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Stability evaluation of cold formed steel pallet racks under seismic condition- A numerical and shake table study

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Abstract

In this paper, studies on global behaviour of cold formed steel pallet rack systems using a second-order frame analysis formulation are reported. Calibration studies on the developed second-order beam formulation have been carried out. The different global analysis procedures stipulated in the popular code of practice for the design of cold formed steel storage racks (EN 15512 and RMI (2012)) are briefly reviewed. Using the formulation, studies are carried out on tall racks, especially focusing on semi-rigidity of connections and stability. Later, a shake table test is conducted on a two-level pallet rack to investigate the dynamic behaviour of cold formed steel racks subjected to base excitation. A typical earthquake input of El Centro (1940) North-South component is applied, and the behaviour of the cold formed steel racks is studied. The connection flexibility of the upright – connector tab has been taken from an earlier publication by the author. All joints in the numerical model and experimental work are treated as semi rigid. The paper then describes the effect of connection rigidity on the dynamic performance of the racks. Although the racks could not be subjected to its maximum design load per level, the dynamic characterization that is observed during the test is reported in this paper. It is identified that, a combined dynamic analysis calibrated with numerical solutions is the correct way to assess the seismic performance of cold formed storage racks.

1. Introduction

There has been a steady rise in the requirements for cold formed steel pallet storage racks especially after an impressive economic activity in Asia, primarily China and India. The requirements for cold formed steel pallet racks have increased in the fast-moving consumer goods sector. Today, for every project that comes up in Asia, global players can participate in the tender process, which resulted in designs made using a particular code of practice are being installed as a system in completely different geographical locations of the world. This becomes a big challenge, especially if the seismic design compliance is enforced. For seismic design, the site specificity of the dynamic characteristics is very important. In India, the EN 15512 and RMI codes are popular, since there are no codes of practice available, exclusively for the design of storage pallet racks. So far, this practice of adopting simple design methods for storage rack design is considered to be adequate in India. But today there is an increase in demand for tall

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racks in seismically active areas. Hence, the traditional static analysis by taking dynamic loads as equivalent static loads has become increasingly inadequate. Designers are unwilling to change into dynamic analysis procedures as their design office effort is getting increased. As the height of the rack goes up, the stability design becomes more and more important. Hence, to investigate the second order effects on the behaviour of cold formed steel pallet racks, there have been continuous efforts for developing an accurate second-order analysis formulation for the analysis of tall racks. One such formulation developed by the author Arul Jayachandran and Don White (2007) is used to study the second order behaviour of steel pallet racks and few results are reported in this paper. Seismic analysis of the racks on a shake table is carried out and the results are presented in this paper. Although the author wanted to have the same loading that was used in the numerical study in the shake table specimen, due to safety considerations of the shake table, only a partial load was applied during the seismic evaluation of the pallet racks. However, the results of the dynamic analysis can be directly correlated for increased gravity loading also.

2. Review of literature

Liusi Dai et al. (2018) proposed a preliminary theoretical model using a component method, to predict the initial rotational stiffness of beam-to-upright bolted connections in steel storage pallet racks. The authors have shown good agreement between the initial rotational stiffness derived from the theoretical model and the experimental tests. Adamakos et al. (2018) investigated the behaviour of how the pallets and the pallet beams on which they are resting, interact during seismic events. Claudio Bernuzzi et al. (2017a, 2017b, 2015a, 2015b) who made significant contributions to the body of literature on the behaviour of storage racks, presented an appraisal of the key differences on structural performance associated with the different code provisions with respect to bi-symmetricity of the cross-section of the uprights. They also investigated the effect of warping, which is generally neglected by the designers and manufacturers. They presented a complete design example, which includes all design options that could be used as a benchmark design for researchers and designers. One of the contributions of the authors is in bringing out the effect of a wide range of design parameters of practical interest. They also suggested regarding the selection of an analysis method whether a first or second order elastic analysis, depending on the rack deformability to horizontal loads. Jacobsen and Tremblay (2017) reported tests on shake-table and a companion numerical modelling of inelastic seismic response of semi-rigid cold-formed rack moment frames. Prabha et al. (2010) studied about connection behaviour of cold formed steel racks. Rack connections are boltless and semi- rigid in nature. Since different types of beam end connectors are available, it is very difficult to generalize the properties of the connection. In this study, experiments are carried out on commercially available pallet racks, by changing various influencing factors such as the thickness of the column, depth of the beam and depth of the connector, and a moment – rotation model is proposed. Sarawit and Pekoz, (2006) carried out investigations to evaluate the ‘Effective Length Method’, and to examine the ‘Notional Load Method’ as an alternative design procedure. Finally, they concluded that the notional load method can be considered as an alternative means for industrial steel storage rack design. Alper Kanyilmaz (2016) and Castiglionni (2003) presented the seismic evaluation of pallet racks. The aspect of hysteretic behaviour of rack connection was reported by Saravanan et al (2014).

EN 15512 (2009) and RMI (2012) specifies the structural design requirements applicable to all types of adjustable beam pallet rack systems, fabricated from steel members intended for the storage of unit loads, and subject to predominantly static loads. Both un-braced and braced systems are included. Gross section properties are properties of the gross section without any reduction for perforations or local buckling. Gross section properties are generally used in global calculations for internal forces and deflections. Minimum section properties are the properties of a perforated element corresponding to the gross cross section, with the maximum reduction for the effect of the perforations. Effective section properties are the reduced section properties taking account of local buckling. But, some of the uprights have arrays of perforations causing significant reduction in moment of inertia. In such cases, reduced moment of inertia should be used for global calculation. By far, these two codes are the most adopted, in the design of cold formed steel storage racks and construction.

3. Numerical Formulation and analysis of pallet racks

In line with what is stipulated in EN 15512 and RMI code for second order analysis, a numerical formulation for the advanced second order analysis is presented by Arul Jayachandran and Don White (2007). For brevity, the details are not presented here. The reader may refer to the paper. To validate this formulation for second order analysis of frames, a benchmark frame problem of Australian Institute of Steel Construction is investigated which is subjected to predominant gravity load and a small lateral load (Fig.1). Comparison of results of the present study with that of Petrolito and Legge (1995) is presented in Table 1. The results of sway deflection and moments compare extremely well with the benchmark results even with one element per frame member.

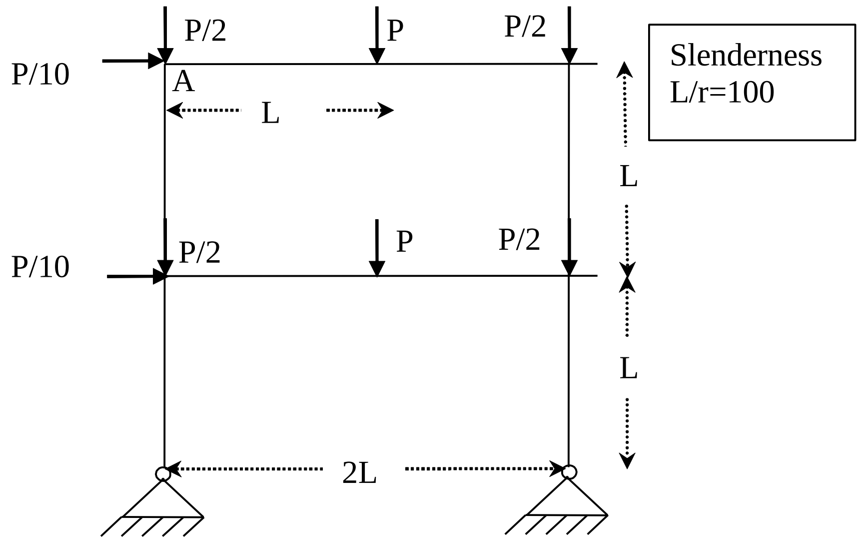


Figure 1: Two storey frame under compression and sway loads
(Benchmark problem of Australian Institute of Steel Construction)

Using the formulation, some representational rack problems are studied, to understand effects of semi-rigidity. The effect of semi-rigidity on behaviour of rack structures is taken from the paper Prabha et al (2010), in which the author is a co-author. A typical 3×3 rack (Fig.2) which is loaded by 4T/level/bay, is analyzed using the formulation. Although the dimensions are not practical, initial intent of the author was to have the same model in numerical analysis and shake table tests. Later, due to practical reasons, the dimensions of the shake table tests were changed.

The material and cross-sectional properties of the cold formed steel columns and beams are: Young's modulus: E=203 N/mm^2 (MPa); Column: box section with I_c=0.7492×10^6 mm^4, area, A=774.24 mm^2 and thickness t=2.54 mm; and Beam: shelf-beam with I_b=2.4738×10^6 mm^4, area A=904.38 mm^2 and thickness t=3.2 mm. As explained earlier, column to beam connection of rack structure are considered as semi rigid. Most of the connection falls in the lower regime of the semi rigid stiffness spectrum. To find the effect of semi rigidity on the structure, a study was carried out with various rotational stiffnesses of the joint. The results are presented in Table 2.

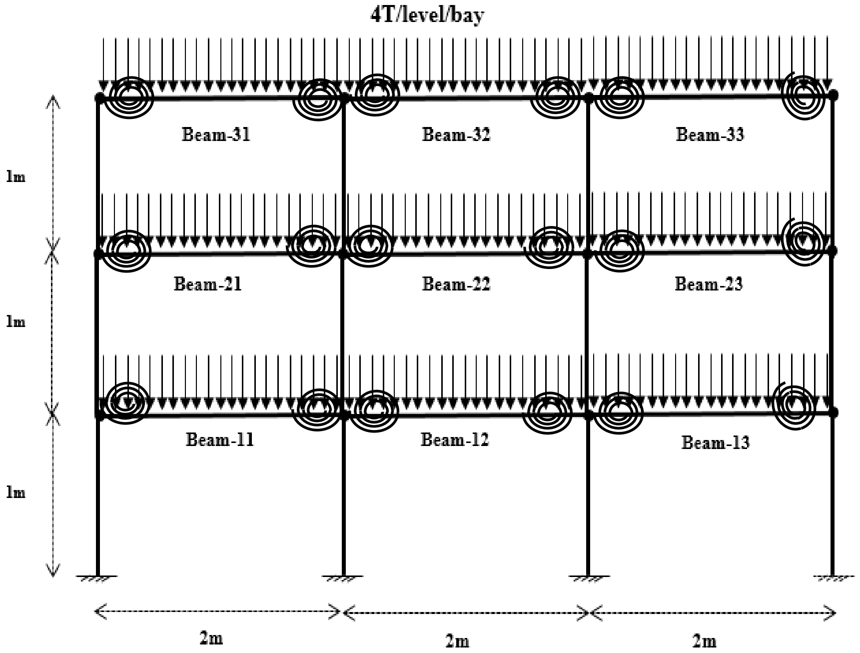


Figure 2: Rack with 3 bays × 3 level configuration and loaded with UDL

Table 1: Benchmark result of Australian Institute of Steel Construction- Beam under compression and shear

	Present 1element/ member 1increment	**Present** 2elements/member 1 increment	Petrolito & Legge (1995)	**Present** 1element/ member	**Present** 2elements/ member	Petrolito & Legge (1995)
PL^2/EI	Deflection Δ/L at **A**			Moment at fixed end ML/EI		
0.5	.021	.021	.021	.060	.060	.060
1.0	.055	.055	.055	.155	.155	.155
1.5	.121	.123	.123	.331	.334	.334
2.0	.279	.285	.285	.741	.760	.760
2.25	.404	.419	.419	1.111	1.114	1.114

The above rack is analyzed by simulating various plausible field conditions. Beam column joint stiffness is altered from rigid to semi-rigid connection stiffness. The study is limited to connection stiffnesses in the range of 50 kNm/rad to 200 kNm/rad.

Table 2: Beam mid span moment variation

Beam No	Mid Span Moment (Nm)					% Change
	Initial stiffness of semi-rigidity(kNm/rad)				Rigid	
	50	100	150	200	Rigid	
31	5751.6	5701.1	5654.7	5611.9	4597.6	25%
32	4751.0	4671.3	4598.5	4531.8	2982.4	59%
21	5416.1	5346.5	5283.0	5225.0	3927.6	38%
22	4850.5	4778.7	4713.3	4653.4	3287.3	48%
11	5427.7	5368.8	5315.2	5266.4	4171.4	30%
12	4845.8	4769.4	4699.6	4635.4	3128.8	55%

Using the same formulation, a typical semi-rigid 3 bays×9 level rack, which is loaded by 2T/level/bay is analyzed. The numbering of the beams in the 3×9 rack is followed in the same way. The material and cross-sectional properties of the cold formed steel column and beam are: Young's modulus: E=203 N/mm^2 (MPa); Column: box section with $I_c=2.08\times10^6$ mm^4, area, A=436.54 mm^2 and thickness t=2.54 mm; and Beam: shelf-beam with $I_b=2.4738\times10^6$ mm^4, area A=407.43 mm^2 and thickness t=1.6 mm. Height of each storey is 1.5 m and bay width is 2 m. A study is made, with a second order analysis for the tall rack, with and without considering initial imperfections. In the first case, initial imperfections are mot modelled. In the second case, initial imperfections are modelled as notional loads, specified in direct analysis (DA). Material nonlinearity is taken care, by adjusting the stiffness as per DA stipulations. The frame is analyzed to understand the effect of various provisions of Direct Analysis, especially the effect of initial imperfections in the design.

Table 3: Direct analysis vs Normal analysis- Notional loading

				Moment (kN-m)		
			Element No	Without notional load	DA	% change
Top storey		Column	125	-1.678	-1.660	-1%
	Beam	Mid span	115	3.051	3.050	0%
		End	115	-1.678	-1.696	1%
Ground storey		Column	13	-0.803	-0.586	-37%
		Column base moment	1	0.325	0.378	14%
		Column base moment	14	0.325	0.157	-107%
	Beam	External span moment	3	2.903	2.314	-25%
		External end moment	3	-1.872	-1.581	-18%
		Internal span moment	7	2.697	2.152	-25%
		Internal End moment	7	-2.340	-1.943	-20%

Table 3 presents the result of a study, which compares a storage rack with and without modelling imperfections. If imperfections are modelled in the analysis, there is a reduction in span and support moments of the beam.

4. Details of the specimen used in the shake table tests

The author wanted to carry out numerical evaluation and the shake table test on the same geometric parameters of the pallet racks. However, with safety of the shake table infrastructure in mind the following geometric dimensions are used. The rack which is used in the shake table test is shown in Fig 3. The frame has a total height of 3.2 m, in which both the first storey and the second storey are of 1.5 m height. The bay width is 1.850 m and width of the upright is 0.920 m in the cross-aisle direction.

The upright used is called as 'heavy duty' with upright section of thickness 2.5 mm, total height 3200 mm, breadth 110 mm width 90.5 mm and pitch of the slot 50 mm are used. The cross section of the upright section is shown in Fig.4 (the dimensions in Fig.4 is in mm). The four numbers of beam sections of total length 1700 mm, width 50 mm, depth 100 mm and thickness 1.6 mm are used, and the beam cross section is shown in Fig 5. The beam and the upright are connected using the beam end connectors. The lip connector is used, as beam end connector as shown in Fig 5, which is locked into the tabs present in the upright, and a lock in key is used for better safety. Four numbers of lipped connectors of width 39.5 mm, height 64 mm, depth 200 mm, thickness 3.5 mm and pitch of the slot 50 mm are used. The coupon tests are performed and the obtained average values of modulus of elasticity, yield stress, and ultimate stress are 204000 MPa, 260.544 MPa and 425.232 MPa respectively.

5. Sweep sine tests

Sweep sine test is performed by varying the frequency of sinusoidal excitation progressively, in successive steps, to determine the natural frequency of the frame. Sweep sine test is conducted in the direction of moment resisting frame of storage rack. Since the natural frequency obtained through free vibration test is an approximate one, the sweep sine test is conducted to get the nearest actual natural frequency of the frame. But, to start sweep sine test, it is necessary to fix the range of varying frequency of sinusoidal excitation which is decided from free vibration test.

The range of frequency is varied from 0 to 20 Hz for sweep sine test which is conducted on both pallet rack for two different cases, one for the frame without any masses and another for the frame with mass of 400 kg. The acceleration response of each floor is measured, to find the acceleration response ratio between the second-floor response with base acceleration and first floor response with base acceleration using FFT (Fast Fourier Transforms) analyzer. Fig.6 and Fig.7 shows the response of heavy-duty pallet rack without floor mass and with floor mass. The dominant frequency of HD (Heavy duty) rack is 6.25 Hz and 2.875 Hz respectively, for with and without floor mass. As per free vibration test, the second mode of frequency is 8.875 Hz, but in sweep sine test, it shows that the frequency of 8.75Hz is in the torsional mode. Therefore, the author is of the opinion that, sweep sine test is necessary for the determination of realistic fundamental frequencies of the cold formed steel pallet racks. Table 4 shows the experimental results of fundamental frequency for HD racks.

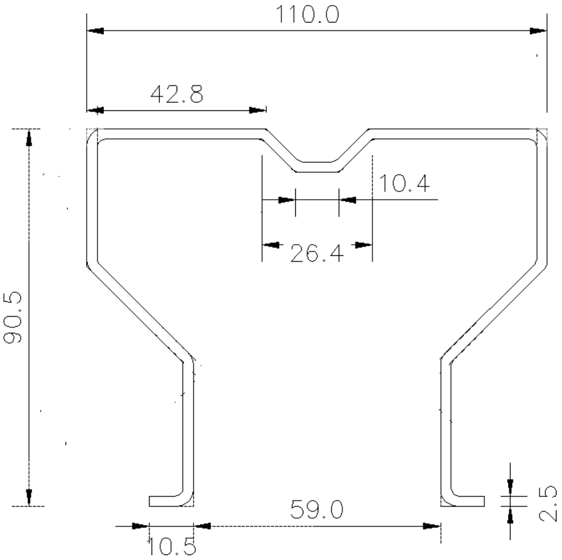


Figure 4: Cross section details of the upright

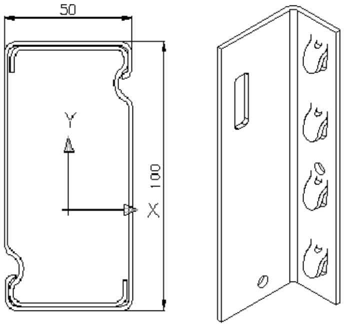
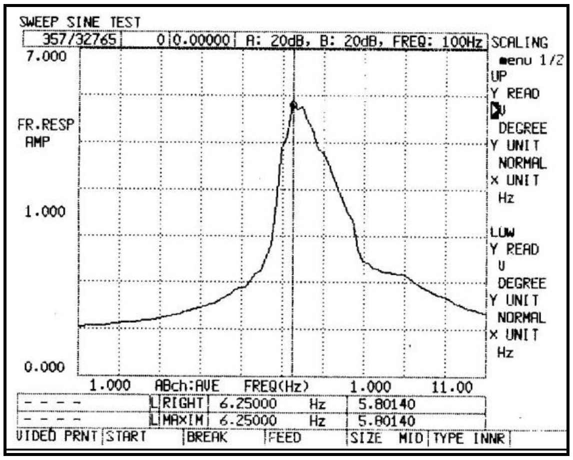


Figure 3: Steel pallet rack mounted on a shake table

Figure 5: Beam cross section and lipped connector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SWEEP SINE TEST
 357/32765      0 0.00000  A: 20dB, B: 20dB, FREQ: 100Hz
 - - - -            L RIGHT  6.25000    Hz   5.80140
 - - - -            L MAXIM  6.25000    Hz   5.80140
VIDEO PRNT START      BREAK      FEED      SIZE  MID TYPE INNR
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Figure 6: Sweep sine test results for HD rack without floor mass

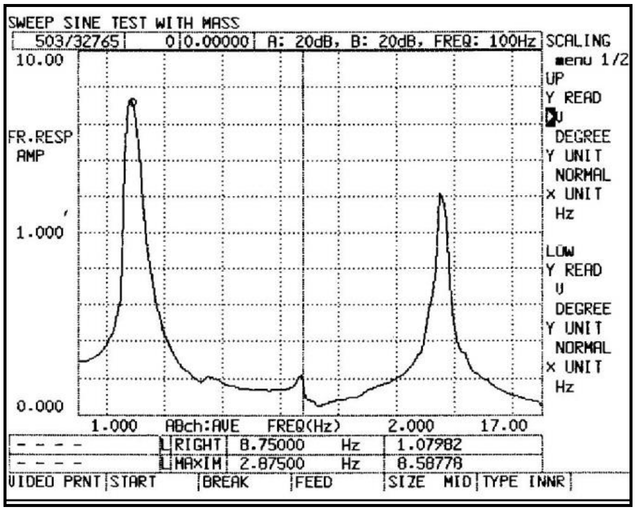

Figure 7: Sweep sine test results for HD rack with floor mass

Table 4: Experimental results of Fundamental frequency of HD

Specimen	Case	1st Mode	2nd Mode
Heavy Duty rack	Without mass	6.25 Hz	-
	With mass	2.875 Hz	13.5 Hz

6. Shake table tests with base excitation

After the calculation of natural frequency, the loaded rack frame is subjected to seismic excitation, with various intensities of records obtained from the past El Centro acceleration of N-S component ground acceleration. The seismic behaviour of pallet rack in the direction of moment resisting frame only, is studied. The experimental studies on heavy duty rack are conducted for the excitation of 25, 50, 62.5, 75 and 100 percentage of scaled El Centro acceleration. The base acceleration input is shown in Fig.8. From the experimental investigations, the maximum accelerations obtained at second floor are found to be 5.72, 9.5 and 14.817 m/s^2 respectively, which are 2.87, 3.973 and 4.65 times higher than the recorded acceleration values of the base input respectively.

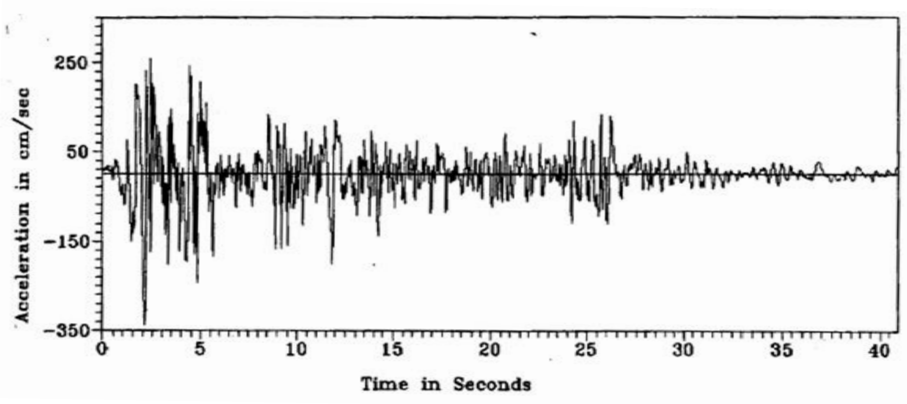

Figure 8: Time history of accelerations El Centro (1940) North – South component

Fig.9 shows the first and second floor acceleration response of heavy-duty pallet rack with input acceleration. From the results, the base shear and storey drifts are calculated and from the strain gauge readings, it is observed that the maximum strain obtained for the full-scale El Centro acceleration is 672 µm/m and no permanent strain has been observed in all the base of the columns. Fig.10 shows the strain response at the base of the upright, where the maximum strain has occurred. From Fig. 9 and Fig.10, it can be seen that, the response is not similar in both compression and tension region, even within the elastic limit, which is due to the unsymmetrical flexibility offered by the hook in end connector.

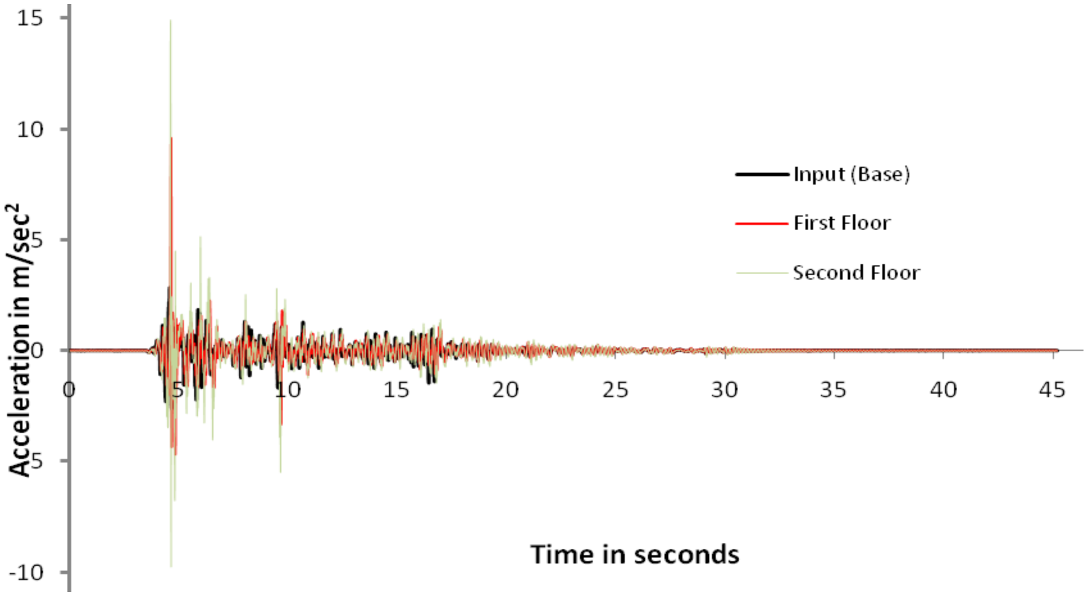

Figure 9: Acceleration response of heavy-duty pallet rack

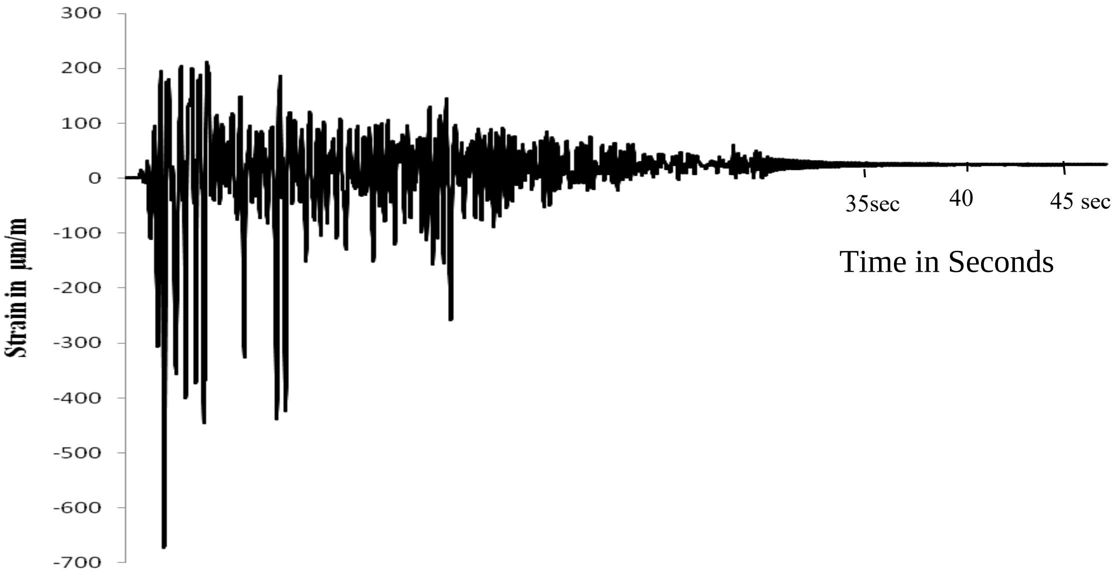

Figure 10: Strain response of heavy-duty pallet rack at the base of upright

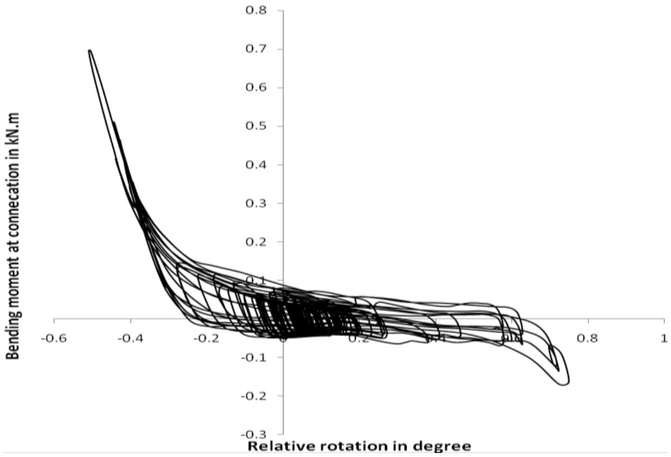

Figure 11: Hysteretic moment-rotation behaviour of connection at second floor in HD rack

The beam moment and relative rotation between the beam and column is plotted for heavy duty rack, for the full scaled El Centro earthquake excitation. The maximum bending moment and relative rotation of connection is found to be 0.985 kNm and 0.813 degree respectively, for heavy duty pallet racks. The hysteretic moment-rotation behaviour of connection shows the pinching effect due to the slip of the tabs present in the hook in the end connectors. Fig.11 shows hysteretic moment-rotation behaviour of connection at first and second floor in HD rack. Even though the strains are within the linear range, the frame has behaved nonlinearly, which represents the connection nonlinearity predominant in the behaviour of racks. From the seismic test, it can be observed that the chosen pallet rack, heavy duty, with chosen loads is demonstrated to be adequate against seismic hazards. However, the mass per level of the racks in the shake table tests is much lower than the actual, practical values.

7. Summary and conclusions

A finite element beam formulation for the numerically exact second order analysis of beams and frames, is used in the numerical study of a short and tall storage rack frames. Numerical studies on 3×3 and 3×9 storage racks bring out the significance of considering initial imperfections and semi-rigidity of the beam to upright connector flexibility. Based on the experimental results and shake table test results, the following conclusions were reached. The natural frequencies obtained as 6.25 Hz and 2.875 Hz for the frame without mass and with mass respectively, shows that the natural frequecies are much higher than normal building systems of two floors with a similar stiffness-mass ratio. This study suggests that, a sweep sine test for the evalution of natural frequency of the rack structure will be ideal. This paper also identifies that, a combined dynamic analysis calibrated with numerical solutions is the correct way to assess the seismic performance of cold formed storage racks.

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