Earthquakes and Structures, *Vol. 7, No. 6 (2014) 955-967*
DOI: http://dx.doi.org/10.12989/eas.2014.7.6.955

Seismic characterization of cold formed steel pallet racks

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(Received February 10, 2014, Revised May 6, 2014, Accepted June 29, 2014)

Abstract. Storage racks are used worldwide in industries and commercial outlets due to the advantage of lighter, faster erection and easy alteration of pallet level as required. The studies to understand the behaviour of cold formed steel pallet racks, under seismic action is one of the emerging area of research. The rack consists of perforated uprights and beams with hook-in end connector, which enables the floor height adjustments. The dynamic characteristics of these racks are not well established. This paper presents the dynamic characteristics of 3-D single bay two storey pallet rack system with hook-in end connectors, which is tested on shake table. The sweep sine test and El Centro earthquake acceleration is used to evaluate the seismic performance of the cold formed steel pallet racks. Also an attempt is made to evaluate the realistic dynamic characteristics by using STAAD Pro software. Modal analysis is performed by incorporating the effective moment of inertia of the upright, which considers the effect of presence of perforations and rotational stiffness of the beam-to-upright connection to determine the realistic fundamental frequency of pallet racks, which is required for carrying out the seismic design. Finite element model of the perforated upright section has been developed as a cantilever beam through which effective moment of inertia is evaluated. The stiffness of the hook-in connector is taken from the previous study by Prabha *et al.* (2010). The results from modal analysis are in good agreement with the respective experimental results.

Keywords: pallet rack; shake table test; cold formed steel; modal analysis; effective moment of inertia

1. Introduction

Generally cold formed steel pallet rack components are light weight, which helps in faster erection and easy handling. The beam-to-upright connections and uprights (columns) are configured in such a way that the pallet levels can be easily modified. Most of the beam-to-upright connections used in the storage racks are proprietary one. All of them are almost conceptually similar. However, the shapes of elements such as beams, uprights and tabs present in connector, which simply hangs in the perforations in upright have small variation.

In general, storage racks are designed to resist gravity loading. However, to resist the lateral loading, due to earthquake, bracings are provided in the cross aisle direction. The storage racks behave as moment resisting frames in the down aisle direction. These moment resisting frames pose a major complexity in the prediction of behaviour under seismic loading, like seismic character of structure or modelling problems, due to the unsymmetrical semi-rigid nature of

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http://www.techno-press.org/?journal=eas&subpage=7 ISSN: 2092-7614 (Print), 2092-7622 (Online)

connections and perforations present in the upright. To address these complexities many of the researchers proposed different modelling procedures for the seismic design of storage racks (Filiatrault *et al*. (2006), Alavi and Gupta (2008), Bajoria *et al*. (2008) and Haque and Alam (2013)).

The usage of storage racks has grown significantly during the past few decades by industries and big box stores across the world. Huge loss of material and lives have been reported (FEMA-460) due to the collapse of racks under seismic action. Hence, it is mandatory to design the storage racks for seismic loading. One of the important dynamic characteristics of a structure is fundamental period. According to Rack Manufactures Institute (RMI), no approximate method is allowed to find natural period of racks, which is recommended in building codes of practice. RMI prescribes a Rayleigh method. Alternatively, it also suggests a simplified equation presented in FEMA-460 to obtain fundamental period. This simplified equation was validated based on the experimental work conducted by Filiatrault and Wanitkorkul (2004) on hot-rolled steel pallet racks. In order to verify the equation presented in FEMA-460 for particular type of cold formed steel plate racks, Bajoria *et al*. (2010) conducted modal analysis by using finite element analysis software. They compared results obtained from numerical analysis with analytical model developed by utilizing FEMA-460 with little modification. They showed that the results closely match with frequency obtained through numerical analysis.

Experimental studies on cold formed steel pallet racks to obtain the seismic behaviour are scarce and often those works are on proprietary racks. Castiglioni *et al*. (2003) carried out shake table test on four full scale cold formed steel storage racks to study seismic performance. Also

Fig. 1 Pictorial view of pallet rack

sliding test was performed in order to characterize and investigate a phenomenon, which represents a limit state for the racking system. They showed that sliding of pallets occurs at a base acceleration lower than the acceleration that might be associated to structural failure. Filiatrault *et al*. (2008) conducted a shake table test to study the performance of new base isolation system in cross aisle direction and demonstrated that the proposed system satisfied the requirements of FEMA-460. Rosin *et al*. (2009) studied the seismic behaviour of the steel pallet racks to assess the design rules under earthquake conditions. They also characterized the interaction between the pallets and rack beams with sliding and proposed a model to capture such behaviour. Further, based on the studies, evaluation of response reduction factor was carried out. Sideris *et al*. (2010) also studied interaction between loaded pallets and rack shelves and proposed a slightly inclined shelving to mitigate merchandise shedding. From the literature, it is observed that the studies on seismic behaviour of pallet racks are inadequate.

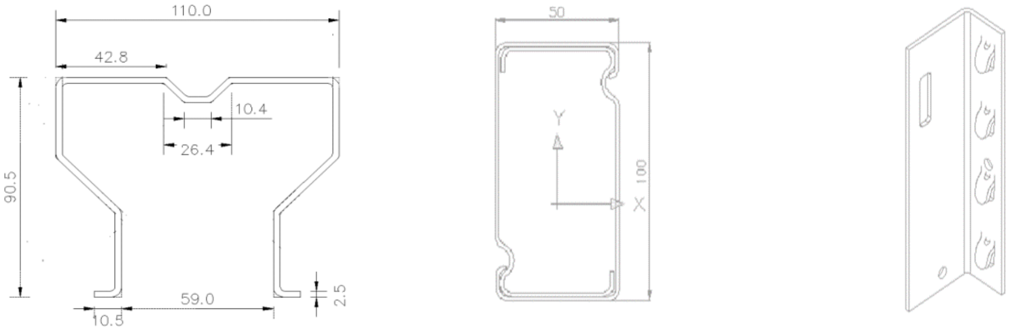
In this paper, an attempt is made to assess the fundamental frequency of particular type cold formed steel storage racks through the modal analysis by using STAAD Pro software. The effect of perforations in the upright and actual rotational stiffness of beam-to-upright connections, which is obtained from Prabha *et al*. (2010) is considered in the analysis. The obtained fundamental frequency is compared with the corresponding results from shake table test.

2. Experimental investigations

2.1 Specimen details

Two numbers of 3-dimensional single bay two storey rack with storey height of 1.5 m, bay width of 1.85 m and 0.92m cross width are chosen for this study. The thickness of upright (column) are varied as 1.8 mm and 2.5 mm, which are called as Medium Duty (MD) rack and Heavy Duty (HD) rack, respectively. Fig. 1 shows the pictorial view of Cold Form Steel (CFS) pallet rack under study. The cross-section of the upright, beam and isometric view of hook-in end connector are shown in Fig. 2. The beam section is made from two channel sections placed front to front and welded at the edges and thickness of channel section is 1.6mm as shown in Fig. 2(b). The modulus of elasticity, yield stress, and ultimate stress of CF steel obtained from the tension coupon test are 205000, 260 and 425 MPa respectively. The beam and the upright are connected by hook-in end connectors, which is welded at end of the beam and locked into the perforations present in the upright and a lock-in key is used for better safety. The connector is four lipped hook-in end type having 39.5mm width, 64mm length, 200mm depth, 3.5mm thickness and 50mm pitch of the slot. This configuration of beam end connector presents the unsymmetrical nonlinear moment-rotation behaviour. The perforation details of the upright in the exploded view are shown in Fig. 3. These perforations help to erect the pallet rack easier, faster and to fix the bracings in cross aisle direction.

The mass of 400 kg on each floor is simulated by using the concrete slabs of 200 kg each as shown in Fig. 1. Floor mass is tied firmly with the floor beams by using rope to avoid the movement of slab during the experimental investigation. Three accelerometers and six LVDT’s are connected to measure acceleration and displacement of each floor and beam rotation. Also, the rack is instrumented with twenty two stain gauges at beam-to-upright and base plate junctions to monitor the strain value.



(a) upright section (b) beam section (c) hook-in end connector

Fig. 2 Detailed view of components in pallet rack

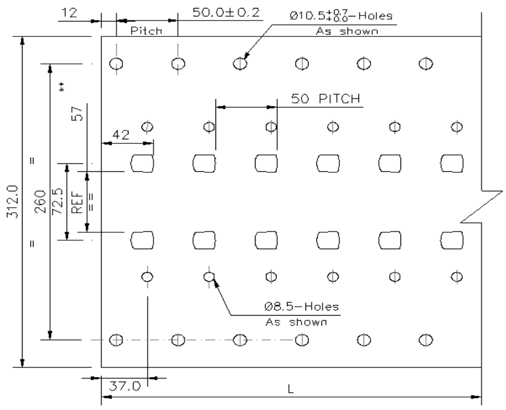


Fig. 3 Details of perforations in uprights

2.2 Free vibration test

Experimental evaluation of fundamental natural frequency is generally obtained through free vibration test. Free vibration tests have been conducted by releasing the tied rope at the midway of the top of the frame on both type of pallet rack without floor mass as the first case and with floor mass of 400 kg in the down aisle direction as the second case. Fast Fourier Transform (FFT) analyzer is used to determine the frequency response spectrum. Fig. 4 shows the typical free vibration test results for the HD pallet rack with floor mass. The frequency obtained from free vibration test is used for fixing the frequency range during sweep sine test.

2.3 Sweep sine test

The natural frequency obtained through free vibration test is an approximate one. The sweep sine test is conducted to get the nearest true natural frequency of the frame. Sweep sine test is performed by varying frequency of sinusoidal excitation progressively in successive steps. Sweep sine test is conducted in the down aisle direction of storage rack. For conducting sweep sine test, it is necessary to fix the range of varying frequency of sinusoidal excitation, which is decided based

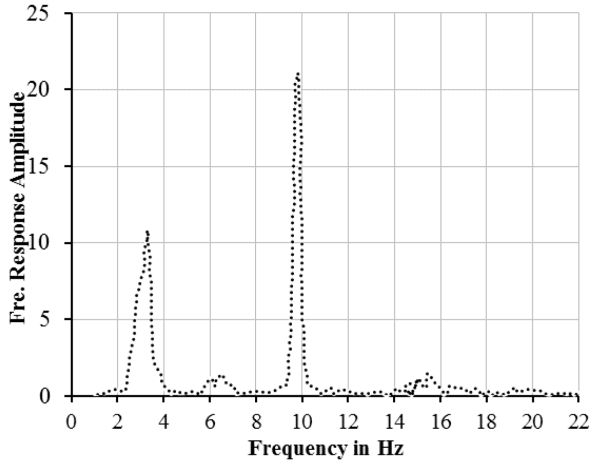


Fig. 4 Free vibration test results for HD rack

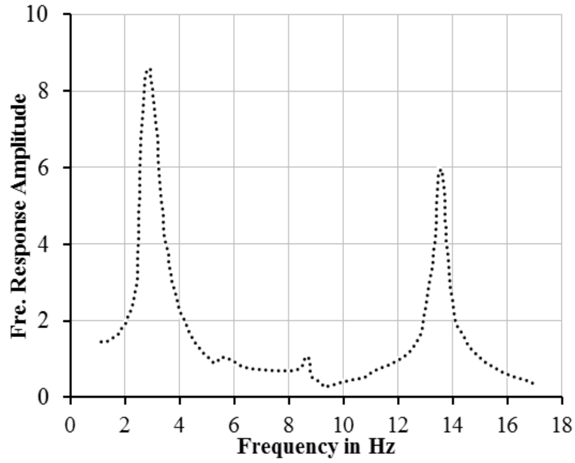


Fig. 5 Sweep sine test results for HD rack with mass

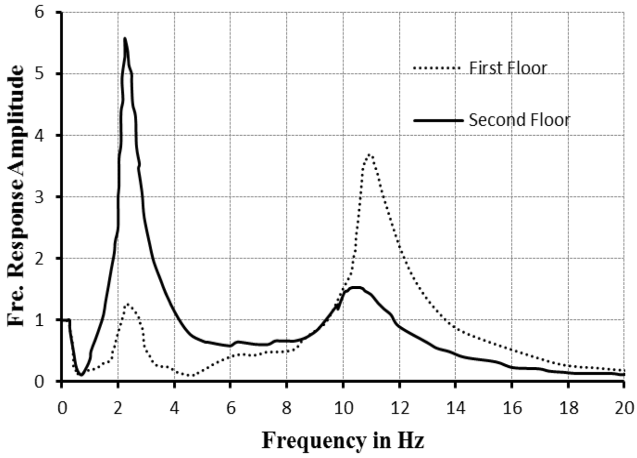


Fig. 6 Sweep sine test results for MD rack with mass

Table 1 Experimental results of fundamental frequency of HD and MD pallet rack

SPECIMEN	CASES	1st MODE	2nd MODE
HD rack	Without mass	6.25 Hz	-
	With mass	2.875 Hz	13.5 Hz
MD rack	Without mass	4.00Hz	-
	With mass	2.25 Hz	11.00 Hz

on the free vibration test. The range of frequency is varied from 0 to 20 Hz. Sweep sine test is conducted on both type (HD and MD) of pallet rack for two different cases, one for the frame without any mass and another for the frame with mass of 400kg. The acceleration response of each floor is measured and the floor wise acceleration response ratio with respect to base acceleration is evaluated by using FFT analyzer. Fig. 5 shows the typical response of HD pallet rack with floor mass at second floor. The fundamental frequency of HD rack are 2.88 and 6.25 Hz respectively for with and without floor mass. By comparing Figs. 4 & 5, it can be observed that the first mode of frequency closely matches with the free vibration test results. However, for the second mode, it differs from free vibration test results. As per free vibration test, the second mode of frequency is 8.875 Hz, but during sweep sine test, frequency is observed as 8.75Hz which represents the torsional mode. Therefore, it is necessary to conduct sweep sine test for the determination of realistic fundamental frequencies and corresponding mode shapes.

Fig. 6 shows the results of sweep sine test on MD pallet rack with floor mass for the first and second floor responses. From Fig. 6, it can be observed that the second floor response is 4.42 times higher than the first floor response in first mode, whereas in second mode first floor response is 2.4 times higher than the second floor response. Further, it can be observed that the peak response amplitude in second mode occurs at 11 Hz and 10.5 Hz, respectively for first and second floors. Table 1 shows the results of fundamental frequency for HD and MD pallet rack obtained through shake table test.

It may not be feasible to conduct these experiments at all times and hence, development of alternate method is necessary. In view of this, analytical model is developed and explained in later section to evaluate the natural frequency of storage rack accounting for the effect of flexibility of beam-to-upright connection and perforations present in the upright.

2.4 Seismic test

The loaded pallet rack frame is subjected to seismic excitation with various intensities of El Centro ground acceleration of N-S component. The seismic behaviour of pallet rack only is studied in the direction of moment resisting frame. The experimental studies on HD rack are conducted for the excitation of 50 and 100 percentage of scaled El Centro acceleration. From the shake table test, the maximum accelerations obtained at second floor are 3.973 and 4.65 times higher than the recorded respective acceleration values of El Centro. Through the strain gauge readings, it is observed that the maximum strain obtained for the full-scale El Centro acceleration is 672 µm/m and permanent strain is observed in all the base of the uprights, which may be due to the dislocation of connector tabs. Similarly for the MD frame, the maximum accelerations obtained at second floor are 1.03 and 1.14 times higher than the respective applied acceleration. From the strain gauge readings, it is found that the maximum strain of 525 µm/m occurred during the seismic tests. Also, it is observed that the response is not similar in both compression and tension region, which is due to the unsymmetrical flexibility of hook-in end connector.

The base and storey shear are compared between HD and MD pallet racks. The base shear is calculated by summing the force in each floor, which is calculated by multiplying the respective floor weight and response acceleration. Though the stiffness of HD rack upright is 39% more than MD rack upright, the obtained base shear in HD pallet rack is 3 times higher than the base shear obtained for MD pallet rack as shown in Fig. 7.

The beam moment and relative rotation between the beam and column is plotted for HD rack for the full scaled El Centro earthquake excitation as shown in Fig. 8. As the stain is within the range of elasticity, the moment is calculated by multiplying the strain, modulus of elasticity and elastic section modulus of beam. The relative rotation is calculated by dividing the displacement by distance between the LVDT to the center of upright. The maximum bending moment and

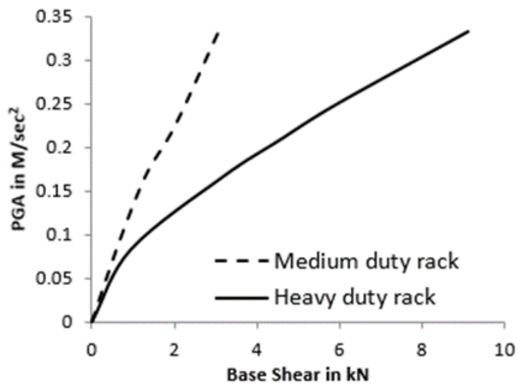


Fig. 7 Base shear Vs PGA response

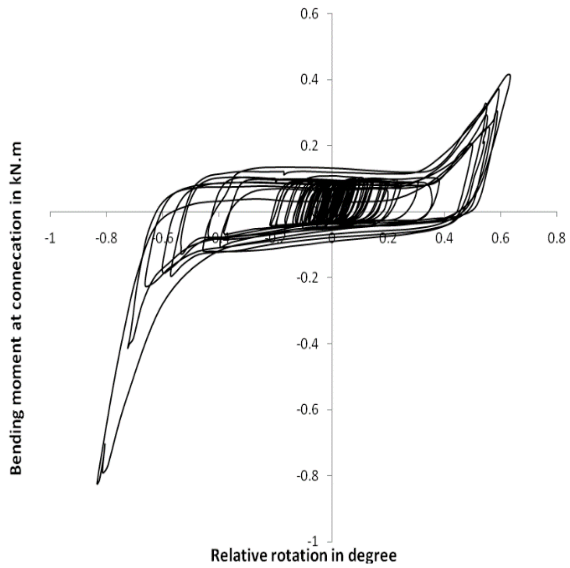
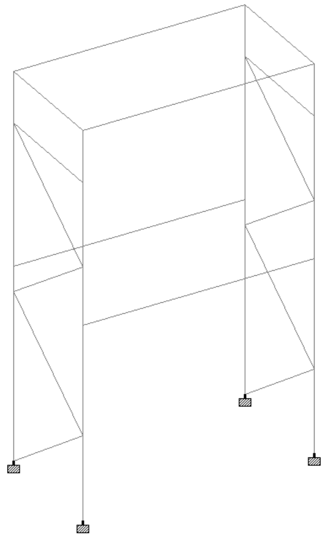


Fig. 8 M-θ curve of beam-to-upright connection at first floor in HD rack

(a) Pallet rack



(b) Analytical model

Fig. 9 Pictorial view of pallet rack and analytical model of CF steel racks

relative rotation of connection is found to be 0.985kNm and 0.813 degree respectively for HD pallet rack and 0.564kNm and 0.45 degree for MD pallet rack respectively. Also, stiffness of connections are measured as about 63 kNm/rad and 57 kNm/rad for HD and MD rack respectively, which have considerable variation during cycles. The hysteretic behaviour of connection shows the pinching effect due to the slip of the tabs present in end connectors and unsymmetrical behaviour due to the geometry of connector. Even though the strains are within the linear range, the frames behaviour is nonlinear, which may be due to the connection nonlinearity and localized yielding. From the seismic test, it can be observed that the chosen pallet rack, HD and MD, with chosen loads, is adequate against seismic hazards.

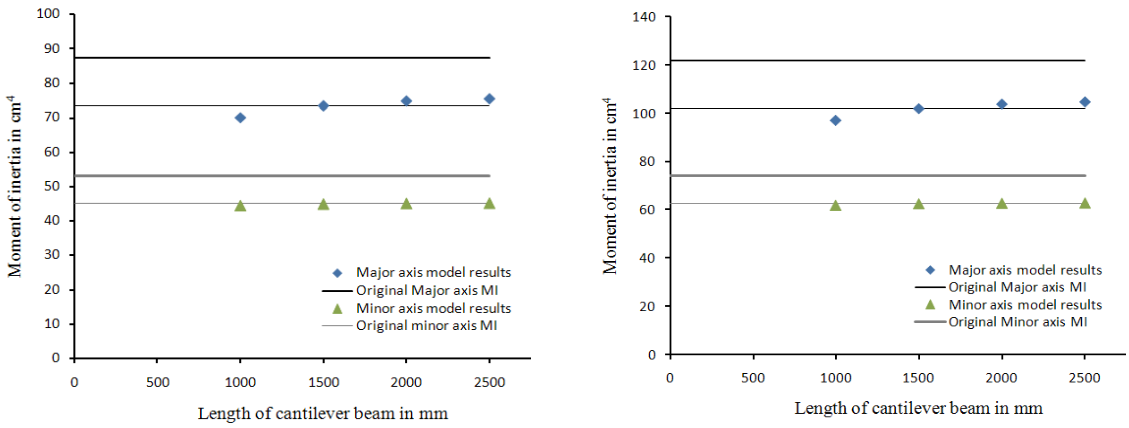
3. Analytical model description

Fig. 9 shows the pictorial view and analytical model of CF steel pallet racks. The cold formed steel pallet rack is modelled by using STAAD Pro software to carry out the modal analysis. Initially, cold formed steel pallet rack is modelled with the beam-to-upright connection as pinned in first case and fixed in second case. Gross section properties of the upright section without considering the effect of perforations are used to determine the range of natural frequency between these two extreme cases. Later, to determine the realistic natural frequency of pallet rack through modal analysis, the actual stiffness of connection and the effective moment of inertia accounting for the effect of perforations in upright are incorporated in the analysis as third case. The effective moment of inertia is found out from the finite element model, which is explained in next section and the connection stiffness of beam end connector is taken from the experimental investigation on beam-to-upright connection tests (Prabha *et al*. 2010). The connection stiffness of hook-in end connector can also be determined from the polynomial equation proposed in the same paper for various parameters of similar type of connections. The connection stiffness of beam end connectors are taken as 71.62 and 57.29 kNm/rad for HD and MD pallet racks respectively. The upright base connection stiffness is assumed to be equal to the flexural rotational stiffness of base upright end.

3.1 Evaluation of effective moment of inertia

The effect of perforations present in the upright sections in terms of moment of inertia is found from the finite element analysis. For this purpose, the upright section is modelled by using shell element (S4R) and analysed as cantilever beam by varying the span of 1000, 1500, 2000 and 2500 mm as shown in Fig. 10. The model is linearly analysed by applying 1mm deflection at the free end in major axis direction as one case and in minor axis direction in another case. Based on the analysis, equivalent stiffness and effective moment of inertia are evaluated. The results of finite element analysis for MD and HD upright are shown in Fig. 11. The effective moment of

Fig. 10 Finite element model of upright section



(a) MD rack (b) HD rack

Fig. 11 Graphical view of FEM results

inertia is compared with full section moment of inertia and it is found that the ratio between the effective moment of inertia and gross section moment of inertia is 0.85. Hence, in order to capture the distributed nature of perforations in the upright, reduction of about 15% of thickness of upright section is taken for the current configuration of perforated upright. Further, weighted average method is used to compare the effective moment of inertia with numerical analysis. There are two ways of performing weighted average method, such as, weighting the area of the net section and weighting thickness of section in portion of hole. It is found that through these approaches the moment of inertia predicted is about 6% less than the respective gross section moment of inertia. However, this value is much less, when compared with effective moment of inertia found through numerical analysis. Hence, in the present study, the results of numerical analysis are utilized, which are on the conservative side.

4. Results and discussions

Table 2 shows the fundamental frequency (Hz) obtained from experimental and modal analysis results and Fig. 12 shows the first and second mode shape of pallet rack frames. From the results, it is observed that the fundamental frequencies obtained from the experimental investigation fall between the results of two extreme cases (hinged and fixed) obtained through the modal analysis. Therefore, actual value of connection stiffness and effective moment of inertia of upright section are incorporated in the modal analysis to get the realistic fundamental frequency (case 3). From the modal analysis, with actual stiffness of connection and effective moment of inertia, the first and second modes of natural frequency of HD rack is 2.71 and 13.51 Hz against the corresponding experimental results of 2.88 and 13.50 Hz respectively. For MD pallet rack, the respective values are 2.38 and 11.63 Hz against the corresponding experimental results of 2.25 and 11 Hz. It is found that the frequencies obtained through modal analysis are in closer agreement with the respective experimental values. Further, the natural frequencies are compared with IS 1983:2002 (approximate fundamental frequency for buildings) and FEMA-460. It can be observed from Table 2 that the approximate frequency found by using the equation presented in IS 1983:2002 agrees closely with fixed case of analytical model. However, it significantly differs

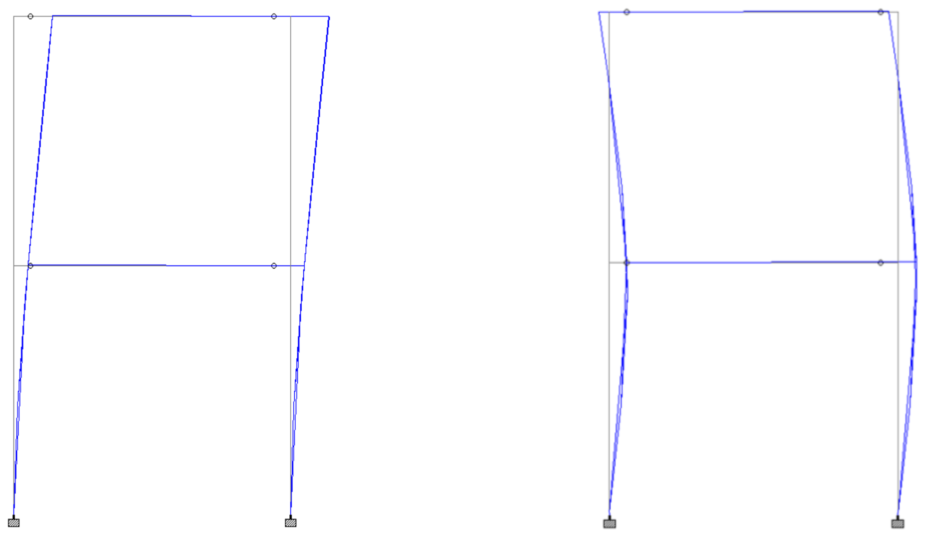
Table 2 Comparison of natural frequency (Hz) obtained from experimental and modal analysis results

ID	Experimental Results		Modal Analysis						As per IS 1893:2002	FEMA-460	
			Case 3		Pinned		Fixed				
	First mode	Second mode	First mode	Second mode	First mode	Second mode	First mode	Second mode	Approx. natural frequency	First mode without perforations	First mode with perforations
HD	2.88	13.50	2.71	13.51	2.38	15.37	5.62	18.98	5.16	3.03	2.85
MD	2.25	11.00	2.38	11.63	2.03	13.15	5.16	16.65	5.16	2.63	2.50

with realistic frequency of storage rack found from the shake table test. Further, it is observed that the frequencies obtained by using FEMA-460 without accounting the perforations matches well with realistic frequency of storage rack, as it considers connection flexibility. The values are further improved by accounting for perforations through the concept of effective moment of inertia.

5. Summary and conclusions

An effort has been made to evaluate the fundamental frequency of CFS pallet rack. The frequencies obtained from experiments, modal analysis, Indian codal equation and FEMA-460 are compared. Fundamental frequencies of 3-dimensional single bay two storey CFS storage pallet rack obtained through experimental investigation are 2.25Hz for MD pallet rack and 2.875 Hz for HD pallet rack respectively. A methodology is proposed to evaluate the effective moment of inertia of upright, accounting for perforation, based on the finite element analysis. Based on the studies, it is concluded that a reduction coefficient of 0.85 for the moment of inertia (for the configuration of perforations considered) is recommended. Also, the polynomial model proposed by Prabha *et al*. (2010) for rotational stiffness can be incorporated for realistic evaluation of fundamental frequencies of the pallet racks of a particular system. This methodology can be extended for other configurations of CFS pallet racks to evaluate the dynamic characteristics for seismic design. Also, from the seismic test with El Centro earthquake acceleration history, it is demonstrated that the chosen pallet rack, HD and MD, with chosen loads is adequate against seismic hazards.



(a) First mode (b) Second mode

Fig. 12 Typical mode shapes for MD and HD pallet rack

Acknowledgements

The authors are thankful to Dr. Nagesh R. Iyer, Director and Dr. K. Ravisanker, Advisor (Mgmt.), CSIR-Structural Engineering Research Centre, Chennai, for their constant support and encouragement. Authors also thank to Dr. S. Arul Jayachandran for his technical support and guidance during the experimental investigations. The paper is being published with the kind permission of the Director, CSIR-SERC.

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