Journal of Constructional Steel Research 122 (2016) 520–531

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

The cross-aisle seismic performance of storage rack base connections

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ARTICLE INFO

Article history:
Received 28 October 2015
Received in revised form 6 April 2016
Accepted 13 April 2016

Keywords:
Seismic response
Storage racks
Base connections
Finite element simulation

ABSTRACT

Steel storage racks used in retail stores and warehouses are seismically designed as moment resisting frames in the down-aisle direction, and braced frames in the cross-aisle direction. While their down-aisle response is relatively well understood, there is little understanding of their cross-aisle response, especially as it pertains to the desired mode of inelastic deformation and associated design methods. Results are presented from six full scale tests on braced frames representing storage racks in the cross-aisle direction. These tests investigate the base plate thickness and dimensions, and the upright (column) cross section. The experiments indicate that inelastic deformation in the base plate provides stable hysteretic response with significant ductility and energy dissipation. Ductile tearing is also observed in welds connecting the base plate to the upright. However, it does not appear to negatively influence the hysteretic response. The tests are complemented by Finite Element (FE) simulations of the base connections. These simulations provide insights into internal force distributions within the connections. Based on these insights, analytical equations are proposed for characterizing the backbone curve of the hysteretic response, for use in displacement based design methods. It is determined that the current approach for characterizing design forces in the anchors is unconservative, since it does not incorporate the effects of strain hardening or the membrane action as the base plate undergoes large deformations. A new approach which incorporates these phenomena is presented, and determined to be significantly more accurate. Limitations of the study are outlined and directions for future work are identified.

1. Introduction

Steel storage racks are commonly used in facilities such as warehouses and “big-box” retail stores. Shown in Fig. 1a, these racks are typically 8–30 ft tall, although racks exceeding 100 ft high are not uncommon, and support heavy loads (often 30–50 times their self-weight). The structural performance of these racks has obvious implications for structural safety, since collapse (due to overturning in the cross-aisle direction) has the potential of causing serious injury or fatality. This type of collapse has been documented in prior earthquakes, most notably in retail stores in Santa Clarita, California, and Canoga Park, California, during the 1994 Northridge earthquake; see Fig. 1b, adapted from FEMA 460 [1]. While the result of overloading, these failures demonstrate the potential for personnel danger and property loss. More recently, some damage to racks (element buckling) was also observed during the smaller 2001 Nisqually, Washington earthquake.

Referring to Fig. 1a, the racks are configured as moment-resisting frames in the down-aisle direction (parallel to the shopping aisle), to facilitate placing and removal of inventory. In the cross-aisle direction, the racks are configured as braced frames. In this direction, the racks are narrow and more susceptible to overturning, as compared to the down-aisle direction, where the main issue is sidesway collapse. Several studies have investigated the response of storage racks. These include quasi static tests by Krawinkler et al., [2], Higgins [3], and Bernuzzi and Castiglioni [4], as well as dynamic tests by Blume [5], Chen et al., [6], Castiglioni et al., [7], and more recently by Filiatrault and Higgins [8], and Filiatrault and Wanitkorkul [9]. These studies have been complemented by analytical and numerical studies, e.g., by Coutinho [10], cumulatively resulting in design practices for storage racks; FEMA 460 [1] outlines these practices in detail. Referring to FEMA 460 [1] and these studies, it is noted that –

1. A majority of the studies has focused on the down-aisle response, and associated design practices. As a result, the understanding of cross-aisle response is limited, and unlike the down-aisle (moment frame) response in which the beams yield, the ductile/dissipative mechanism in the cross-aisle direction is not as well defined. In fact, the shake table tests by Chen et al. [11] indicate that inelastic deformations in the cross-aisle directions are highly localized (in the connection region between the bracing elements and the uprights).

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http://dx.doi.org/10.1016/j.jcsr.2016.04.014
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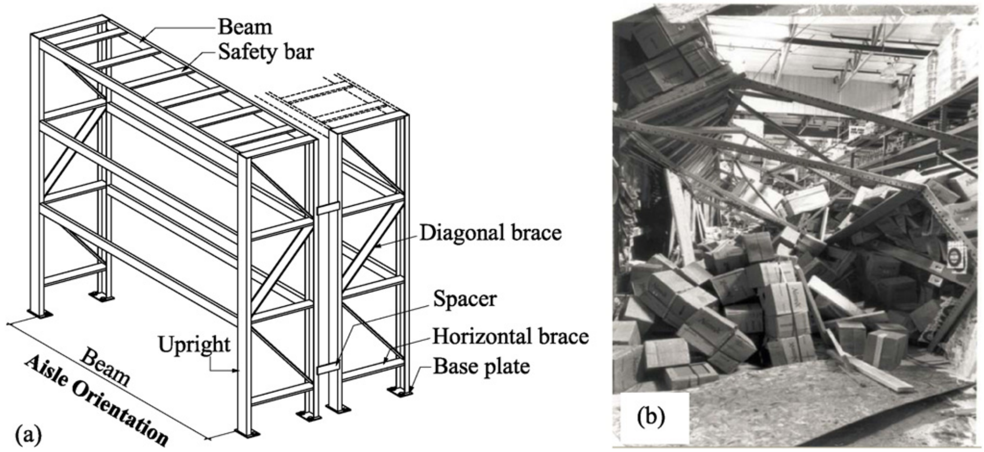

Fig. 1. (a) Schematic illustration of rack system (b) collapse in Santa Clarita store.

Consequently, the overall dissipative/inelastic response of the system in the cross-aisle direction is minimal. On the other hand, the studies indicate that the down-aisle response is highly ductile, with story drifts as large as 7% before incipient collapse [6].

2. The methods currently used for the design of these racks are force-based, i.e., they rely on an equivalent lateral load, which is calculated through a strength reduction (or R) factor. Typically, the R factor is taken as 6.0 in the down-aisle direction, and 4.0 in the cross aisle direction.
3. While commonly used for design, the current R factors are empirical. They arise (as working stress values) from Standard 27-11 of the 1975 Uniform Building Code [12], and have survived with little change (aside from conversion to LRFD equivalents) in RMI/ANSI MH16.1 [13], the rack design standard incorporated into ASCE-7 [14]. The ASCE-7 code accepts the R values of ANSI MH16.1 [13], but has increased the demands for anchorage in section 15.5.3. While [13] outlines Displacement Based Design (DBD) criteria in both directions, it is primarily used in the down aisle direction. This is a result of the extensive testing done over many years (e.g., [6–8]) to characterize this response. A design method for the down-aisle direction is suggested in FEMA 460 [1]. While the DBD fundamentals apply equally to both directions, at the time of writing FEMA 460, little data was available for response in the cross-aisle direction. Accordingly, a design method was not proposed.

Motivated by these issues, the main objectives of this study are the following:

1. To examine through quasi-static tests, and finite element simulations, the potential for using base connection yielding accompanied by frame rocking as a dissipative mechanism for the seismic response of racks in the cross-aisle direction. Previous experimental studies by Midorikawa et al. [15] and Huckleridge [16] have demonstrated the feasibility of rocking structural systems with energy dissipation in the base connection. More recently, full-scale shake table tests by Ma et al. [17] and analytical studies by Acikgoz et al. [18] have confirmed this to be an attractive mechanism for dissipating seismic energy and controlling the risk of excessive deformations or collapse. However, being focused on building systems, these have not specifically considered base connections in storage racks (which are constrained in terms of size and layout), or their inelastic response within the overall dynamic response of the structure. Fig. 2 schematically illustrates a typical base connection in a storage rack, indicating that it is subjected to predominantly one-dimensional (vertical) cyclic loading as the frame undergoes lateral motions and rocking in the cross-aisle direction.
2. To develop a framework for characterizing the load-deformation response of base connections when subjected to cross-aisle loading, with two aims: (1) to provide an aid for displacement-based design of racks when the base-yielding mechanism is desired (2) to provide a framework for simulation of cross-aisle response, ultimately supporting parametric simulation for development of generalized design guidelines.
3. To provide guidelines for the design and detailing of the bases themselves. Referring to Fig. 2, the base connections consist of the upright (the column, which is typically a box or a channel section) welded to a base plate, which in turn is anchored to the concrete floor using post-installed anchors. Yielding of the base plate is the preferred mode of inelastic dissipation. As a result, from a connection design perspective, two issues are relevant: (1) detailing of the base plate, including size, thickness, and weld details to ensure ductile response under expected deformation demands, and (2) estimation of design forces in the anchors to withstand the demands imposed by the yielding base plate. The latter is critical, since post-installed anchors (which are the most common method of connecting the base plate to the warehouse floor) are brittle (Gesoglu et al. [19]), and consequently must be designed using capacity design principles. Moreover, the response of the base plate itself is controlled by material hardening, geometric nonlinearity due to the membrane action of the plate as the deformations increase, and phenomena such as contact and prying. These phenomena warrant consideration in any method to compute design forces in the anchor rods.

The main scientific basis of this study is a series of 6 quasi-static experiments, and complementary Finite Element (FE) simulations of base connections in storage racks. The experiments feature braced

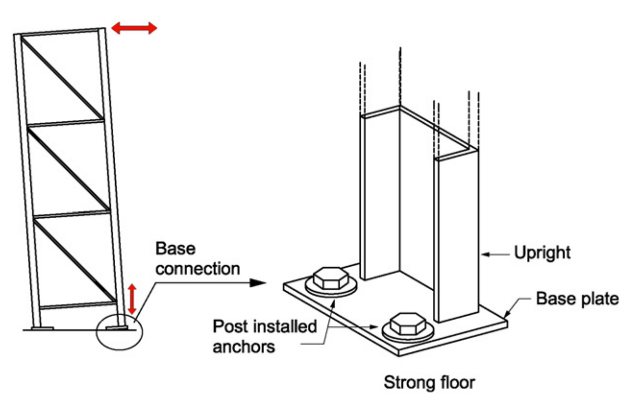

Fig. 2. Schematic illustration of frame response mode and base connection.