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Efficient Configuration of Storage Rack System as Per Nonlinear Static Pushover Analysis under Triangular and Uniform Pattern of Lateral Loading Pattern

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ABSTRACT

The individual components of cold-formed storage rack system are most vulnerable to local and torsional buckling lateral loads in addition to under gravity. Deterministic allotment of strength and ductility in the structural components and performance evaluation of appropriate techniques is considered in the capacity based design of cold-formed pallet rack system. Nonlinear time history analysis (NTHA) and nonlinear static pushover analysis (NSPA) are most commonly followed techniques for seismic performance evaluation of any structural systems. Although, NTHA is the most correct technique of seismic demand forecasting and performance evaluation, it is computationally heavy and even requires the selection and application of relevant set of ground excitations. A simple method for the nonlinear static analysis of complicated structures subjected to gradually increasing lateral loads (pushover analysis) is presented here. This paper presents investigation of efficient configuration of conventional pallet racking system on the basis of seismic performance by using NSPA. Finite element models of two different configurations of conventional pallet racking system are prepared and analyzed on the general purpose FE platform using ABAQUS 6.12 under monotonic unidirectional lateral loads. Results show that conventional pallet racking system with horizontal and inclined bracing is more efficient as evidenced from a fair judgment of the overall displacement, base shear and yielding demands.

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1. Introduction

The cold-formed steel members are predominantly used for drive in and drive through steel pallet rack structures. In usual storage rack structures, the box cross sections are used for beams, while open thin walled perforated sections are used for columns, which connects beams and columns together without bolting or welding. Therefore the design of storage rack structures is quite complicated. The behaviour of the perforated columns is influenced by various buckling modes e.g. local, distortional and global as well as by their common correlations. Usually the response of beam to column is nonlinear. Besides, bracings are usually placed in the cross-aisle direction. The requirement for organizing pallet racks in such a way that the material is effectively stored and sufficiently available, affects the presence of bracings in the down-aisle direction. The lateral stability is exclusively provided by the degree of continuity related with beam to column connections in addition to base plate connections. Presently, for the design of these frames, no particular code of practice available. The specifications given by Rack Manufacturer's Institute [1] followed by United States and other countries as a guidelines. For seismic demand prediction and performance evaluation of structures nonlinear time history analysis (NTHA) is the most correct method available. The selection and employment of relevant set of ground excitations is the basic requirement of this method and needs a sophisticated mathematical gadget which handles the analysis and gives results within the time. For professional practice designers, a simpler analysis tool with less computational effort is required. The nonlinear static pushover analysis (NSPA) method is a popular method and good alternative method to time history analysis. To examine the performance of conventional pallet storage rack systems using numerical analysis is the primary objective of the study demonstrated in this paper. The analytical tests include nonlinear static pushover analyses of various configurations of storage rack frames. The past research on static pushover analysis and on conventional pallet rack systems is briefed in following section. Section 3 deals with details storage rack frame and its configurations. Finite element modeling with validation and NSPA of rack frames are presented in subsequent sections. Final section summarized the important findings from the numerical tests on cold formed storage rack systems.

2. Review of past research

2.1. On push over analysis

To evaluate the structural attainment by calculating the strength and deformation capacities using static nonlinear analysis and comparing these capacities with the demands at the equivalent performance levels is the primary objective of the pushover analysis. The primary process of this method is to execute a series of static analysis under gradually increasing lateral loads in its principle directions to simulate the loading of the structure during the failure. The potential of the pushover analysis has been conceived in the last 20 years and it is covered in the seismic guidelines ATC-40 [2]. The pushover analysis is expected to provide information on many responsive features that cannot be found from an elastic or dynamic analysis.

The following primary response characteristics are aimed from NSPA:

i. Estimation of strength and deformation capacities structural system for fundamental mode of vibration.
ii. Location of the crucial areas, where the inelastic strains are likely to be more.
iii. Consequences of strength deterioration of particular elements of the total structural stability.
iv. Order of members yielding and collapse and the progression of the total capacity curve of the structure.

The history of pushover analysis was highlighted by Krawinkler and Seneviratna [3]. Initially the study was focused on discussions of the scope of suitability of the technique and its merits and demerits, compared to static or nonlinear dynamic methods. Asawasongkram et al. [4] studied the seismic performance assessment of the semi-rigid steel pallet rack structures located in Thailand. A mathematical model of the structure was prepared by incorporating nonlinear behaviour of semi-rigid beam to column joint. Chopra and Goel [5] attempted to extend pushover analysis for taking into account higher failure modes. Kalkan and Chopra [6] was presented a modal pushover based scaling (MPS) procedure to scale ground motions for the use in a nonlinear response history analysis of buildings. Fajfar [7] was presented a simple nonlinear (N2-method) for the seismic analysis of structures. This method composes the pushover analysis results of a multi degree of freedom (MDOF) model with the response spectrum analysis of an equivalent single degree of freedom (SDOF) system in typical acceleration-displacement format. Thus, this method enables the visualization of the seismic response of the system and establishes the relation between the fundamental quantities regulating seismic response. Among the different techniques of pushover analysis, NSPA is more favored as it is simple, computationally light and still provides more accurate results for fundamental mode of vibration. In the current study NSPA on two different configurations of conventional pallet racking system is conducted to examine the strength and deformation capacities of storage rack systems. The pattern of lateral load adopted for NSPA conforms to the equivalent static force distribution pattern of UBC-1997specifications.

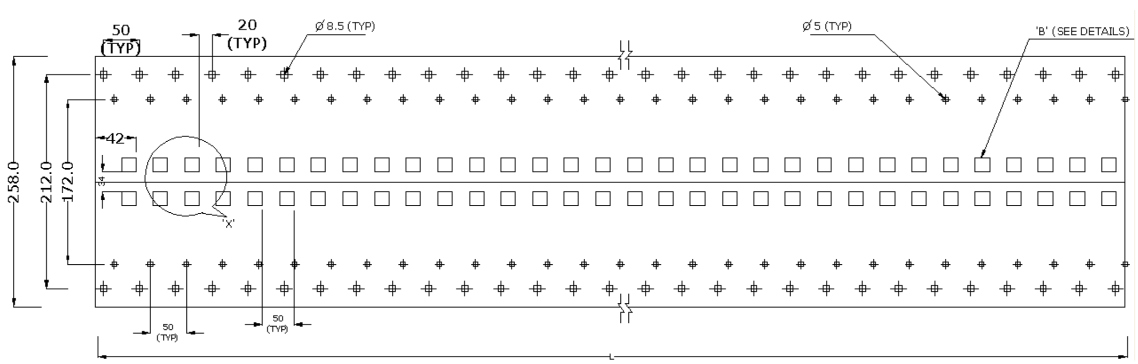
2.2. On conventional pallet racking systems

A three dimensional (3D) FE model of storage rack systems prepared by Sangle et al. [8] using ANSYS [9] software and free vibration modal analysis carried out in a conventional semi-rigid storage rack structure with 18 types of column sections developed. The finite element buckling and dynamic analyses of two dimensional (2D) single frames and 3D frames of cold-formed steel sections with semi-rigid connections used in the conventional pallet racking system also performed. The results obtained from buckling analysis of the single 2D frames, experimental study and effective length approach given by RMI were compared. The buckling analysis results were obtained for FE model used for the single 2D frames further extended to 3D frames with semi-rigid connections. However, Sangle et al. does not consider material as well as geometric nonlinearity in their research. Bajoria et al. [10] prepared finite element 3D models using ANSYS and modal analysis are carried on pallet rack structures. A parametric study is carried out for finding fundamental mode shapes and time period. Sangle et al. [11] studied elastic buckling analysis of 2D and 3D pallet rack frames with semi-rigid connections. Experimental results, effective length approach of RMI and FEM analysis of single 2D frames were compared. The main object is to determine the linear buckling load of single 2D frames and to determine the stability of 3D frames of typical cold-formed steel storage rack structures, with semi-rigid connection. Use of stiffeners in the column section enhances the buckling load capacity considerably. Thombare et al. [12] considered the material as well as geometric nonlinearity in their research further to extend their study. The procedure to perform the multi mode pushover (MMP) method was studied by Sasaki and Paret [13] and this method was applied to various structures. MMP uses the capacity spectrum method to correlate graphically the pushover plot to the earthquake demand. Kalavagunta et al. [14] investigated the progressive collapse of cold-formed steel pallet rack structures subjected to earthquake loading using pushover analysis. Moghadam and Tso [15] continued the pushover method for seismic damage estimation of unsymmetrical structures. It is shown that the exactness of the proposed 3D pushover analysis is identical to those applied to planar frames with the help of an illustration. This method is found to be more advantageous in calculating the overall response parameters such as inter storey drifts than local damage indicators such as beams or column ductility demands.

3. Details of storage rack frames

The column cross sections used in the study are Medium Weight (MW) sections having three thicknesses 1.6 mm, 1.8 mm, and 2.0 mm each and Heavy Weight (HW) sections having three thicknesses 2.0 mm, 2.25mm and 2.5mm each. Their cross sectional details of medium weight and heavy weight columns are shown in Fig. 1 and in Fig. 2 respectively. Three different thicknesses are selected to know the variation in behaviour when the sections are made locally strong by having a higher thickness. Fig. 3 to Fig. 5 presents the particulars of the finite element models. Spacer bars are also used to avoid local buckling of the column sections in the present study.

For the cross sections shown in Fig. 1 and in Fig. 2, cross sectional properties are estimated based on the weighted average section. A weighted average section is a section that uses an average thickness in the portion of web to account for the absence of the material due to the perforations along the length of the section. Table 1 shows the cross sectional properties of the column sections and Table 2 presents of material properties of the same column sections.



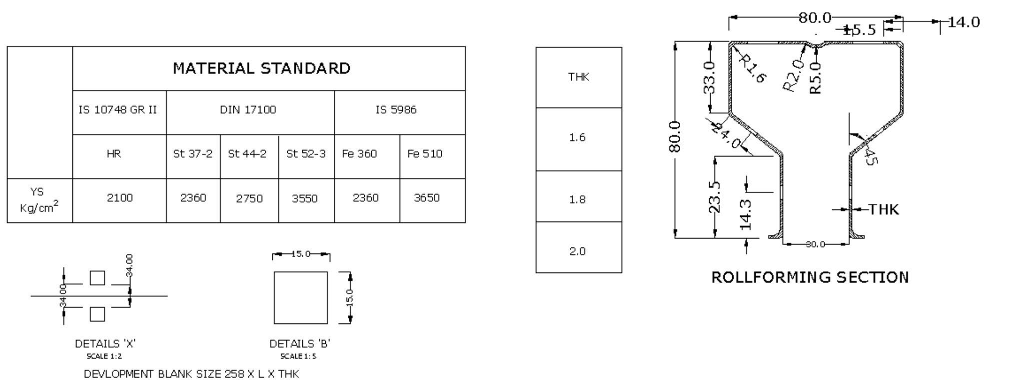


Fig. 1. Medium weight column section 1.6mm, 1.8mm and 2.0 mm thick[12].

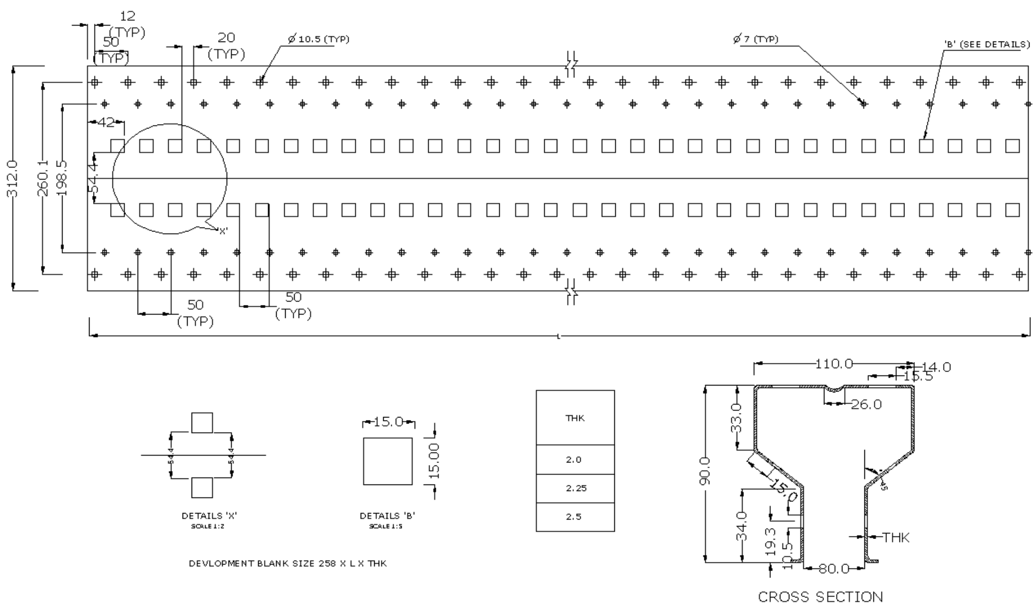


Fig. 2. Heavy weight column section 2.0mm, 2.25mm and 2.5mm thick [12].

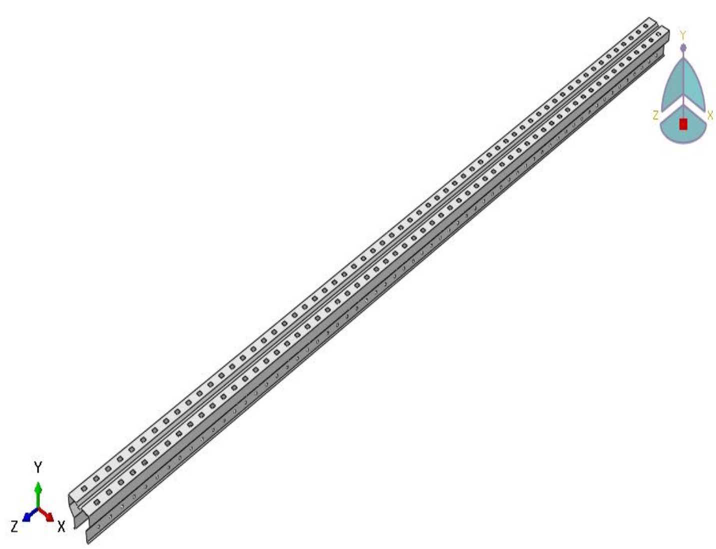


Fig. 3. Heavy /Medium Weight column section in ABAQUS [12].

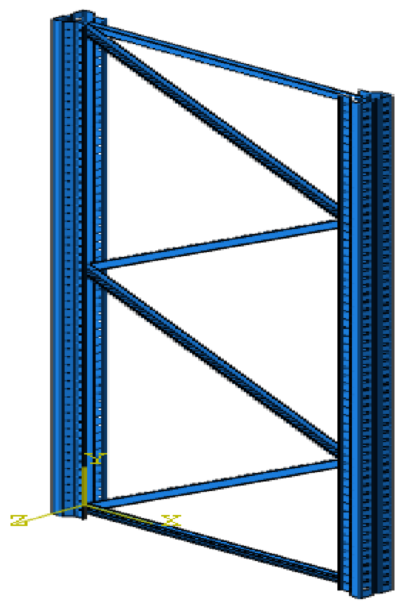


Fig. 4. Typical B1 type frame with inclined bracing only [12].

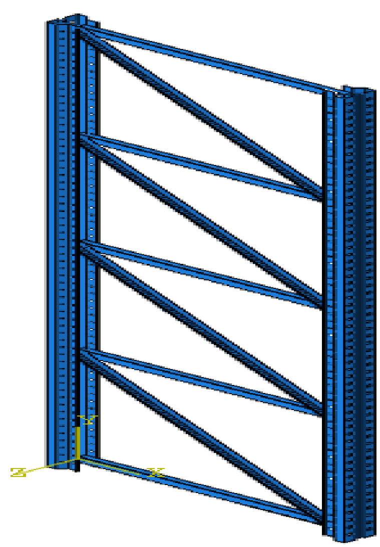


Fig. 5. Typical B2 type frame with inclined and horizontal bracing only [12].

Fig. 4 and Fig. 5 shows two distinct categories of storage rack frames. Fig. 4 shows B1 type frame which consists of inclined braces only and Fig. 5 shows B2 type frames which consist of inclined as well as horizontal bracing. Columns are typical HAT sections with and without spacer bars. For the purpose of easy connection between the beam and end connector the column sections in pallet racks are perforated. The local buckling load of the member is reduced due to the presence of perforations and increases the global buckling load of the system. The perforated flat plate loaded with uniform compressive load decreases the elastic local buckling load; however, due to perforations in the flat plate, there causes a change in the wavelength of the buckling mode which actually increases the buckling load away from the perforations [16]. The geometry, material properties and the boundary conditions will affect this increase in load carrying capacity of the member. Use of non perforated section properties is allowed in the current specifications to predict the elastic buckling strength of perforated members, by assuming that the reduction in the overall elastic buckling strength does not have a significant effect due to the presence of such perforations in the members.

Table 1
Sectional Properties of columns (uprights) in pallet storage rack frames.

Type of section	A (mm^2)	I_{xx} (mm^4)	I_{yy} (mm^4)	J (mm^4)	CG (x, y) (mm)	Warping Coefficient (mm^6)
MW-1.6	389.53	269028	302208	311.6	0, 46.31	7.68×10^8
MW-1.8	438.21	302626	339983	443.58	0, 46.32	8.64×10^8
MW-2.0	487.00	336369	377784	608.774	0, 46.31	9.61×10^8
HW-2.0	593.02	514270	854484	744.669	0, 54.66	1.89×10^9
HW-2.25	667.06	578437	961214	1060.02	0, 54.66	2.13×10^9
HW-2.5	741.21	642731	1068050	1454.09	0, 54.67	2.36×10^9

Table 2
Properties of cold formed steel (CFS) [12].

Yield stress (MPa)	Ultimate stress (MPa)	Modulus of elasticity, *E* (MPa)	Density (kg/m^3)	Poisson's ratio, υ
365	569	212×10^3	7860	0.29

Each of the B1 and B2 frame are subdivided into following category.

1. B1 Heavy Weight frames without Spacer bars in upright/column
2. B1 Heavy Weight frames with Spacer bars in upright/column
3. B1 Medium Weight frames without Spacer bars in upright/column
4. B1 Medium Weight frames with Spacer bars in upright/column
5. B2 Heavy Weight frames without Spacer bars in upright/column
6. B2 Heavy Weight frames with Spacer bars in upright/column
7. B2 Medium Weight frames without Spacer bars in upright/column
8. B2 Medium Weight frames with Spacer bars in upright/column

The typical designation of storage rack frame used in this study is as follows:

MW1.6B1-100

Spacing of Spacer Bar 100 or 200 mm

Type of Column Section Either Medium Weight (MW) or Heavy Weight (HW)

Thickness of Column Upright Section 1.6, 1.8, 2.0 mm for MW & 2.0, 2.25, 2.5 mm for HW

Type of Bracing B1 or B2

4. Finite element modeling and validation

For numerical analysis ABAQUS [17], general purpose FE software is used. In FE Model of storage rack tie constraint is used to connect translational degrees of freedom (U1, U2 and U3) of a shell element to those of solid element. S4R shell element and C3D8R brick elements are used to model columns and bracings respectively for all finite element models presented in this study. To find local buckling of individual components like flange, web and lip of the cross sections, shell (S4R) and brick (C3D8R) elements are used to model components of a storage rack structures. Table 3 presents the details of these elements.

Table 3
Details of the elements used for finite element analysis [12].

Part of frame	Element	Description
Column upright section	S4R	4-noded, quadrilateral, stress/displacement shell element with reduced integration and a large-strain formulation
Horizontal bracing	C3D8R	8-noded general purpose linear brick element, with reduced integration (1 integration point) and hourglass control.
Inclined bracing	C3D8R	8-noded general purpose linear brick element, with reduced integration (1 integration point) and hourglass control.
Spacer Bar	C3D8R	8-noded general purpose linear brick element, with reduced integration (1 integration point) and hourglass control.

Table 4
Validation of FE model with experimental study by Sangle et al. [8].

Column frame	P_e in kN (Experimental)	P_e in kN (Analytical)	% Difference
MW-1.6-B1	103.51	116.02	-12.09
MW-1.6-B2	115.45	129.52	-12.19
MW-1.8-B1	166.78	132.68	20.45
MW-1.8-B2	176.88	147.14	16.81
MW-2.0-B1	200.41	149.7	25.30
MW-2.0-B2	215.46	164.86	23.48
HW-2.0-B1	223.45	236.2	-5.71
HW-2.0-B2	235.26	269	-14.34
HW-2.25-B1	264.24	268.65	-1.67
HW-2.25-B2	275.56	304.4	-10.47
HW-2.5-B1	295.46	301.63	-2.09
HW-2.5-B2	305.56	340.12	-11.31

Table 5
Results of the convergence study [12].

Mesh size of the frame HW-2.0-B1 (height 3.1m)	50mm	40 mm	30mm	20 mm	10mm	5mm
Linear Buckling Load in (kN)	256.11	242.97	240.70	239.21	236.2	236.09

Sangle et al studied the three dimensional FE planer model and validated it with experimental results of stability analysis. Analytical results of finite element models are shown in Table 4 and compared with experimental results, they are in good agreement with each other. Thus the model is validated. For a frame HW2.0B1 of height 3.1m convergence study is carried out for obtaining the appropriate mesh size of the various parts of the frame such as column sections, bracings and spacer bar, etc. Table 5 highlights the results of convergence study. For convergence study automatic mesh (size 10 mm x 10 mm) was found to be appropriate and same is adopted for present work. Fig. 3 to Fig. 5 presents the details of the finite element models. The load magnitude as an additional unknown used by the Riks method; it solves simultaneous for loads and displacements [18]. Fig. 6 presents, the load displacement response that can exhibit the type of behaviour for unstable problems. That is, the load and/or the displacement may decrease as the solution evolves during periods of response.

Typical meshing at upright and braces junctions are shown in Fig. 7 to Fig. 9. The frames of the rack structure are subject to monotonic unidirectional incremental lateral load at each floor level till complete inelastic deformation are induced in the system as shown in Fig. 10. 'Static Riks' analysis step of ABAQUS 6.12 is used in theses numerical analyses. The 'Nlgeom' option is kept on to account for geometric nonlinearity. The lateral displacement of the top of the uprights is monitored to control the analysis. Sometimes geometrically nonlinear static problems involve collapse behaviour, where the load displacement response shows negative stiffness and the structure must release strain energy to remain in equilibrium.

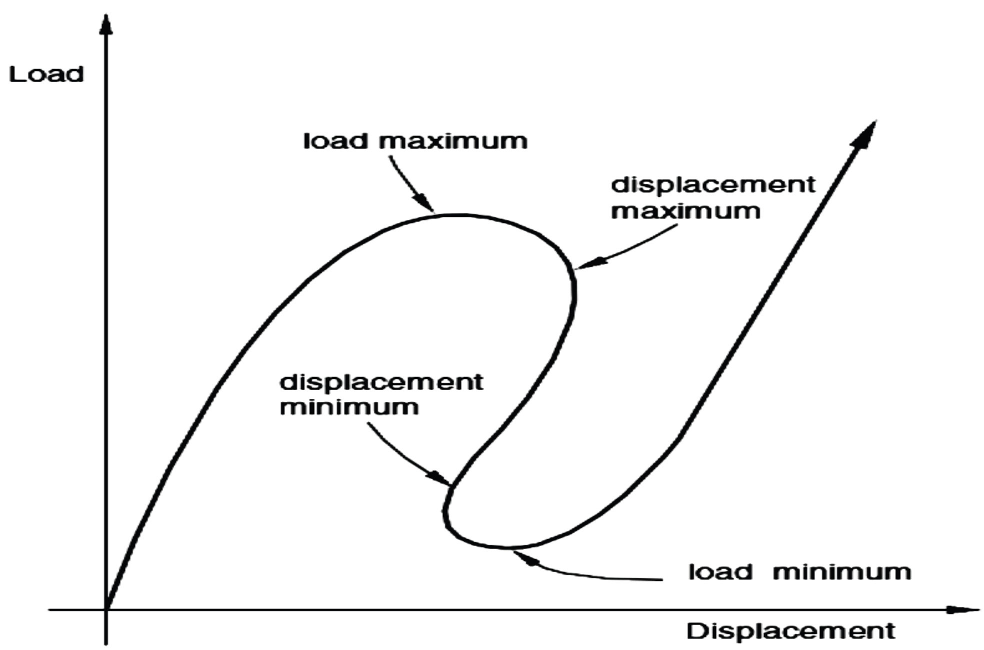


Fig. 6. Typical unstable static response [18].

The nonlinear pushover analysis behaviour of storage rack structures investigated in the present study. With geometric nonlinearity on (Nlgeom: ON), finite Element models are analyzed in Static Riks step. This numerical analysis is monitored by load and discontinued when LPF (Load Proportionality Factor) is negative.

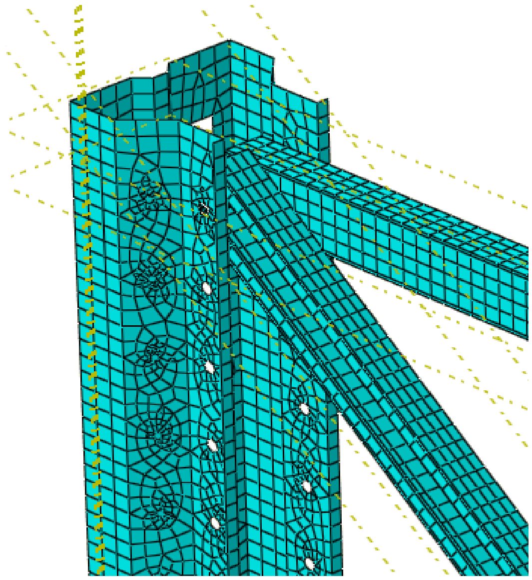


Fig. 7. Details of joint of frame and meshing of column section without spacer bar [12].

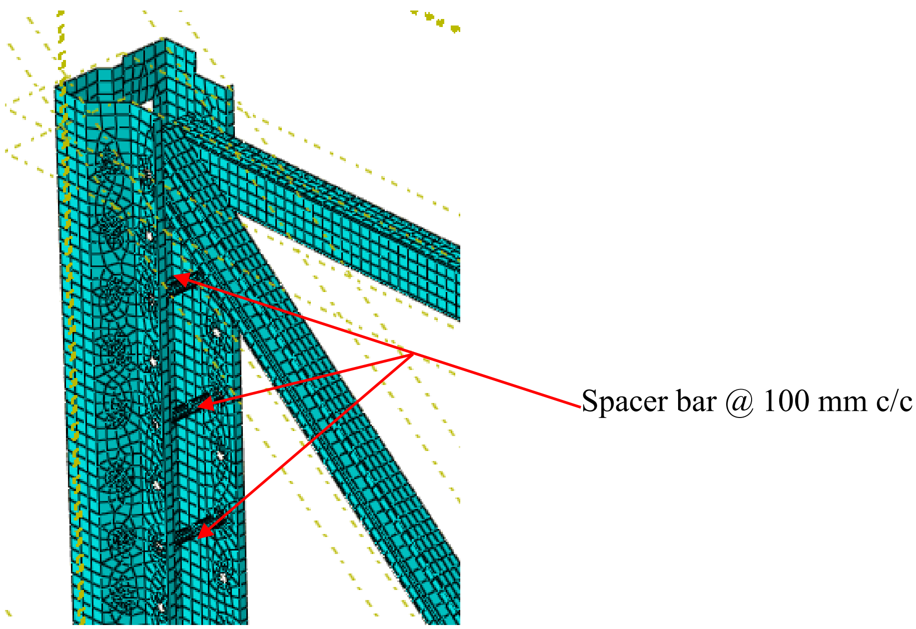


Fig. 8. Details of joint of frame and meshing of column section with spacer bar @ 100 mm c/c [12].

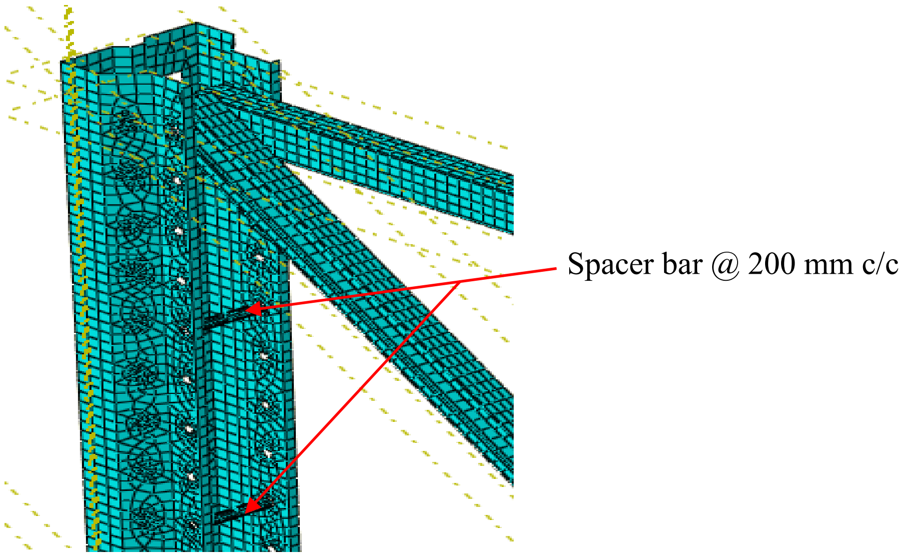


Fig. 9. Details of joint of frame and meshing of column section with spacer bar @ 200 mm c/c [12].

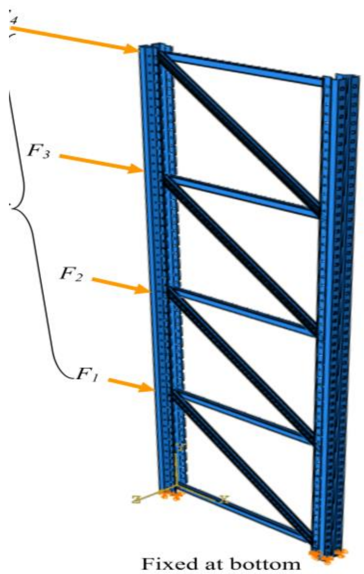


Figure 10: Boundary condition and loading for storage rack frames

For finite element analysis following assumptions are made:

i. The connection between the braces and columns (uprights) are considered to be rigid.
ii. All three rotations and displacements are allowed at the loading end of the upright and at the bottom base are assumed as fixed.

The structural details of the rack structures used in this study are as follows:

- Upright sections = i) Medium Weight Hat Section of 1.6mm, 1.8mm and 2.0mm thick.

ii) Heavy Weight Hat Section of 2.0 mm, 2.25 mm and 2.5 mm thick

- Width of bay= 1 m.
- Depth of rack shelve =0.75m.
- Height of the frame =3.1m.
- Centre to centre distance between beam= 0.9m

Following categories summarizes the criterions that have an impact on the value of base shear and displacement at collapse of complete pallet rack structure in the down-aisle direction.

i. First criterion is a type of column upright section, to account for this; here 6 types of upright sections as shown in Fig. 2 are selected.
ii. Second criterion is of column (upright) frame configuration, two type of upright frame configuration in a cross aisle direction is considered (i.e. horizontal with inclined bracing and only inclined bracing).
iii. Third criterion is spacing of spacer bars for column (uprights) frame configuration, three types of arrangements are considered:
   a) without spacer bar,
   b) with spacer bar @ 100mm spacing and
   c) with spacer bar @ 200mm spacing

5. Analysis and results

Nonlinear static pushover analysis (NSPA) is performed for various configurations of storage rack frames subjected to two distinct lateral load distribution patterns to estimate the capacities both in the form of base shear and inelastic deformation. These distribution patterns are: UBC - 1997 “Inverted Triangular Distribution”, and “Uniform Distribution”

5.1. UBC-1997 Loading

Lateral load distribution (Inverted Triangular) pattern is applied transversely to the structures across the height of the structure based on the following Eq. (1) mentioned in FEMA-356 [19] and in Uniform Building Code (UBC- 1997) [20]:

$$F_x = \frac{W_x h_x^k}{\sum_{i=1}^{n} W_i h_i^k} V \tag{1}$$

where, ‘F_x’ = the applied lateral force at level ‘x’,

‘W’ = the story weight,
‘h’= the story height and
‘V’= the design base shear, and
‘n’= the number of stories.

The summation in the denominator is carried through all story levels. This results in an inverted triangular distribution when ‘k’ is set equal to unity.

Table 6
Variation of ultimate base shear of B1 and B2 type frames with respect to section thickness and use of spacer bars (as per UBC-1997 and FEMA-356 Inverted Triangular Loading).

Type of frame	Thickness of elements (mm)	Ultimate Base Shear (N)					
		B1	B1-200	B1-100	B2	B2-200	B2-100
MW: Medium Weight	1.6	27490	28308	28508	43362	43792	44751
	1.8	29146	30093	30261	44053	45764	46279
	2.0	30622	31950	32155	44272	47652	48269
HW: Heavy Weight	2.0	33704	34399	34565	44651	49334	49598
	2.25	35690	36659	37052	44944	50743	50898
	2.5	39841	40469	41398	45332	54795	55674

Table 6 shows ultimate base shear obtained from non linear static pushover analyses on B1 and B2 type frames with inverted triangular loading. Fig. 11 and Fig. 12 represent some of typical pushover plots for two distinct configurations of storage rack frames. The objective of pushover plot is to obtain the maximum capacity of the system in terms of lateral load resistance under the action of the monotonic unidirectional lateral load representing the fundamental mode of vibration. As observed from these graphs B1 type of frames (with inclined bracing only) offers almost 45% less lateral load resistance in comparison with B2 type of frame (with inclined and horizontal bracing only). Moreover the use of spacer bar in uprights delays the torsional buckling and enhances the lateral load resistance. For very thin sections, under inverted triangular loading, the pushover analysis is aborted in between because of local instability. The system over the strength of B2 type of frame is significantly more than that of B1 type of frame. Moreover the use of spacer bar in uprights delays the torsional buckling and enhances the lateral load resistance. These plots also highlight that frame with section thickness less than 2.25 mm the local buckling in braces and columns restricts the ultimate lateral load resistance capacity. For very thin sections the pushover analysis is aborted in between because of local instability.

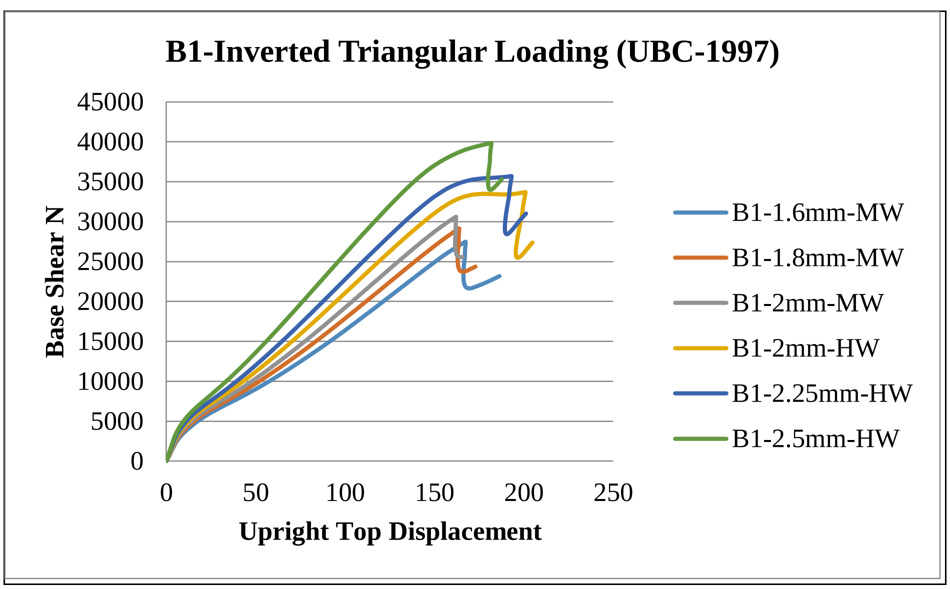


Fig. 11. Base shear verses upright top displacement for B1 (UBC-1997) Loading.

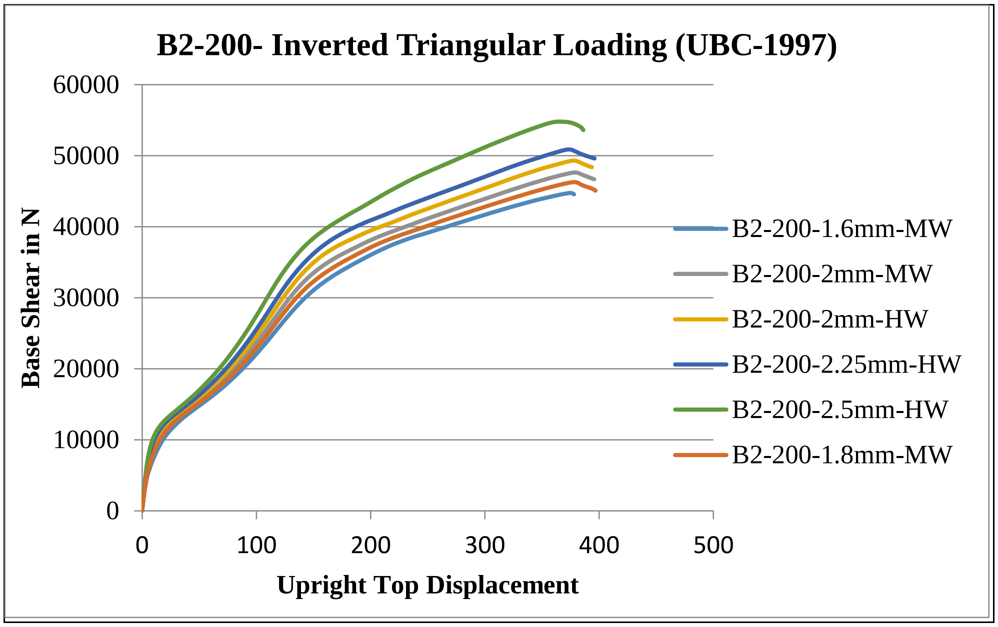


Fig. 12. Base shear verses upright top displacement for B2-200 (UBC-1997) Loading.

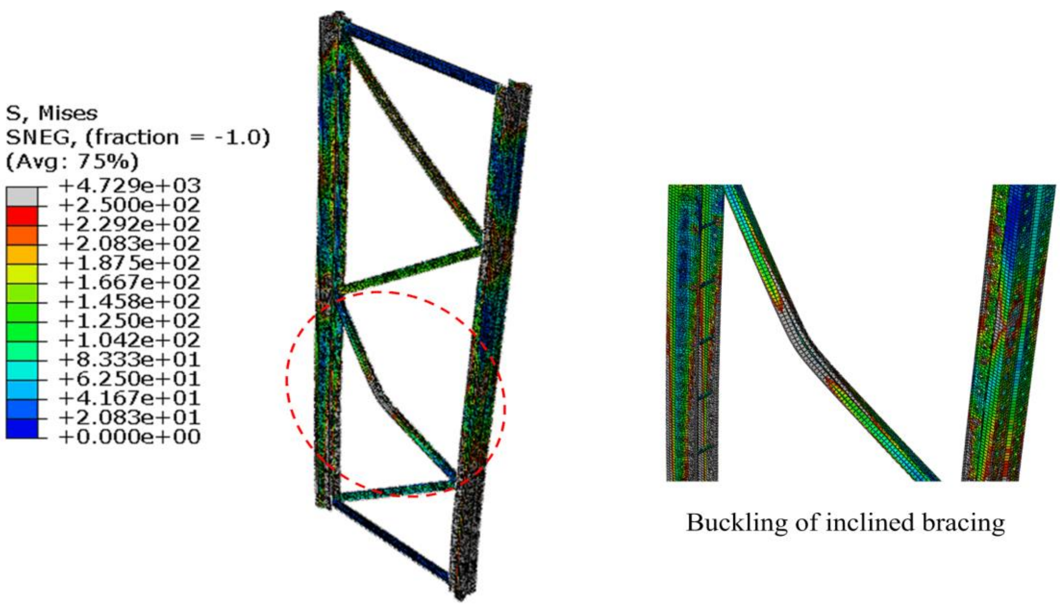


Fig. 13. B1-200-1.6 mm MW frame von Mises stress contours at an instant of maximum top displacement.

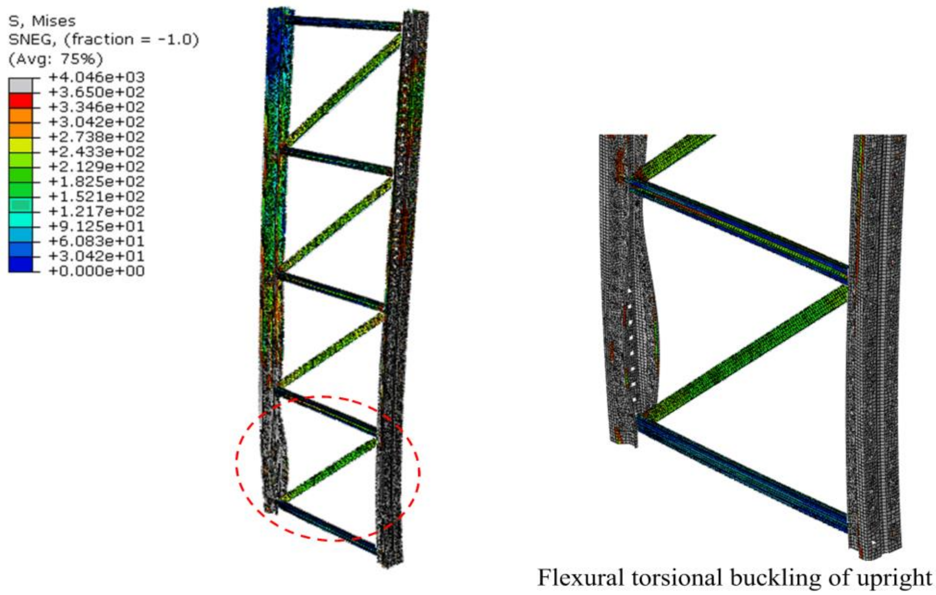


Fig. 14. B2-1.6 mm MW frame von Mises stress contours at an instant of maximum top displacement.

The von Mises stress contours for 1.6 mm thick B1 and B2 types of storage rack systems are shown in Fig. 13 and Fig. 14. These stress contours are captured in an instant of maximum lateral drift as obtained from pushover analyses. Theses stress contours provide valuable information regarding spread of inelastic deformations as well as identify the critical locations where local instability restricted the maximum lateral load carrying capacity of the system. For B1 type frames with very thin section (= 1.6 mm) the local buckling of inclined braces and for B2 type frame flexural torsional buckling of upright without spacer bars restricts the optimum lateral strength of the system.

5.2. Uniform distribution

The uniform distribution pattern is ideally suited for low rise and low inertia structural system and hence adopted for the storage rack frames [21]. A constant load distribution consists of lateral forces at each floor level proportional to the floor mass is adopted. Table 7 shows ultimate base shear obtained from non linear static pushover analyses on B1 and B2 type frames subjected to uniform loading. Fig. 15 represents some of the typical pushover plot for B2-200 configuration of storage rack frames subjected to uniform loading.

Table 7
Variation of ultimate base shear of B1 and B2 type frames with respect to section thickness and use of spacer bars (as per UBC Loading).

Type of frame	Thickness of elements (mm)	Ultimate Base Shear (N)					
		B1	B1-200	B1-100	B2	B2-200	B2-100
MW:	1.6	38367.82	39555.93	41342.56	56081.52	60150.16	61137.90
Medium	1.8	39406.64	42170.41	43536.25	58101.28	61067.68	61807.20
Weight	2.0	41846.99	44812.41	45872.28	58893.64	62191.80	63088.86
HW:	2.0	44661.43	47396.84	48103.07	62401.36	62710.90	65834.14
Heavy	2.25	46662.28	49063.76	51107.06	63518.81	65545.55	68616.12
Weight	2.5	50096.45	53857.46	55932.79	66339.65	71339.65	76218.83

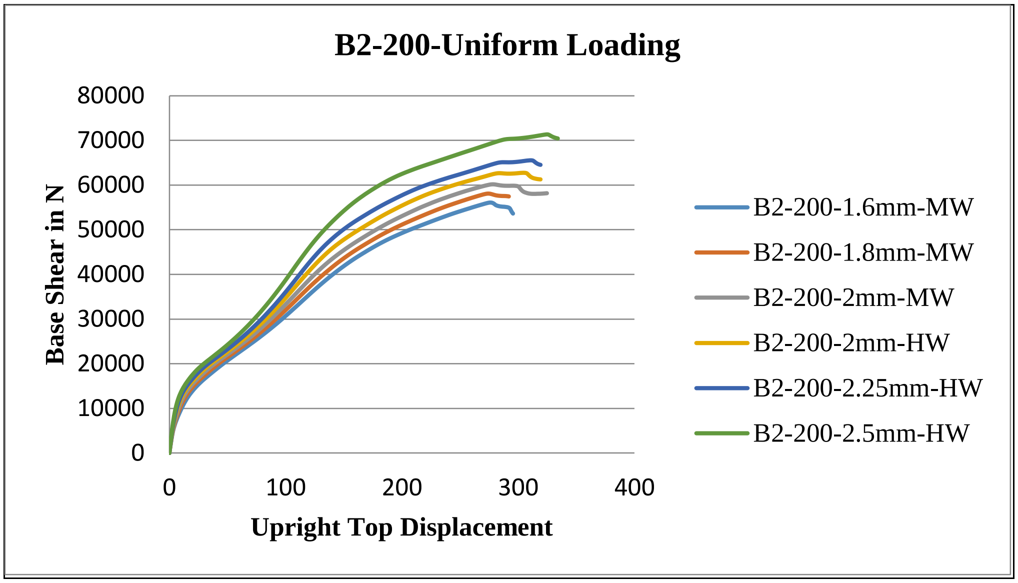


Fig. 15. Base shear versus upright top displacement for B2-200 (UBC-1997) Loading.

6. Conclusions

To calculate the base shear at the time of collapse and maximum drift, to study the formation of plastic hinges, to study the collapse mechanism and to improve the base shear at the time of collapse of cold-formed steel pallet rack structure are the objectives of this study. The cold-formed steel pallet rack structures are analyzed using NSPA method under different parameters like the thickness of members and the type of the frame structure. NSPA is a more efficient tool for analysis for the pallet rack structures that gives fair judgment of the base shear, displacement and development of plastic hinges at each incremental load.

Following significant observations and findings are highlighted below:

- As observed from base shear verses lateral displacement graph initial elastic stiffness is more for B2 type frame (inclined bracing with horizontal bracing) than B1 type frame (inclined bracing).
- B2 frame shows the gradual yielding up to 7% drift whereas B1 type frame shows the gradual yielding up to 5% drift.
- Failure due to buckling of braces (local failure) having a thickness less than 2.5 mm is observed in both types of frames.
- Considering the gradual yielding (i.e. sufficient inelastic deformation capacity) and lateral load resistance, B2 type frame is more efficient than B1 type frame.
- Use of spacer bars in uprights proves to be efficient to avoid flexural torsional buckling of columns.
- B1 type frame without spacer bars with inverted triangular loading (UBC-1997) offers almost 45% less lateral load resistance than uniform loading.

- Among two distinct lateral distributions adopted for NSPA, for all configurations of storage rack systems “uniform distribution patterns” provide upper bound estimate of base shear and drift.

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