Engineering Structures 116 (2016) 40–55

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Monotonic and cyclic response of speed-lock connections with bolts in storage racks

Lingfeng Yin [a,*], Gan Tang [a,b], Min Zhang [a], Bingjing Wang [a], Bo Feng [a]

[a] School of Civil Engineering, Southeast University, SiPaiLou 2, Nanjing 210096, China
[b] Department of Civil Engineering, Nanjing University of Aeronautics and Astronautics, YuDao Street 29, Nanjing 210016, China

ARTICLE INFO

Article history:
Received 3 April 2015
Revised 18 February 2016
Accepted 22 February 2016
Available online 8 March 2016

Keywords:
Speed-lock connections
Storage racks
Monotonic tests
Cyclic tests
Energy dissipation

ABSTRACT

The purpose of this paper is to explore the bearing capacity and energy dissipation of several variations of speed-lock connections of cold-formed steel storage racks. Commonly used speed-lock connection exists large slippage and low energy dissipation capacity, new speed-lock connections with additional bolts (and welds) are investigated in order to enhance its performance. Their monotonic behavior and hysteretic response under cyclic loading were studied experimentally using a cantilever test method. The tests were conducted using both the EN 15512 monotonic protocol and AISC seismic provisions' cyclic-test protocol for each specimen. The failure modes, moment–rotation response, and associated stiffnesses, bearing capacities, and energy dissipation capabilities were fully investigated. Both monotonic and cyclic responses showed that the additional bolts (and welds) significantly enhanced the bearing capacities and deformability of the connections, though the initial stiffness and equivalent stiffness (i.e., according to the EN 15512 specification) showed little improvement. The hysteretic responses of all connection variations investigated demonstrated pinching behaviors. The energy dissipation capability has been greatly improved with additional bolts (and welds) except of the one with only lower bolts, which could also be corroborated through the analyses of the calculated equivalent viscous damping coefficient and the displacement ductility factor. In addition, the stiffness degradation has been observed for both positive loading and negative loading, and adding bolts and welds could effectively reduce this effect.

1. Introduction

Storage rack structures constructed with cold-formed steel members are widely used in industry to store goods. Rack structural system, as shown in Fig. 1, usually consists of the following components: upright (or upright column), frame bracing, pallet beam, beam-end-connector, plan bracing, spine bracing, and bracing bracket. The most commonly used upright column is singly symmetric thin-walled open sections (e.g., cold-formed steel "Cee" shape with returns) with perforations or slots punched up and down the column at standard intervals so the load beam can be mounted into it. The pallet beam often uses thin-walled closed sections (see Fig. 1) and is locked into the upright column by beam-end-connector that is welded onto the end of beam by making a speed-lock connection into the perforations of the uprights [1,2]. The two upright columns and their frame bracings form an upright frame that supports vertical loads and cross-aisle-direction loads. The spine bracing system is generally placed at the rear of the rack to bear the load in the down-aisle direction.

Many connections of rack structures using cold-formed thin-walled steel have been explored by researchers, such as bolted moment connections [3], sleeve connections with sigma sections [4], and angle connections [5]. However, due to the intricate features and the complex shapes of uprights, beams and beam-end-connectors, it is almost impossible to obtain the accurate flexural characteristics of storage rack beam to upright connections utilizing analytical methods [6]. In particular, the rack dissipates energy mainly through the plastic deformation of the beam-to-upright connections under seismic loading. Therefore, to accurately decode the ductility and energy dissipation capability of beam-to-upright connections necessitates a careful examination through cyclic loading test [3,5]. For instances, international storage rack design specifications, such as Australian Standard AS 4084 [7], the Rack Manufacturers Institute (RMI) specification [8], and the European Standard EN 15512 [9], all recommend experimental approach to obtain the bearing capacity and rotational stiffness of a beam-to-upright connection, which are

* Corresponding author.
E-mail address: eking@seu.edu.cn (L. Yin).

http://dx.doi.org/10.1016/j.engstruct.2016.02.032
0141-0296/

Nomenclature

f_y	the yielding stress
f_u	the tensile stress
E	the elastic modulus
θ	the relative rotation of the beam and upright
θ^0	the connection rotation
θ^c	the upright rotation
θ_u	the limit state rotation (correspond with the ultimate moment)
θ_y	the yielding rotation
h	the height of the upright
a	the distance between the loading point and upright
F	the loading force
d_1	the distance between C1 and C2, which is 100 mm
d_2	the distance between C5 and C6, which is 100 mm
δ_1 and δ_2	the displacements measured by C1 and C2
δ_5 and δ_6	the displacements measured by C5 and C6
δ_u	the limit state displacement
δ_y	the yielding displacement
I_c	the inertia moment of the upright
M_u	the ultimate moment capacity
K_0	the initial stiffness
K_{EN}	the equivalent stiffness
$\overline{K}$	the secant stiffness of each cycle
h_e	the equivalent viscous damping coefficient
μ	the ductility factor
E_i	the dissipation energy for each connection type
n_i	the loading level for each connection type

two major characteristic of energy dissipation capability. The following studies focused on speed-lock connections of pallet racks made with cold-formed steel, a much thinner member that has notorious buckling issues. Bernuzzi and Castiglioni [10] adopted a single cantilever test setup to investigate the moment–rotation curve of beam-to-column joints (speed-lock connections without bolt) subjected to monotonic and cyclic loadings and found that the slippage associated with plastic deformations during earthquakes was expected to cause large swaying of the uprights and thus lead to significant second-order effects. Aguirre [11] conducted experimental tests for rack connections under monotonic and cyclic loads and identified that the failure mode was initiated by tab yielding and the connection demonstrated significant nonlinearity. The flexibility of speed-lock connections (without bolt) in pallet racks was studied by Bajoria and Talikoti [12] using both single and double cantilever experimental methods with comparison to a full-scale frame test. Prabha et al. [13] conducted eighteen experiments to study the flexibility of pallet rack's connection by varying several influential parameters, such as the thickness of the upright, the depth of the connector and the depth of the beam. Stiffness and bearing capacity of bolted beam-to-upright connections were explored by Cheng and Wu [14] under monotonic and cyclic loadings. Zhao and Wang [15] investigated the flexural behavior of connections associated with the cold-formed steel storage pallet racks, and the results showed that the deformation modes of the connections were similar prior to failure, while the failure modes depended on the relative thickness between upright and beam-end-connector. In addition, the common speed-lock connections (without bolt, JZ1/JD1 shown in Fig. 2) demonstrated obvious slippage under seismic loading and relatively low energy dissipation capability. Ślęczka and Kozłowski [16] proposed component method to assess main joint properties, i.e. the moment resistance and initial stiffness of storage rack connections and verified well with the test results.

Therefore, to improve the seismic performance of the storage racks of cold-formed steel members, additional bolts and/or welding are configured into the speed-lock connection in this paper and their stiffness and energy dissipation capabilities are explored experimentally. This investigation consists of a variety of beam-to-upright speed-lock connections made with cold-formed steel. More specifically, five types of beam-to-upright speed-lock connections, namely common speed-lock connections, speed-lock connections with upper bolts, speed-lock connections with lower

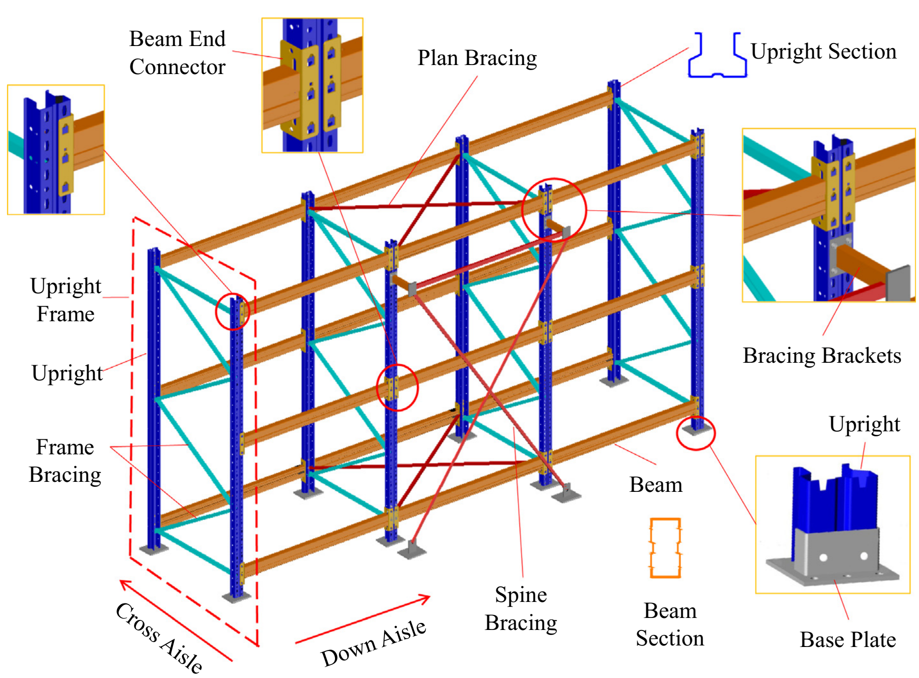

Fig. 1. Cold-formed steel storage rack schematic diagram.