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Cyclic behaviour of composite joints with reduced beam sections

Rui Li, Bijan Samali, Zhong Tao *, Md Kamrul Hassan

Centre for Infrastructure Engineering, Western Sydney University, Penrith, NSW 2751, Australia

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ABSTRACT

Some design recommendations or standards, such as FEMA-350 and Eurocode 8 Part 3, recommend reduced beam section (RBS) connections to be used in earthquake-prone zones and practical design guidelines are provided accordingly. These recommendations, however, are mainly based on research conducted on joints without floor slabs. In reality, steel beams are often connected to reinforced concrete (RC) floor slabs by shear connectors. Thus, it is important to explore the performance of RBS joints with floor slabs. In this paper, cyclic test results of four such joint specimens are reported, where concrete-filled steel tubular (CFST) columns were connected to the RBS beams by utilising through-diaphragms. To compare with the RBS joints, two reference joint specimens with or without slab were also tested. The experimental results are analysed to evaluate the influence of floor slabs on the cyclic performance of composite joints with RBS beams. It is found that composite joints with floor slabs still exhibit favourable seismic performance, and have good potential to be widely used in seismic regions. However, the presence of the floor slab should be considered in designing RBS connections.

1. Introduction

Concrete-filled steel tubular (CFST) columns have many structural and constructional benefits [1]. The steel tube of a CFST column normally provides confinement to the concrete, and the concrete restrains the local buckling of the steel tube. In addition, the steel tube provides formwork for concrete pouring during construction, which reduces the construction cost and time. Therefore, the combined utilisation of CFST columns and steel/concrete composite beams in composite building construction has greatly increased in recent years.

In using CFST columns, rigid beam-column joints are often recommended in seismic regions due to their good stiffness, high strength and easy transfer of bending moment. To form these rigid joints, through-diaphragms [2], internal diaphragms [3], and external diaphragms [4] are commonly used to connect steel beams and CFST columns. Ricles et al. [5] conducted cyclic tests on joints with square CFST columns and wide flange steel beams, where internal diaphragms were used in four specimens to connect the beams to the columns. They found that the use of internal diaphragms locally stiffened the joint, but also led to stress concentrations and fracture of the beam flanges at the weld access holes. To alleviate the stress concentrations at the beam ends, Qin et al. [6] proposed to add horizontal stiffeners at the beam ends to form tapered beam flanges. They conducted tests on two identical joints with internal diaphragms to investigate the influence of the horizontal stiffeners. It was found that fracture still occurred in a beam flange at the tip of the tapered plate. It happened at the 1st cycle of 3% or 4% rotation in either specimen. It should be noted that no floor slabs were provided by Ricles et al. [5] and Qin et al. [6] for their test specimens.

In reality, shear connectors are often used to connect concrete floor to the top flange of the steel beam to develop composite action. This composite action between the two components can provide significant benefits to enhance both the stiffness and strength of the beam under sagging moment. However, it also increases the strain development of the bottom flange of the steel beam near the panel zone, and may lead to possible column failure [7]. Han and Li [8] tested 6 composite beam-CFST column joints with external diaphragms and RC slabs. Four out of the six specimens exhibited flexural failure in the beam under cyclic loading. When a beam failure occurred, fracture was observed at the weld between the bottom flange of the beam and the diaphragm corresponding to rotations as low as 2.5%. By comparing the test results reported by Han and Li [8] with those reported by Qin et al. [6], it might be inferred that the presence of slabs might promote fracture of the bottom flange of the beam.

To delay or even avoid the brittle fracture near the beam flange-to-column welds, a design of reduced beam section (RBS) has been widely used by removing a portion of the beam flanges a short distance away from the column face [9]. RBS may also be used to

* Corresponding author.
E-mail address: z.tao@westernsydney.edu.au (Z. Tao).

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make the beams weaker than the columns [10], which reduces the flexural resistance and inelastic deformation demands on the column. There have been extensive studies conducted on joints with RBS steel beams [11–13]. But concrete slabs were seldom provided, which could not reveal the realistic performance of RBS beams in construction. In particular, only very limited information is available for joints with CFST columns and RBS composite beams. To improve ductility of rigid joints, Wang et al. [10] tested five external diaphragm joints composed of RBS steel beams and CFST columns subjected to cyclic loading. No slabs were provided to the test specimens. It was shown that the RBS joints exhibited better seismic performance and ductility despite that the ultimate load reduced slightly compared with joints without RBS. In the presence of RBS, no fracture in the beam flanges was reported for the tested joints. Zhang et al. [14] studied the seismic behaviour of RBS composite joints with deep wide-flange columns, where composite floors with zinc-coated metal decks were used for the test specimens. For a typical test specimen with slab, a flange fracture at the centre of the RBS developed at 6% story drift. The reference specimen without slab developed a fracture in the heat affected zone of the beam bottom flange upon completing the first cycle of 5% story drift. Zhang and Ricles [15] conducted further finite element analysis and it was found that the presence of a floor slab can significantly reduce the column twist, leading to enhanced connection performance. Li et al. [16] proposed a type of exterior joints with extended endplates welded to RBS composite beams. Transverse ribs were welded to the circular column surface for providing planes to connect with the plane endplates. High strength bolts passing through PVC conduits in the steel tube were used to connect the RBS beams to the circular CFST columns. The test results showed that the RBS could relocate the plastic hinge from the endplate face to the reduced beam section even in the presence of the RC slab. The inelastic rotational angles of all specimens were more than 0.03 rad. Fracture of the RBS beam occurred at a rotational angle of 0.05 rad. Ciutina et al. [17] tested 6 moment-resisting beam-column connections, where three out of the six specimens had concrete slabs, and the RBS steel beam was directly welded to the steel column flange through full penetration weld. Significant RBS plasticisation was observed in all the test specimens. In the presence of the slab, the top flange of the steel beam in the RBS region was restrained from buckling. Huang et al. [18] developed an analytical formulation to investigate mechanical performance of joints with RBS composite beams, and an amplification factor was proposed to consider the slab contribution to the plastic moment of the beam section at the column face based on a parametric analysis.

The above literature review clearly indicates that research on CFST column joints with RBS beams is still very limited, and further research is required to fill the following gaps:

(1) Little attention has been paid to joints with through-diaphragms to connect RBS beams and CFST columns.
(2) Limited experimental data is available to clarify the influence of floor slabs on CFST joints with RBS beams.
(3) There is no information on the influence of cut depth of RBS composite beams on the joint performance. FEMA-350 [19] and Eurocode 8 Part 3 [20] provide guidelines for RBS mainly based on studies of RBS steel beams without floor slabs [18].

Set against this background, six through-diaphragm joints composed of circular CFST columns and RBS composite beams were tested. These specimens included one joint with a steel beam, one joint with a composite beam and four joints with RBS composite beams. The use of through-diaphragms can achieve the following benefits: (1) Compared with external diaphragms, extrusion of the through-diaphragms out of the tube is very minimal and can easily meet the architecture requirements. (2) The welding is easier and residual stresses resulting from welding are relatively moderate compared with using internal diaphragms. (3) The bond strength between the steel tube and concrete can be enhanced due to the presence of the diaphragms inside the steel tube [21]. The main variables considered in the test program were the beam height, cut depth of RBS and the presence of the RC slab. Effects of these parameters on the strength, ductility, strength degradation, stiffness degradation, energy dissipation capacity, and strain developments are analysed and compared in this paper based on the test results.

2. Experimental program

2.1. General

Six composite cruciform joint specimens were designed and constructed based on the provisions of EC3 [22], EC4 [23], EC8 [20] and AS 2327.1 [24]. No slab was provided for specimen CN-1 (reference specimen), whereas RC slabs were provided for the rest specimens. Meanwhile, RBS beams were used for four specimens, namely, CS-2, CS-3, CS-4, and CS-5. The geometric details of the four specimens with RBS beams are illustrated in Fig. 1(a)–(d), where different cut lengths (b) and cut depths (c) presented in Table 1 were adopted for the beams. The details of the other two joint specimens were the same as those of the joints with RBS beams except that no cut was made for the steel beams (CN-1 and CS-1) and no slab was provided for CN-1.

The specimens were designed representing joints at half scale. The profiles of circular steel tubes were 250 mm in diameter (D) with 6 mm wall thickness (t_s), as shown in Fig. 1(c). Two types of universal steel beams (200UB25.4 and 250UB25.7) were selected with a length of 1500 mm from the centre of the column to the assumed inflection point of a beam. The width and depth of the RC slabs were 800 and 60 mm, respectively. Through diaphragms with a thickness of 10 mm were used to connect the column to the steel beam. The outer diameter, inner diameter and vent hole diameter of the through diaphragms were 300, 120 and 20 mm respectively, as shown in Fig. 1(b). Sixteen M19 headed shear studs with a length of 50 mm and a diameter of 19.3 mm were welded at a spacing of 200 mm along the steel beam to connect the steel beam to the floor slab, as shown in Fig. 1(a) and (d). A layer of reinforcement (ϕ10 mm) was placed in the RC slab, which were longitudinally and transversely distributed along the slab at a spacing of 100 mm. The clear cover to the reinforcement was 20 mm. The CFST columns were the same for all six joints. Complete joint penetration (CJP) groove welds were used to connect the through diaphragm and the beam.

Each CFST column with two end plates was 1600 mm in length, and was fabricated in three segments separated by the two through diaphragms, as shown in Fig. 2. The through diaphragms were welded to the steel tube by double-fillet welds. Then the beam flanges were welded to the through diaphragms, and the beam web was welded directly to the steel tube. The thicknesses of all weld seams were around 6 mm. Each end of the steel tube was welded to a 350×350 mm^2 steel plate; the steel plate on the top end had a 160 mm diameter hole used for pouring concrete.

2.2. Design of the RBS beam

Circular radius cuts were utilised in both top and bottom flanges of the beam to reduce the flange area near the ends of the beam, as shown in Fig. 3. FEMA-350 [19] proposes general