EXPERIMENTAL PERFORMANCE EVALUATION OF INCLINED SHELVING FOR STEEL PALLET TYPE STORAGE RACKS

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ABSTRACT

This paper focuses on the earthquake response of merchandise stored in steel storage racks and introduces the concept of inclined shelving as a measure for reduction of the seismically induced life safety hazards due to falling rack contents. The concept of inclined shelves refers to back-to-back or back-to-wall rack configurations with their shelves slightly tilted towards the inside or towards the wall, respectively, and represents the anticipated tendency of the merchandise to move inwards, when in motion, due to the contribution of the weight component parallel to the inclined shelf. The efficacy of this concept is verified experimentally through a series of shake table tests for a single level shelving system using two sets of ground motions associated with the seismicity of Western United States and Eastern North America. The experimental fragility at the 2% in 50 years seismic hazard level is computed for the case of horizontal and slightly tilted shelves for both sets. The results clearly show that the concept of inclined shelving can provide significant reduction of the pallet shedding fragility.

KEYWORDS: Shake table tests, steel storage racks, inclined shelves, experimental fragility, merchandise shedding

1. INTRODUCTION

During the past few decades, the number of large public warehouse stores, also known as big-box stores, has grown significantly across North America and Europe. Large steel storage racks are used in such facilities in order to satisfy two conflicting requirements: (i) effectively take advantage of the available space and (ii) put on display, for the shopping public, the maximum possible amount of goods. While traditional retailers used to store products outside the retail space in limited access storage rooms and warehouse facilities, big-box stores, nowadays, keep goods in close proximity to the consumers at all times of operation, abiding by the latest marketing trends. Typically, shoppers in these stores browse in the aisles formed by steel storage racks, which are usually 4.25m to 5.5m (14 to 18 feet) high and hold pallets of inventory that, in many cases, might be very heavy.

Occupant safety in these facilities during earthquake events depends both on the structural performance of the building and the performance of the storage racks. In turn, the performance of the racks is determined by both the performance of the rack frames and the performance of the contents stored in them. Earthquake shaking may cause contents to spill or topple off and rack frames to collapse or overturn if they are not properly designed, installed, maintained and loaded. Both occurrences pose a significant life-safety hazard to the exposed shopping public and, therefore, the mitigation of this hazard should be a part of the objectives of any seismic design procedure.

Despite the fact that the use of racks in retail warehouse stores dates back to the early 1980s, the number of big-box stores that utilize racks in public areas has increased significantly only during the past 10 to 15 years. Considering the short period of extensive use of racks, only limited information exists in the literature about their performance during major earthquakes, which intensifies the need for experimental investigation of the seismic behavior of these systems. Recognizing the need for evaluation of the performance of racks under strong earthquake shaking and considering that much work has been done to date regarding the seismic response of rack frames (FEMA 2005), the present experimental study focuses on the response of palletized merchandise.

The experimental investigation described herein consists of series of shake table tests conducted on a full scale – single level shelving system formed by two back-to-back connected racks, and its major objective is to evaluate the efficacy of inclined shelving as a measure for the mitigation of the seismically induced life safety hazards due to falling rack contents. The concept of "inclined shelving" is illustrated in Figure 1. The inward tilting of shelves in the transverse direction of racks may considerably reduce the "tendency" of contents to shed, since the contribution of the weight component "pushes" the merchandise to move inwards of the shelves. Considering that the beam-to-column connections of most rack frames are of tear-drop type and that the columns (called upright in the material handling industry) of typical racks are perforated (usually at every 5.1 cm or 2.0 in) allowing the owners flexibility in the height of their shelves, the inclination of these shelves can be easily adjusted just by placing the front beams of the rack frames slightly higher than the rear beams. Although this measure is applicable mainly to back-to-back or back-to-wall rack configurations, its easy and cost-effective implementation even to existing racks, makes it appealing for implementation.

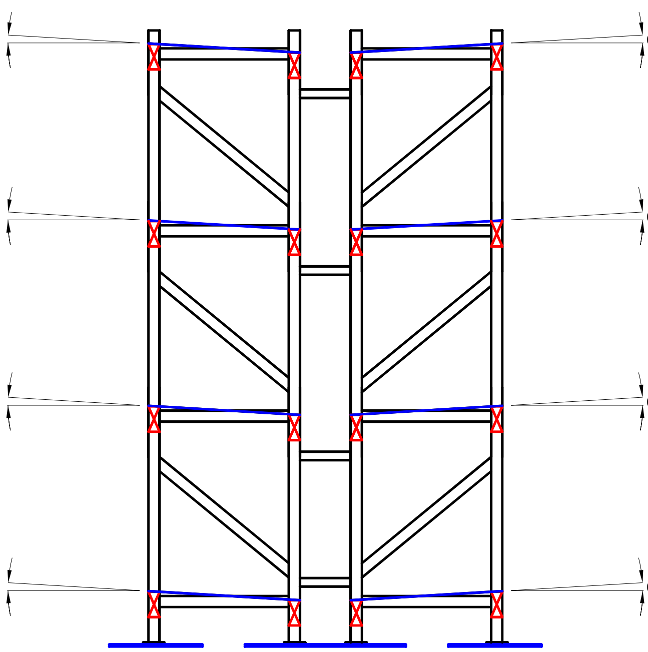


Figure 1: Concept of inclined shelving – Back-to-back rack configuration in the transverse direction

2. SHAKE TABLE TESTS

2.1. Specimen Description

The specimen used in the experiment was a single level shelving system consisting of two racks connected back-to-back with row spacers. This configuration is typical of the steel pallet-type storage racks in most big-box stores in North America. Each rack consisted of two concentrically braced frames in the transverse direction, four beams in the longitudinal direction and two metallic grillages that were placed side by side on the lower two beams of each rack. The beam-to-upright connections were of tear-drop type, which is typically used in most rack configurations and allows easy assembly and disassembly of the rack frames. The lower beams were attached to the columns of the cross-aisle frames as closer to the shake table floor as possible in order to minimize the amplification effects on the shelf motion due to the flexibility of the rack frame, while the upper beams were connected relatively high in order to permit the loaded pallets to move freely on the shelf and provide stability and stiffness to the system. The metallic grillages had dimensions of 100 cm x 117 cm (37”x46” – transverse x longitudinal) with wires spaced at 5.10 cm x 10.2 cm (4”x2”) – transverse x longitudinal) and were reinforced with metallic planks along the transverse direction of the rack so as to provide the required strength. On the grillages and in the middle of the configuration along the direction of the beams, loaded wooden pallets of dimensions 122 cm x 102 cm x 11.4 cm (48.0”x40.0”x4.5”) were placed. In order to protect the shake table from the loaded pallets that could fall off during testing, a protection barrier made of lumber and plywood was placed on each side of the table. The rack specimen on the shake table is shown in Figure 2.

Four geometric variations of this rack configuration were considered in this study as a combination of two angles of inclined shelving: horizontal and inclined by 3.45^{o}, and two positions of palletized merchandise on each shelf: centrally and eccentrically placed pallets. The eccentrically placed pallets accounted for cases where palletized merchandise is misplaced on rack shelves either by warehouse staff or by foreshocks or the main shock (if aftershocks occur) of an earthquake. For this configuration, the pallets were placed 36 cm (14”) outwards with respect to their central positions. Regarding the shelf inclination, the angle of 3.45^{o} was achieved by attaching the front beam of each rack at the next higher set of column holes with respect to its initial position. The four variations of the test specimen are presented in Figure 3.

In order to limit the number of tests, only one case of merchandise weight was considered. Loaded pallets of about 6670 N (1500 lbs) were deemed to represent average storage conditions in most warehouse stores and were used throughout the experimental procedure. Fifteen concrete pavers of dimensions 61 cm x 61 cm x 5.10 cm (24.0”x24.0”x2.0”) and weighting of 445N (100 lbs) each were used to provide this weight. The pavers were tightly banded to the pallets in order to remain attached to them during testing.

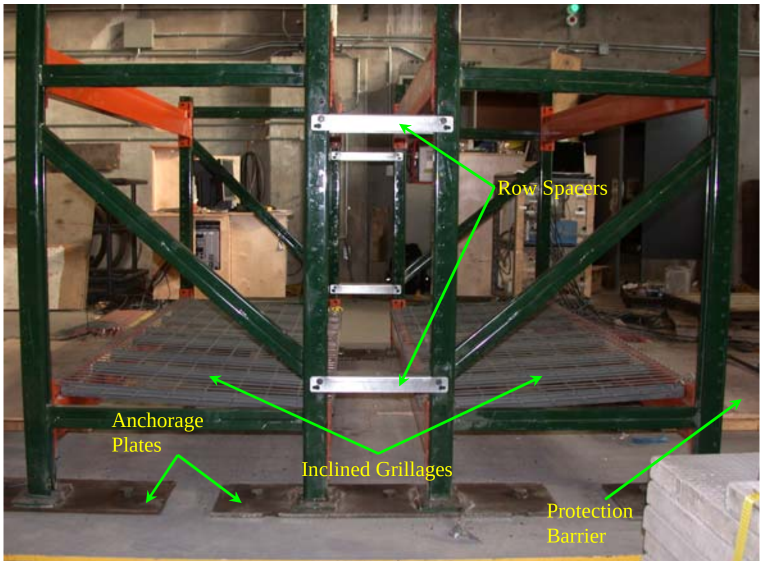


Figure 2: Unloaded test specimen anchored on the shake table


(a)


(b)


(c)


(d)

Figure 3: Specimen configurations: (a) Centered pallet and horizontal shelf, (b) Centered pallet and inclined shelf, (c) Eccentrically placed pallet and horizontal shelf, (d) Eccentrically placed pallet and inclined shelf

2.2. Test Ground Motion Ensembles

Two ground motion ensembles were used to excite the rack specimen in its transverse direction. The first ensemble was a subset of the ATC-63 Far Field ground motion set (FEMA 2008), which is representative of the seismicity in the Western United States. The ATC-63 Far Field ensemble was developed during the ATC-63 research project and has been intended to be used for the prediction of structural collapse in code-compliant buildings. It contains 22 ground motions recorded during strong earthquakes from all over the world. Each motion consists of two horizontal components recorded at the same station, resulting in a total of 44 accelerograms. These accelerograms have been scaled so that the median of the spectral acceleration of all records at a period of 1 second is approximately equal to 1g.

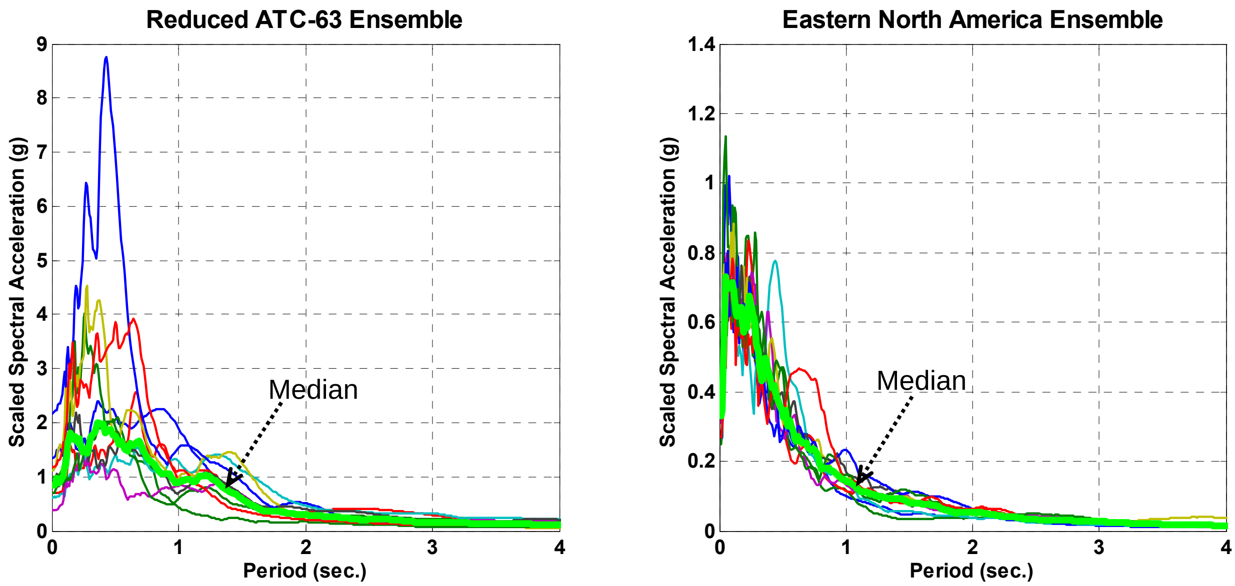
Considering that one of the objectives of this study was also to evaluate the fragility of content shedding at the Maximum Considered Earthquake (MCE) hazard level per ASCE 7-05 (ASCE 2006) in the Western United States, the full ATC-63 Far Field ground motion set should have been used. However, in order to limit the total number of shake table tests, only 10 out of the 44 acceleration histories of the original set were included in the test ground motion subset. The records of the ground motion subset were selected so that they provided similar seismic fragility of content shedding to that obtained by the original set. In order to achieve such an objective, basic statistical values of some of the critical ground motion parameters were calculated for the original ensemble, and the records of the reduced ensemble (or subset) were chosen so that they yielded similar statistical trends. The spectral acceleration at a period of 1 second (SA_1) and the peak ground acceleration (PGA) were selected as the ground motion parameters of interest and, as it is shown in Table 1, the two sets are "statistically" in good agreement. The reduced ground motion set was also compared with the original one in terms of the probability of content shedding using a numerical analysis program developed by Sideris (2008). The motions of the reduced set were further scaled to a median of spectral acceleration of 0.9 g at a period of 1 second so as to be representative of the MCE hazard level in several populated areas of the Western United States per ASCE 7-05.

Table 1: Comparison of statistical parameters in ATC-63 Far Field (original) and reduced ground motion sets, before scaling to SA_1=0.9g

	SA_1 (g) for ζ=5%		PGA (g)	
	44 EQs	**10 EQs**	**44 EQs**	**10 EQs**
Median	0.961	0.961	0.951	0.903
Arithmetic Mean	1.029	1.028	1.012	1.002
Geometric Mean	0.943	0.945	0.940	0.904
Standard Deviation	0.434	0.441	0.425	0.500
Maximum	2.119	1.888	2.271	2.161
Minimum	0.394	0.436	0.388	0.388

The second ground motion set considered in this study may be regarded as representative of the seismicity in Eastern North America. It contains ten synthetic ground motions generated for five magnitude – hypocentral distance scenarios that dominate the 2% in 50 years Uniform Hazard Spectrum adopted by the 2005 Edition of the National Building Code of Canada for the Montreal region (NRC 2005). The hazard at this location is representative of that of many large cities situated in moderately active seismic regions of Eastern North America such as Boston, New York and Ottawa. Further information on the generation of these motions may be found in Tremblay and Atkinson (2001).

The response spectra and the median spectrum for both sets of ground motions used in the experimental study are shown in Figure 4. The intensity of earthquake shaking at the same seismic hazard level (2% in 50 years) is much higher in the Western United States than in the Eastern North America, since the median spectral acceleration is higher in the first plot of this figure at all periods. Also, the earthquake energy of the first set is distributed over a wider frequency range (0.1sec to 1.5sec) in comparison to the second set which has its energy concentrated in high frequencies.



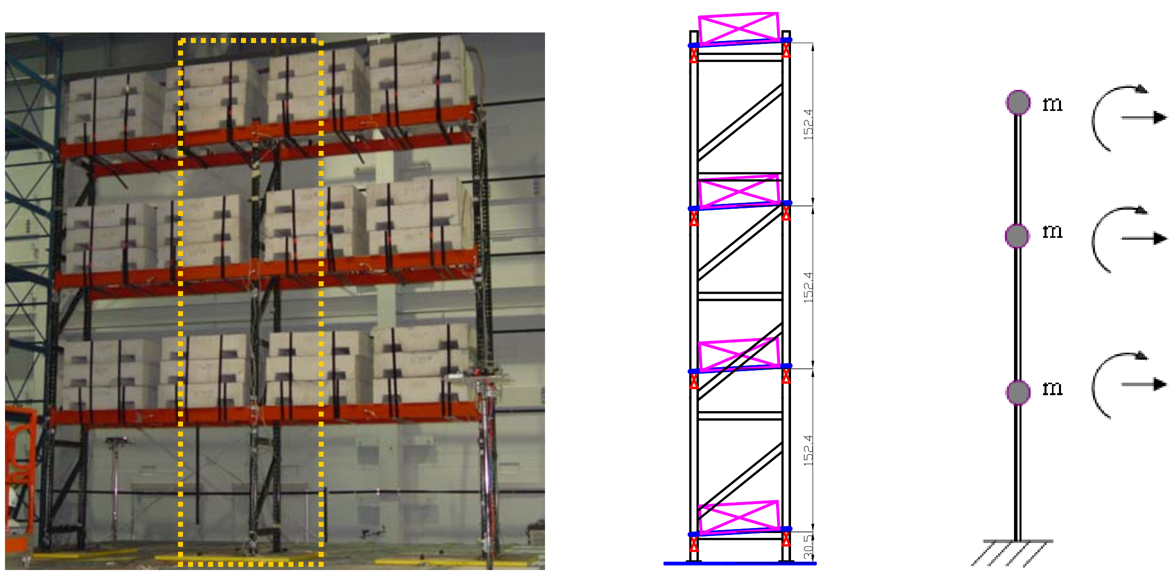
(a) (b)

Figure 4: Acceleration Response Spectra: (a) Reduced ground motion ensemble from ATC-63 Far Field ground motion set scaled to SA_1=0.9g, (b) Eastern North America ground motion set

2.3. Amplified Shelf Excitations

By imposing the motions presented above at the base of a loaded rack, the motion that is generated at each shelf depends strongly on the structural properties of the rack frame, the loading conditions and the height of the shelf. In this study, a generic rack model (Higgins 2006) was used to determine the shelf excitations. This simplified model represents average properties for the central frame of a two (or more) bay – four story 4.90 meters (16 ft) high rack which is representative of rack systems widely used in most warehouse stores. The derivation of the generic rack model is schematically presented in Figure 5. Considering that the height of the lowest shelf is small (30.5cm – 12 in), this shelf may be assumed to experience the same motion as that imposed at the base, and, thus, only the upper three shelves are considered in the dynamic model of this rack. The stiffness properties and damping properties of the simplified model are presented in Table 2, while the first three natural frequencies for average storage loading conditions along with the associated cumulative modal mass ratios are shown in Table 3. Obviously, these modes are well separated and the dynamic response is mainly dominated by the first two modes. The high value of the viscous damping ratio assigned to each mode accounts for the energy dissipated due to inelastic response of the connections of the rack frame and the base plates that anchor the rack to the ground, and to sliding of the pallets on the shelves. Further information on the derivation of the generic rack model may be found in Sideris (2008).

Using the SAP2000 computer program (CSI 2005), time history dynamic analyses were conducted for the generic rack model and the total acceleration histories at each shelf level were obtained. Comparing histories from different shelves, it was observed that the response of the top/third shelf was the most intense for all earthquake histories, and, for this reason, only the top shelf motions were used for the shake table tests. Note that no sliding of the pallets on the shelves was considered in the generic rack model, which was a conservative assumption on the inertia forces applied to the system.



(a) (b) (c)

Figure 5: Generic Rack Structure: (a) full scale experimental model at University at Buffalo with horizontal shelves – identification of generic model, (b) cross-aisle frame, (c) generic model – active degrees of freedom

Table 2: Structural properties of generic rack model

Modulus of Elasticity	**$2.9\text{x}10^3$ ksi**
Equivalent Sectional Area	0.8 in^2
Equivalent Moment of Inertia	360 in^4
Damping Ratio at each mode	10 %

Table 3: Natural periods of generic rack model

Mode	Period (sec.)	Cumulative Modal Mass Ratio (%)
1st	0.287	72.67
2nd	0.044	94.21
3rd	0.016	100.00

2.4. Test Execution

The tests were conducted in the Structural Engineering Laboratory of Ecole Polytechnique in Montreal, Canada. According to the original testing protocol, tests were to be executed by imposing the original and amplified ground motions of both the reduced ATC-63 and the Eastern North America ensembles to the two specimen configurations that included pallets placed at the center of the shelves (Figure 3 (a) and (b)). Additional tests were to be conducted for the two configurations that incorporated eccentrically placed pallets (Figure 3 (c) and (d)) with only the amplified motions of the reduced ATC-63 ground motion ensemble. Although most of the tests were conducted according to the schedule, some of them were skipped as explained later.

3. TEST RESULTS

From the experimental data, the probability of pallet shedding was determined for all the combinations of specimen configurations and ground motion ensembles that were tested. The probability of pallet shedding was computed as the ratio of the number of pallets that shed from the rack during testing with a specific ground motion ensemble over 20 (10 records for each ensemble times 2 pallets on the rack specimen during each test).

During testing with both the original and the amplified Eastern North America ensemble and for the specimen configuration with horizontal shelves and centered pallets (Figure 3 (a)), no pallet shedding was observed. For this reason, the corresponding tests for specimen configuration with inclined shelves (Figure 3 (b)) were not conducted, since shedding was not expected to occur. On the contrary, during testing with the amplified records of the reduced ATC-63 set, 1 failure (1/20) occurred for the centered pallet configuration and 3 failures (3/20) for the configuration with eccentrically placed pallets. For the same records, the response of the loaded pallets improved significantly resulting in a zero probability of failure when the shelves were tilted only by an angle of 3.45^o. This observation demonstrates the effectiveness of the concept of inclined shelving in the reduction of the probability of pallet shedding. The experimental fragility for the reduced ATC-63 set is presented in Table 4.

An additional observation made during testing was that as soon as the earthquake motion was applied to the specimen, both pallets tended to move inwards towards the axis of symmetry of the specimen. In most tests, when they reached this axis, one of them overturned and blocked the other. Thus, it was highly unlikely for them to go up again and fall off the shelves. This type of response is illustrated in Figure 6.

Table 4: Experimental pallet shedding fragilities for reduced ATC-63 ensemble at the MCE hazard level

	Centered Pallet		Eccentric Pallet by 14 in.
	Original Motions	Top Shelf Motions	Top Shelf Motions
Horizontal Shelves	0%	5%	15%
Inclined Shelves	0%	0%	0%

4. CONCLUSIONS

The experimental investigation described herein shed light on issues associated with the seismic behavior of loaded pallets in steel storage racks. It clearly showed that the concept of inclined shelving can be regarded as a simple and effective measure for the mitigation of the seismically induced life safety hazards due to falling rack contents. Shelf angles of 3.5^{o} or more seem to be sufficient to considerably reduce the pallet shedding fragility. The fact that inclined shelving can be implemented at small or no cost even to existing rack systems makes this measure very appealing.

It was also observed that the probability of content shedding at the 2% in 50 years seismic hazard level is much greater in the Western United States than in the Eastern North America, which is reasonable considering that the spectral acceleration demand is much greater in the first region along the whole period range of interest. More specifically, no pallet shedding was observed for the Eastern North America set, whereas the probability of failure reached 15% for the reduced ATC-63 ensemble.

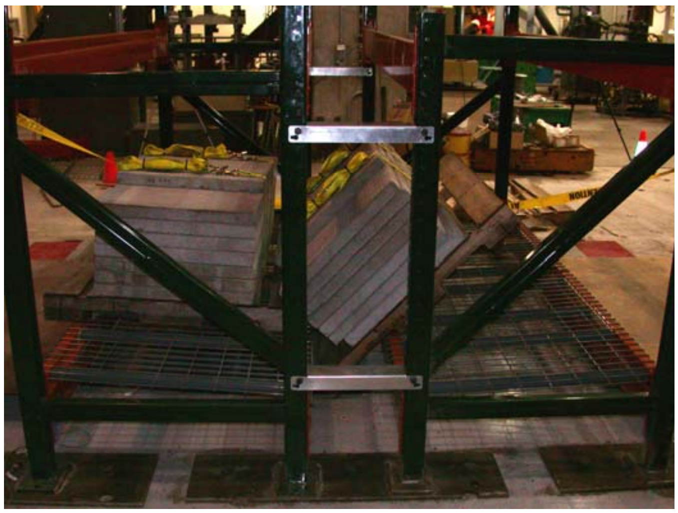


Figure 6: Pallets at the end of test with a motion from the amplified reduced ATC-63 set – Test P9_121211, after Sideris (2008)

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