

# Structural Behavior of Storage Rack under Seismic Ground Motion

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## Abstract

Seismic safety of storage racks in large warehouse-type stores has become a safety issue to the public due to the potentially serious hazards they pose to patrons. Hearings on the inherent dangers to consumers/patrons in large retail stores such as Costco and Home Depot type stores were conducted in the past. Members of the public testified about day-to-day accidents in which warehouse store patrons are injured or even killed by merchandise being pushed off shelves or falling off shelves. Though many of these accidents are related to shelves being shaken by a forklift truck when backing into the rack, it is also possible that earthquake induced shaking on these storage racks could similarly result in causing merchandise to fall from stacks on unprotected shelves. For this reason, a preliminary study was performed using the finite element method to model a typical storage rack loaded with sizeable merchandise and to evaluate its dynamic behavior under seismic ground motion simulation. Based on the simulation outcome, conclusions on potential hazards posed to patrons are made.

## Introduction

Large storage racks have become a public safety concern for the past few years. Between 1992 and 2000, there are over ten warehouse casualties documented across the country as reported by the television media [60 Minutes, 2002]. While most of the incidents were caused by forklift hitting the rack to cause falling of merchandise [Seismic, 2001], there is a growing concern that earthquake induced ground motion may cause similar accidents. This concern is being supported by a Home Depot training video showing extensive damage to racks and contents after the Northridge earthquake.

The objective of this work is to perform a preliminary study of dynamic behavior of a typical storage rack loaded with merchandise subjected to earthquake ground motion using finite element simulation. ABAQUS finite element code [ABAQUS, 2002] was used for this study, and the structural improvement was recommended based on the simulation outcome. In this study, a finite element dynamic analysis procedure was implemented for the simulation since inertia effects are important during an earthquake. The dynamic analysis procedures in ABAQUS are broken down into two steps: natural frequency extraction and acceleration response spectrum analysis of the rack. In the frequency extraction step, the natural frequencies of a storage rack model were evaluated using eigenvalue analysis. Then based on the extracted natural frequencies, an estimate

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of the peak linear response of the storage rack to earthquake ground motion was computed in the response spectrum analysis step. Though the response spectrum method is only approximate, it is often useful and adequate for preliminary design studies. This approach is often used to analyze structural response in a seismic event.

### Finite Element Simulation

A typical storage rack shown in Figure 1 is commonly found in many warehouse-type retail stores including Costco and IKEA. This type of storage rack was selected for the finite element modeling. The manufacturer for the rack is United Steel Products Company (USP). The rectangular shaped storage rack of approximately 3 feet by 9 feet by 15 feet in size consisted of four vertical columns, one at each corner. The columns were connected together by two parallel step beams running along the rack's longitudinal direction. The rack has three shelving levels and a ground level; each level was approximately 60 inches apart. Pin joint was used at each beam-column connection. Each step beam was 108 inches long with a wall thickness of 0.125 inches. The cross section of rack column was a 3 inches by 3 inches square with 0.165 inches wall. On each side section of the storage rack, columns were welded together by reinforced beams oriented diagonally across the open space between levels. The reinforced beam had the same cross section as the column beam but its wall thickness was 0.11 inches.



Figure 1 Typical Storage Rack in Warehouse-Type Store

For the purpose of simulation, each stack level was assumed to be loaded with four merchandise and they were placed on top of wood pallets, which in turn were placed on step beams and positioned apart from each other by approximately 9 inches. All merchandise had approximately a 4-inch clearance from next level step beam, and a 3-inch overhang beyond the step beam. Furthermore, there was a 5-inch side clearance between the frame column and the merchandise. This arrangement is similar to the schematic shown in Figure 2. Since there were three levels of shelving in the storage rack model, the total number of merchandise was twelve as shown in Figure 3 (assuming no merchandise placed on the ground level). Each connecting joint of step beam to column was modeled with two pin joints.

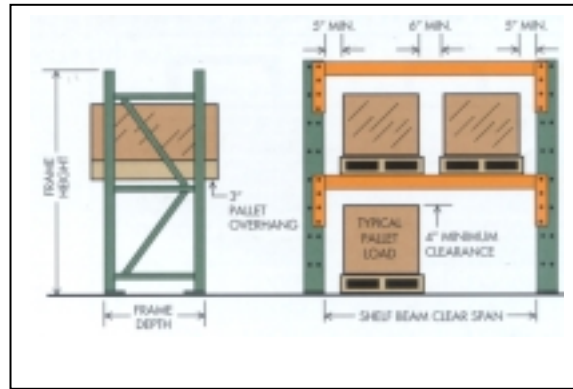


Figure 2 Schematic of a Storage Rack Model (Single Level)

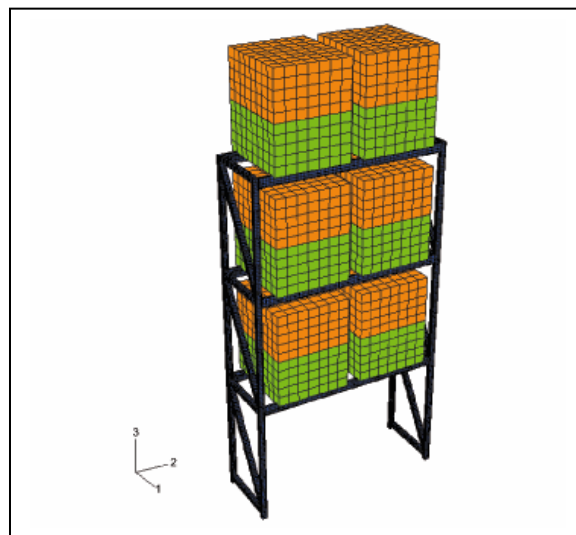


Figure 3 Storage Rack Finite Element Model (Three Levels)

El Centro earthquake information [Chopra, 1995] was used as representative ground motion input data; the data is well characterized and frequently applied in the structural engineering community. The data were applied to both longitudinal (2-direction as shown in Figure 3) and transverse (1-direction) directions independently to study the structural behavior of the storage rack. To minimize the run time and computer memory required for analysis, the bottom piece of merchandise and wood pallet for each shelf were lumped together as a single rectangular shaped deformable body of 1,000-pound in weight (in green color in Figure 3). Friction was assumed to exist at the contact surfaces between merchandise, and between wood pallet and step beam. The coefficient of friction at each pallet/step beam interface was assumed to be 0.5, which falls within the range of 0.4 to 0.7 for wood and steel surface interaction [Avallone, 1978]. The coefficient of friction between upper and lower merchandise surfaces was about 0.2. For each level, the top piece of merchandise was modeled as a rigid rectangular body ranging from 200 pounds to 500 pounds (in orange color in Figure 3).

In many linear dynamic problems, a proper specification of damping is important to obtain accurate results since structural members have some levels of inherent capability to minimize vibration by damping. Damping is approximate in the sense that it models the energy absorbing characteristics of the structure without attempting to model the physical mechanisms that cause this characteristic. For a steel frame, the damping factor of 2% was used in the earthquake dynamic analysis.

Linear solid 8-node brick elements and 4-node tetrahedral elements were employed for the finite element analysis. Over 200,000 elements were used for modeling a single unit of storage rack. A “reduced integration” scheme was used in the numerical analysis to minimize “shear locking” in elements for better accuracy. Fixed boundary conditions were prescribed to the bases of the columns to simulate the rack being firmly attached to the ground. For the earthquake simulation, El Centro earthquake ground acceleration data (above 7.0 in Richter Scale) was applied to the elements/nodes at the ground level.

To simulate earthquake excitation to the storage rack model, two analysis steps were performed. For the first step, natural frequency analysis of the storage rack model was performed and over 30 natural frequency modes were evaluated and stored for subsequent analysis. For the second step, spectrum response analysis was performed. The El Centro earthquake acceleration data in time domain was converted into a frequency domain response spectrum. This was accomplished by combining the frequency analysis results with the El Centro earthquake ground acceleration to generate an acceleration versus frequency plot similar to the one shown in Figure 4 for spectrum response analysis. From the analysis, peak displacements of the structure were evaluated within the frequency range of interest. The displacements of the structure due to earthquake were used to compute strains and then stresses in the structure. The maximum stress locations in the storage rack were identified in this finite element analysis. In addition, the relative displacements of the merchandise to the rack were observed, and the extent of potential hazard posed to public due to the falling of merchandise from the shelves was evaluated.

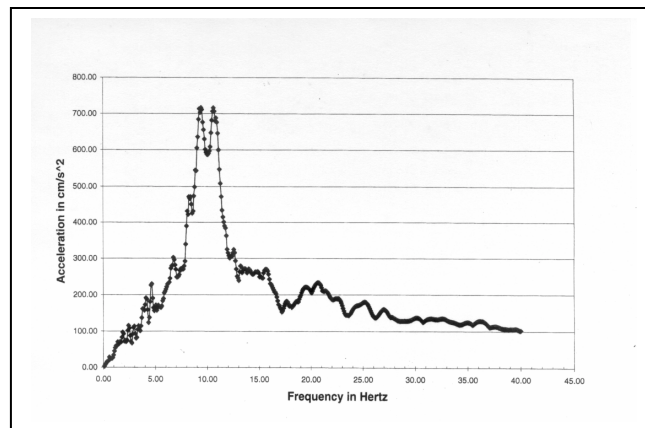


Figure 4 El Centro Acceleration Versus Frequency Plot

## Results

The first 30 natural frequency mode shapes of the storage rack were extracted. The first few selected mode shapes of the rack are shown in Figures 5 to 8. The finite element analyses were performed with seismic ground motion applied in the longitudinal direction (2-direction as shown) of the rack and transverse direction (1-direction as shown) of the rack in separate runs.



Figure 5 First Mode Shape of Rack



Figure 6 Third Mode Shape of Rack



Figure 7 Fourth Mode Shape of Rack

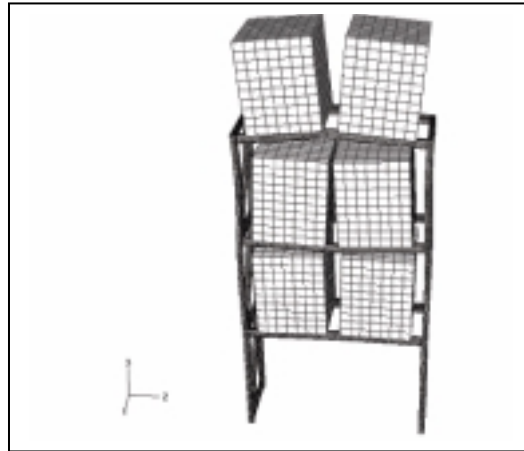


Figure 8 Fifth Mode Shape of Rack

When the frequency domain acceleration response spectrum was applied to the ground in the 2-direction, the maximum displacement of the rack loaded with merchandise was about 6.5 inches and the corresponding maximum Von Mises stress was over 150 ksi. The displacement and stress contour plots are shown in Figures 9 and 10, respectively. Though the stress seems high but it was occurred at few localized regions in the rack as shown in Figure 11. These localized stresses were due to geometric effect at the step beam-to-column connections in the finite element model. Since the analysis was linear elastic and the peak stress was localized in the rack, the local stresses are expected to redistribute to lower magnitudes upon local yielding. Therefore, no catastrophic failure or gross distortion of the rack is expected to occur. However, further investigation should be performed to verify that this is indeed the case. The merchandise on the top level (level 3) experienced maximum displacement but did not show any sign of tipping over or falling off the shelf due to the earthquake acceleration.



Figure 9 Displacement Contour Plot

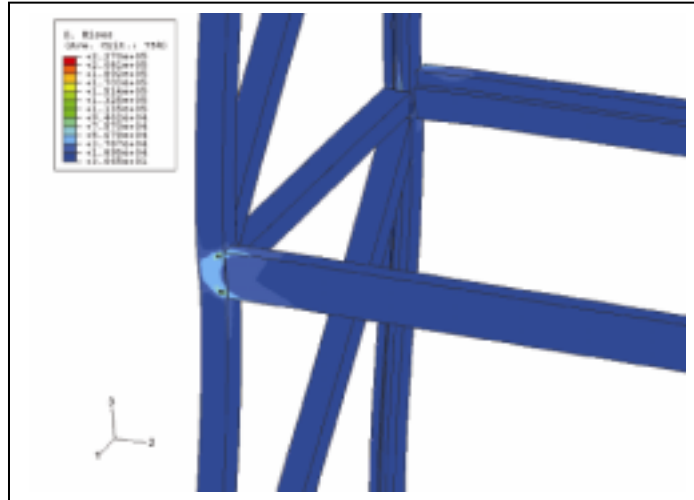


Figure 10 Von Mises Stress Contour Plot  
(Merchandise not shown)

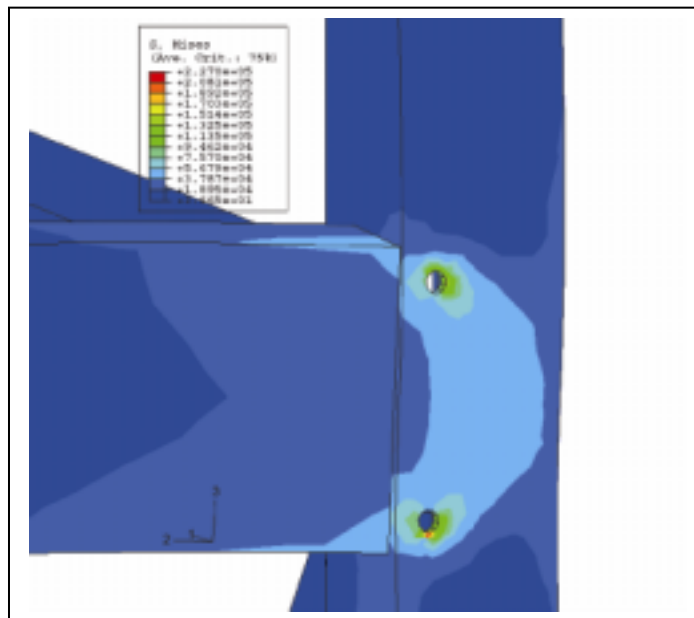


Figure 11 Close View of Stress Contour in Rack  
(Merchandise not shown)

When the acceleration response spectrum was applied in the 1-direction as shown, the displacements of the merchandise and the rack were much lower (under 2 inches), and the stress at the connection joint of the rack was reduced to one-third of the previous value. The lower stress and displacement results are probably due to the applied ground acceleration direction (transverse direction) not in-phase with the extracted natural frequency mode shapes of the rack.

## **Conclusions**

From this preliminary finite element simulation, the dynamic behavior of storage rack under the El Centro ground motion was observed. The rack moved the most when the ground motion was applied in the longitudinal direction (2-direction) of the rack. The storage rack displacement at the top shelf level was about 6.5 inches in the longitudinal direction under maximum merchandise load condition (500 pounds per piece). When lower merchandise load was used, lower displacements were observed. In all the cases in this study, no merchandise tipping over or falling off the rack was observed in the preliminary investigation.

Though merchandise did not fall off the rack in this simulation, certain natural frequency modes had a tendency to cause the merchandise to tilt somewhat with the frame at the top level, such as the fifth mode shape shown in Figure 8. Therefore, it maybe a good practice to put metal straps, restraining bars, or safety nets at the very top level of the rack to prevent merchandise from shifting when storage rack undergoes greater ground motion than the El Centro data used in this study.

In this simulation, the maximum Von Mises stress was found at the step beam to column connection with magnitude above 150 ksi. Although this value was above the yield strength of the steel material for the rack, it was rather localized at the beam to column pin joint areas. These high stresses were believed to be created by the geometric effect of the pin connection in the finite element model; and therefore, further evaluation at the joint region is recommended.

## **Acknowledgments**

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## **References**

ABAQUS Finite Element Code, 2002, Version 6.3-1, Hibbitt, Karlsson & Sorensen, Inc, Rhode Island.

Avallone, Eugene A., Marks' Standard Handbook for Mechanical Engineers, 1978, 9<sup>th</sup> Edition, McGraw Hill.

Chopra, Anil K., 1995, Dynamics of Structures, 1<sup>st</sup> Edition, Prentice Hall.

Seismic Safety Commission Monthly Meeting Minutes, April 2001.

“60 Minutes” Television Program, September 2002, broadcasted by CBS Company.