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Experimental study of sustainable high strength steel flush end plate beam-to-column composite joints with deconstructable bolted shear connectors

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A B S T R A C T

The design of engineering structures for deconstructability can reduce the energy and cost required for their demolition and for the disposal of their construction waste, and it also enhances the sustainability of a building by allowing for easy dismantling and the reuse or recycling of structural components and construction materials at the end of the service life of the building. In addition, using high performance materials such as high strength steel can improve the sustainability of a structure by providing for higher design stresses and accordingly reducing the self-weight of the structure. This paper describes the results of four full-scale beam-to-column deconstructable composite joints with high strength steel S690 flush end plates. The structural behaviour of the new system in conjunction with application of post-installed friction-grip bolted shear connectors for developing deconstructable composite floors is investigated. The test results show that the proposed composite beam-to-column joints can provide the required strength and ductility according to Eurocode 3 and Eurocode 4 specifications, and that the system can be easily deconstructed at the end of the service life of the structure as a proof of concept.

1. Introduction

Among different construction materials, steel has a great potential to significantly improve the sustainability of the construction industry; steel structures have high strength to weight ratios, they can be erected rapidly and their construction and demolition waste can be minimised by employing prefabricated and deconstructable systems. Moreover, using prefabrication and deconstruction in conjunction with steel frames can drastically facilitate the full recycling and reuse of the construction materials and structural components. Accordingly, over the past decade several attempts have been made to enhance the sustainability of steel structures by either using high-strength durable steels [1–4] or developing prefabricated demountable steel framing systems [5–20]; however, the application of HSS in conjunction with deconstructable frames remains unexplored and this is the main focus of the present study.

The use of high strength steel (HSS) with yield stress in excess of 400 MPa has recently gained popularity in the construction industry owing to its higher yield strength, greater corrosion resistance and higher toughness compared with mild steel. In HSS construction, design stresses can be increased and thickness of plates may be reduced which, in turn, can save on the costs of labour, welding, transportation, erection and fabrication. The cost of the foundation may also be reduced owing to lower self-weight of HSS structures compared to mild steel structures [2]. However, the efficient use of HSS in structural members has been hampered by problems associated with its lower ductility, weldability and fatigue resistance. In particular, the lower ductility of the HSS can potentially affect the structural performance of beam-to-column connections where the steel plates can experience large strains well-beyond the yield strain [3,4]. Girão Coelho and Bijlaard [3] carried out an experimental investigation of moment connections with end plates made from high strength steel of Grades S460, S690 and S960 to provide insight into the non-linear behaviour of these joints and it was concluded that the extrapolation of the design philosophy in the current EC3 provisions, based on the semi-continuous/partially-restrained concept, can provide accurate strength predictions. In addition, it was shown that the HSS end plate connections can provide the rotation demands required for beam-to-column connections of rigid and semi-rigid moment resisting frames.

Apart from its attributes of high-strength and high-performance, design for deconstruction in conjunction with the use of recycled steel can significantly enhance the sustainability of steel structures. In a fully deconstructable steel–concrete composite frame, the beam-to-column connections as well as the floor

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slab to steel beam connections should have the potential to be easily dismantled. Bolted beam-to-column connections with flush or extended end plates can partly provide the ease required for dismantling steel frames, but existing composite steel–concrete floor systems typically take advantage of monolithic construction to ensure adequate performance (*i.e.* near to full composite action) and hence they cannot be easily disassembled and reused at the end of the service life of the structure. Furthermore, the demolition of monolithic concrete–steel composite floors in which the shear studs have been permanently buried in cast *in situ* concrete (or pockets filled with grout), requires much energy and leads to large amounts of construction waste and environmental intrusion. Because of this, there is a need to develop deconstructable steel–concrete composite floors that can be easily dismantled at the end of a structure's service life.

Post-installed Friction-grip Bolted Shear Connectors (PFBSCs) installed through bolt holes placed in precast slabs and pre-drilled in the top flange of the steel beams is a novel method for developing composite action between precast concrete slabs and steel girders. The composite floors employing PFBSCs can be easily dismantled at the end of their service life, and this in turn can minimise the construction waste associated with the demolition of composite floors and can maximise the possibility for future reuse of the structural components [7–24]. Furthermore, demountable composite floors with precast slabs and prefabricated steel girders can increase the speed, accuracy and quality of construction and reduce the time and environmental impact (*viz.* noise, disruption to traffic and pollution) of the construction.

The first tests on bolted shear connectors appear to date back to the late 60s [7], but surprisingly limited studies have been conducted on the behaviour and application of bolted shear connectors since then [8–24], and most of these studies are related to bolted shear connectors permanently buried in concrete or grout-filled pockets [8–12] with less attention being paid to the potential application of PFBSCs for developing deconstructable steel–concrete composite floors [13–24]. In general, the available test results show that bolted shear connectors exhibit higher load capacity and significantly higher fatigue strength than those of stud shear connectors [8–11]. Moreover, limited experimental studies on bridge decks have demonstrated the adequacy of PFBSCs for strengthening non-composite bridge girders by increasing their stiffness, load carrying capacity and fatigue strength [10,11].

This paper presents the results of static tests conducted on four full-scale Flush End Plate Semi-Rigid (FEPSR) beam-to-column joints made up of Grade S690 HSS in a steel–concrete composite frame that takes advantage of deconstructable PFBSCs and precast "Green Concrete" (GC) slabs associated with reduced ordinary Portland cement content [25]. The main objective is to determine the failure mode and characterise the moment and rotation capacity, moment–rotation relationship and ductility of this new sustainable composite system with high strength steel FEPSR beam-to-column joints. Moreover, the provisions of Eurocode 3 (EC3) [26] and Eurocode 4 (EC4) [27] are employed to investigate the structural performance of the HSS FEPSR joints with deconstructable composite beams and the influence of the type of bolted shear connectors, degree of shear connection and type of columns (open sections and concrete filled steel tubes) on the structural behaviour of the proposed composite joints are investigated.

2. Test specimens

2.1. Specimen design

Four full-scale cruciform beam-to-column joints with flush end plates were designed and constructed according to the provisions of EC3 [26] and EC4 [27] to evaluate the stiffness, ductility, bending moment capacity and rotation capacity of the proposed deconstructable composite joints with HSS flush end plates. The beam-to-column assemblages were symmetric to simulate behaviour of an internal joint in a semi-rigid frame. The specimens were tested under a displacement-controlled vertical load applied at the tip of the beam. A schematic outline of the deconstructable composite beam-to-column joint is shown in Fig. 1. The geometry, dimensions and details of all specimens are illustrated in Figs. 2 and 3 and the details of composite beams and the PFBSCs are given in Table 1.

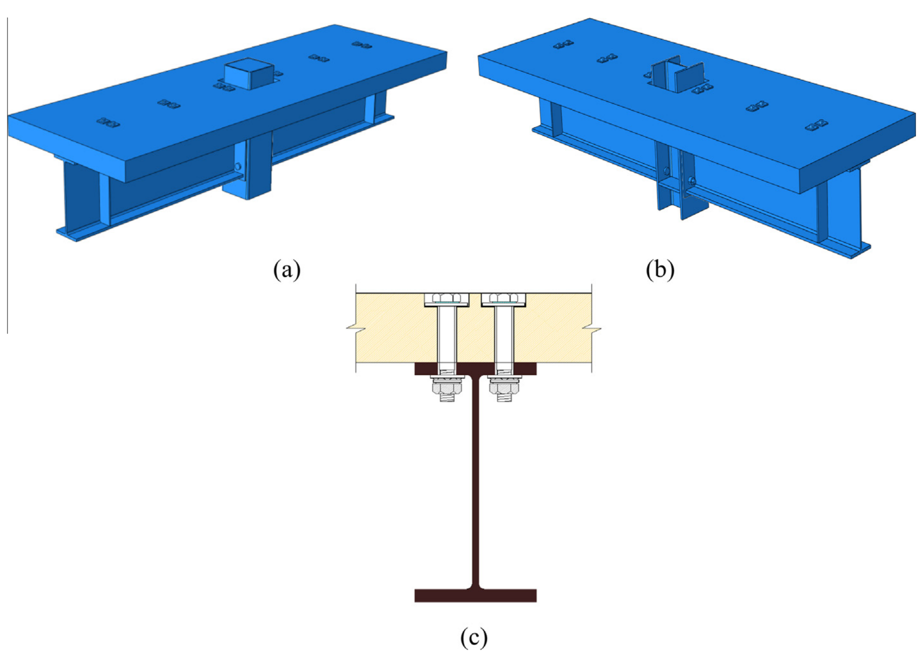

Fig. 1. Schematic outline of deconstructable composite beam-to-column joint with flush end plate connection: (a) pictorial view of CJ1 and CJ2; (b) pictorial view of CJ3 and CJ4; and (c) bolted shear connection.