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Cyclic performance of steel storage rack beam-to-upright bolted connections

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ABSTRACT

Steel storage pallet racks are slender structures sensitive to the second-order effects. Therefore, the stability and seismic response of unbraced pallet racks are greatly influenced by the behaviour of the connections between pallet beams and uprights. In recent applications, a bolt has been installed in the otherwise boltless connections broadly used in pallet racks, in order to improve the behaviour of the connections and the stability of the overall structure. In this paper, an experimental study is presented to evaluate the cyclic performance of bolted connections in cold-formed steel storage pallet racks. Seven groups of bolted connections were tested under cyclic loads in a single pallet beam cantilever test setup. Upright thickness and beam height, the number of tabs and the number of bolts in the beam-end-connector were varied to assess their impact on the performance of a bolted pallet beam-to-upright connection. The moment-rotation hysteretic and backbone curves of all tested connections were obtained, as were the behavioural factors corresponding to their stiffness degradation, ductility and energy dissipation capacity. The focus of the paper is to investigate the cyclic behaviour of steel storage rack beam-to-upright bolted connections, and to identify the most significant influencing geometric parameters. Comparisons of the cyclic response and failure modes between connections with and without bolts are also provided. Finally, based on the experimental results, the so-called *Pinching4* model is used to characterise the hysteretic performance of bolted pallet beam-to-upright connections for further use in the design by advanced analysis of rack structures under seismic loads.

1. Introduction

Cold-formed steel sections are widely used in the main structural frames of storage racks, such as for uprights, beams and brace members, due to their structural and economic efficiency [1]. Various types of storage racks are available with different structural schemes and/or picking methods, for example adjustable (selective) pallet racks, drive-in/drive-through racks and cantilever racks [2]. Steel storage pallet racks are generally self-supporting structures, which are assembled on-site as prefabricated components. In pallet racks, beams are welded to beam-end-connectors, and uprights have arrays of holes along the length for the assembly of the brace members and the attachment of pallet beams. Boltless connections are broadly used, in which the tabs or hooks on beam-end-connectors are inserted into the upright holes to connect the pallet beams to the uprights [3]. This design makes the pallet racks adjustable and easily assembled. Substantial research has been conducted on the static behaviour of cold-formed steel storage racks, including the stability behaviour of structural members and upright frames (e.g. [4–6]), the stiffness and strength of connections (e.g. [7,8]), and the down-aisle behaviour of structural frames (e.g. [9,10]). However, as storage racks are now increasingly being used in seismic areas, increasing attention is being paid to the seismic performance of rack structures, notably with regards to their failure mechanism, stiffness, strength, ductility and energy dissipation capacity (e.g. [11]). Distinct from the structural design of traditional steel frames, several critical issues need to be considered for evaluating the seismic response of steel storage pallet racks, including the peculiar mechanical beam-to-upright connections used for racks and the fact that the component members are produced by cold-forming and have complex shapes. Specifically, the uprights have open singly- or non-symmetric cross-sections and are continuously perforated along the length. It has been demonstrated that the cyclic behaviour of the beam-to-upright connection is a key parameter influencing the seismic performance of a rack structure [11–15].

Because of the variable and complex geometric details in steel storage rack beam-to-upright connections, experimental test methods,

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i.e. cantilever tests and portal tests, are provided in current design codes [16–18]. Many publications can be found on the structural performance of steel storage rack beam-to-upright connections, including their deformation patterns, failure mechanisms, connection stiffness and strength (e.g. [7,19,20]). However, boltless connections are the focus of the above studies. For the purpose of improving the connection properties, bolted connections are gradually being employed in steel storage racks, and research to clarify their behaviour has been conducted very recently [21–23]. The authors presented an experimental study on the flexural behaviour of steel storage rack beam-to-upright bolted connections under monotonic loading [23]. The study indicated that bolted connections, classified as "semi-rigid" and "partial-strength" connections, exhibit ductile moment-rotation behaviour, and that the dominant failure mode is the combination of weld cracking and local buckling of the beam end. Comparisons between bolted and boltless connections were also performed, demonstrating that the strength and ductility of a bolted connection are greatly improved in comparison with the corresponding boltless connection. Additionally, since storage racks are being increasingly used in seismic zones, beam-to-upright bolted connections are generally expected to undergo large inelastic reversed cyclic deformations when subjected to seismic loads.

Over recent decades, extensive research has been conducted to study the cyclic performance of beam-to-upright connections in steel structural frames (e.g. [24,25]), and design provisions have been provided for these connections in seismic specifications, such as AISC [26] and Eurocode 8 [27]. Few studies have been performed to evaluate the cyclic behaviour of steel storage rack beam-to-upright connections [11,28–30], which highlighted that the connections possess severely pinched moment-rotation hysteretic loops. Existing research is insufficient to fully understand the cyclic behaviour of beam-to-upright connections in steel storage racks, and hence the linear elastic connection model is commonly employed in the structural analysis [31,32]. Most importantly, design by advanced analysis [33,34] has been introduced in many specifications, such as AS4048-2012 [16], and it has been noticed that one of the main impediments in the computer-based direct design of rack structures under seismic loads is the lack of a hysteretic model to characterise the cyclic behaviour of beam-to-upright connections [11,14]. Recently, the authors adopted the *Pinching4* model [35] to simulate the hysteretic behaviour of beam-to-upright boltless connections [30], and thus further investigations are required to apply the hysteretic model to other types of beam-to-upright connections in storage racks, including bolted connections.

In the paper, an experimental study was conducted to investigate the cyclic performance of steel storage rack beam-to-upright bolted connections. A total of fourteen specimens were tested under cyclic loads in a cantilever pallet beam test setup. The objectives of this investigation are: a) to study the cyclic behaviour of steel storage rack beam-to-upright bolted connections, including the moment-rotation hysteretic and backbone responses, failure mechanisms and stiffness degradation, ductility and energy dissipation capacity; b) to consider the influences of the governing geometric parameters on the cyclic behaviour of a bolted connection, i.e. the upright thickness and the height of the pallet beam, the number of tabs and the number of bolts; c) to compare the cyclic behaviour between typical boltless and bolted connections; and d) to characterise the hysteretic behaviour of a bolted connection using the *Pinching4* model for further use in the seismic analysis of a rack structure to advance the design-by-analysis ("direct design") approach.

2. Experimental programme

2.1. Specimen details

A total of fourteen cyclic tests were performed on steel storage rack beam-to-upright bolted connections, considering three different nominal upright thicknesses, pallet beams with three nominal heights, beam-end-connectors with two or three tabs, and connections with one or two bolts (see Table 1). The geometric details of the specimens are illustrated in Fig. 1. In addition to the tabs, one or two M10 bolts were installed to join the beam-end-connector to the upright (see Fig. 1). Each specimen was labelled according to its geometric configuration. For example, the label '2.3C2-B120-3TB' indicates a bolted connection with an upright of C2 type, an upright thickness of 2.3 mm, a beam height of 120 mm, a tab number of three and a single bolt. Note that except the connection type '2.3C2-B120-3TDB' with two bolts, only an upper bolt was installed in all other bolted connections (see Fig. 1(d)). The actual material properties of the specimens were obtained from three nominally identical tensile coupons fabricated and tested according to GB/T228-2002 [36]. Table 2 summarises the material properties in terms of the average 0.2% proof stress and the average ultimate tensile strength for each component of the connections. The maximum deviations from the mean were 5.1% and 2.3% for the 0.2% proof stress and ultimate tensile strength respectively. Note that the yield stress of 1.8 mm material was about 20% less than that of the thicker material, and the difference in yield strengths of structural elements with varied thicknesses commonly exists in cold-formed steel members, which is mainly due to the cold-forming process and uncertainties in structural fabrication. Thus in experimental investigation, it is complicated to separate the influences of upright thickness from the influences of the material properties caused by different upright thicknesses. Under the circumstances, herein in comparing the performance of the various connections, the effects of material properties were included in evaluating the effects of upright thickness on connection behaviour.

2.2. Test setup and instrumentations

Fig. 2(a) shows the test setup employed for a typical specimen type '2.3C2-B120-3TB'. The test was carried out in a multifunctional reaction frame, featuring two cantilever beams to provide approximately rigid restraints at both ends of the upright and a 20 kN electric actuator supported by a sliding device. Note that the sliding device was designed to move freely in the horizontal direction, which ensured the loading remained vertical during the test. The load was exerted to the flanges

Table 1
Specimen details.

Specimen label	Upright type	Upright thickness (mm)	Beam type	Beam-end-connector type	Bolt number	Loading protocol	Number of specimens	Variation
2.3C2-B105-3TB	C2	2.3	B105	3TB	One	RMI	2	Beam height
2.3C2-B120-3TB	C2	2.3	B120	3TB	One	RMI	2	
2.3C2-B145-3TB	C2	2.3	B145	3TB	One	RMI	2	
1.8C2-B120-3TB	C2	1.8	B120	3TB	One	RMI	2	Upright thickness
2.8C2-B120-3TB	C2	2.8	B120	3TB	One	RMI	2	
2.3C2-B120-2TB	C2	2.3	B120	2TB	One	RMI	2	Tab number
2.3C2-B105-3TDB	C2	2.3	B120	3TDB	Two	RMI	2	Bolt number