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Responses of cold-formed steel storage racks with spine bracings using speed-lock connections with bolts II: Nonlinear dynamic response history analysis

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ABSTRACT

The objective of this paper is to investigate the seismic response of cold-formed steel storage racks with spine br acings using two types of connections: a speed-lock connection, JD1, and a speed-lock connection with two bolts and full flange welding, JD5, using the incremental dynamic analysis (IDA) as a companion paper to the pushover analysis. The racks analyzed are racks using only JD1 and JD5 connections given the insights in terms of their performances observed from the pushover analysis in the companion paper. This paper presented the structural models for the IDA analysis with the hysteretic behaviors of the connections based on the previous experimental studies. With selected ground motion records, a total of 44 IDA curves were produced for each rack model studied: a single entry unit rack (SEU) and a double entry unit rack (DEU). The impact of the ground motion records was studied based on the IDA and associated fractile curves. The response modification factor R were then calculated for each rack and compared with those from the pushover analysis. The collapse mechanisms were also studied from the IDA results and compared with those from the pushover analysis. Moreover, the seismic performances of the racks were evaluated based on nonlinear dynamic response history analysis under the ground motions that were closely matching with fractile curves.

1. Introduction

In the companion paper [1], the pushover analysis has been employed to investigate the responses of the considered rack structures. However, the pushover analysis by ignoring the dynamic and duration effects and equating the structure to a single degree of freedom (SDOF) system renders it less favorably compared to the nonlinear dynamic response history analysis [2,3]. As a time domain analysis, utilizing a detailed structural model the nonlinear dynamic response history analysis is able to assess the structural performance under a combination of ground motion records, which is capable of producing estimates of responses with relatively low uncertainty. In particular, a probabilistic framework is usually preferred, such as those based on the incremental dynamic analysis to obtain the fragility curve of the structures [4] in order to overcome numerous modeling uncertainties involved [2,3,5].

Though related full-scale experimental tests on pallet and braced racks can be found in literatures, for instance, Kanyilmaz et.al. [6,7] for different rack topologies, the nonlinear dynamic analysis has been also used to study the behaviors of the rack structures by numerous researchers, in particularly by Degée and Rossi [8], Filiatrault [9], and Haque [10] on the pallet rack structures related to the seismic behaviors and collapse performance subjected to the ground motions. More recently, Bernuzzi and Simoncelli [11,12] identified key open problems related to the seismic design of racks and proposed a combined nonlinear time history method of analysis with the low cycle fatigue damage approach in order to investigate the damage distribution, assess the residual fatigue life, and estimate the effective load-carrying capacity after an earthquake, and summarized development of more reliable approaches for designing racks against earthquakes.

To evaluate the seismic performance of the five beam-end connector types (i.e., JD1-JD5) experimentally studied by authors [13], this paper, as a continuing effort of the pushover analysis in the companion paper [1], is intended to investigate the performance of the spine bracing racks with these connections using a more rigorous analysis approach: the nonlinear dynamic response history analysis. More specifically, the studies took a probabilistic approach, thus the analysis performed for the racks was actually the incremental dynamic analysis (IDA). However, the racks analyzed using IDA were racks using only

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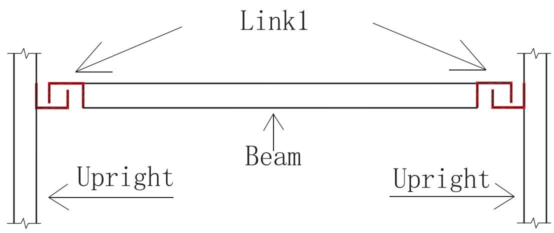


Fig. 1. The link element used in IDA analysis.

Table 1
Calibrating parameters of the EPHM model.

		K_0	F_0	K_d
JD1	$f(x) \geq 0$	88.13	17.77	−168.34
	$f(x) < 0$	84.13	−17.42	179.46
JD5	$f(x) \geq 0$	87.25	30.20	−174.79
	$f(x) < 0$	61.67	29.36	160.04

JD1 and JD5 connections given the insights in terms of their performances observed in the pushover analysis. This paper presented the structural models for the IDA analysis with hysteretic behaviors of the connections based on the experimental studies in [13]. The seismic performances of the racks were then evaluated and compared with results from the pushover analyses in the companion paper [1].

2. The considered rack structures

Similar to the pushover analysis in the companion paper [1], the Incremental Dynamic Analysis (IDA) was performed on the single entry unit (SEU) and Double Entry unit (DEU) racks instead of the global rack structure. As detailed in the companion paper, the global structure was a cold-formed steel spine bracing rack designed based on Chinese specifications [14,15] with a height of 19.8 m and consisting of two single entry and four double entry racks and every entry rack consists of four units (SEU or DEU). The rack used Chinese Q235B steel material with a yielding stress of 235 MPa [15] and the members were standard cross sections available in Chinese steel member category as listed in the companion paper. Other details can be found in the companion paper. However, for the pushover analysis in the companion paper, all five-type connections JD1-JD5 were considered and their impacts on the capacity, deformability, plastic hinges, and seismic response modification factors were investigated. Compared to JD1, the commonly used one, the other configurations of the bolts (JD2-JD5) demonstrated uneven improvements. JD5, with bolts and welds, demonstrated the best performance out of them. Also, from the experimental studies of the connections in [13], JD5 had the best energy dissipation capacity. Thus, for IDA, the analyses in this study were narrowed down to two connections types: JD1 and JD5 instead of all five types.

3. Mathematical modeling of the consider racks

3.1. Mathematical structural model

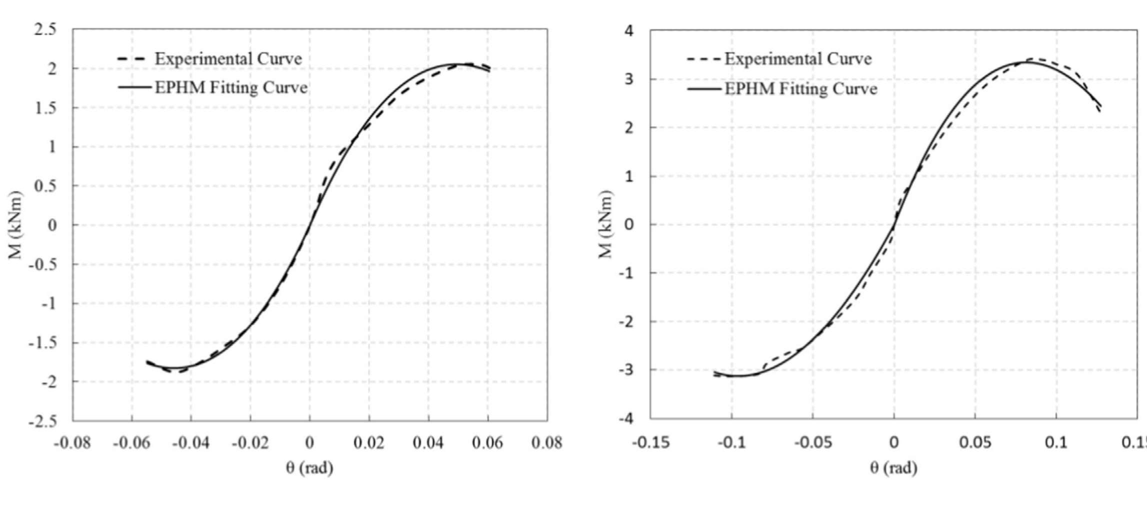
A reliable structural model for the nonlinear dynamic analysis is critical in obtaining the accurate response of the rack structure. A similar model using the concentrated plastic hinge model for the pushover analysis was adopted for the nonlinear dynamic analysis. Thus, plastic hinges and link elements, which can efficiently capture the hysteretic behaviors of rack components, were employed to the structural models of unit rack structures (i.e., SEU and DEU), and the layout of plastic hinges was demonstrated using a representative spine bracing rack in the companion paper [1] and the link elements replacing the plastic hinges at beam end connectors are illustrated in Fig. 1, which are designated as Link1 as shown.

Moreover, while the default plastic hinges, such as the PMM, P, and MM hinges stayed the same as the pushover analysis, the kinematic hardening hysteretic behavior was also taken into consideration in IDA analyses. In addition, the beam end connectors in down-aisle direction were modeled differently using a link element (Link1) with a multi-linear plastic model considering the pivot hysteretic behavior that were calibrated from the experimental studies using cyclic tests in [13].

3.2. Connection behavior model

This multi-linear plastic model of the link element for the beam end connectors consists of two components: the multi-linear behavior model and the pivot hysteretic behavior model. While the backbone curves of the connections from [13] clearly indicated the multi-linear behavior, the hysteresis loops of the cyclic tests of the connections also showed the slippage and pinching characteristics. The multi-linear plastic model adopted here was intended to capture both of the two behaviors.

First, the multi-linear behavior model for the connections JD1 and JD5 studied in this paper was calibrated from the backbone curves of the cyclic tests in [13] using the EPHM method [16]. The backbone



(a) Multi-linear Model of JD1 (b) Multi-linear Model of JD5

Fig. 2. Comparison of the experimental backbone curves and calibrated EPHM models.