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# DEVELOPMENT OF A NEW BASE ISOLATION SYSTEM FOR SEISMIC ISOLATION OF STEEL PALLET STORAGE RACKS

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## ABSTRACT

This paper provides an overview of a new base isolation system developed for seismic isolation of steel pallet storage racks. The new isolation system provides seismic isolation primarily in the cross-aisle direction by incorporating heavily damped elastomeric bearings and friction plates. The paper consists of two focus areas: a summary of experimental results from actual tests performed on the triaxial shake table in the Structural Engineering and Earthquake Simulation Laboratory (SEESL) at the University of Buffalo and optimization of the seismic mount through hyperelastic material modeling to achieve characteristics that expand the use of the isolation system from lightly loaded racks to heavily loaded racks.

## Introduction

Industrial steel storage racks have been essential elements in warehouses and distribution centers throughout the world for many decades. Their use in public areas however, is a relatively recent development. Introduced in the mid 1970's, "warehouse stores" have become widespread, particularly in North America and Europe. The transition from lightly loaded hand stacked displays to an environment of machine loaded racks with perhaps many tons of material stocked high above the floor has profoundly altered the face and cost structure of retailing. It has also challenged designers and manufacturers of these racks to ensure adequate safety for the customers and workers.

A primary concern is falling material, particularly from the upper levels of these racks. An object falling from below eye level is far less dangerous than one coming from perhaps 12 feet or more above the customers head. While operational procedures may mitigate this hazard during normal in-service conditions, an earthquake poses unique design challenges.

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Storage racks can be made sufficiently strong to resist any reasonably expected earthquake motion. Unfortunately, the same methods used to strengthen the racks also stiffen them, thereby introducing higher acceleration levels in the rack during an earthquake causing shedding of material, which might otherwise stay on the racks.

This work investigates the use of a novel “base isolation” technique which incorporates all of the flexibility needed for a long period into the bottom of the structure. The rack can then be a conventional design while still having the desired long period and superior earthquake performance. Base isolators have been used in large buildings and bridges for decades. Their behavior is well understood, and they can be easily configured for optimal performance with such structures. This is not so easily done for a storage rack. The period of any structure, base isolated or not, is a function of the mass to stiffness ratio. For buildings and bridges the mass of the structure may vary by a factor of perhaps 2-3 over its design life. This allows the designer to provide an isolator with a similarly narrow range of stiffness. Storage racks have a much wider range of loads, with a factor of 40 being quite common. Accommodating this range of loads with satisfactory performance is an unprecedented challenge.

Because of increased concerns regarding the seismic safety of pallet-type steel storage racks located in areas accessible to the public, the FEMA-460 document (FEMA 2006) was created as a resource document. The FEMA-460 document provides recommendations for the design of pallet-type steel storage racks and for best retail industry practices to increase the seismic safety of rack structures. Chapter 5 of the FEMA-460 document suggests the following seismic performance objectives for storage racks:

> *“The seismic performance of storage racks consists of two components: the seismic performance of the rack itself and the response of stored contents. Racks can pose safety hazard if they collapse, partially collapse, or overturn. Contents can pose falling hazards if they become dislodged and fall into accessible areas.”*

## Proposed Base Isolation System for Storage Racks

The base isolation system considered in this study is designed to provide base isolation in the cross-aisle direction of a rack only, while providing similar restraints as conventional bolted base plates in the down-aisle direction. The objective of the isolation in the cross-aisle direction is to reduce the horizontal accelerations of the rack in order to reduce content spillage and structural damage during a major seismic event, without interfering with normal material handling operations. The base isolation is not designed to provide isolation in the down-aisle direction since the range of down-aisle natural periods of typical rack structures is already similar to typical base isolated structures (1.5 sec and above). The flexible and ductile moment-resisting lateral load-resisting system used in the down-aisle direction of racks behaves in a similar manner as an isolation system in that it shifts the period of the rack to longer periods where spectral accelerations are lower. Furthermore, horizontal accelerations in the down-aisle direction do not contribute substantially to content spillage.

Figure 1 shows a general view of the proposed isolation system. The system consists of a U-shape plate (horizontal support plate) inserted inside a steel box. The base plate of the box is anchored to the building slab and encloses two multi-layered high damping laminated elastomer mounts (referred to as seismic mounts). Each seismic mount is connected to the horizontal support plate and the box. The weight of the rack is carried by the uprights alone, while the lateral seismic shear forces are carried by the mounts and by friction between the horizontal support and bearing plates. Under seismic loading in the cross-aisle direction, the horizontal support plate can slide on the base plate of the box that is made of a low friction bearing material. Therefore, the lateral stiffness of the isolation system is provided only by the two parallel mounts. The mounts also provide stiffness in the vertical direction until contact is made between the horizontal plates and box frame. In the down-aisle direction, the rubber mounts are restrained by the side walls of the horizontal support plate, effectively restraining displacement in that direction.

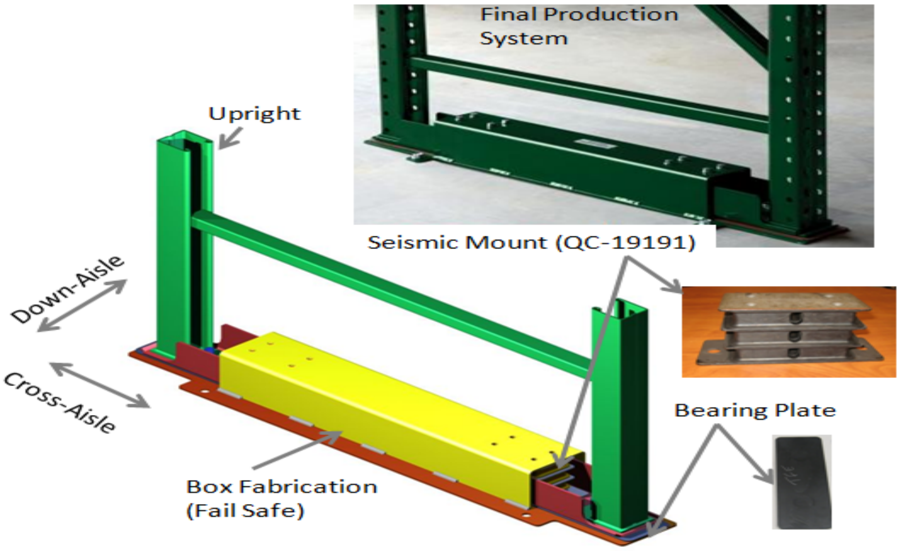

Figure 1. General View of Base Isolation System for Steel Storage Racks (Solid Models from Corry Rubber Corporation, Photo from RuR).

## Description of Test Storage Rack Structures

### Rack Geometry

Both traditional rigid based and new base isolated racks were tested. Two different rack geometries (one 3-level, the other 4-level) typical of warehouse retail store configurations were tested in this study. All rack specimens incorporated two bays and were made of A1011 HSLAS Grade 50 cold formed steel beam, upright and cross-brace sections. The two racks had identical upright and beam sections. The rigid based racks were attached to the shake table surface through standard bolted base plates, while the base isolated racks were mounted on the base isolation system described above.

The rack structures used in this study were typical in geometry, components, and loading to those found in many retail warehouse stores. The frame depth was the minimum (least stable) commonly machine loaded size. In anticipation of the forthcoming ANSI MH16.1 and ASCE 7 revisions, the storage racks were designed for a minimum equivalent lateral LRFD seismic base shear of 0.051W longitudinal and 0.38W transverse, for a rated capacity of 2.5 kips per pallet position, and W = 2/3P, where P is the product load per the RMI/ANSI MH16.1 specifications and W is the seismic weight of the rack. More details on the rack geometry are given in Filiatrault et al. (2008).

## Content Weights and Merchandise Configurations

Twelve different shake table test series were performed on the directly anchored and base isolated storage racks loaded with simulated and real merchandise. Two types of content weights were used for the test series. For the first two test series involving 3-level racks, the content weight was simulated by precast concrete blocks stacked and rigidly banded to the beams of the rack specimens. Each concrete block weighted 21.8 kN (0.7 m x 1.0 m x 0.3 m). Each beam could accommodate two standard concrete block widths along its span. Therefore, each rack could contain 12 block widths over its three beam levels. The simulated content weight included three concrete blocks stacked on top of each other at each location for a total content weight of 176.5 kN.

For the other ten test series, real merchandise was utilized as content weight. Three different merchandise/rack configurations involving four beam levels were used for these ten test series. The first "light" merchandise configuration had a total merchandise weight of 23.1 kN. The second "intermediate" merchandise configuration had a total merchandise weight of 94.1 kN. The third "heavy" merchandise configuration had a total merchandise weight of 176.5 kN. More details on merchandise configuration are given in Filiatrault et al. (2008).

# Laboratory Equipment and Instrumentation

## Shake Table

The tests were performed on a testing platform of the tri-axial shake table in the Structural Engineering and Earthquake Simulation Laboratory (SEESL) at the University at Buffalo. The shake table used for the tests has six controlled degrees-of-freedom that are digitally programmable with feedback control to simultaneously control displacement, velocity, and acceleration. Only three translational degrees-of-freedom (two horizontal and one vertical) were utilized for the shake table tests reported herein. All measurements were recorded at a rate of 256 samples per second (Hz) for all shake table tests. The data were converted to ASCII files with a common time reference. The data were then biased and filtered with a low-pass (5 Hz) filter (10th order Butterworth).

## Input Motions for Seismic Tests

The Maximum Considered Earthquake demand for a Site Class D in a high seismic zone of the United States (e.g. California) is defined in ASCE 7-05 by a short-period spectral acceleration $S_{MS} = 1.5\,g$ and a 1-second spectral acceleration $S_{M1} = 0.9\,g$. For seismic design of structural systems, ASCE 7-05 defines also the Design Earthquake (DE) demand as two-thirds of the MCE demand. For the seismic tests, a set of bi-axial horizontal synthetic input motions was generated to match the MCE response spectral shape for 5% damping. The required response spectrum for the vertical direction was developed based on amplitude of two-thirds of the horizontal spectra. The total duration of the input motions was taken as 30 seconds, with the non-stationary character being synthesized by an input signal build-hold-decay envelope of 5 seconds, 20 seconds, and 5 seconds, respectively.

The MCE and DE spectral shapes of ASCE 7-05 were compared with the Test Response Spectra (TRS) obtained from the recorded motions of the shake tables when the synthetic motions were used as input signals at 100% and 150% of their full-scale amplitudes, respectively. Therefore, in the context of this study, the input ground motions scaled to 100% of their full-scale amplitudes (referred herein as 100% test level) are associated with a DE event. Similarly, the input ground motions scaled to 150% of their full scale amplitudes (i.e. 150% test level) are associated with an MCE event.

The objective of the seismic tests was to determine the dynamic response of the conventional and base isolated racks under the set of synthetic ground motions described above scaled to various amplitudes expressed as a percentage of their full-scale amplitudes. More details on the input motions used for the seismic tests are given in Filiatrault et al. (2008).

## Seismic Test Results

### Observed Performance of Racks Loaded with Concrete Blocks

The base isolated rack remained free of structural damage for all the cross-aisle seismic tests conducted up to 100% test (DE) level. Only minor scouring was observed on the interior side walls of the U-shape horizontal support plate as a result of the sliding of the base isolator against these surfaces during the seismic tests.

Under a cross-aisle excitation corresponding to 50% test level, slight local inelastic buckling of the central uprights along with uplifting and yielding of the corresponding base plates were observed in the rigid based rack. At the 65% test level, more severe local inelastic buckling was seen in the same central uprights of the rigid based rack along with weld cracking between the uprights and the central horizontal bracing member. After this damage it was decided that the rigid based rack was not structurally sound to undergo a final tri-axial test at 100% (DE) test level and the seismic testing program was stopped for this rack.

These observations clearly indicate the superior performance of the base isolated rack tested in over the similar conventional (rigid based) rack. The rigid based rack did not meet the life safety performance objective recommended in the FEMA-460 document since severe structural damage occurred at intensity less than the DE level (100% test level). The base isolated rack, on the other hand, met the DE life-safety performance expectation of FEMA-460 since no structural damage was observed and the acceleration levels in the cross-aisle direction were low and would not cause merchandise spilling. Figure 2 compares for various seismic excitation amplitudes the measured top level peak accelerations in the cross-aisle direction of the base isolated rack with that measured on the rigid based rack tested. The base isolated rack configuration substantially reduced the accelerations in the cross-aisle direction. For all seismic tests conducted on the base isolated rack in these test series, the peak cross-aisle accelerations did not exceed 0.24 g at 100% (DE) test level. It is expected that this level of acceleration would not cause spilling of merchandise from the base isolated rack.

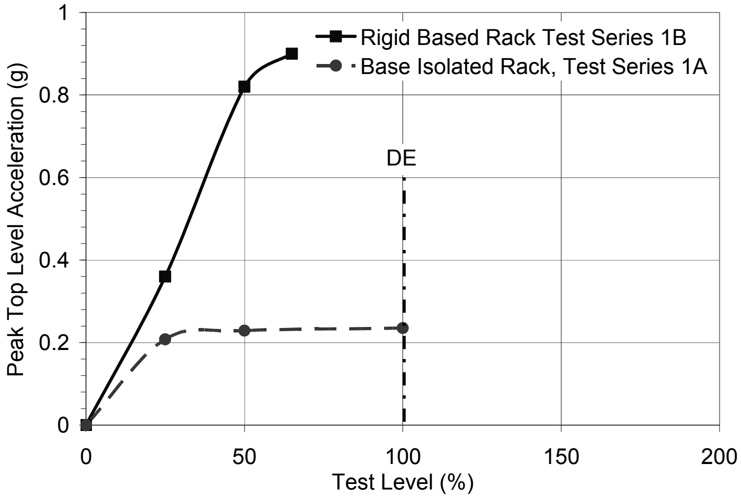

Figure 2**.** Variations of Peak Top Level Cross-Aisle Accelerations with Excitation Amplitudes (from Filiatrault et al. 2008).

## Observed Performance of Racks Loaded with Real Merchandise

The base isolated rack configurations did not suffer any significant structural damage during the tri-axial seismic tests. More pronounced scouring was observed on the interior side walls of the U-shape horizontal support plate as a result of the sliding of the base isolation against these surfaces during the seismic tests.

In contrast, the conventional (rigid based) racks suffered significant structural damage as a result of the tri-axial seismic tests. The rigid based rack loaded with heavy merchandise suffered severe damage. Following a tri-axial seismic excitation at 100% (DE) test level, yielding, local buckling and cracking at the base of the central uprights were observed. During the following seismic test at 150% (MCE) test level, both central uprights sheared off completely from their base plates just above the welds. As a result of this failure, this 150% amplitude test was aborted in mid-run. Again, while this testing was more realistic of expected exposure in actual service, it still represented a cumulative exposure greater than demanded by code. Accordingly, these results should not be extrapolated or directly applied to in-service racks.

Except for a single one-gallon paint can that fell off, none of the base isolated rack configurations shed merchandise during the tri-axial excitations corresponding to 100% (DE) test level, thereby meeting the life safety DE performance objective recommended in the FEMA-460 document. Only under a tri-axial seismic excitation at 200% test level, the base isolated rack loaded with light merchandise lost some tall water heaters located at the top level. When the base isolated rack was loaded with heavy merchandise, on the other hand, no merchandise fell off even under a tri-axial excitation at 200% test level, as shown in Fig. 3a. Under the same 200% excitation, the rigid based rack lost almost all of its merchandise as shown in Fig. 3b. Note that the rigid based rack used at the 200% test level incorporated larger size welds at the base of the uprights in order to avoid the failure of the uprights observed in earlier tests.

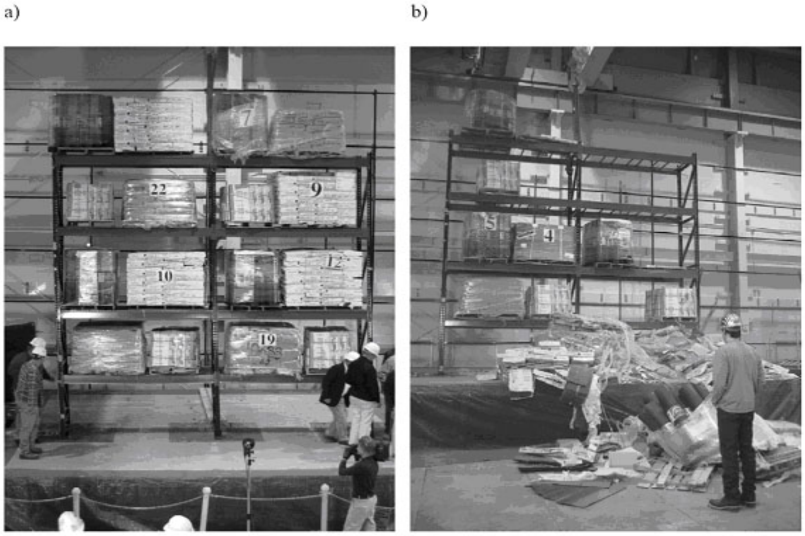

Figure 3. Heavy Merchandise Configurations after 200% Test Level Tri-Axial Seismic Excitations, a) Base Isolated Rack, b) Rigid Based Rack.

## Optimization of the Seismic Isolation System

Experimental results detailed above have shown that the current production isolation system provides adequate performance for heavily loaded racks (i.e. total content weight > 10 kips/bay). Storage racks have a wide range of loads; with a load factor of 40 being quite common (max load capacity/weight of rack only). In practice, steel pallet racks may contain content weights from 0.5 kips (static weight of rack) up to 21 kips per bay. The challenge, therefore, is to determine a set of seismic isolation parameters that satisfy the whole range of possible content weights. A numerical study suggests a linear isolator with shear stiffness of 100 lb/in and a non-linear mount with $F_i = 50x^3$ with a coefficient of friction of 0.05 will meet the performance objectives for total content weights per bay of 1kips up to 21 kips. Note that the performance objectives used in the numerical model were the following two constraints: 6.25 in. limit on peak isolator displacement and 0.35g limit on peak rack acceleration.

### The Optimal Seismic Mount

Figure 4 below shows measured static shear load-deflection curves for the current production mounts (50 and 60 duro butyl blends) plotted with the optimal non-linear and linear cases as determined from the numerical study. The seismic mount can be redesigned to achieve these optimal curves. In practice, however, the non-linear mount may offer advantages over the linear mount. The non-linear mount will stiffen considerably at larger deflections and the higher elastic force will help the rack return to its equilibrium (neutral) position upon impact. The improved stability might be important for day to day occurrences such as forklift impacts.

Nonlinear finite element analysis with hyperelastic material properties was used to redesign the seismic mount to achieve the non-linear curve shown in Figure 4. Several design options were considered. Three possible designs are shown in Figure 5. A brief description of each follows.

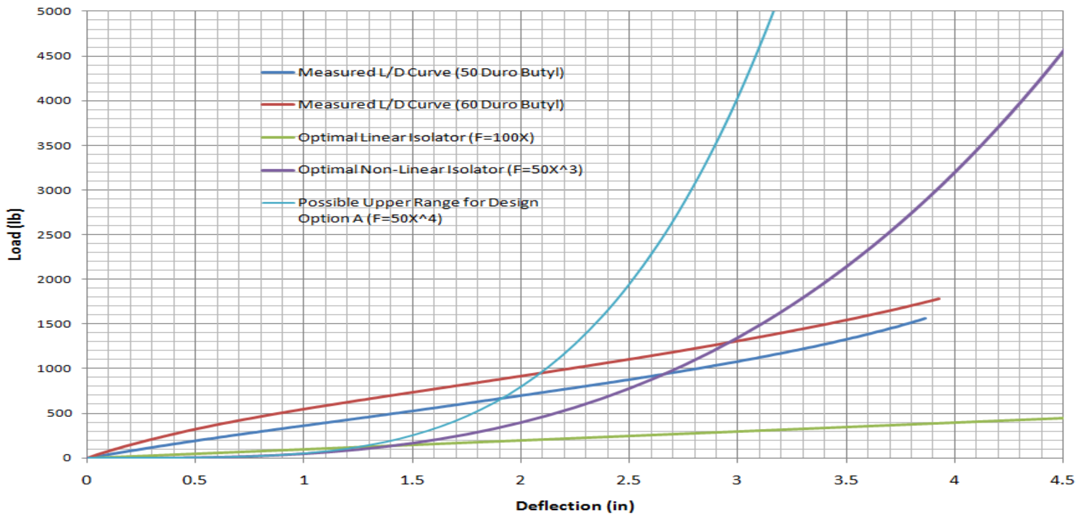

Figure 4 – Measured Production Static Shear Load-Deflection Curves Plotted with Optimal Linear and Non-Linear Curves.

## Design Option A - Semi Focalized

Semi focalizing the mount means the mount is titled in the planar view at some angle, θ, so the lateral stiffness will include a compression component, $K_c$, acting in parallel with a shear component, $K_s$.

$$K_{\text{lateral}} = K_s \cos^2\theta + K_c \sin^2\theta \tag{1}$$

As the angle of inclination, θ, increases the contribution from the compression component increases. The mount can be designed in such a way that the compression stiffness is significantly higher than the shear stiffness. This is achieved by incorporating multiple thin layers of elastomer bonded between steel shims. As the ratio of loaded area to bulge area (i.e. shape factor) increases for a given layer, the compression stiffness increases substantially with increasing deflection. High shape factor parts exploit the incompressibility of the elastomer by driving up the compression modulus with little effect on the shear modulus. Therefore, the combination of higher inclination angles and high shape factor (multiple thin layers) can produce force-deflection curves that are initially soft but stiffen considerably at large deflections. For example, the 4 layer design shown in Figure 5.A. is capable of producing a highly non-linear curve, $F_i = 50x^4$. This curve is shown in Figure 4 above. A semi-focalized design offers great flexibility and can be designed to achieve virtually any condition between the optimal linear and non-linear curves shown above. The self-centering nature of this design is an added benefit.

## Design Option B – Integrating Compression Section into Mount

This design option includes a compression section integrated directly into the mount. This can be achieved several ways some of which are shown. For example, the shims can be bent over at the ends or a horseshoe shaped core can be added to the middle of the mount. For all cases, initially the mount will produce pure shear stiffness but after an initial clearance is exceeded (i.e. >0.5 inch) the compression section will engage. The compression section will act in parallel with the main shear section thus increasing stiffness.

### Design Option C – Add Separate Secondary Isolator

A secondary isolator can be added to the base isolation system as shown in Figure 5.C. At small deflections (i.e. less than 2 inches), the main isolator will act alone so the cross-aisle stiffness the system will see will be that of the seismic mount alone. At large deflections, an initial clearance is exceeded and the secondary isolator engages. The stiffness of the secondary isolator will act in parallel with the main isolator. The secondary isolator can be "tuned" to produce virtually any stiffness shown in Fig. 4 so it offers great flexibility. Furthermore, the secondary isolator can be a retrofit able add-on, creating two separate seismic isolations systems: a low rating (no secondary isolator) and high rating (with secondary isolator) design. The secondary isolator also lends itself to a fluid mount type design whereby silicone fluid or gel can be added to drive up the damping considerably which will reduce displacement demands and therefore allow the overall isolation system to get softer without violating maximum displacement constraints. This would then yield lower peak acceleration.

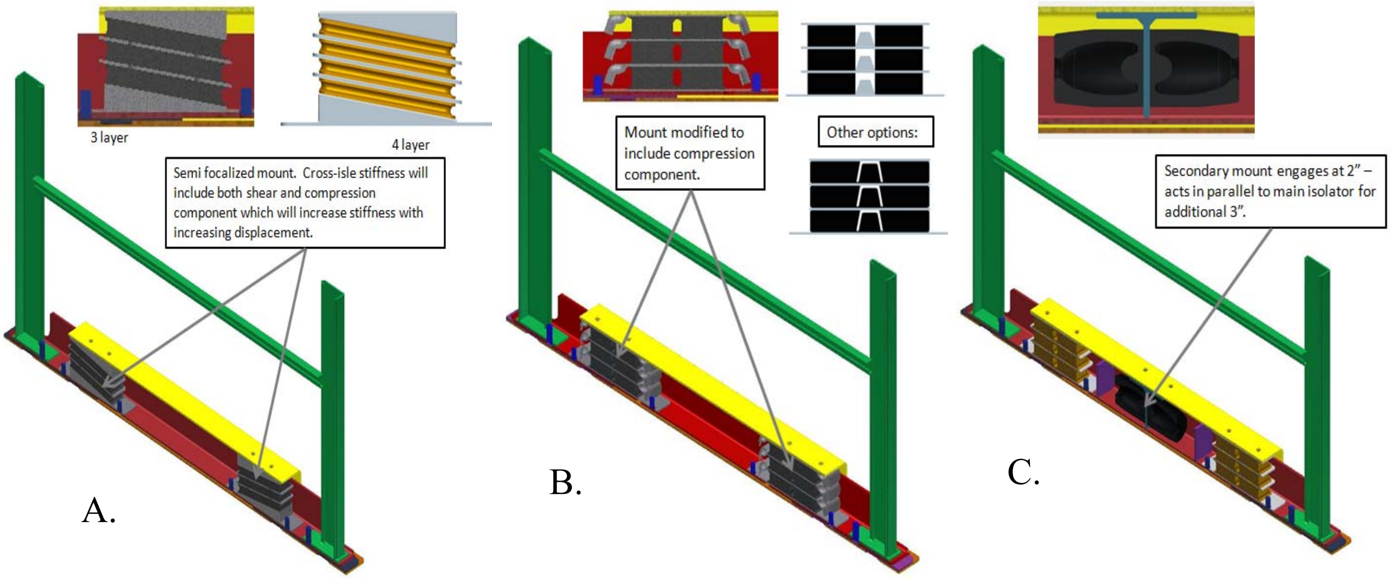

Figure 5 – Three Possible Optimized Isolation Systems for Meeting Performance Objectives at Total Content Weights of 1K to 21K per Bay (Solid Models from Corry Rubber Corporation).

### Conclusions

The current production base isolation system has been shown to provide superior performance as recommended by FEMA 460 for heavily loaded racks based on shake table tests performed at the University at Buffalo. A simplified analytical model was used to determine a set of optimal parameters for the seismic isolation system to expand the use from lightly loaded to heavily loaded racks. These parameters were then designed into a new seismic isolation system. Three optimized designs were presented.

## Acknowledgements

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