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Shake-table testing and numerical modelling of inelastic seismic response of semi-rigid cold-formed rack moment frames

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A R T I C L E I N F O

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A B S T R A C T

An experimental program consisting of quasi-static cyclic, pull-back and seismic shake table tests was conducted to examine the inelastic seismic response of cold-formed selective rack structures. Hysteretic response of the connectors and base plates are presented. In the seismic tests, racks could sustain up to 10% drifts without collapse. Pallet sliding was observed in the tests. A numerical model is proposed in OpenSees to predict the rack seismic response, including pallet sliding. It is used to study the response of 6-bay racks having 3–6 levels. Displacements are sensitive to assumed viscous damping, base plate properties and pallet sliding.

1. Introduction

Collapse of steel rack structures in recent earthquakes have raised concerns on the ability of steel rack structures to safely withstand seismic effects [1–3]. Selective steel rack structures are commonly used for storage in commercial and industrial buildings. These structures form semi-rigid moment frames to resist lateral loads in the down aisle direction while braced frames are used for stability and lateral resistance in the cross-aisle direction. For seismic design, most design standards rely on a force-based analysis method wherein design forces determined from anticipated elastic inertia loads reduced to account for the system ductility e.g [4–6,50]. For rack moment frames, ductility is achieved through inelastic rotations in the beam-to-column connectors and column base plates.

Recently, studies have been performed to examine the possibility of using the direct-displacement based design procedure for the seismic design of selective racks structures along their moment frame direction [7,8], and [9]. Displacements are evaluated using a linear structural model having a period based on the structure secant lateral stiffness and an equivalent damping ratio reflecting the structure energy dissipation capacity, both properties being determined at peak displacement [10]. In design, the structure properties are modified iteratively until the desired drift is attained. A displacement-based evaluation procedure for racks has been proposed in FEMA 460 [11]. In that procedure, the structure stiffness is based on the secant stiffness of beam-to-column connectors and base plates, as obtained from cyclic test data. All connections are assumed to experience the same rotation and stiffness of base plates can be taken equal to that of the connectors when base plate data is not available. In the RMI Specification [6], seismic design using a displacement-based method is permitted to be used as an alternative to the force based method. In 2016, a displacement-based approach has been introduced in CSA S16 standard for seismic design of rack structures [12]. In view of the relative immaturity of this approach and lack of experimental and numerical validation, the method is limited to racks up to 7.6 m high, stringent drift limits apply, predicted connection rotations are amplified to account for variability and the structure must meet minimum lateral strength and P-delta effects requirements.

Further development of the method requires nonlinear response analysis of representative prototype structures which, in turn, requires robust nonlinear models that can accurately predict the seismic inelastic response of racks including global stability effects. Various such models have been proposed by [13–17]. Emphasis should be put on the hysteretic response of the beam-to-column connectors and base plates. Limited data, especially cyclic data, is available for the latter and previous experimental and numerical studies e.g [14,18–25]. have shown that base plates have a significant influence on lateral response of racks. For the former cyclic tests with non-linear modelling have been carried out by [26–28]. Sliding of pallets on beams also may also affect the seismic response of racks; this has been observed and quantified in [14,29–34]. Shake table tests of rack frames have been performed by [19,35,36].

This article first presents an experimental program that was performed to generate data on the cyclic inelastic response of beam-to-column connectors and base plates used in typical cold-formed rack

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Nomenclature

a	base-plate dimension (see Fig. 6)
a′	base-plate dimension (see Fig. 6)
AF	strength adjustment factor of base-plate material model
b	base-plate dimension (see Fig. 6)
c	base-plate dimension (see Fig. 6)
C	compressive axial load in a column
d	base-plate dimension (see Fig. 6)
E	modulus of elasticity
EDC	energy dissipated per cycle
EDC_c	energy dissipated per cycle in a connector
EDC_{bpl}	energy dissipated per cycle in a base-plate
h	rack height
I_{col}	column moment of inertia
j	number of oscillations
k_{rack}	lateral stiffness of a rack
$k_{rack,red.}$	rack lateral stiffness reduced to account for P-delta
k_{sec}	secant stiffness
f_y	yield strength
F	total applied lateral load
FEM	Finite Element Method
$m_{p,bpl}$	yield moment per unit length
M_{bpl}	base-plate moment
M_c	connector moment
$M_{y,bpl}$	base-plate yield moment
RMI	Rack Manufacturer's Institute
SF	ground motion scale factor
t_p	base-plate thickness
T_n	natural period
u_i	ith decrement of between two successive peaks of displacement amplitude
V	base-shear
W	total weight of the rack
$\mathscr{W}_E$	external work
$\mathscr{W}_I$	internal work
$\beta_{hyst.}$	hysteretic damping
$\beta_{el.}$	rack damping coming from other sources than hysteretic damping
β_{eff}	equivalent viscous damping
δ	displacement of the rack at beam level
Δ	drift i.e. δ/h
Δ_{avg}	average drift
Δ_{bpl}	drift due to base-plate deformation
Δ_{col}	drift due to deformation of the column
Δ_{top}	drift of the top level of a rack
Δ_{tot}	total drift
θ_{bpl}	base-plate rotation
θ_c	beam-column connector rotation
μ_s	static friction coefficient
μ_k	kinetic friction coefficient
ζ	equivalent viscous damping
$\bar{\zeta}$	mean viscous damping

structures and develop knowledge on the seismic response of that rack system close to or up to collapse. The test program included quasi-static cyclic, pull-back and shake table seismic tests on one-level, one-bay rack specimens. Ground motions expected in eastern and western North America were used in the seismic tests and the records were scaled to reach large drifts. Gravity loads were applied on all specimens such that P-delta effects could be examined. One seismic test was conducted up to collapse of the specimen. The test results are then used to develop a detailed model of the racks studied using the OpenSees platform [37]. The model accounts for the nonlinear response of the connectors, including strength degradation. Sliding of pallets is also included to reproduce the sliding behavior observed in the tests. Appropriate viscous damping to match experimental results is also examined. In the last part of the article, the model is used to examine the seismic response of more realistic 6-bay multi-level racks structures to illustrate the capabilities of the proposed model. Effects of ground motion amplitude, viscous

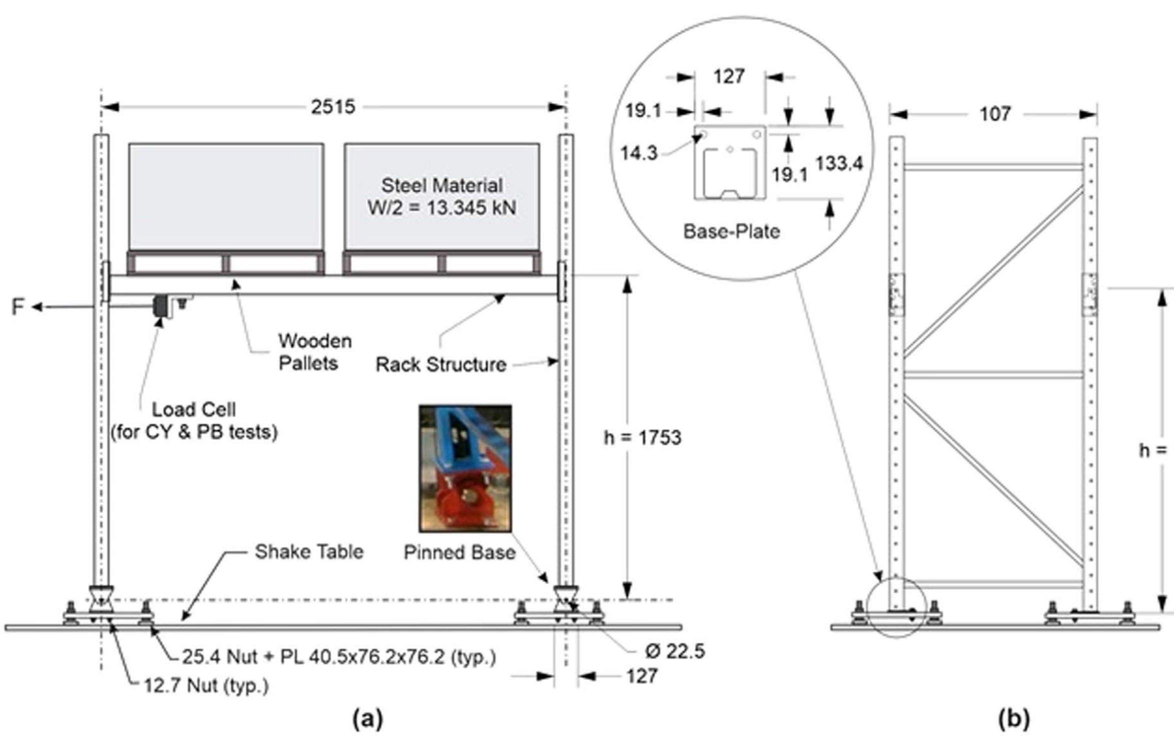

Fig. 1. Test setup (all dimensions in mm): a) Elevation view; b) Side view.