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Flexural behaviour of steel storage rack beam-to-upright bolted connections

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ABSTRACT

Steel storage pallet racks are usually unbraced in the down-aisle direction in order to make palletised goods always accessible. The down-aisle stability of unbraced rack structures mainly depends on the performance of beam-to-upright connections and column bases. Beam-to-upright boltless connections are commonly employed for their convenience in assembly and adjustment. Since storage racks are being designed to considerable heights for the purpose of improving warehouse efficiency, steel storage rack beam-to-upright *bolted* connections are gradually being introduced to improve the structural stability. The paper presents an experimental investigation into the flexural behaviour of beam-to-upright bolted connections of steel storage pallet racks. A total of twenty-one specimens were tested under monotonic loading in a single cantilever test setup, including three different size pallet beams, three different upright thicknesses, and beam-end-connectors with two or three tabs. This study examines deformation patterns and failure modes of the connections, their rotational stiffness, moment resistance and corresponding connection rotations. The results show that steel storage rack beam-to-upright bolted connections, classified as "semi-rigid" and "partial-strength" connections, generally experience ductile failure modes. The effects of critical geometric parameters, i.e. upright thickness, beam height and the number of tabs, on the flexural behaviour of bolted connections are also investigated. In addition, comparisons of performance and failure modes between bolted and boltless connections are made. Moreover, in order to promote the design by advanced analysis of rack structures, a preliminary theoretical model based on the Component Method is proposed to predict the initial rotational stiffness of beam-to-upright bolted connections in steel storage pallet racks. A good agreement is obtained between the initial rotational stiffness derived from the theoretical model and the experimental tests.

1. Introduction

One of the significant applications of cold-formed steel is storage racks [1], which are widely used in fields such as warehouses and other short and long term storage facilities. In practical use, a variety of rack structures are available which can be distinguished based on the structural scheme and the picking modalities, such as selective pallet racks, drive-in/drive-through racks and cantilever racks [2]. This study focuses on the behaviour of steel storage selective pallet racks, and their typical configuration is illustrated in Fig. 1. The main structural frame of storage pallet racks is composed of cold-formed thin-walled steel members, such as uprights, pallet beams and bracings. Pallet beams are welded to beam-end-connectors, and upright members have arrays of holes along the length, which allow pallet beams to be connected at variable heights and brace members to be bolted to form upright frames (see Fig. 1). The lateral loads in the cross-aisle direction are resisted by the upright frames, which consist of two uprights and diagonal bracings (see Fig. 1). In the down-aisle direction, bracings are rarely installed in order to make palletised goods always accessible, and thus the down-aisle stability of steel storage pallet racks largely depends on the performance of beam-to-upright connections and column bases [3–6].

Boltless beam-to-upright connections are commonly used in steel storage racks for their convenience in assembly and adjustment, and they are categorised on the basis of the connector features by Markazi et al. [7] as Class A-Tongue and slot design, Class B-Blanking design, Class C-Stud-incorporated design and Class D-Dual integrated tab design. The complex constructional details make numerical analysis too complicated to be adopted in the design of beam-to-upright connections associated with storage racks. Therefore, experimental test methods are provided to evaluate the stiffness and strength of beam-to-upright connections in the main international design codes for steel storage racks, such as Australian Standard AS 4048 [8], the Rack Manufacturers Institute (RMI) specification [9] and European Standard EN 15512 [10]. Two alternative test setups, i.e. cantilever tests and portal tests,

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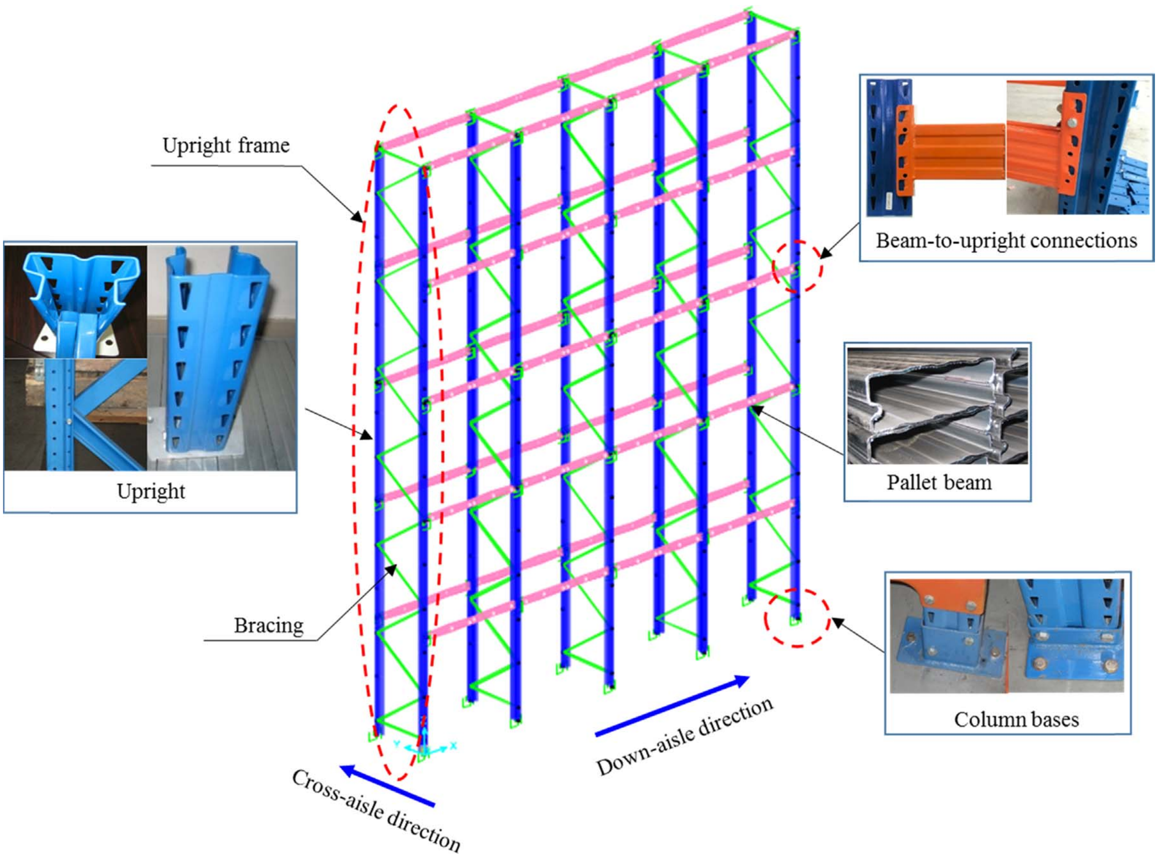

Fig. 1. Configuration of steel storage selective pallet racks.

are included in AS 4048 [8] and RMI specifications [9], while only the cantilever test method is included in EN 15512 [10]. Note that in cantilever tests, the full-range moment-rotation behaviour of beam-to-upright connections can be obtained including the initial rotational stiffness and strength. However, a monotonic cantilever test applies to one direction, upward or downward, each of which has different moment-rotation response. When a rack buckles by sway, the relative rotations between the pallet beam and the upright are in opposite directions at the two ends. Also, the moment-shear ratio is different from the actual frame. These difficulties can be overcome by performing a portal test which determines an average connection stiffness for the correct moment-shear ratio, as required [11,12]. However, portal tests are laborious to set up and difficult to conduct to full collapse. Consequently, usually only the initial stiffness is obtained from a portal test, whereas a cantilever test is used when the full-range moment-rotation response is required, as in this paper.

Over recent decades, substantial investigations have been conducted to evaluate the behaviour of boltless beam-to-upright connections in terms of stiffness, strength and cyclic behaviour [7,13–17]. As highlighted in [16], boltless connections generally experience brittle-type failure modes relating to the fracture of tabs and/or upright walls, and a sudden decrease is observed in the moment capacity of a connection after the peak load. When the down-aisle stability of an unbraced pallet rack is mainly provided by the beam-to-upright connections and column bases, the sudden loss in the strength of beam-to-upright connections may give rise to the collapse of the overall structure, especially when the rack is subjected to accidental dynamic loads, such as sudden impacts and seismic loads [18–20]. Moreover, in order to improve the efficiency of warehouses, storage racks are designed to considerable heights, which makes the improvement of the structural stability especially important. Under these circumstances, beam-to-upright bolted connections are gradually being applied in steel storage pallet racks in order to improve the connection properties.

Compared with traditional boltless connections (Fig. 2(a)), in bolted beam-to-upright connections (Fig. 2(b)), a single bolt is installed to replace the locking pin, the purpose of which is to resist accidental uplift loads. Extensive studies [12,21–24] have been reported to evaluate the behaviour of bolted connections between cold-formed steel members, and design formulae have been proposed for use in codes [25–27]. Limited research has been conducted on bolted connections used in cold-formed steel storage racks. Gilbert and Rasmussen [12] performed portal tests to investigate the behaviour of bolted connections in drive-in and drive-through storage racks, and pointed out that compared with tab connectors bolted connections are feasible and economical with a higher moment resistance and stiffness. Yin et al. [24] carried out experimental tests on speed lock connections with bolts to examine the monotonic and cyclic connection behaviour. This study focuses on comparisons between five types of beam-to-upright speed-lock connections to determine the effects of additional bolts and welds on the behaviour of the connections. However, due to the increasing use of bolted connections in pallet racks, further studies are required to evaluate the flexural behaviour of bolted connections in storage pallet racks. In addition, detailed comparisons between boltless and bolted connections are required to determine the improvement of connection behaviour in terms of stiffness, strength and ductility achieved by adding a bolt. Moreover, current design of beam-to-upright connections in steel storage racks largely relies on experimental tests, which are expensive and time-consuming. As an alternative method, finite element analyses have been applied for evaluating the behaviour of beam-to-upright connections, but currently high accuracy numerical analysis requires great computational efforts mainly due to the complex nature of beam-to-upright connections in steel storage racks [28,29]. Therefore, considering the limitations of the finite element method, a theoretical model based on the Component Method has been proposed to