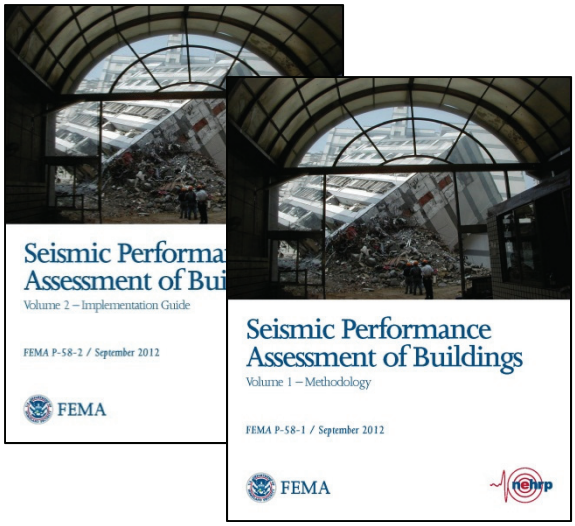

Background Document

FEMA P-58/BD-3.9.5

Fragility Curves for Storage Racks

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Background Documentation

FEMA P-58 Background Documents are a series of reports documenting the technical background and source information for key aspects of the FEMA P-58 methodology and its implementation. These reports were developed over the course of the 10-year ATC-58/ATC-58-1 Projects funded under FEMA Contracts EMW-2001-RP-0056 and HSFEHQ-06-D-1105.

Background Documents were developed by consultants, serving at various levels within the project hierarchy, reporting the results of: (1) decisions on technical development protocols; (2) focused studies on the development of key aspects of the methodology; (3) documentation of recommended procedures; and (4) collection of available data for the development of structural and nonstructural fragilities. They were initially intended to serve as a record of the technical state-of-knowledge at the time they were produced, and as resources for the development of the eventual project reports. As such, they represent a snapshot in time, and may, or may not, match the technical content, recommended procedures, or data incorporated into the final methodology and its implementation.

This Background Document is intended for the purpose of providing supplemental knowledge to users of the FEMA P-58 methodology. Information contained herein has not been independently verified for accuracy as a stand-alone document, and may have been superseded in its final implementation within the methodology. Specifically in the case of certain nonstructural component fragilities, the NISTIR fragility classification numbering scheme was modified over the course of the project, and the fragility classification number assigned in this document might be different from numbers assigned in the final fragility database. Users of information in this document assume all liability arising from such use.

Notice

Cover illustration – Primary resource documents for the FEMA P-58 *Seismic Performance Assessment of Buildings, Methodology and Implementation* series of products: FEMA P-58-1, *Volume 1 – Methodology*, and FEMA P-58-2, *Volume 2 – Implementation Guide*.

Fragility Curves for Storage Racks

Developed for the ATC-58 Project NPP Team

by

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Table of Contents

1. Introduction and Scope

This document summarizes the development of fragility curves for storage racks, such as pallet-type steel storage racks located in occupancies open to the general public. The fragility curves developed in this document are consistent with the fragility reporting requirements developed for the ATC-58 Project (Porter 2007) and were obtained from experimental shake table test data on full-scale rack structures where the actual damage states were observed (Method A). The test data used to construct the various fragility curves came from shake table experiments conducted by Chen et al. (1980a, 1980b, 1981), Filiatrault (2001), Castiglioni et al. (2003) and Filiatrault et al. (2006, 2008). This experimental database is representative of storage racks designed and installed before 2007.

Figure 1 illustrates the type of storage racks for which fragility curves were developed. Two basic types of lateral load-resisting systems are typically used for these types of pallet-type steel storage racks: braced frames in the cross-aisle (transverse) direction and moment-resisting frames in the down-aisle (longitudinal) direction. Storage racks do not usually incorporate horizontal diaphragms or cross bracing and therefore behave as structures with flexible diaphragms.

The steel braced frames used in the cross aisle direction of steel storage racks appear similar to steel ordinary concentrically braced frames defined in the 2003 NEHRP Recommended Provisions (FEMA 2004). Because horizontal struts and bracing members in racks are typically light gage open sections welded directly to open section columns (note that in the rack industry, the columns are commonly called uprights), the inelastic response of rack structures is very different than building braced frames (FEMA 2006). Based on available shake table test results (Chen et al. 1980a, 1980b, Filiatrault 2001), the fundamental period of steel storage racks in the cross-aisle direction typically ranges from 0.5 sec to 1.0 sec.

The moment-resisting frames used in the down aisle direction of steel storage racks while appearing very similar to steel moment-resisting frames defined in the 2003 NEHRP Recommended Provisions (FEMA 2004) also behave very differently than the systems used in buildings. While moment-resisting connections in buildings are designed to cause inelastic deformations in the beams away from the connections, storage racks have their inelastic behavior occur directly in the beam-to-upright connections (FEMA 2006). Based on available shake table test results (Chen et al. 1980a, 1980b; Filiatrault 2001), the fundamental period of steel storage racks in the down-aisle direction typically ranges from 1.5 sec to 3.0 sec.

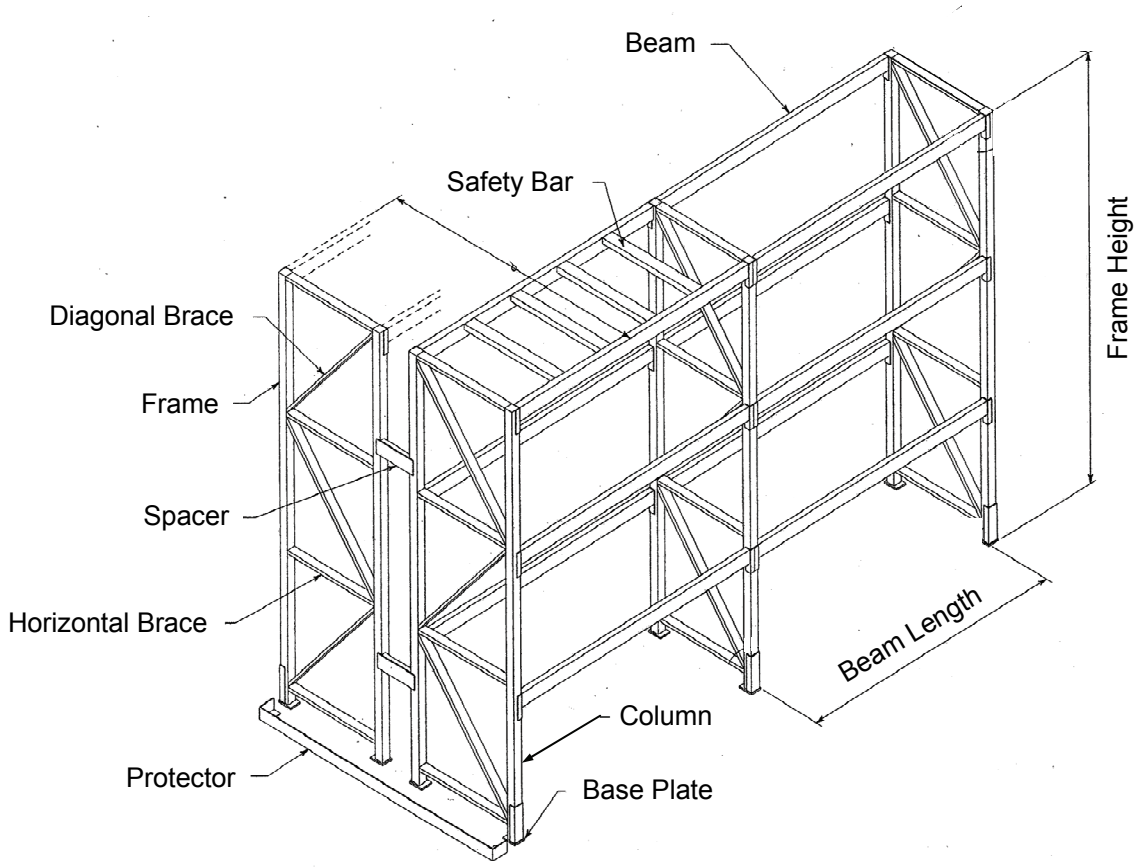


Figure 1- Typical Pallet-type Steel Storage Rack Configuration (from Filiatrault et al. 2008).

For the storage racks considered in this study, a demand parameter (DP) and two damage states (DS1 and DS2) were developed. The demand parameter (DP) considered was the Peak Floor Acceleration (PFA). Although merchandise content shedding would be better correlated with the peak accelerations occurring at the various shelving levels of rack structures, the PFA was used because it is currently available in the PACT software developed in the ATC-58 Project (Porter 2007) and were recorded in all shake tables tests reviewed. Note that most storage racks are typically located on the ground floor of warehouse facilities and the Peak Ground Acceleration (PGA) at the site of the warehouse facility can be substituted for the PFA.

The experimental data used was checked for outliers using both the procedure of Appendix C of the ATC-58 35% Draft Guidelines (ATC 2007) and of the ASTM-E178 standard (ASTM 2002). The DP was graphed against the probability of exceedance as shown in Appendix A. The probability of exceeding each damage state was calculated using the Hazen plotting position, $P = (i-0.5)/n$, since it does not imply a zero probability of damage for any specified DP value. The fragility functions were then checked for goodness of fit using the Lilliefors Test (Lilliefors 1967).

2. Fragilities for Storage Racks

The storage racks considered in the development of the fragility curves were based on shake table experiments conducted by Chen et al. (1980a, 1980b, 1981), Filiatrault (2001), Castiglioni et al. (2003) and Filiatrault et al. (2006, 2008). The main properties of the storage racks used in these tests are listed in Table 1. This experimental database is representative of storage racks designed and installed before 2007.

2.1 Definition of Damage States

Two damage states were defined for storage racks based on the consequences of the damage and the extent of the replacements required to return a storage rack to its pre-earthquake condition. The two damage states considered are 1) DS1: significant shedding of merchandise from the rack shelves, and 2) DS2: significant structural damage to the rack structure. The consequence of the significant merchandise shedding damage state DS1 would be the replacement of most or all of the merchandise that was contained in the rack. This merchandise shedding damage state is also associated with serious life safety hazard. The consequence of the significant structural damage state DS2 would be the replacement of the storage rack. Note that it is not common practice for store owners to field repair damage racks after an earthquake and, therefore, the damage state DS2 is associated with the threshold of structural damage for which a rack would need to be replaced. Note that structural collapse of the rack is also included in the damage state DS2, which pauses also a serious life safety hazard. These two damage states for storage racks are listed in Table 2 and illustrated by photographs in Figs. 1 and 2.

Figure 1 - Damage State DS1 for Storage Racks: Significant Merchandise Shedding (from Filiatrault et al. 2008).

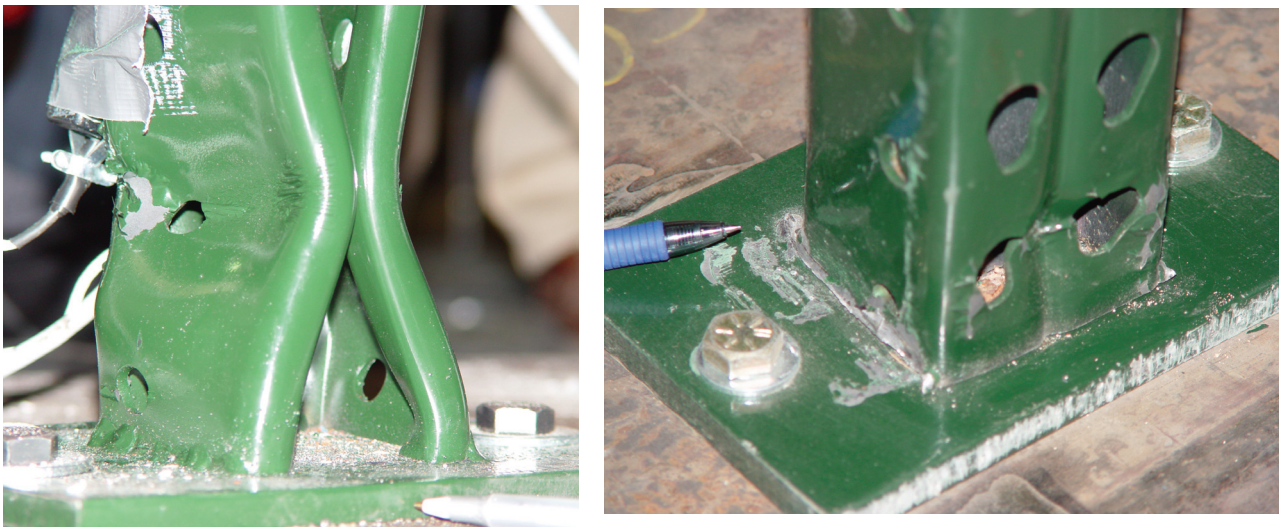
Table 1 – Properties of Storage Racks Tested.

Properties	Values	References
Rack types	Standard pallet	Castiglioni et al. (2003), Filiatrault et al. (2006, 2008)
	Standard pallet; back-to-back pallet; Drive-in; Stacker	Chen et al. (1980a, 1980b, 1981)
	Back-to-back pallet	Filiatrault (2001)
Rack configuration	3 levels - 2 bays wide - 1 bay deep 3 levels - 2 bays wide - 2 bays deep 3 levels - 2 bays wide - 3 bays deep 5 levels - 4 bays wide - 2 bays deep	Chen et al. (1980a, 1980b, 1981)
	4 levels - 2 bays wide - 2 bays deep	Filiatrault (2001)
	3 levels - 2 bays wide - 1 bay deep	Castiglioni et al. (2003)
	4 levels - 2 bays wide - 1 bay deep	Filiatrault et al. (2006)
	3 levels - 2 bays wide - 1 bay deep 4 levels - 2 bays wide - 1 bay deep	Filiatrault et al. (2008)
Total storage weights	24 to 80 kips	Chen et al. (1980a, 1980b, 1981)
	32 to 55 kips	Filiatrault (2001)
	22 kips	Castiglioni et al. (2003)
	35 to 53 kips	Filiatrault et al. (2006)
	5 to 40 kips	Filiatrault et al. (2008)
Storage weight types	Anchored/banded concrete blocks	Chen et al. (1980a, 1980b, 1981), Filiatrault et al. (2006)
	Concrete on wood pallets	Castiglioni et al. (2003)
	Real palletized or loose merchandise	Filiatrault (2001), Filiatrault et al. (2008)
Total rack heights	15 to 25.5 ft	Chen et al. (1980a, 1980b, 1981)
	20 ft	Filiatrault (2001), Castiglioni et al. (2003)
	16.5 ft	Filiatrault et al. (2006, 2008)
Total rack widths	16.5 ft	Filiatrault (2001), Filiatrault et al. (2006, 2008)
	12.2 to 16.5 ft	Chen et al. (1980a, 1980b, 1981)
	12 ft	Castiglioni et al. (2003)

Table 2 - Description of Damage States for Storage Racks.

Damage States (DSi)	Description of Damage State
DS_1	Significant Merchandise Shedding (Fig. 1)
DS_2	Significant Structural Damage to Rack Structure (Fig. 2)

a) b)



c) d)

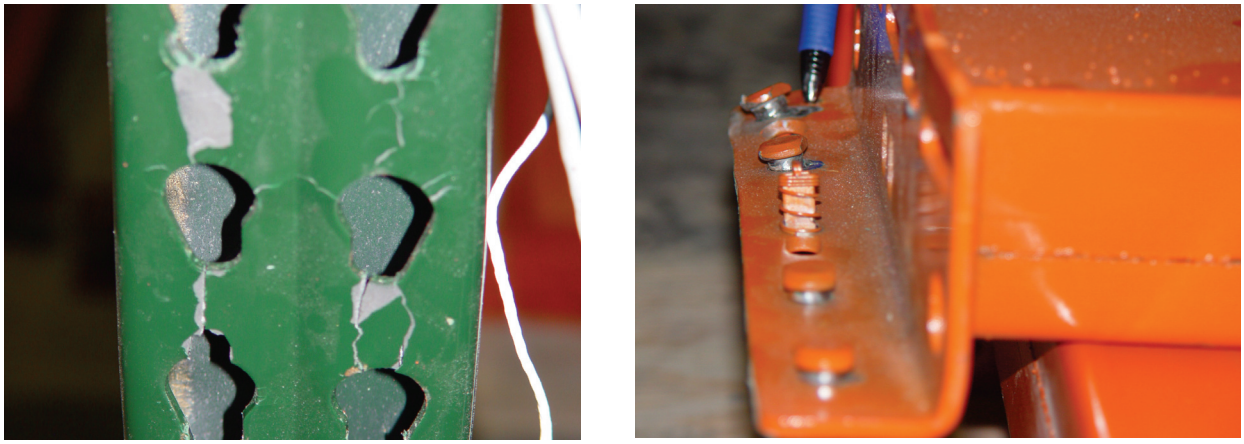


Figure 2 - Damage State DS2 for Storage Racks: Significant Structural Damage to Rack Structure, a) Buckling of Upright, b) Base Weld Fracture, c) Cracking and Tearing Across Down-Aisle Connector Perforations in Uprights and d) Damage to Beam Connectors (from Filiatrault et al. 2008).

2.2 Development of Fragility Curves

The fragility curves for the two damage states of storage racks are shown in Fig. 3. The median and dispersion for each fragility curves are listed in Table 3. Note that the median values for both damage states are almost identical.

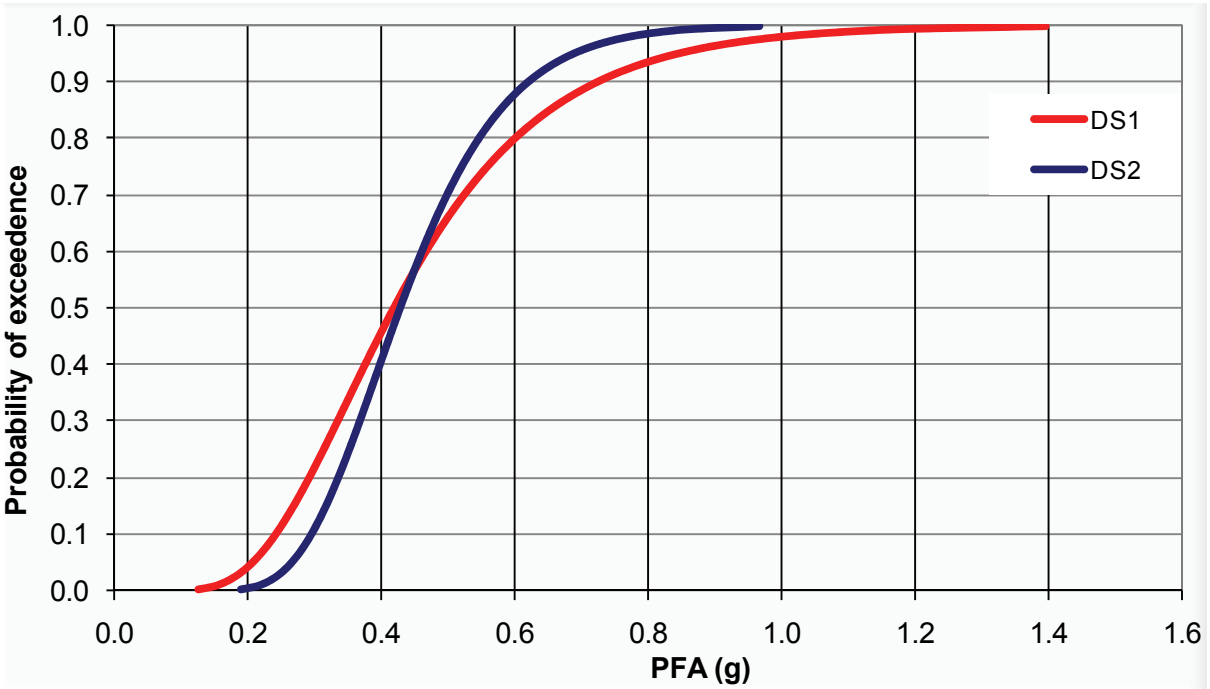


Figure 3 - Fragility Curves for the Two Damage States of Storage Racks.

Table 3 - Medians and Dispersions for the Two Damage States of Storage Racks.

Damage States	Demand Parameter (DP)	Median (θ)	Dispersion (β)
DS1	Peak Floor Acceleration PFA (g)	0.42	0.43
DS2		0.43	0.29

After discussion with the NPP team, it is recommended to characterize the fragility of storage racks in the PACT software with the two damage states (DS1 and DS2) being mutually exclusive with a median value of $\theta = 0.42$ g and a dispersion $\beta = 0.40$ and with the probability of DS1 occurring 60% of the time and probability of DS2 occurring 40% of the time. Therefore, the final fragility curve to be used for storage racks is shown in Fig. 4.

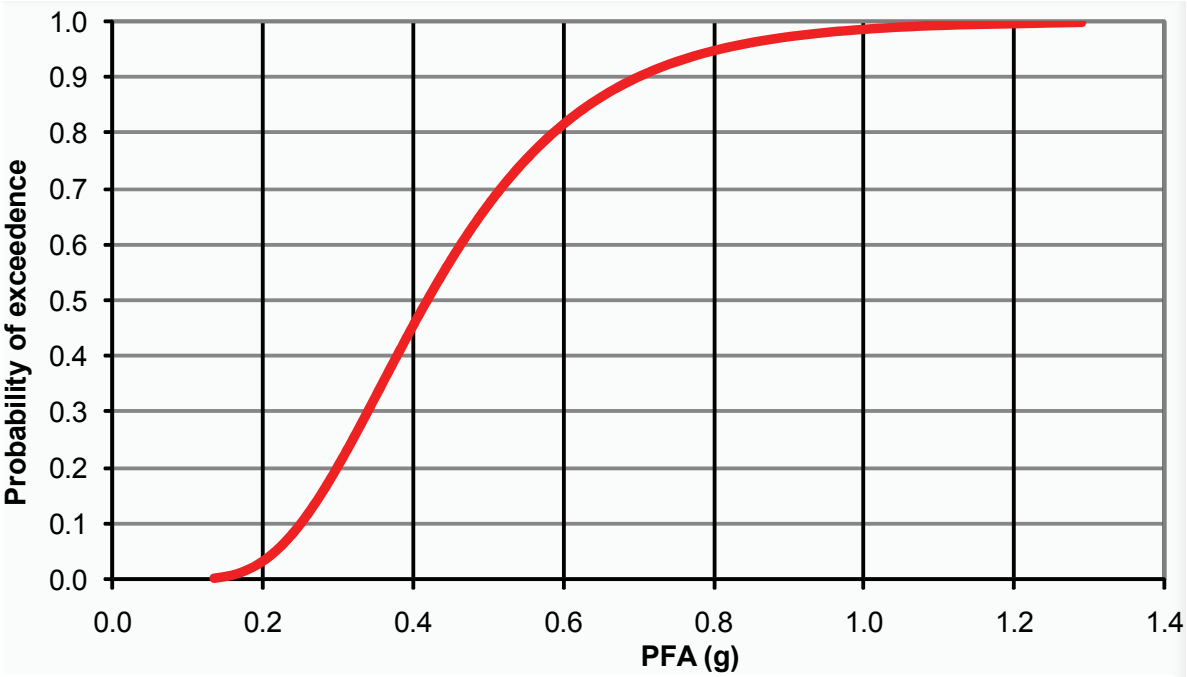


Figure 4 – Recommended Fragility Curve for Storage Racks, θ = 0.42 g, β = 0.40.

3. References.

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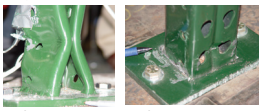
4. Acknowledgements

The work described in this report was conducted as part of the ATC-58 Project "Guidelines for Seismic Performance Assessment of Buildings," pursuant to a contract with the Federal Emergency Management Agency. The substance of such work is dedicated to the public. The author(s) are solely responsible for the accuracy of statements or interpretations contained in this publication. No warranty is offered with regard to the results, findings and recommendations contained herein, either by the Federal Emergency Management Agency, the Applied Technology Council (ATC), its directors, members or employees.

Appendix A – Results Summary

Fragility, damage measures, and consequences for			
Component category:	**Storage Racks designed and installed before 2007**		
Basic composition:	Standard pallet, back-to-back pallet, Drive-in and Stacker Steel Racks designed and installed before 2007. Three to five levels with total height varying from 14.5 ft to 20 ft.		
Normative quantity (unit):	Ea		
Demand parameter (DP):	PFA (geometric mean)		
Number of damage states:	2		
If multiple damage states:	☐ ordered; ☒ mutually exclusive; ☐ simultaneous		
Author and date:	A. Filiatrault xx March 2008		
Damage states, fragilities, and consequences			
	DS1	**DS2**	
Description:	Significant Merchandise Shedding from rack shelves	Significant Structural Damage to Rack Structure	
Illustrations: Filiatrault et al. 2008 DS2: a) Buckling of Upright, b) Base Weld Fracture, c) Cracking and Tearing Across Down-Aisle Connector Perforations in Uprights and d) Damage to Beam Connectors.		a) b)  c) d) 	
Median DP:	0.42g	0.42g	
Beta[(1)]:	0.40	0.40	
Probability:	0.60	0.40	
Correlation:			

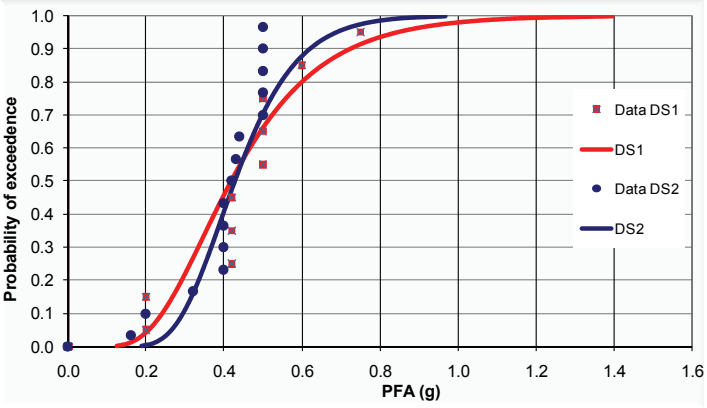
Repairs required:	Replace spilled merchandise	Replace rack structure	
Possible consequences			
Replacement cost (Y/N/?):	Y	Y	
Death or injury (Y/N/?):	Y	Y	
Inoperative facility (Y/N/?):	Y	Y	
Comments:			
Cost per unit[(2)]			
Max cost to lower quantity			
Min cost over upper qty			
Beta (cost)			
Lower quantity			
Upper quantity			
Repair duration per unit[(2)]			
Max duration to lower qty			
Min duration over upper qty			
Beta (duration)			
Life-safety consequences[(2)]			

Appendix B – Summary of Supporting Information

Results of shake table experiments conducted/reported by Chen et al. (1980a, 1980b, 1981), Filiatrault (2001), Castiglioni et al. (2003) and Filiatrault et al. (2006, 2008).	
Number of specimens observed:	20
Construction quality:	□ exceeds □ meets □ does not meet requirements of: Comply with various editions of the Rack Manufacturing Institute Seismic Provisions and Eurocode 8
Seismic installation conditions:	Varies
Loading protocols applied:	Uni-axial, bi-axial and tri-axial shake table testing under various historical and synthetic ground motions.
Method for observing damage:	Observations after testing.

Appendix C – Table of Test Results

ID	Specimen Test No.	Specimen Description	Testing Direction	DP @ DS1	DP @ DS2	Reference
1	170178.6	Standard pallet-type 3 levels - 2 bays wide - 1 bay deep	Uni-axial (down-aisle)	N/A	0.43g	Chen et al. (1980a, 1980b, 1981)
2	240178.3		Uni-axial (cross-aisle)	N/A	0.16g	
3	060278.4	Standard pallet-type 3 levels - 2 bays wide - 2 bay deep	Bi-axial (cross-aisle + vertical)	N/A	0.20g	
4	140278.8			N/A	0.44g	
5	Specimen B Test No. 7	Standard pallet-type 3 levels - 2 bays wide - 1 bay deep	Uni-axial (down-aisle)	0.20g	N/A	Castiglioni et al. (2003)
6	Specimen D Test No. 7			0.20g	N/A	
7	Configuration 1 Tests HD-S6 and HD-S7	Back-to-back pallet-type 4 levels - 2 bays wide - 2 bays deep	Uni-axial (cross-aisle)	0.42g	0.50g	Filiatrault (2001)
8	Configuration 2 Test HD-S9			0.42g	0.42g	
9	Configuration 3 Tests HD-S11 and HD-S12			0.42g	0.50g	
10	Configuration 4 Test HD-S15			0.50g	0.50g	
11	Configuration 5 Test HD-S17		Uni-axial (down-aisle)	N/A	0.50g	
12	Rack No. 1	Standard pallet-type 4 levels - 2 bays wide - 1 bay deep	Uni-axial (down-aisle)	N/A	0.40g	Filiatrault et al. (2006)
13	Rack No. 2			N/A	0.40g	
14	Rack No. 3			N/A	0.40g	
15	Rack No. 4			N/A	0.40g	
16	Test Series 1B	3 levels - 2 bays wide - 1 bay deep	Uni-axial (cross-aisle)	N/A	0.32g	Filiatrault et al. (2008)
17	Test Series 6	4 levels - 2 bays wide - 1 bay deep	Tri-axial	0.60g	N/A	
18	Test Series 7			0.50g	N/A	
19	Test Series 8			0.75g	0.75g	
20	Test Series 9			0.50g	0.50g	



Appendix D – Quality Tests

Quality test	DS1	DS2	
Passes Lilliefors goodness of fit test? (Type A only)	No	No	
Are θ and β within 20% of past results? If not discuss.	Yes	Yes	
Are $0.2 \leq \beta \leq 0.6$? If not discuss.	Yes	Yes	