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Behaviour and design of demountable beam-to-column composite bolted joints with extended end-plates

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ABSTRACT

This paper presents a novel structural form of demountable beam-to-column composite bolted joints that can be dismantled at the end of its service life. An experimental programme was conducted to investigate the static and hysteretic behaviour of the demountable composite joints. The initial stiffness, moment capacity and failure modes of the demountable beam-to-column joints were evaluated through experimental results. The demountability of the joints was verified by dismantling the specimens during testing. Finite element models were developed, which incorporated the nonlinear contact interaction, ductile damage and plastic damage. The accuracy of the numerical models was validated with the relevant experimental outcomes. A parametric analysis was thereafter conducted to evaluate the effect of the end-plate thickness, width-to-thickness ratio of the column, bolt diameter and number of bolts on the moment-rotation response. A comparison between the test results and Eurocode was conducted to assess the applicability of the existing design guidance. It is found that the specimens designed with bent reinforcing bars exhibit satisfactory performance, and possess a higher level of hogging moment resistance compared to those with straight reinforcing bars. The designed joints are able to be dismantled readily and all steel components remain elastic when they are loaded up to 40% of the ultimate capacity which is equivalent to the typical service load. The end-plate thickness, width-to-thickness ratio of the column and bolt diameter impose the significant effect on the performance of the bolted joints. Two bolt-rows in tension can improve the moment-rotation response for the joints with extended end-plates. The current design standards are not capable of predicting the behaviour of the demountable beam-to-column joints accurately.

1. Introduction

Beam-to-column composite bolted joints have been extensively applied in the building engineering practice due to various advantages like the ease of fabrication and assembly, the favourable performance under seismic loading and the sufficient fire resistance [1–4]. A typical composite joint system consists of universal beams, which are connected to a concrete-filled steel tubular (CFST) column by using end-plates and a number of blind bolts. A concrete slab is normally connected to the top of a beam flange by means of shear connectors.

The initial stiffness, the moment resistance and the rotational capacity are three critical parameters that reflect the behaviour of bolted joints, which have been investigated widely in the past few decades [2,5–13]. Since the steel-concrete composite bolted joints are preferred as an alternative to the steel or reinforced concrete constructions, their performance has been further evaluated so as to optimize the geometrical configuration and improve the moment-rotation response [14–18]. Mirza and Uy [19] tested composite beam-to-column flush end-plate joints under monotonic loading and cyclic loading. Experimental results demonstrated the satisfactory moment capacity and ductility of the semi-rigid joints. Further parametric analysis revealed that the axial loading, shear stud spacing and reinforcement ratio had significant effect on the joint behaviour. Thai et al. [20] and Thai and Uy [21] carried out a series of tests on composite joints with different shapes of column sections and end-plate types. The experimental results were compared against finite element models and analytical models. The comparison demonstrated that the initial stiffness and moment resistance can be enhanced by using extended end-plates instead of flush end-plates. Yang and Tan [22] and Yang et al. [23] presented failure modes of composite beam-to-column joints in the case that a middle column was removed. An analytical model was then proposed on a basis of the component method. Both experimental observation and numerical outcomes highlighted the ductility and load resistance of the constructions.

Apart from the static behaviour, the seismic performance of joints has been specified in literature as well [2,19,24–26]. Wang et al. [27,28], Braconi et al. [29] and Liew et al. [30] carried out extensive

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experimental programmes to assess the hysteretic performance of the beam-to-column composite joints under cyclic loading. Finite element models were proposed to evaluate the strength and stiffness degradation of the joints. However, the joint tests involving the static loading and cyclic loading mentioned above are limited to the structures that are not able to be dismantled. On the other hand, the demountable beam-to-column composite joints, to which have been paid much attention, are expected to lower construction waste [31]. Compared to the conventional composite joints, the demountable beam-to-column joints are capable of maximizing the potential of the material recycle and reuse [32]. Due to a shortage of studies centred on the demountability of the joints, a relevant experimental programme is herein carried out.

The main objective of this research is to explore the behaviour of the beam-to-column composite joints with a novel design type, and validate their demountability. In the experimental programme, four full-scale cruciform joints simulating the internal constructions of a composite frame were designed. Three of them were tested under monotonic loading, whilst the last one was tested under cyclic loading to investigate the hysteretic response. A numerical analysis was thereafter performed to predict the moment-rotation behaviour of the tested joints before parametric studies.

2. Experimental programme

2.1. Specimen design and preparation

Four cruciform composite joints with partial shear connections were designed in accordance with Eurocode 3 (EC3) [33] and Eurocode 4 (EC4) [34]. The details are depicted in Figs. 1 and 2 and summarized in Table 1. All sub-assemblies were abstracted from internal hogging moment regions of a typical composite frame. As for a composite frame with a beam span of 9000 mm, the hogging moment region took up around 21%–25% of the whole length given that the frame was subjected to distributed loads. And thus, a beam length of 1600 mm in this paper was viable for all specimens under hogging moments. Meanwhile, EC4 clarified that the effective beam width with current configurations reached about 1200 mm. Therefore, a concrete slab width of 1000 mm was believed to be reasonable. To achieve the purpose of demountability, the basic design principle was to ensure each component can be dismantled conveniently. Accordingly, the discontinuous concrete slabs and reinforcing bars going across the CFST columns were intentionally designed, which were significantly different from the design concepts mentioned in the literature. In this case, the concrete slabs can be removed readily without additional cutting. There was a 40 mm gap between the concrete slabs due to the formwork preparation, which would be filled at the time of testing. The configurations of all specimens were mostly identical except for the layout of reinforcing bars and the thickness of end-plates. Straight reinforcing bars were applied to BCJ-1, whilst bent reinforcing bars were adopted for BCJ-2, BCJ-3 and BCJ-4. The thickness of extended end-plates was increased from 12 mm for BCJ-1, BCJ-2 and BCJ-4 to 16 mm for BCJ-3. It should be noted that the geometry of BCJ-2 is identical with that of BCJ-4. However, BCJ-2 was subjected to static loading, whilst BCJ-4 was subjected to cyclic loading.

The specimen preparation is specified in Fig. 3. A universal beam was welded to an extended end-plate, which is further connected to a square hollow section (SHS) tubular through a number of M20 (Grade 8.8) blind bolts. The fillet welds between the beam and the end-plate, beam and stiffeners, end-plate and hook were 10 mm, 10 mm and 12 mm, respectively. A torque of 370 Nm was adopted for tightening the blind bolts in accordance with the recommendation of bolt manual. Profiled steel sheeting was then laid on the beam tightened with the shear connectors composed of all-threaded rods and bolt nuts. Each beam segment accommodated eight M16 (Grade 8.8) shear connectors with a staggered and equal interval layout by reference to Pathirana et al. [35]. AS2327.1 [36] required longitudinal spacing of shear connectors shall not exceed four times the depth of concrete slabs or 600 mm, whichever was the lesser, and shall be more than five times the bolt shank diameter. The distribution spacing was taken as the distance between two adjacent shear connectors on elevation view ignoring staggering. Total eight shear connectors on one side were considered enough to provide resistance in case of slips between concrete slabs and steel beams which can be validated in test results. As a result, the staggered layout was adopted which made the arrangement of reinforcements much easier. Four bent reinforcing bars (N12)

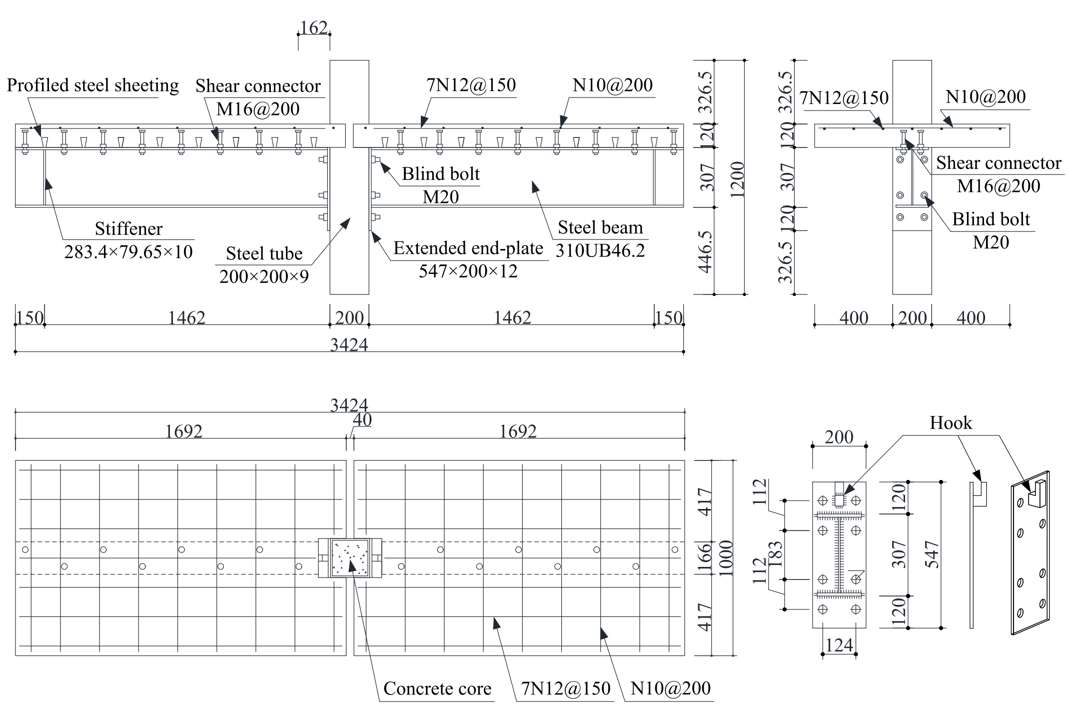

Fig. 1. Detailed geometry of specimen BCJ-1 (Units: mm).