many advantages over steel open sections or reinforced concrete, such as delayed local buckling, high rotation capacity due to the confining effects of the tube, construction efficiency, cross-sectional performance, fire resistance, and economical properties [1,2]. This type of column has been commonly used as part of special moment-resisting frames in high-rise buildings for decades [3,4]. In the presence of a compression load, the efficiency of tubular columns is better than that of open columns, as the load carrying capacity of CFTs can be increased remarkably.

In addition, CFT sections exhibit excellent static and dynamic properties, such as a large bending strength and stiffness, a large torsional stiffness, high ductility and energy dissipation, a large post-buckling strength, a low strength deterioration, a low lateral torsional buckling of the connection, and overall aesthetic characteristics. These advantages make the CFT column more pleasant for designers to use in seismic moment-resisting frames [3,5,6].

Following the 1994 Northridge and the 1995 Kobe earthquakes, many studies have been conducted on the open beam to wide flange column connection. However, limited research is available for the open beam to CFT column connection. Therefore, limited data are available on the CFT column connection to design multi-story construction projects in earthquake zones [6–8].

The American Institute of Steel Construction (AISC) and FEMA 355-D recommended the insertion of two internal continuity plates inside the column webs at the top and bottom flange level with complete joint penetration groove welds to transmit the maximum shear forces to continuity plates [6,7].

However, the continuity plate attachment and the construction of these types of columns are not economical. Furthermore, for the concrete filled column, the continuity plate prevents the concrete from reaching the lower part of the column. Therefore, researchers have modified and proposed a new beam to CFT column load transferring mechanism. The following studies have been conducted to improve the application of continuity plates: through beam connections [9], hunch length optimization using horizontal hunch connections [10], rib plate stiffeners [8], column-tree moment-resisting connections [11], and vertical plates passing through the column [12].

Moreover, other studies have been conducted on the beam to hollow column load transfer mechanism including: extending the web or flange through the CFT column and diaphragm connection [13], external T-shaped stiffeners at the junction of the column and beam [14,15], diaphragm fillet welded to the tube wall [16], web cleat plates and reinforcing bars welded to the top and bottom flanges [17], CFT column T-angle or triangular stiffeners [18–21], reduced beam section (RBS) steel beam to CFT external ring

* Corresponding author.
E-mail address: hafizah_ramli@um.edu.my (N.H. Ramli Sulong).

http://dx.doi.org/10.1016/j.engstruct.2016.10.038
0141-0296/© 2016 Elsevier Ltd. All rights reserved.

column [22], T-stiffeners and penetrated elements for CFT columns [14,23], stiffening the plates around the CFT column [24], continuous beams to a CFT column [25], extended end-plates bolted to the CFT column with steel rods passing through the column or beam passes through the joint with an extra bolted bracket without using any welding between the beam and the column [26], bidirectional bolted beam-to-column connections for a CFT column [27], blind bolted connection to concrete filled tubular column [28,29] and internal diaphragm connections to CFT columns [30].

Nevertheless, more studies are required to propose a suitable beam to CFT column connection. Fabrication of the connections using fillet weld or stiffeners on the column face, insertion of internal continuity plates or rods inside the column and subsequent welding are generally difficult and are costly in terms of both time and money.

This paper proposes a new type of through beam connection known as a through rib stiffener beam moment connection to provide a ductile moment connection. The through rib stiffener connection can be used in all kinds of hollow section columns, such as a built-up section or CFT column. The connection requires less connecting elements and consists of two vertical rib stiffeners welded to the top and bottom of the beam flanges passing directly through the pre-slotted CFT column. The through rib stiffener is proposed to improve the load transfer mechanism of a connection, with high rigidity and enhanced ductility.

Four specimens were tested under cyclic loading to examine the seismic performance of the proposed connection. The experimental results were compared to investigate the connection behaviour. The failure modes, cyclic performance, ductility, strength, stiffness, and energy dissipation of the connections were presented and evaluated. The effects of the new through rib stiffener on the moment-resisting capacity of the connection, stress, and inelastic strain distribution within the beam and column face were discussed. The results provide improvement to the practical design of through beam moment connections.

2. Experimental programme

To determine the required seismic performance for the proposed through beam orthogonal connection, which represents an interior moment frame connection, an experimental programme was conducted and the characteristics of the connection were evaluated. Four half-scale orthogonal through rib stiffener beam to column connections were tested under incremental amplitude quasi-static cyclic loading to monitor the connection behaviour, including failure modes, stiffness degradation, strength ratio, failure modes, ductility and hysteretic energy dissipation.

2.1. Test specimens

The specimens were denoted as TOBC1 to TOBC4, where TOBC denotes the through orthogonal beam connection. Due to the test frame actuator's limited stroke, the specimens were designed to have sufficient elastic behaviour until 1% story drift. All specimens were examined in the ductile regime to observe the behaviour of the plastic hinges on the beam near the connection. The column–beam moment ratio was calculated in such a way to investigate the effects that the through rib stiffeners have on the longitudinal stress and the deformation of the CFT column.

The beam section properties are presented in Table 1. Test specimens TOBC1 and TOBC2 were designed using commercial steel beam sections W12 $\times$ 4 $\times$ 19 as the main beam and W8 $\times$ 4 $\times$ 15 as the orthogonal beam, and TOBC3 and TOBC4 used steel beam sections W16 $\times$ 5–1/2 $\times$ 26 as the main beam and W14 $\times$ 5 $\times$ 26 as the cross beam, as shown in Figs. 1 and 3. This arrangement was proposed to provide adequate beam strength and stiffness and to prevent connection failure. The hollow column height, main beam span, and orthogonal beam span were 1910 mm, 3500 mm, and 2500 mm, respectively. For all specimens, the outer dimension of the circular column was 350 mm, and the column wall thickness was 8 mm. The beams were selected from I-shaped hot-rolled sections.

The following parameters were varied in the tests: through rib stiffener or web stiffener, beam section size, and beam gravity load. The objectives of the testing was: (1) for specimens TOBC1 and TOBC2: to study the effect of the through rib stiffener and the web stiffener on the seismic performance of the connection to compare with the through beam connection, (2) specimens TOBC3 and TOBC4: to study the effect of the rib stiffener and the web stiffener on the seismic performance of the connection and on the longitudinal stress and deformation of the CFT column face to compare with the through beam connection, and (3) specimens TOBC2 and TOBC4: to study the effect of similar through rib stiffeners and web stiffeners with different beam section sizes on the seismic performance of the proposed connection.

2.2. Design of the connections

Four half scale specimens with steel beams and concrete filled circular steel tube columns were designed based on the AISC specification for special moment resisting frames [31–33] and on the two guidelines for designing through beam connection to concrete filled steel tube columns or reinforced concrete columns [34–36] as well as the ACI specification [37]. The connection details and arrangement of the test specimens are illustrated in Fig. 1. The design procedures for the connections are summarized as follows:

The maximum yield strength of the steel tube, the column thickness and diameter, width-thickness ratio of the beam and the column and the concrete compressive strength of the composite column satisfied the AISC specification for special moment resisting frames [31]. The beam flexural capacity is considered as the full plastic moment of the section.

The maximum probable moment at the beam plastic hinge is defined as:

$$M_{Pr} = 1.1 \cdot F_{yb} Z_b \cdot R_y, \tag{1}$$

where F_{yb} is the yield stress of the steel beam, Z_b is the beam plastic section modulus and R_y is a modification factor to specify the yield stress of the beam based on the AISC seismic provisions [31].

The beam shear force (V_b) and flexural strength at the column centreline (M_{bp}) are given as:

$$V_b = \frac{M_{pr}}{l}, \tag{2}$$

$$M_{bp} = V_b\left(L + \frac{B}{2}\right), \tag{3}$$

where L are the distance between the beam mid-span and the column face, l is the distance between the beam mid-span and the plastic hinge position and B is the steel column outer diameter.

The column capacity is derived from a moment curvature analysis for the applied value of the axial load. To ensure that plastic hinging of the beam occurs and the connection withstands the shear forces of the connection, the following equations must be satisfied [31]:

$$\frac{\sum M_c}{\sum M_{bp}} \geqslant 1, \tag{4}$$

$$V_h \leqslant \phi V_n, \tag{5}$$

where $\sum M_c$ is the summation of the nominal flexural strength of the column at the top and bottom of the joint, $\sum M_{bp}$ is the summation of the plastic moment of the beams at the left and right sides of