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# Nonlinear Static Pushover Analysis of Cold-Formed Steel Storage Rack Structures

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**Abstract:** Individual components of cold-formed storage rack system are most vulnerable to local and torsional buckling under gravity as well as lateral loads.The capacity-based design of cold-formed storage rack system consists of deterministic allocation of strength and ductility in the structural elements and performance evaluation by suitable techniques. 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 accurate method of seismic demand prediction and performance evaluation, it is computationally heavy and even requires the selection and employment of an appropriate set of ground motions. This paper deals with analytical investigation of efficient configuration of conventional pallet racking system on the basis of seismic performance by using NSPA. This analytical study on conventional pallet racking system subjected to lateral loads is focused: i) to identify the local buckling failure modes of components of storage rack systems, ii) to evaluate the effect of local buckling on ultimate lateral load carrying capacity, and iii) to propose structural alterations for components of rack system so as to obtain most efficient configuration of conventional pallet racking system. Two different configurations of conventional pallet racking system are modeled and analyzed on the general purpose FE platform under monotonic unidirectional lateral loads. The results of NSPA show that pallet racking system with horizontal and inclined bracing is more efficient as evidenced from good estimates of the overall displacement, base shear and yielding capacities.

**Keywords:** Pallet racks; cold-formed steel; nonlinear push-over analysis; base shear.

## 1. Introduction

One of the most significant uses of cold-formed members is for steel storage racking structures, such as a pallet, drive in, and drive through racking systems. In typical pallet rack structure, generally, beams (stringers) have boxed cross sections, while columns (uprights) are open thin walled perforated sections to accept the tabs of beam end connectors, which join beams and columns together without bolts or welds. Therefore, the design of pallet racks is quite complex. The behaviour of the perforated columns which are generally thin walled members is affected by different buckling modes (local, distortional and global) as well as by their mutual interactions.

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The response of beam to column is typically nonlinear. Moreover, bracing systems are generally placed only in the cross aisle direction. The need for organizing pallet racks in such a way that the product is effectively stored and sufficiently accessible hampers the presence of bracings in the down aisle direction. Lateral stability is, hence, provided by the sole degree of continuity associated with beam to column joints as well as by base plate connections. Presently, for the design of these frames, no specific code of practice exists. Although in the United States and some other countries the specification published by the Rack Manufacturer's Institute [1] serves as a guideline. Therefore, analysis and design of pallet racks are quite complex. The most accurate method of seismic demand prediction and performance evaluation of structures is a nonlinear time history analysis (NTHA). However, this technique requires the selection and employment of an appropriate set of ground motions and needs a sophisticated computational tool which handles the analysis produce ready to use results within the time constraints of design offices. For professional practicing designers a simpler analysis tool with less computational effort is desirable. One method that has been gaining ground, as an alternative to time history analysis, is the nonlinear static pushover analysis (NSPA). The primary objective of research presented in this paper is to investigate most efficient configuration of conventional pallet racking system on the basis of seismic performance of the conventional pallet storage rack systems using numerical tests. For this study, two different categories of five tier storage rack frames with various configurations like section thickness, use of spacer bar in upright (column) section are analytically tested using nonlinear static pushover analysis (NSPA) process. The past research on nonlinear static pushover analysis and on conventional pallet rack systems is briefed in following section. Section 3 deals with details of two different categories of five tier storage rack frame and its configurations. FE modeling with validation and NSPA of rack frames are presented in subsequent sections. Final section summarizes the important findings from the numerical tests on cold-formed storage rack systems.

## 2. Review of past research

### 2.1. On push over analysis

The purpose of the pushover analysis is to evaluate the structural performance by estimating the strength and deformation capacities using static nonlinear analysis and comparing these capacities with the demands at the corresponding performance levels. The basic procedure of this method is to perform a sequence of static analysis under monotonically increasing lateral loads in each of its principle directions to stimulate the loading history of the structure during the collapse. The potential of the pushover analysis has been recognized in the last decade and it has found its way into seismic guidelines ATC-40 [2]. The pushover is expected to provide information on many response characteristics that cannot be obtained from an elastic static 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 critical regions, where the inelastic deformations are expected to be high.
iii. Consequences of strength deterioration of particular elements of the overall structural stability.

iv. Sequence of members yielding and failure and the progress of the overall capacity curve of the structure.

Krawinkler and Seneviratna [3] has highlighted in the history of pushover analysis method. Initially the majority of work concentrated on discussing the range of applicability of the method and its advantages and disadvantages, compared to elastic or nonlinear dynamic procedures. Asawasongkram et al. [4] studied the seismic performance evaluation of the semi-rigid steel storage rack located in Thailand. A numerical model of the structure was created with the incorporated nonlinear behaviour of semi-rigid beam-to-column connection. Chopra and Goel [5] have taken efforts to extend pushover analysis to take into account higher mode. Kalkan and Chopra [6] presented a modal-pushover-based scaling (MPS) procedure to scale ground motions for use in a nonlinear response history analysis of buildings. Fajfar [7] presented a simple nonlinear method for the seismic analysis of structures (N2-method). This method combines the pushover analysis results of a multi degree of freedom (MDOF) model with the response spectrum analysis result of an equivalent single degree of freedom (SDOF) system in typical acceleration-displacement format. Thus, this method enables the visual interpretation of the seismic response of the system and establishes the relation between the basic quantities controlling seismic response. Among the various 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 carried out to investigate the strength and deformation capacities of racking systems. The pattern of lateral load adopted for NSPA conforms to the equivalent static force distribution pattern of IS: 1893-2000 specifications [8].

## 2.2. On conventional pallet racking systems

Sangle et al. [9] studied the three dimensional (3D) model of conventional pallet racking systems using the finite element program ANSYS [10] and carried a free vibration modal analysis on conventional pallet racks with 18 types of column sections developed along with semi-rigid connection. They also performed the finite element buckling and dynamic analyses of two-dimensional (2D) single frames and three-dimensional (3D) frames of cold-formed sections with semi-rigid connections used in the conventional pallet racking system. The results of buckling analysis for the single 2D frames were compared with those from the experimental study and effective length approach given by RMI [1]. The finite element model used for the single 2D plane frame was further extended to 3D frames with semi-rigid connections, for which the buckling analysis results were obtained. However, the study by Sangle et al. [9] does not consider material and geometric nonlinearity in their numerical investigation. Sasaki and Paret [11] studied the procedure to perform the multi mode pushover method and this method applied to various structures. Multi-mode pushover (MMP) uses the capacity spectrum method to compare graphically the pushover curve to the earthquake demand. Kalavagunta et al. [12] have investigated the progressive collapse of cold-formed storage rack structures subjected to seismic loading, using pushover analysis. Moghadam and Tso [13] extended the pushover procedure for seismic damage assessment of asymmetrical buildings. By means of an example, it is shown that the accuracy of the proposed 3-D pushover analysis is similar to those applied to planar structures. The procedure is found to be more successful in estimating the global response parameters such as inter storey drifts than local damage indicators such as beams or column ductility demands.

## 3. Details of storage rack frame

Figure 1 and Figure 2 show two distinct categories of storage rack frames. Figure 1 shows B1 type frame which consists of inclined braces only and Figure 2 shows B2 type frames which consist of inclined as well as horizontal bracing. Columns are typical HAT sections with and without spacer bars. The column (upright) sections in storage racks are perforated for the purpose of easy assembly of the beam end connector. Perforations are generally assumed to decrease the elastic local buckling load of a flat plate loaded in uniform compression; however, hole often causes a change in the wavelength of the buckling mode which actually increases the buckling load away from the hole [14]. The significance of this increase in strength will depend on the geometry and material properties of the member and the boundary conditions. The current specifications allow the use of non-perforated section properties to predict the elastic buckling strength of perforated members, by assuming that the presence of such perforations does not have a significant effect on the reduction of the overall elastic buckling strength.

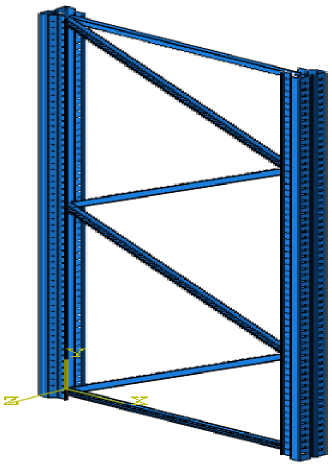



**Figure 1.** Typical B1 type frame with inclined bracing only

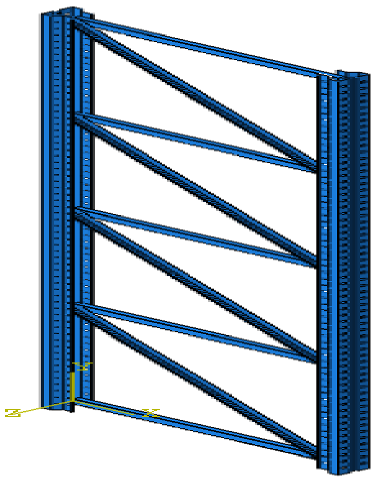



**Figure 2.** Typical B2 type frame with inclined and horizontal bracing only

The column (upright) sections used in the study are MW (Medium Weight) column section having three thicknesses 1.6 mm, 1.8 mm, and 2.0 mm each and HW (Heavy Weight) column section having three thicknesses 2.0mm, 2.25mm and 2.5mm each. Their cross sectional geometry is provided in Figure 3 and in Figure 4. Purpose of choosing three different thicknesses is to know the change in behaviour when the sections are made locally stable by having greater thickness. In the present study spacer bars are also provided to avoid the local buckling of uprights.

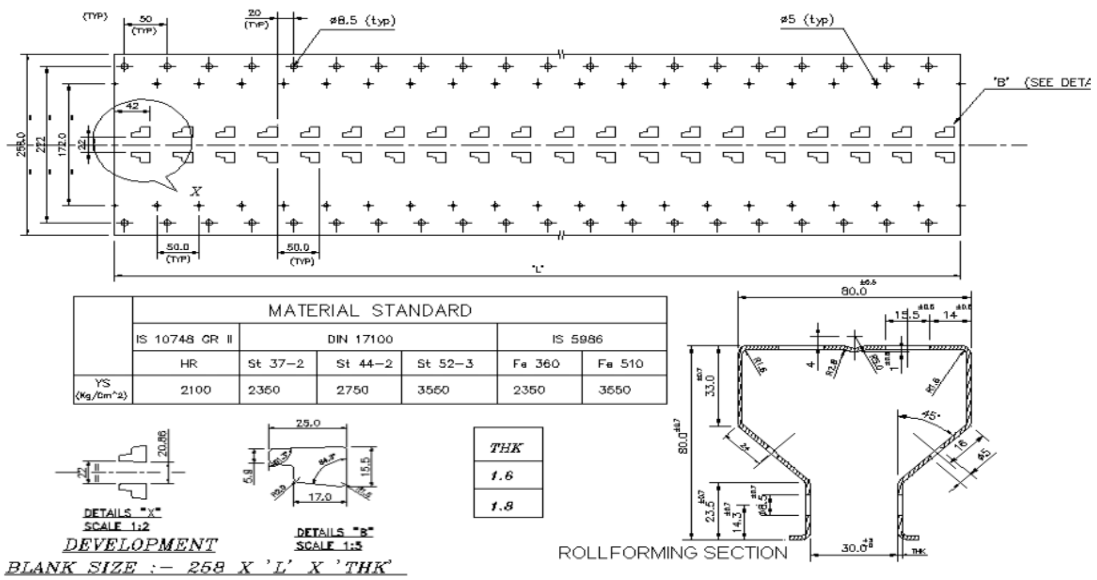



**Figure 3.** Medium weight (MW) column upright section as per Sangle et al. [9]

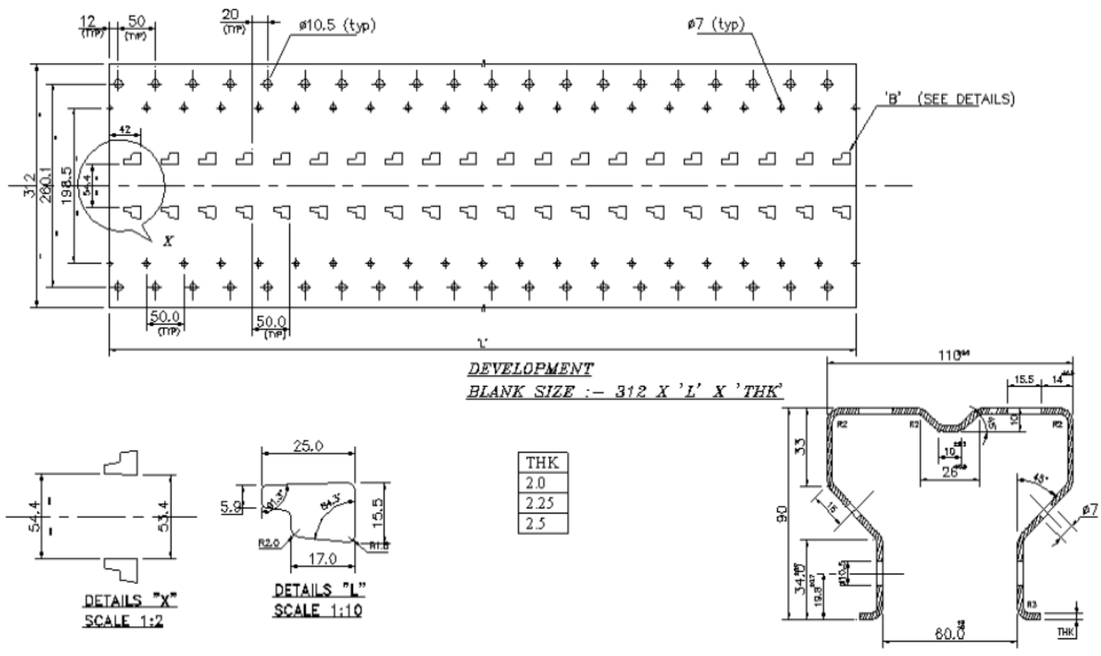



**Figure 4.** Heavy weight (HW) column upright section as per Sangle et al. [9]

For the above sections, sectional properties are calculated based on the weighted average section. A weighted average section is a section that uses an average thickness in the web portion to account for the absence of the material due to the holes along the length of the section. Sectional properties of the sections are given in Table 1 and material properties of the same sections are given in Table 2.

**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 (mm) ($x$, $y$) | Warping Coefficient ($mm^6$) |
|---|---|---|---|---|---|---|
| MW-1.6 | 389.53 | 269028 | 302208 | 311.6 | 0, 46.31 | $7.68\times10^8$ |
| MW-1.8 | 438.21 | 302626 | 339983 | 443.58 | 0, 46.32 | $8.64\times10^8$ |
| MW-2.0 | 487.00 | 336369 | 377784 | 608.774 | 0, 46.31 | $9.61\times10^8$ |
| HW-2.0 | 593.02 | 514270 | 854484 | 744.669 | 0, 54.66 | $1.89\times10^9$ |
| HW-2.25 | 667.06 | 578437 | 961214 | 1060.02 | 0, 54.66 | $2.13\times10^9$ |
| HW-2.5 | 741.21 | 642731 | 1068050 | 1454.09 | 0, 54.67 | $2.36\times10^9$ |

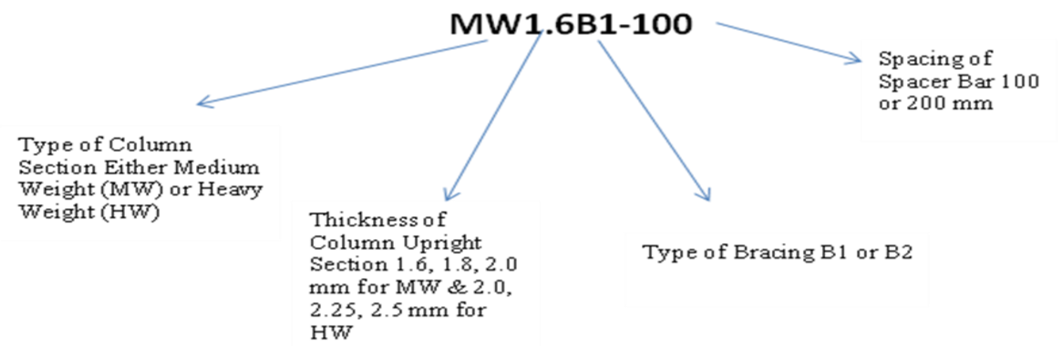
**Table 2.** Properties of cold formed steel (CFS)

| Yield stress, $F_y$ (MPa) | Ultimate stress, $F_u$ (MPa) | Modulus of elasticity, $E$ (MPa) | Density, $\rho$ ($kg/m^3$) | Poisson's ratio, $\upsilon$ |
|---|---|---|---|---|
| 365 | 569 | $212\times10^3$ | 7860 | 0.29 |

Each of the B1 and B2 frame are subdivided into following categories:

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:



## 4. Finite element modeling and validation

ABAQUS [15], a general purpose FE solver is used for numerical analysis. For all FE models presented in this study, S4R shell element and C3D8R brick elements are used to model columns and bracings respectively. Similar elements as available in ANSYS [10] like Shell 63 element for braces and Solid 45 element for column upright were used by Sangle et al. [9] to model the storage rack frames. The purpose of using the shell (S4R) and brick (C3D8R) element to model components of a storage rack system is to trace local buckling of individual components like flange, web, lip of the cross section. Details of these elements are provided in Table 3. .Three dimensional FE planer model is validated with experimental results of stability analysis by Sangle et al. [9]. Table 4 shows analytical results of FE models are in good agreement with experimental results. Thus the model is validated. Further convergence study is carried on a frame HW2.0B1 of height 3.1m for obtaining the proper mesh size of the different parts of the frame such as column upright section, bracing and spacer bar, etc. The results of convergence study are shown in Table 5. For the convergence study automatic mesh (size 10 mm x 10 mm) is found to be appropriate and same is adopted for present work. Figure 5 represents ABAQUS [15] modeling of typical column upright HAT section used in this study. Typical meshing at upright and braces junctions are shown in Figures 6 to 8. Details of the various elements used in finite element model are given in Table 3. As shown in Figure 9, the frames of the rack structure are subjected to monotonic unidirectional incremental lateral load at each tier level till complete inelastic deformation are induced in the system. 'Static Risk' analysis step of ABAQUS [15] is used in theses numerical tests. The 'Nlgeom' option is kept on to account for geometric nonlinearity. The lateral displacement of top of the uprights is monitored to control the analysis.

**Table 3.** Details of the elements used for finite element analysis

| Part of frame | Element | Description |
|---|---|---|
| Column section | S4R | A 4-node doubly curved thin or thick shell, reduced integration, hourglass control, finite membrane strains. |
| Horizontal bracing | C3D8R | An 8-node linear brick, reduced integration, hourglass control. |
| Inclined bracing | C3D8R | An 8-node linear brick, reduced integration, hourglass control. |
| Spacer Bar | C3D8R | An 8-node linear brick, reduced integration, hourglass control. |

**Table 4.** Validation of FE model with experimental study by Sangle et al. [9]

| 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 |

**Table 5.** Results of the convergence study

| 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 |

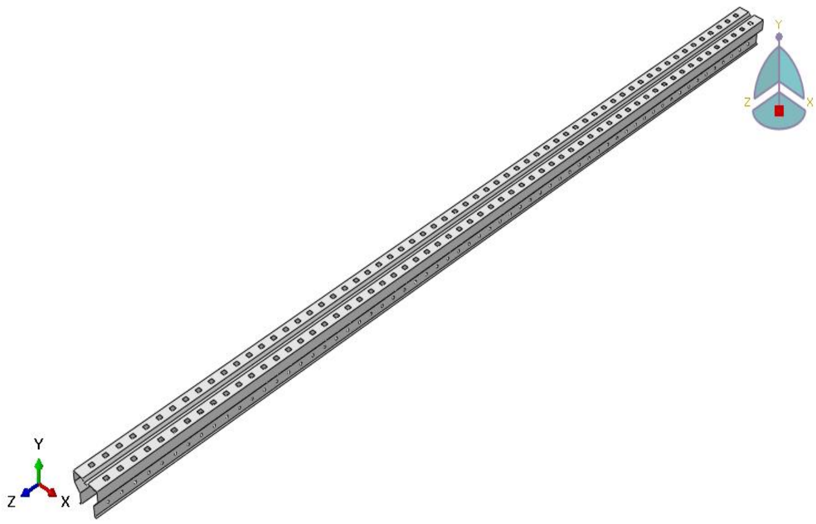



**Figure 5.** HW column section modeled in ABAQUS [15]

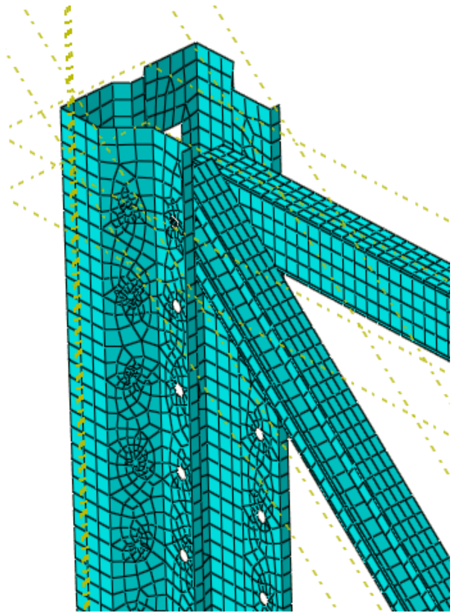


**Figure 6.** Typical meshing of column section and details of joint of frame without spacer bar

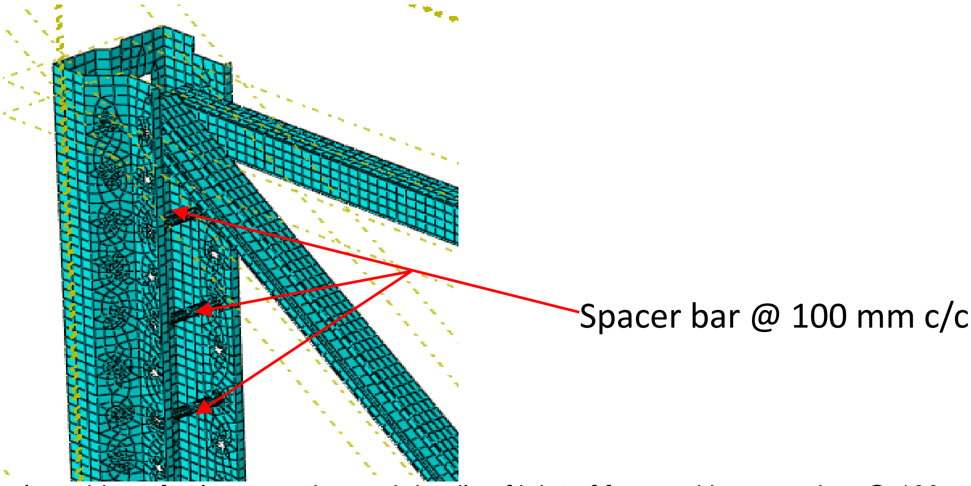



**Figure 7.** Typical meshing of column section and details of joint of frame with spacer bar @ 100 mm c/c

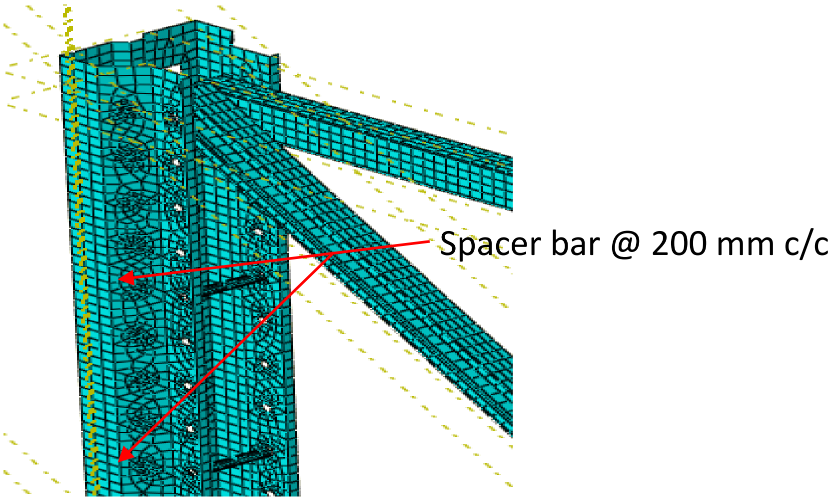



**Figure 8.** Typical meshing of column section and details of joint of frame with spacer bar @ 200 mm c/c

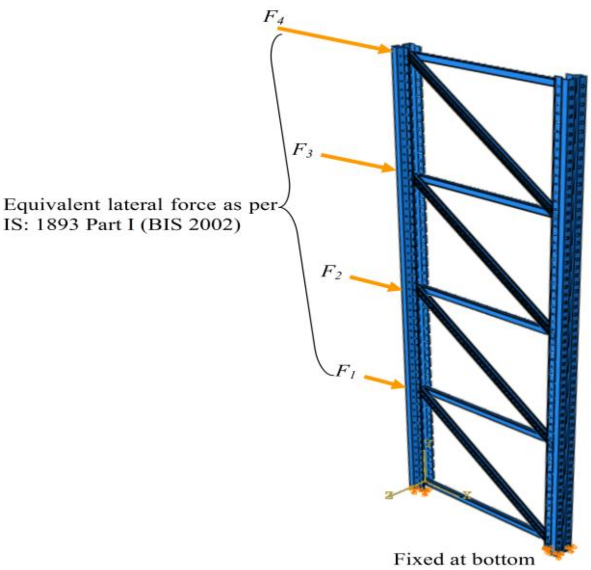



**Figure 9.** Boundary condition and loading for storage rack frames

The following assumptions are made in FE analysis:

i. The connection between the braces and the columns were considered to be rigid.
ii. At the loading end of the upright all three rotations and displacement allowed and at the bottom base is assumed fixed.

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

Parameters that influence the value of base shear and displacement at collapse of complete rack structure in the down aisle direction are summarized in following categories.

i. First parameter is type of upright section, to account for this; here 12 types of upright sections as shown in Figure 2 are selected.
ii. Second parameter is of upright frame configuration, i.e. type of bracing system in a cross aisle direction, to account for this; two type of upright frame configuration is considered (i.e. horizontal with inclined bracing and only inclined bracing).
iii. Third parameter is spacing of spacer bars for upright frame configuration, here 3 types of configurations are considered (i.e. frame without spacer bar, frame with spacer bar @ 100mm spacing and frame with spacer bar @ 200mm spacing).

## 5. Analysis and results

In the present research sizes of individual components of storage rack frames that affect the stability of the rack structure under gravity and seismic load are decided by trial and error method. Ultimate lateral load resistance of the storage rack frame is improved step by step both by changing the bracing combination and by changing the thickness of uprights at points where plastic hinges are forming initially. Base shear at the time of collapse is improved till it is greater than the applied lateral load as per IS 1893-2000 [8]. Equivalent Lateral load distribution factor $C_{vi}$ as per IS 1893-2000 [8] is calculated using following equation (1)

$$C_{vi} = \frac{w_i h_i^2}{\sum_{i=1}^{i=n} w_i h_i^2} \tag{1}$$

where, $n$ is the total number of floors and $w_i$ is the seismic weight of the $i^{th}$ floor and $h_i$ is the height of $i^{th}$ floor from the ground.Few results obtained from the analysis, with different combinations, are presented in this paper.

Table 6 shows variation in ultimate base shear (as obtained from NSPA analyses) for various configurations of B1 and B2 type frames with respect to section thickness and use of spacer bars in upright column sections. As observed from these results, B2 type of frame without spacer bar offer almost 90 % more lateral load carrying capacity when compared with B1 type of frame without spacer bar. These results also highlight that, for both categories for frames (B1 and B2 type frames) the use of spacer bar in uprights delayed the torsional buckling and enhances the lateral load resistance. With the use of spacer bar in upright column section, the increase in lateral load carrying capacity for B2 type of frames with respect to B1 type of frames are about 40 % and 50 % for 100 mm and 200 mm spacing of spacer bars. Figure 10 and Figure 11 represent typical pushover plots for two distinct configurations of storage rack frames. The purpose of pushover plot is to obtain the capacity of the system in terms of both lateral load resistance and inelastic deformation when system is subjected to the monotonically increasing unidirectional lateral load representing the fundamental mode of vibration. As observed from these graphs B1 type of frames (with inclined bracing only) offers almost 50% less lateral load resistance in comparison with B2 type of frame (with inclined and horizontal bracing only). The system overstrength of B2 type of frame is significantly more than that of B1 type of frame. 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.

**Table 6.** Variation of ultimate base shear of B1 and B2 type frames with respect to section thickness and use of spacer bars

| 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 | 21615 | 26943 | 28308 | 43306 | 44831 | 45204 |
| | 1.8 | 22120 | 29046 | 30093 | 43606 | 45388 | 46626 |
| | 2.0 | 22341 | 30686 | 31950 | 43902 | 46432 | 47720 |
| HW: Heavy Weight | 2.0 | 22476 | 33133 | 34399 | 44321 | 47706 | 48527 |
| | 2.25 | 22647 | 35108 | 36659 | 44486 | 50615 | 49218 |
| | 2.5 | 23047 | 39120 | 40469 | 45027 | 54001 | 54794 |

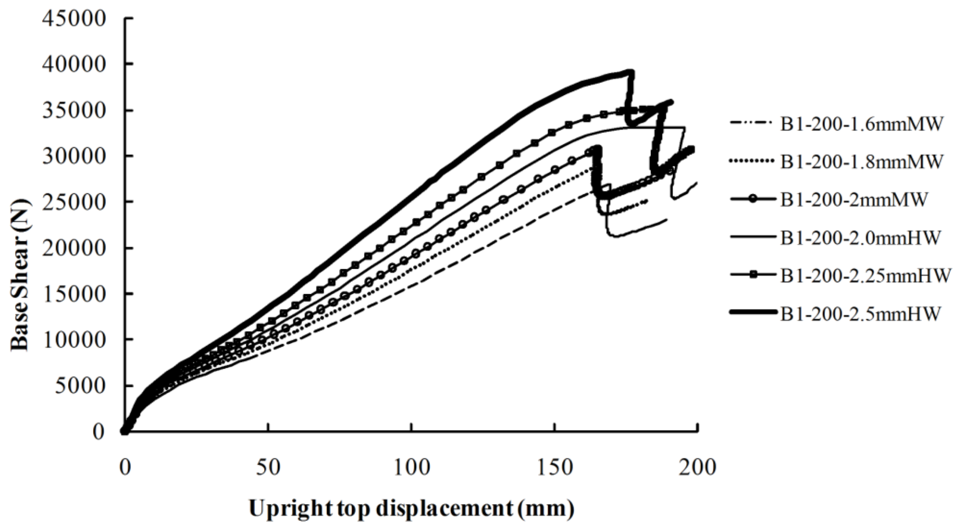



**Figure 10.** Base shear versus upright top displacement for B1-200 type frame

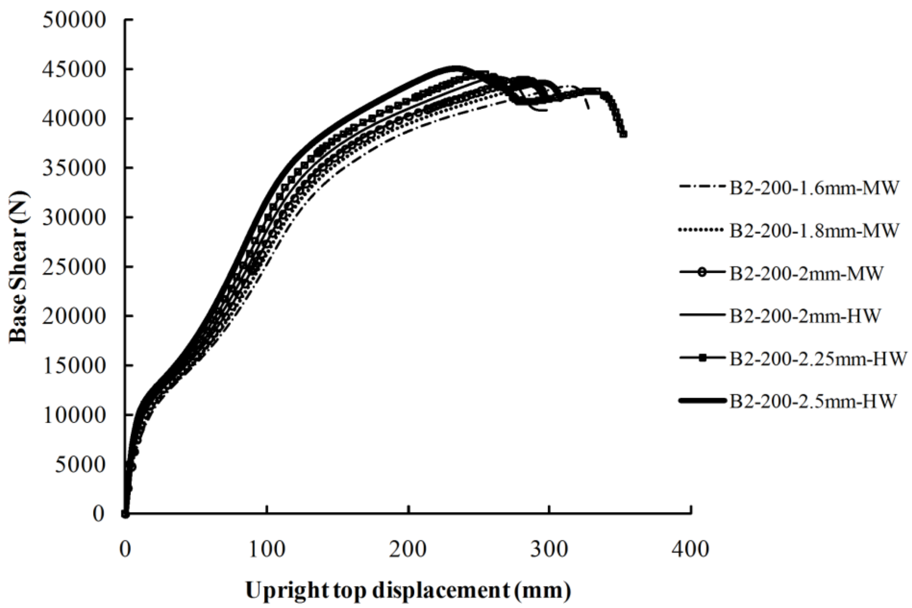



**Figure 11.** Base shear versus upright top displacement for B2-200 type frame

Figures 12 and 13 show the von-Mises stress contours for 1.6 mm thick B1 and B2 types of storage rack systems, respectively. 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 ultimate 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.

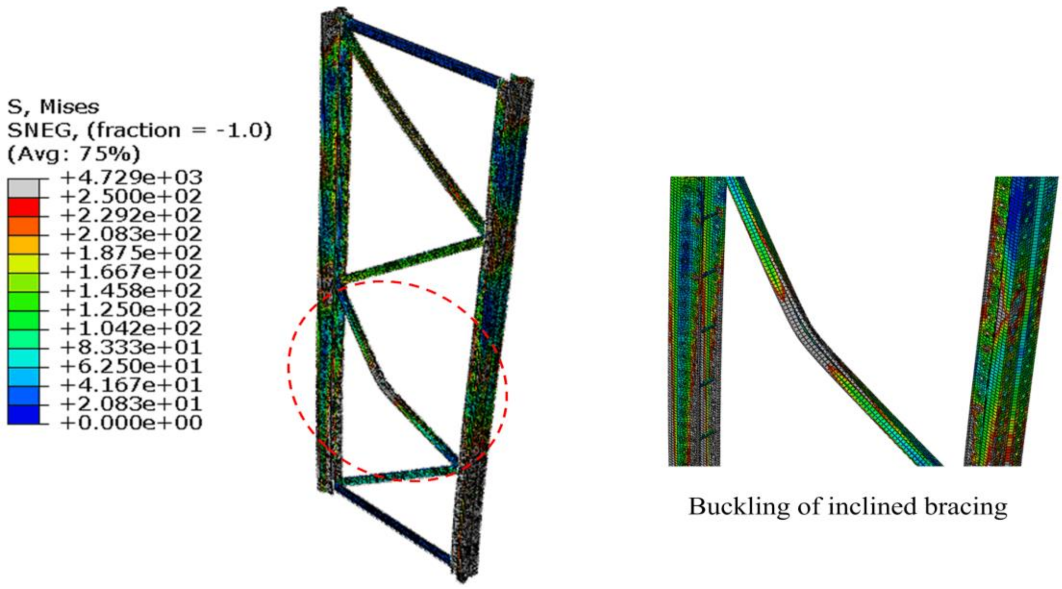



**Figure 12.** von Mises stress contours for B1-200-1.6 mm MW at an instant of maximum top displacement

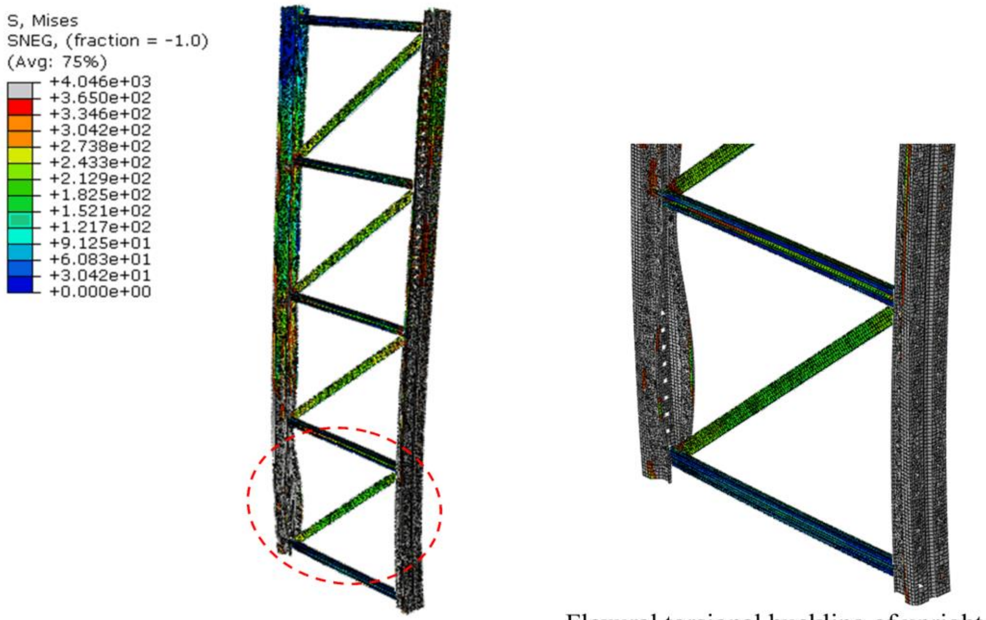



**Figure 13.** von Mises stress contours for B2-1.6 mm MW at an instant of maximum top displacement

Some important 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 most efficient than B1 type frame.
- Use of spacer bars in uprights proves to be efficient to avoid flexural torsional buckling of columns.

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