# Shake Table Study of Dynamic Characteristics of a Typical Pallet Racking System

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**Abstract** Industrial pallet racking system was the commonly used structure for storing palletized goods. They were built up from thin-walled cold-formed steel profiles. The upright (column of the rack) has perforations which ensure the typical functionality, adaptability and flexibility needed for accommodating the variability of dimensions of the stored goods. Connections were custom made, where in the beams were generally hooked on to the upright. These connections were significantly semi-rigid in behaviour. The complexity associated with the nonlinear moment-rotation behaviour of the joints in the design of cold-formed steel structure was to be accounted for a realistic capacity estimation. These racks when installed in seismic prone zones must be qualified for different levels of safety such as collapse prevention and immediate occupancy. To assess these performance levels, static and shake table tests were performed on full-scale racking system simulating earthquake conditions. An attempt has been made to quantify the dynamic behaviour of the structure based on the experimental results of both static and dynamic shake table tests. Based on the test results, it was seen that the requirements with respect to performance levels specified by FEMA 460 were met by the structures. With respect to the behaviour of the pallet under severe dynamic excitation, it was observed that the wooden pallets

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did not have relative body motion and were vibrating integrally with the structure. Therefore, in a full-scale test, the relative performance of pallet/rack system could be quantified for the first time.

**Keywords** Storage rack · Static load–displacement · Shake table test · Pallet rack system · Dynamic characterization · Performance levels · Seismic behaviour

## 1 Introduction

The effects of earthquake on industrial steel storage systems which were widely used for storing goods were a matter of concern. Nowadays, storage racks were more frequently used in distribution centres and supermarkets. Hence, their safety under seismic condition was evaluated. The uprights were open thin-walled members, with omega section stiffened by lips. The uprights usually contain perforations at regular spacing to allow for the beam and the bracing connections. Beams which usually have closed cross sections were provided by endplates which were hooked on to the upright. This hooked beam-column connection was generally semi-rigid, and the performance of this connection depends on the effectiveness of the beam end connector. The connection to the floor was built up by means of base plate which was bolted to the upright and anchored to the floor. The frame diagonal bracings were usually of open cross-section profiles which were bolted to the upright.

The prediction of the behaviour of these structures was complex because the structural components were thin-walled perforated profiles. These profiles were prone to global, local and distortional buckling. Therefore, the most appropriate method of assessing the behaviour of the perforated sections seems to be an experimental approach. Seisrack project, a joint project undertaken by academic as well as industrial collaboration, investigated various issues by conducting component testing and full-scale (push over) testing. The full-scale testing consisted of monitoring racking system in operating warehouses. This project resulted in the development of design guidelines and recommendations for seismic design of racking systems based on static push over tests.

This paper examines the behaviour under dynamic shake table environment with respect to applicability of the above recommendations.

## 2 Literature Review

The first published in-site dynamic investigation of storage racks was performed in the mid-1970s [5, 6]. The first published shake table studies on storage racks in the USA was performed in the late seventies in the shake table at University of California, Berkeley [2]. This study provided the background information for the seismic design provisions for storage racks in the USA. Seismic behaviour of steel storage pallet racking system was studied by Structural Engineering Department of Politecnio, Milano [1].

Within Seisrack project [8], various investigations were done by means of component testing, full-scale (push over) testing and in-site testing of racking systems in operating warehouses. In this Seisrack project, the assessment of the global behaviour of full-scale racks was carried out on the shake table. An experimental study to understand the seismic behaviour of the cold-formed steel pallet racks under El Centro earthquake acceleration was performed, and an attempt was made to evaluate the realistic dynamic characteristics [7].

## 3 Experimental Investigation

The experimental investigation described herein consists of series of shake table tests conducted on a full-scale, single bay rack with 4 levels. Two specimens, one with spine bracing system as shown in Fig. 1 and the other without spine bracing system as shown in Fig. 2, were tested. The objective of this experimental study was to evaluate the stiffness, natural frequency, damping and to observe the modes of failure of the structure using the spectrum of IS 1893:2016 [4].

The specifications of the specimen used for this study were as follows. Overall height, width and depth of the rack were 6.3 m, 2.7 m and 1 m, respectively. The profile of the upright, beam and frame bracing was shown in Figs. 3, 4 and 5, respectively. The section details of the same were listed in Table 1, and the material properties were listed in Table 2. The connection between the beam columns was a typical semi-rigid connection as with the stiffness value arrived from the joint stiffness test. Beams were hooked on to the upright using lip connector. Plan and Back bracings were standard flats as shown in Fig. 1. Uprights were identified as Legs 1, 2, 3 and 4 as shown in Figs. 1 and 2 for both braced and unbraced racks.

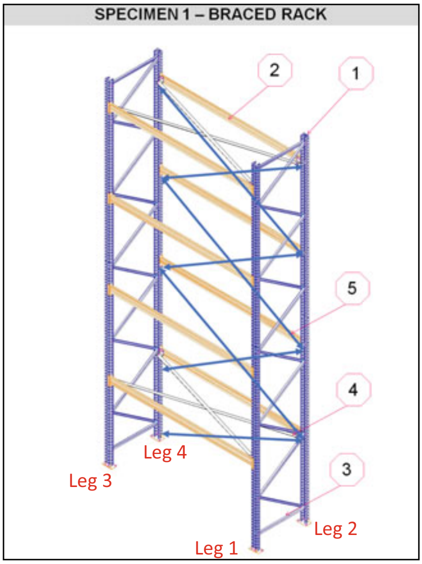



**Fig. 1** Specimen 1—braced rack

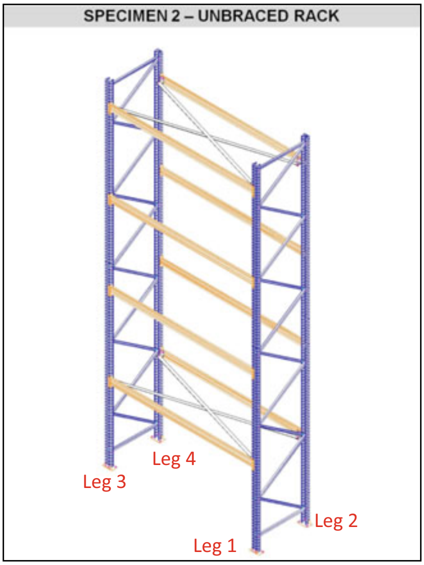



**Fig. 2** Specimen 2—unbraced rack

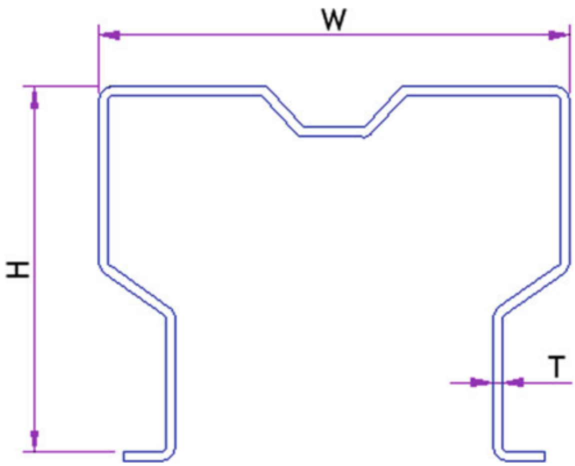



**Fig. 3** Upright section

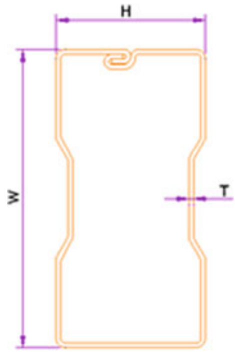



**Fig. 4** Beam section

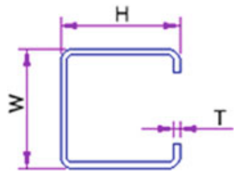



**Fig. 5** Bracing section

**Table 1** Details of cross sections

| S. No | Profile | Web ‘W’ (mm) | Flange ‘H’ (mm) |
|---|---|---|---|
| 1 | Upright | 90 | 70 |
| 2 | Beam | 110 | 50 |
| 3 | Bracing | 30 | 30 |
| 4 | Plan bracing | 50 | – |
| 5 | Back bracing | 60 | – |

**Table 2** Material properties

| S. No | Property | Value |
|---|---|---|
| 1 | Modulus of elasticity, E | 210,000 MPa |
| 2 | Poisson's ratio, U | 0.3 |
| 3 | Min. yield strength (upright) | 355 MPa |
| 4 | Min. yield strength (beam, bracing) | 255 MPa |
| 5 | Min. yield strength (back, plan bracing) | 210 MPa |

# 4 Test Setup, Instrumentation and Testing Procedure

## *4.1 Test Setup*

The test was conducted on the shake table with a platform of 4 m × 4 m normal payload capacity of 50 tonnes at 0.5 g. The specification of the shake table was given in Table 3: horizontal (H) and vertical (V).

Reinforced concrete (RCC) slabs of height 200 mm were cast with holes to match the holes on the shake table. The RCC slab was fixed on the shake table using 4 numbers of M24-diameter high-strength studs. The specimen was installed on the RCC slab by fixing the upright to the base plate and anchoring the base plate on the RCC slab using M12-diameter anchor bolts. A load of 2000 kg at each level was placed on the structure using two wooden pallets (1000 kg each), such that the total load on the structure was 8000 kg. The pallets were placed with a clearance of 100 mm with respect to the frame.

A steel frame supporting structure was provided as a safety fixture around the specimen, so that the added mass and the test specimen can be supported on it in case of failure, if any, during tests. The steel supporting frame was appropriately designed to avoid any interaction with the test structure. The overall assembly of the tested rack was shown in Fig. 6.

**Table 3** Shake table specification

| S. No | Specification | Value |
|---|---|---|
| 1 | Frequency | 0.1–50 Hz |
| 2 | Actuators | 4 × 250 kN (H) and 4 × 250 kN (V) |
| 3 | Displacement | ± 150 mm (H) and ± 100 mm (V) |
| 4 | Velocity | 0.8 m/s (H) and 0.4 m/s (V) |
| 5 | Waveforms | Sine, sine sweep, random and artificial |

**Fig. 6** Overall assembly of the testing specimen on shake table

## *4.2 Instrumentation*

Three sets of instrumentation were used to evaluate the seismic response of the test specimen. Displacement, acceleration and strains were measured at salient locations identified based on the performance requirement of the structure. The details of the instrumentation were given in Table 4.

Non-contact-type displacement transducers (NCDTs) were fixed on a reference frame kept outside the shake table; hence, the measured displacements were absolute displacement inclusive of table displacement. Horizontal displacement of each structure was measured at levels 2, 3 and 4 on all four uprights. Strain gauges were pasted on the tension and compression flanges of the upright as well as the beam near the

**Table 4** Instrumentation details

| S. No | Parameter to be measured | Instrument | Make | Range |
|---|---|---|---|---|
| 1 | Displacement | NCDT | Micro epsilon | 200 mm |
| 2 | Acceleration | Accelerometer | Bruel & Kjaer | $\pm$ 140 $ms^{-2}$ |
| 3 | Strain | Strain gauge | TML | 2 mm |

joints. This could measure the strain response at levels 1 and 4. For measuring acceleration response of the structure, triaxial accelerometers were fixed on the beams of levels 1, 3 and 4. For measuring the acceleration of the pallets placed on the beams, triaxial accelerometers were fixed on one pallet each on levels 3 and 4. All the measured accelerations are absolute acceleration responses. For instrumentation details for specimen 1 and specimen 2, refer Figs. 7 and 8, respectively.

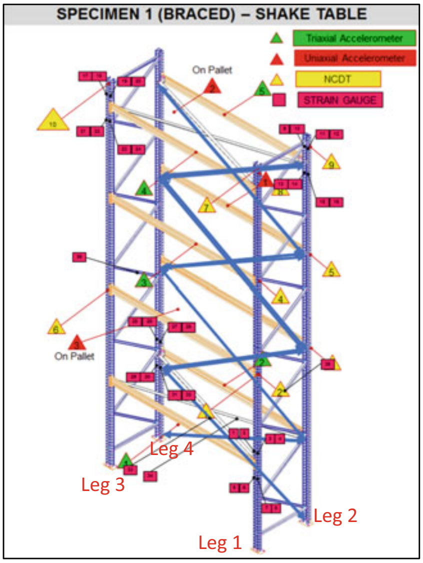



**Fig. 7** Specimen 1—instrumentation

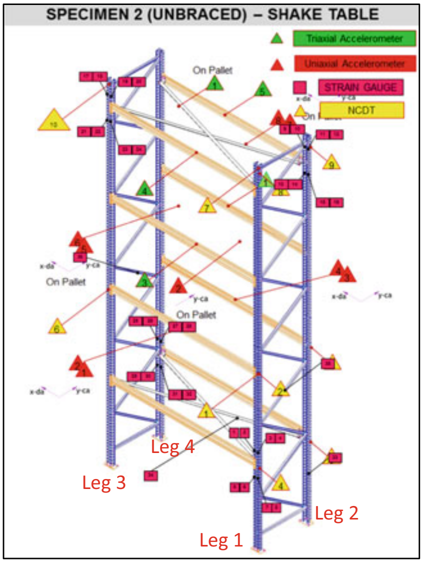



**Fig. 8** Specimen 2—instrumentation

## 4.3 Testing Procedure

Seismic testing of full-scale pallet racking system was carried out by applying three non-correlated acceleration-time histories at the base of the pallet racking structural system in three orthogonal directions. PGA applied in the vertical direction (*Z*) was two-third of that applied at horizontal directions (*X* and *Y*). IS 1893:2016, based on Housner's average spectrum for medium-type soil, was applied. This has a peak plateau region between 0.1 and 0.5 s (2–10 Hz). The spectrum-compatible time history for the medium soil type defined in IS 1893:2016, Part 1, was generated and applied. The time periods and corresponding acceleration coefficient are marked in Fig. 9 for specimen 1 and specimen 2.

The test specimen without pallet mass was rigidly fixed on the shake table along with the instrumentation. The specimen was subjected to free vibration using pulse excitation of both 1 and 3 mm in *X* and *Y* directions independently using shake table. Response acceleration was recorded separately in each direction for both the specimens. Natural frequency of the rack structure was estimated from this free vibration test. After this, the specimen was loaded with 2000 kg of mass at each floor level, and free vibration tests were repeated. Subsequently, the specimen was subjected to seismic ground motion progressively increasing triaxial earthquake input of ground acceleration equivalent to 0.01, 0.025, 0.05, 0.075, 0.1, 0.16, 0.2, 0.24, 0.3 and 0.36 g (Fig. 10). The response values of NCDTs, accelerometers and strain gauges were recorded for every acceleration cycle of 60 s each. After every test, the structure was inspected for any component-level damage.

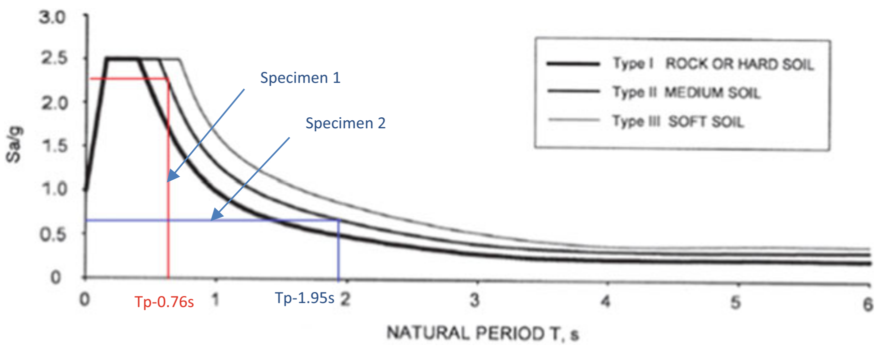



**Fig. 9** IS spectrum as per IS 1893:2016 [4]

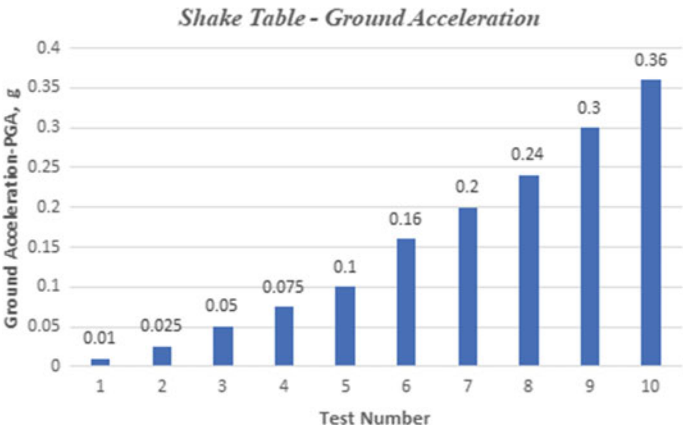



**Fig. 10** Ground acceleration details

# 5 Results and Discussions

## 5.1 *Free Vibration Test*

Response acceleration measured at the last loading level of the loaded specimen was used to calculate natural frequency and damping using Fast Fourier Transform (FFT) and half power bandwidth method, respectively. A typical time history response of a free vibration test is shown in Fig. 11. Free vibration tests were carried out on the structure, with and without added pallet mass.

The predominant frequencies and its corresponding damping values of both the specimens are listed in Table 5.

It was observed that the frequency of the braced system (specimen 1) remained same for both the pulse excitations, though there was an increase in damping. For

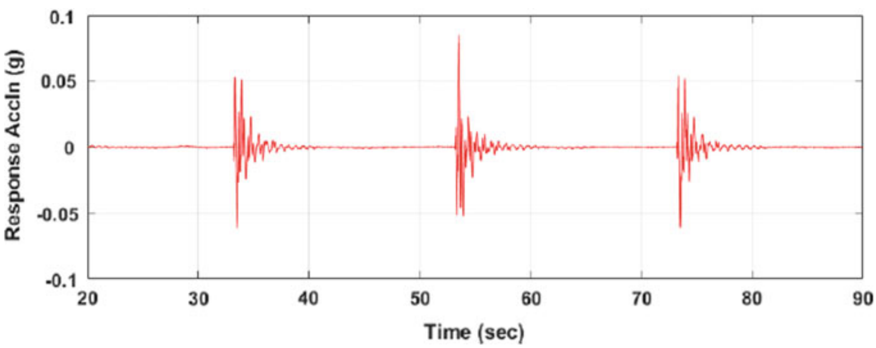



**Fig. 11** Typical time history response for free vibration (pulse excitation)

**Table 5** Predominant frequencies and damping

| | Specimen 1 | | Specimen 2 | |
|---|---|---|---|---|
| | 1 mm pulse | 3 mm pulse | 1 mm pulse | 3 mm pulse |
| Frequency (Hz) | 1.318 | 1.318 | 1.929 | 0.5127 |
| Damping | 0.021 | 0.068 | 0.021 | 0.07 |

unbraced system (specimen 2), the frequency dropped drastically with increase in pulse associated with increase in damping. It should be noted that the damping values of both braced and unbraced system are same. However, a change is noticed for the frequency of the two systems.

### 5.2 Shake Table Test

In shake table test, the displacement–time history, acceleration-time history and dynamic strains were recorded for every acceleration cycle. The recorded displacement was the total displacement (structure displacement + table input). Suitable corrections were made on the recorded responses to arrive at absolute displacement response of the structure. This is presented in Figs. 12 and 13 for specimens 1 and 2, respectively. From the figure, it is seen that for 0.36 g acceleration, the maximum displacement of level 4 with respect to the base was 1.84 times that of specimen 2 as shown in Figs. 12 and 13, respectively. The maximum inter-storey drift between levels 3 and 4 of the specimen 1 was 2 times that of inter-storey drift between levels 1 and 2 of specimen 2 in the down aisle direction. The acceleration response of braced system being stiffer falls in the plateau of the spectral acceleration curve. Hence, it experiences very high lateral loads. Unbraced system having higher time period experiences lesser lateral loads.

For each shake table test, the accelerometers were placed on all levels and on pallets as shown in Figs. 7 and 8. The recorded acceleration response of the structure for specimen 1 and specimen 2 is shown in Figs. 14 and 15. From these figures, the magnification of the response acceleration in the last loading level is clearly seen.

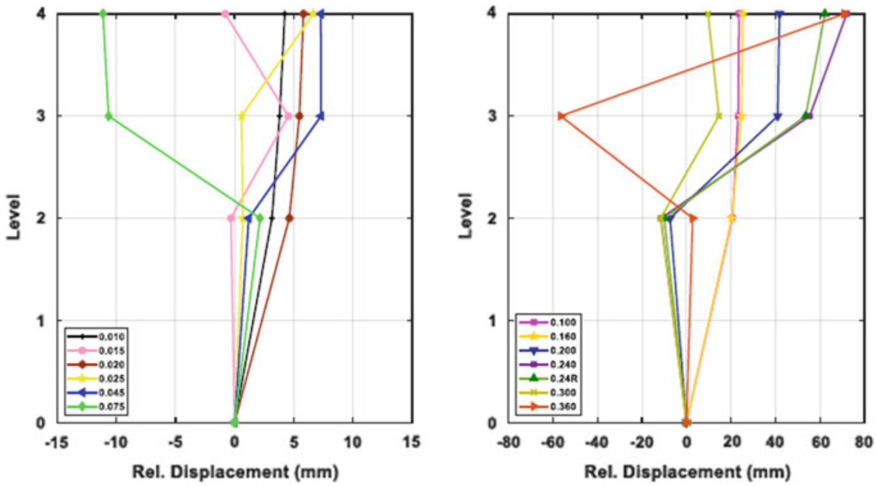



**Fig. 12** Variation of mean displacement in down aisle direction across levels—specimen 1

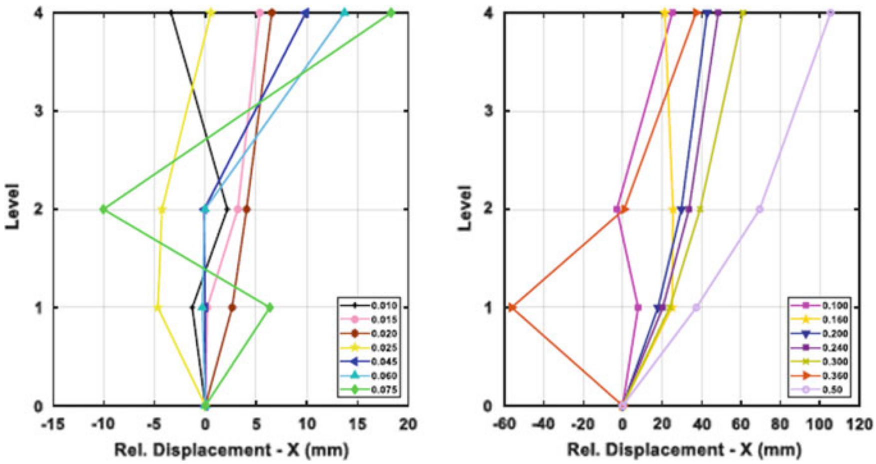
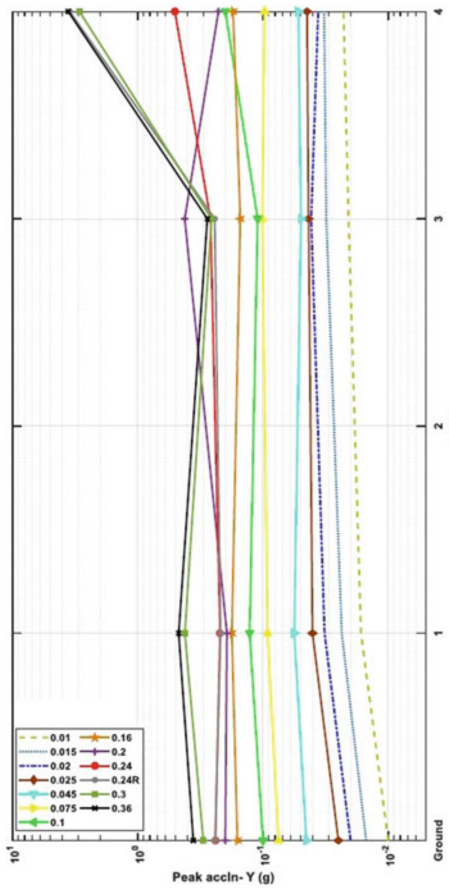



**Fig. 13** Variation of mean displacement in down aisle direction across levels—specimen 2

## 6 Observations from the Test

After every test, the overall structure was inspected to check for any component-level damages. No global collapse or component damage occurred at the end of seismic tests. Some loosening of bracing fasteners—M10 Hex Nut—above 0.16 g PGA was witnessed. No pull out of anchor bolts or damage to the base plate was seen during the entire test.

**Fig. 14** Variation of peak acceleration across levels in specimen 1




Both specimen 1—braced racks—and specimen 2—unbraced racks—withstood the seismic ground acceleration up to 0.36 g without any failure or collapse. The recorded permanent displacement of the structure when subjected to an acceleration of 0.36 g is listed in Table 6. The maximum residual horizontal deflection for the specimen 1 (braced) was 22.78 mm (Leg 1) and specimen 2 (unbraced) was 52.08 mm (Leg 2). It is surmised that the spine bracings have played a positive role in bringing back the system closer to the initial condition as compared to the unbraced system.

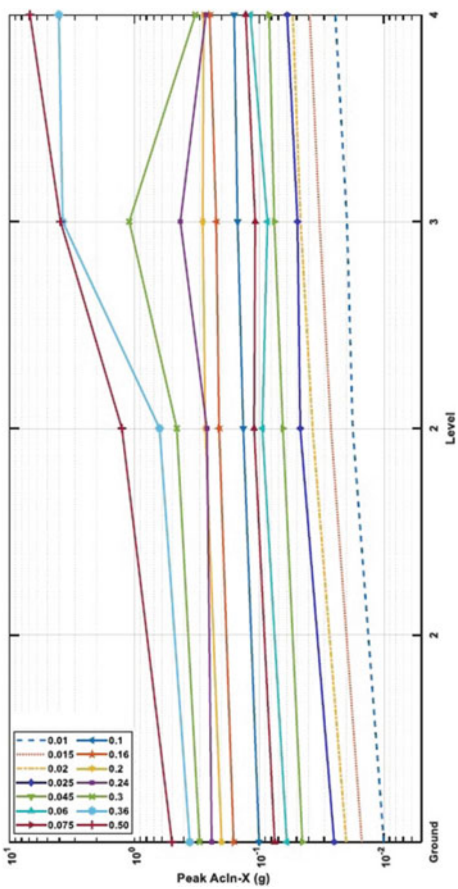



**Fig. 15** Variation of peak acceleration across levels in specimen 2

Careful examination of the members after dismantling revealed bent/deformed bolts used for the connection between diagonal bracing and upright. It was observed at 0.16 g that tabs of the connectors were slightly cutting into the upright slots at corners. However, it was not propagating further up to 0.36 g. No pallet displacement was observed till 0.36 g acceleration. Indentations and paint peel-offs were seen on all four base plates. Removal of base plates from the RCC slabs revealed concrete chip-offs near the anchor bolts.

## 7 Conclusions

The full-scale shake table tests could quantify the natural frequencies and damping of both unbraced and braced pallet racking system. The performance of braced system was significantly better compared to unbraced system with respect to stiffness and

**Table 6** Permanent displacement of the structure after 0.36 g

| | Leg 1 | Leg 4 | Leg 1 | Leg 4 | Leg 1 | Leg 2 | Leg 1 | Leg 2 | Leg 1 | Leg 2 |
|---|---|---|---|---|---|---|---|---|---|---|
| | L1-CA | L6-CA | L7-CA | L10-CA | L2-CA | L3-CA | L4-DA | L5-DA | L8-DA | L9-DA |
| Specimen 1 | 17.22 | − 0.66 | 22.78 | − 4.8 | − 8.61 | − 4.51 | − 11.37 | − 6.46 | − 12.3 | − 5.89 |
| Specimen 2 | − 10.87 | − 14.93 | − 16.33 | − 26.8 | 7.78 | 9.5 | 20.84 | 24.1 | 48.77 | 52.08 |

consistent natural frequency. The damping witnessed during testing agrees well with those adopted based on codal stipulation. The pallets resting on the beam did not have relative motion with respect to the beam and frame up to 0.36 g. The pallets also did not show any relative motion or slipping between frame and beam which indicate that the friction between the pallet and the support beam was adequate to prevent falling of the pallet during an earthquake. The shake table test has revealed limited damages and no collapse under a severe acceleration of 0.36 g at foundation level. This can be considered as satisfactory performance meeting the requirements of both life safety under Design Basis Earthquake (DBE) and collapse prevention performance under Maximum Considered Earthquake (MCE) as prescribed in FEMA 460 [3].

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