LOWERING THE INITIAL AND LIFETIME COSTS OF ISOLATION IN BUILDINGS

Justine Woo
Saint Martin's University

REU Site: University of California, Berkeley
PI: Stephen Mahin
Graduate Student Advisors: Tracy Becker and Charlotte Wong

National Science Foundation Award Numbers: 0724208 and 1005054

ACKNOWLEDGEMENTS

This research work was overseen and partially supported by the Pacific Earthquake Engineering Research (PEER) Center as a part of the 2010 PEER Internship Program. Financial support for the author was provided by the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) and the National Science Foundation. The author would also like to thank Professor Stephen Mahin, Tracy Becker, Charlotte Wong, Heidi Faison, and the faculty and staff at PEER and University of California, Berkeley, for their mentorship during the research process. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the sponsors.

ABSTRACT

Since the turn of the 21st century, the damage cost due to natural disasters has risen substantially. This brings forth the need to limit these damages as much as possible to keep the economic impact lower. Isolation provides one of the best ways to do so. However, building developers and owners are unwilling to pay for the additional initial cost of isolation because projects focus on first budgets, rather than long-term gain. To limit the initial and lifetime cost of isolation, this study seeks to find where inter-story drift and acceleration substantially impact the damage cost. This allows engineers to design buildings that perform well under seismic motion while being more affordable. In this analysis, three configurations were taken into account: a fixed-base building, a base isolated building, and a building with isolators placed on the 1st story columns. Each of them has a different construction cost and was tested to observe which one would perform reasonably under seismic motion to prevent a substantial increase in damage costs.

TABLE OF CONTENTS

BACKGROUND

In the United States, isolation is limited due to high initial costs, buildings that must operate in emergencies or that have important content, and historical sites. These include hospitals, government buildings, and technology and research centers. However, taking into account downtime, in the event of an earthquake nonstructural damages, repair, and possible demolition and reconstruction, make up a majority of the damage cost in all buildings. This is due to a high standard of living, inventory costs and loss of operations [Bandyk, 2010]. By improving a building's performance post-earthquake, these losses decrease. However to keep a potential economic setback from occurring, the use of base isolation needs to extend to residential and commercial buildings in order to maximize post-earthquake operability.

Base Isolation Theory

Base Isolation is one of the few ways to mitigate story-drift and acceleration, the two main causes of damage. Base isolation separates a superstructure from its foundation through the use of elastomeric bearings, sliding bearings, or a combination of the two. Collectively, these bearings act as a layer with low lateral resistance and reduce seismic-induced deformations by concentrating deformations to the isolated layer. This increases a building's natural period from 1 second or less to 2.0 to 2.75 seconds (these are typical values and may not apply to all buildings) so that lateral load factors are reduced 50 to 80%; this is visible in Figure 1 below. In effect, the transmissibility and pseudo-acceleration decreases, removing the fundamental tradeoff between decreasing story-drift at the expense of increasing acceleration and vice versa [Morgan & Mahin, 2007].

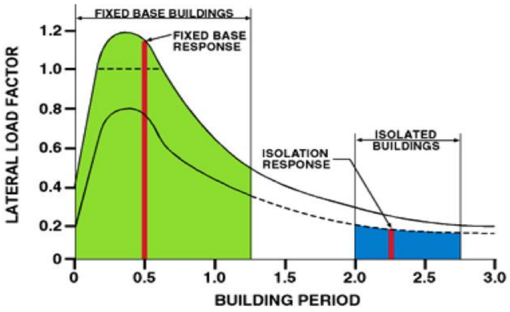


Figure 1: Effect of Building Period on Lateral Load Factor

Although this knowledge is known to the engineering community, building developers do not fully understand the fundamental ideas behind earthquake design. Social misconceptions on the subject have led to many impediments to base isolation that prevent it from being used.

Earthquake Economics

Base isolation has a higher initial cost than conventional construction. The cost increase comes from isolators, excavation, construction of an extra level that provides no additional usable or rentable space, stiffening of the superstructure, and a moat that surrounds the isolated layer. This leads to an additional cost of $50 per square foot [Enscoe, 2010]. Building owners and developers are reluctant to pay this additional cost. However, the benefits of isolation far exceed the initial cost of installing isolation, especially in today's society.

The costs associated with earthquake damages have risen since the turn of the 21st century. Higher living standards and technological improvements that increase efficiency have elevated costs. A prime example of this is shown in comparing the Gross Domestic Product GDP and loss of life in the Chilean and Haitian earthquakes. In Chile, the GDP per capita is $14,700, compared to $1,300 per capita in Haiti [Bandyk, 2010]. In the event of an earthquake, as loss of life is limited, the costs due to damage increase. Even with moderate ground motion, however, recent earthquakes show that even in code compliant buildings, large economic losses and major societal disruptions may occur [National Science Foundation, 2008]. Therefore, making more involved and educated choices on isolating buildings is beneficial, not only for life safety, but also from an economic and societal perspective.

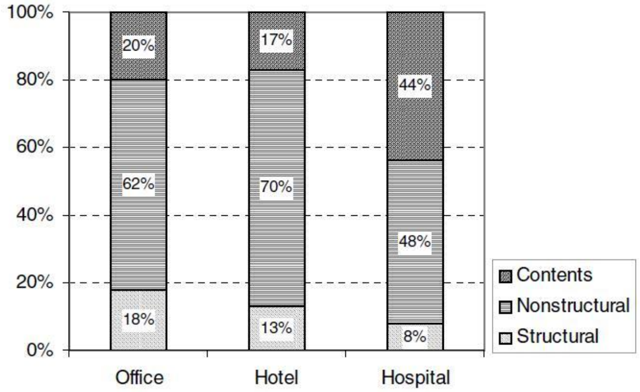


Figure 2: Cost percentage of structural components, non-structural components, and contents in offices, hotels, and hospitals (adapted from Taghavi and Miranda 2003)

In Figure 2, the damage costs are split into three groups: contents, nonstructural, and structural. As shown, over 80% of losses may come from nonstructural elements including but not limited to downtime, repair and potential demolition. In effect, research has been focusing on nonstructural elements. In building analyses, the mean annual loss has been proven to be as much as five times higher for fixed-based buildings than isolated buildings. Most of the cost is due to business interruption. Interestingly enough, nonstructural damage is more likely to occur at lower earthquake levels [Miranda, 2004]. These damages are mainly caused by two seismic responses: story-drift and acceleration.

Applied Technology Council – 58 (ATC – 58) has developed the programs, Performance Assessment Calculation Tool (PACT) and PACT II, to estimate these costs. ATC - 58 was developed under a contract with the Federal Emergency Management Agency (FEMA). The goal of ATC – 58 is to develop "Performance-Based Seismic Design Guidelines" by taking into account hazard levels and the model building's response and translating it into probabilistic losses. PACT was created June 2007 and acts as a companion to the Performance Assessment Guidelines [Applied Technology Council]. PACT is used to demonstrate the benefits protective systems provide to owners, in terms of economics that they can relate to, such as a long term monetary return on their investment [Sayani & Ryan].

PACT allows the user to enter a building's design components, such as story-height and area, and choose performance groups to evaluate the total loss that may occur in an earthquake. The components and content that are evaluated are already integrated into the program, as are the fragility curves. From user inputted information, the program then assembles a building performance model. The program then forms a series of realizations that reflect a possible response from the building, which the user can change. The more realizations are entered, the more exact the damage loss estimate will be. From the realizations, a loss distribution curve is formed [Applied Technology Council]. PACT II differs from PACT mainly in the fact that there are more fragility curves available for use.

In addition, ATC- 58 had also hired Dr. Judith Mitrani-Reiser to create a MATLAB program that achieves the same objectives as PACT II. This program was edited by Dr. Keri Ryan. The MATLAB program is an open-source program and therefore is more flexible, allowing users to enter more performance groups and to alter the program, as opposed to PACT II which is currently a black box. PACT II, however, is more user friendly than the MATLAB program, in which the user needs to understand the scripts and its associated Excel files. However, the program does not allow a user to enter hazard curves, population data or limited collapse data.

These two programs allow us to collect data on where damage costs in a model building will increase. Currently, it is unknown at which accelerations and story-drifts costs increase dramatically. With these two programs, designers can target where the increases occur substantially and design around those parameters.

Intent

The motivation behind this research project is to extend the use of isolation to office and residential type buildings. Because cost is the core issue impediments are built on, lowering the cost of isolation through reverse designing is a fundamental step to adoption. Essentially, this involves designing a building so that, under chosen ground motions, damage costs can be limited by analyzing where costs due to inter-story drift and peak floor acceleration start increasing dramatically.

MODEL BUILDING

The model building used in this analysis is an office building, chosen from ten model buildings, designed by Forell-Elsesser Engineers and evaluated by Tools for Isolation and Protective Systems [NEES TIPS]. It is labeled as “Isolated Ordinary Concentric Braced Frame (OCBF)” with a building height of three stories. The building meets minimum code standards designed by the Equivalent Lateral Force Method. The model building has 64 performance groups and only a fraction of them are taken into account in this analysis.

COST ANALYSIS

PACT II

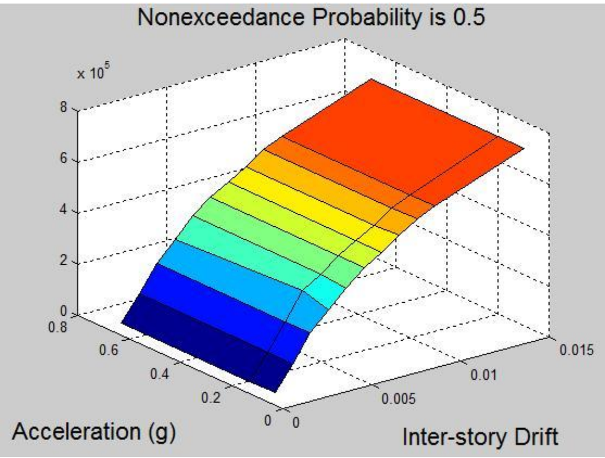
To investigate where damage cost associated with inter-story drift begins to increase dramatically, an analysis incorporating PACT II was used. Story-drift values between 0.001 and .05 were inputted with accelerations ranging from 0.1 to 0.7g. Damage costs were then retrieved from PACT II after the building was modeled by inputting the nonstructural components shown in Table 1.

Table 1: List of Nonstructural Components Taken Into Account in PACT II

No.	Component	Quantity
B2011.003a	Exterior Wall OSB and stucco Type 3a	27360
C1011.009a	Interior Partition Type 9a	86830

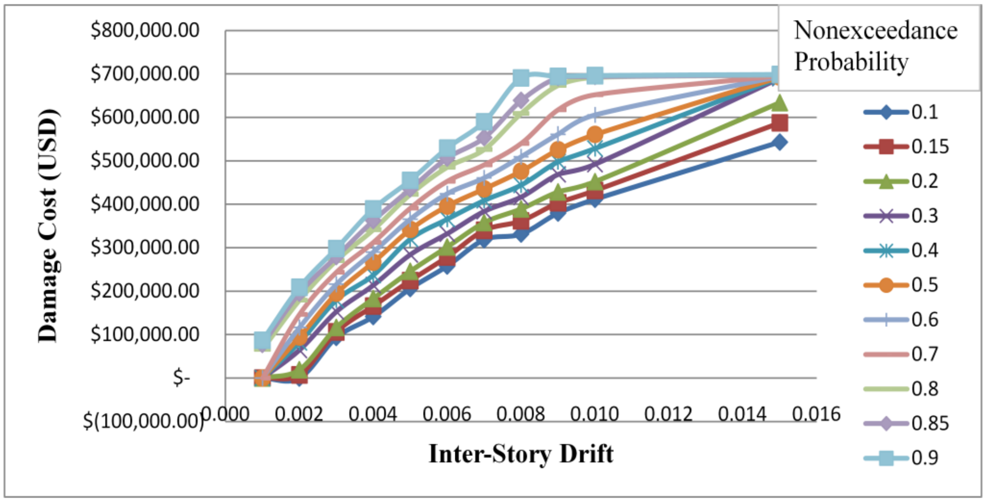
These components are primarily drift sensitive and make ups 8% of the total cost of construction of the model.

Graph 1 and 2 display the results from PACT II.



Graph 1: Example of Damage Costs Due to Inter-story Drift and Acceleration from PACT II

Damage costs do not increase substantially at any point due to acceleration because the components are not acceleration dependant.



Graph 2: Damage Costs Due to Inter-story Drift at 0.7g

Evaluating where the steepest cost increase is located, the average percents by which the damage costs increased divided by the inter-story drift step were recorded. Table 2 shows the results.

Table 2: The Average Increase in Damage Costs Divided by the Inter-story Step with All the Exceedance Probabilities Taken into Account

	Acceleration (g)		
Inter-story Drift	0.1	0.2	0.7
0.002	155	155	155
0.003	504	504	504
0.004	120	120	115
0.005	113	113	118
0.006	90	90	90
0.007	80	80	80
0.008	73	73	73
0.009	84	84	84
0.01	46	46	46
0.015	41	41	41

When all the exceedance probabilities are taken into account, 0.003 story drift has the greatest amount of increase followed by 0.002 story-drift, then 0.004 or 0.005 (when acceleration is equal to 0.7). Because these values are so close together, it is best to keep story-drift lower than 0.002; although in reality, this is unreasonable.

However, with only two nonstructural components taken into account, we do not have an accurate amount of data to determine where damage cost due to story-drift and acceleration will increase the most. With these two fragility curves taken into account, the maximum amount of damage is $704,016. In reality, the costs can reach $17,776,263 for the OCBF model building. This analysis using PACT II only serves as a means by which one may see how PACT II is able to show variations in cost.

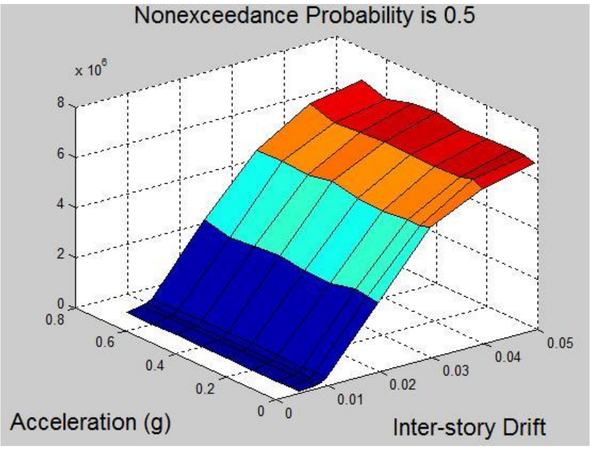
MATLAB Program by Judith Mitrani-Reiser

As in PACT II, story-drift values between 0.001 and 0.05 were inputted with accelerations ranging from 0.1 to 0.7g. However, more performance groups are available in Mitrani-Reiser's program and more can be added by the user. Table 3 summarizes the components taken into account in this analysis.

Table 3: List of Nonstructural Components Taken Into Account in Mitrani-Reiser's MATLAB Program

No.	Component	Quantity
B1035.000	Moment Connections	116
B2022.001	Aluminum Framed Windows	8208
C1011.009a	Interior Partitions and Finish, 2 Sided	86630
C3032.001	Suspended Acoustical Tile Ceiling	68392
D4011.002	Automatic Sprinklers (braced)	72192

These make up 15% of the total cost of structural and nonstructural systems in the model building. The suspended acoustical tile ceiling and automatic sprinklers are acceleration sensitive while the other components are story-drift sensitive.



Graph 3: Example of Damage Costs Due to Inter-story Drift and Acceleration from Judith Mitrani-Reiser's MATLAB Program

The results from MATLAB program are show in Graph 3. The increase in damage costs due to inter-story drift is substantially greater than those due to acceleration. This is because story-drift makes up 29% of the total possible cost of damage. No data can be collected in accordance to where acceleration costs increase because the damage costs decrease at various points throughout the graph. This may be occurring because the acceleration components are limited, compared to the story-drift oriented ones. Thus, they are more affected by probability variations. When the story-drift is kept constant the damage costs do not vary much, especially if compared to the rate by which story-drift increases.

Table 4: The Average Increase in Damage Costs Divided by the Inter-story Drift Step with Acceleration Values of from 0.05g to .7g Taken into Account

	Inter-Story Drift						
Nonexceedance Probability	0.008	0.009	0.010	0.020	0.030	0.040	0.050
0.10	9.79	2.51	8.11	13.84	3.54	1.14	0.46
0.15	10.51	2.80	8.18	12.60	3.13	1.05	0.43
0.20	11.11	3.04	8.24	11.69	2.83	0.98	0.41
0.30	12.22	3.46	8.33	10.33	2.37	0.86	0.37
0.40	13.32	3.84	8.42	9.28	2.01	0.77	0.34
0.50	14.49	4.22	8.51	8.38	1.70	0.68	0.31
0.60	15.85	4.62	8.61	7.56	1.42	0.60	0.28
0.70	17.39	5.08	8.72	6.75	1.13	0.51	0.24
0.80	19.48	5.65	8.87	5.88	0.82	0.40	0.20
0.85	20.98	6.04	8.97	5.38	0.63	0.34	0.18
0.90	23.21	6.59	9.12	4.76	0.40	0.27	0.14

Where damage costs increase due to inter-story drift is shown in Table 4. Inter-story drift increases at 0.008, 0.010, and 0.020. For exceedance probabilities above 0.2, 0.02 story-drift has the greatest amount of increase in the price. However, as the exceedance probability increases, the damage costs increases shift toward lower values of story-drift (0.008, 0.009, and 0.01). The exceedance probability of 0.2 acts as a shifting point before the damage costs are predominantly toward low story-drifts.

Limitations Encountered with PACT II

The limitations that were encountered in this test are due to the fact that PACT II is currently an alpha program. Once PACT II is complete, this test will need to be rerun for more accurate data. At that time, 85% of the total damage cost, if not more, may be taken into account. PACT II will not be able to make up the total cost because some components are exclusively for base isolated buildings in the OCBF model building; PACT II is used to determine damage to fixed-base buildings. While NEES TIPS includes the cost of base isolators, base isolator pedestals, and a moat cover, PACT II does not.

In comparison to MATLAB, although PACT II is more user-friendly, MATLAB, at the moment, provides more accurate data because it is more complete. PACT II has a greater potential to be used by practicing engineers, cost estimators, and building developers. However, the limitations of PACT II are visible at the moment, especially when comparing the graphs. The PACT II graph is concave in shape while the MATLAB program provides a more cubic graph.

This is not to say that PACT II is unable to have the same amount of variations as MATLAB. Although in the analysis above, the increases in cost gather toward the beginning, this does not occur for all buildings.

Conclusion

Although many limitations were encountered in the damage cost analysis, points where damage costs increased substantially were identified. Model buildings were then designed in Open System for Earthquake Engineering Simulation (OPENSEES). This allowed us to compare their performance, which is determined by how much story-drift occurred when they were subjected to ground motion, to the results from PACT II and MATLAB. Once comparisons between the two are made, an engineer will be able to communicate the amount of loss one would expect from the results. For example, damage costs begin at .8% story-drift according to the MATLAB results. If a building has 1% drift, it will expect to have some damage and the engineer can communicate to the developer or owner how much damage is expected. However, if the damage is less than .8%, then no damage will be expected.

Therefore, a comparison of the performance of the buildings analyzed in OPENSEES will provide users with the data that is comparable to those given in the MATLAB and PACT II programs.

OPENSEES BUILDING ANALYSIS

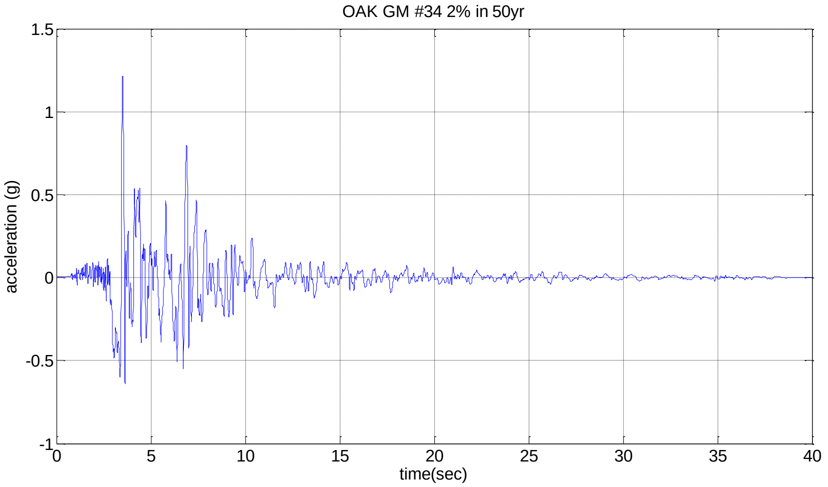
Model Building

Two NEES TIPS moment frame buildings designed by Dr. Troy Morgan are used to carry out the structural analysis part of this study. The first moment frame structure is a three-story fixed base Special Moment Resisting Frame (SMRF), while the second one is an isolated Intermediate

Moment Resisting Frame (IMRF). Considering the aforementioned costly aspect of constructing a moat in a traditionally base isolated building, another isolation configuration, namely 1st story isolation, is being analyzed in this study. These three model buildings – fixed base SMRF, base isolated IMRF, and 1st story isolated - are modeled in OPENSEES by Charlotte Wong.

Ground Motions

Due to insufficient time and limitations of this study, only one ground motion is used so far. It is used as a tool to obtain a preliminary study of the behavior and responses of the model buildings. The ground motion selected for this analysis is the fault normal Northridge maximum credible earthquake (MCE) level motion, shown in Graph 4. It was selected from a suite of ground motions created by Jack Baker, a professor at Stanford. One of the main reasons why this motion was selected is because the Peak Ground Acceleration (PGA) of the ground motion is 1.2157g. Another important reason for the selection of this ground motion is its small time step. When conducting response history analysis (RHA), especially with a highly nonlinear model, it is advantageous to have as small time step (dt) as possible to facilitate numerical analysis and prevent any convergence issue.



Graph 4: Oakland Ground Motion from Jack Baker

Fixed Base Fiber Model

The fixed base fiber model has 2% Rayleigh Damping. An illustration of the building model is shown in Figure 3. This model provides a visual aid that can be compared to the other building models.

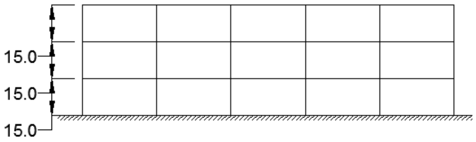
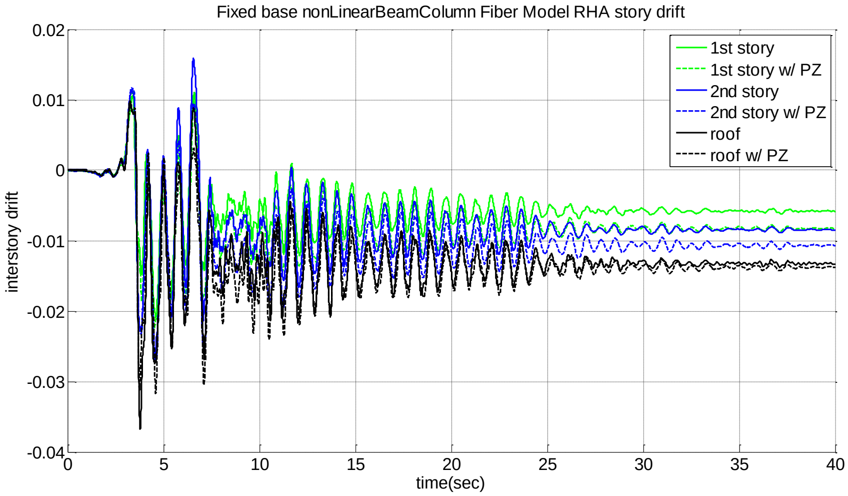


Figure 3: Fixed Base Elevation View



Graph 5: Inter-story Drift for a Fixed Base Fiber Model

Graph 5 shows the inter-story drift that occurs once Figure 3 is subjected to ground motion. For the fixed-based fiber model, the inter-story drift maximum is 3.5%.

Base Isolated Fiber Model 5% Rayleigh on the superstructure

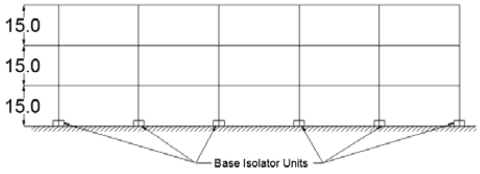
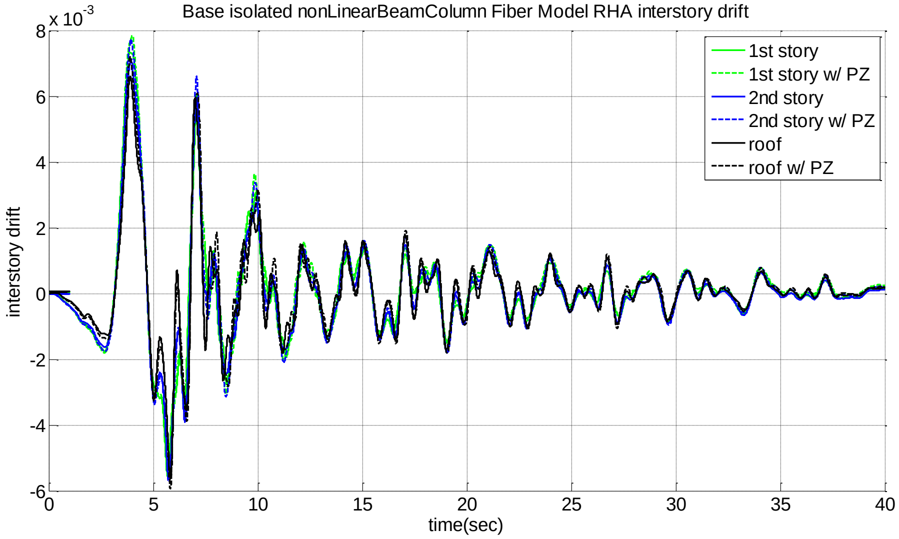


Figure 4: Base Isolation Elevation View



Graph 6: Inter-story Drift for a Base Isolated Model with 5% Rayleigh Damping

Graph 6 shows that, for the base isolated model shown in Figure 4, the story-drift does not exceed 0.8%. This is 77% less than the amount of drift in the fixed base building. The base isolator displacement also stayed within range of the maximum moat size, 33 inches. At most, it displaced 25 inches.

Base Isolated Fiber Model 5% Rayleigh with Isolators on the 1st Story Columns

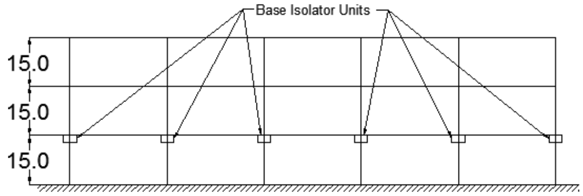
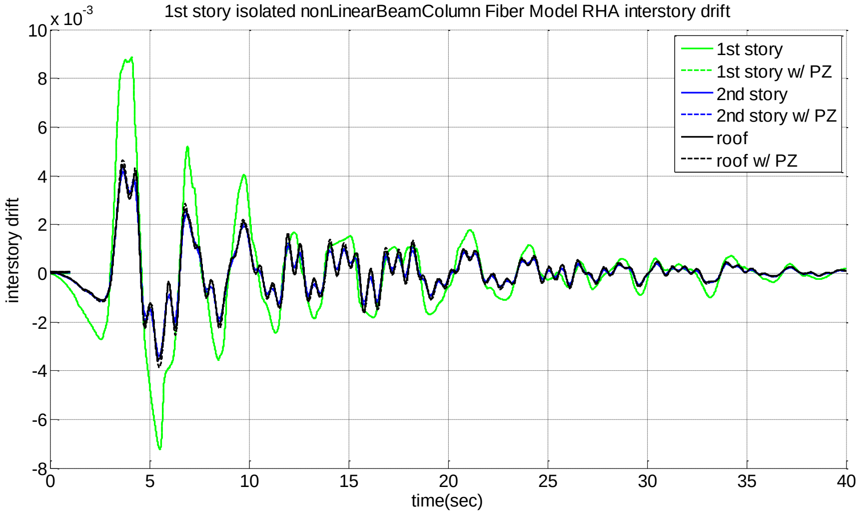


Figure 5: 1st Story Isolation Elevation View



Graph 7: Inter-story Drift for a Base Isolated Model 5% Rayleigh with Region on Mode 2-4 with Isolators on the 1st Story Columns

This isolated model with 5% Rayleigh on the superstructure has the isolators located on the first story columns in an attempt to reduce costs by eliminating the need for a moat and reducing the building frame cost. Isolation on the first story columns also provides other advantages such as using the building plot effectively, displaying new technologies so that people are more aware of isolation, and decreasing wall movement in the event of an earthquake [SDR Technology Co. Ltd]. The story-drift for this first story isolated model is 0.88%, 0.1% higher than that of the base isolated configuration. This observation can be made on Graph 7. In this analysis, the isolator displacement stayed within range of the maximum moat size. At most, it displaces less than 23 inches.

CONCLUSION

The story-drifts determined in this analysis are shown in Table 5.

Table 5: Story-Drift Comparisons

	Maximum Inter-story Drift	Peak 1	Peak 2	Peak 3
PACT II		0.2%	0.3%	0.4%
MATLAB		0.8%	1%	2%
Fixed Base Building	3.5%			
Base Isolated Building	0.8%			
1st Story Isolated Building	0.88%			

None of the buildings meet the requirements set by PACT II. PACT II requires the story-drift to be less than 0.4% or all the peaks will be exceeded, which is unreasonable. The maximum cost is reached at 0.8% story-drift when the nonexceedance probability is 90%. However, these errors are caused by the limited fragility curves in PACT II. The amount of loss possible in PACT II is less than that in MATLAB by a factor of ten. This leads to the main issue with PACT II; the loss amount is less than the cost it takes to install isolation. Because the building area is more than 500 sq. ft., the amount of loss possible will be less than the cost of isolation while only Exterior Wall OSB and Stucco and Interior Partitions are being taken into account. However, in reality, for the NEES TIPS model building, the cost of installing isolation is much less expensive than the possible loss. Therefore, the data from PACT II is not completely reliable. PACT II is included in this report only to show how it can be an effective tool once it is complete.

The MATLAB results show that using base isolation and isolation on the 1st story columns are both viable options. The base isolated building experiences damage at 0.8% story-drift, where the first peak in cost is reached. Therefore, the first peak is unavoidable and designers must plan for damage less than the second peak (1%). The 1st story isolated building stays below this percentage, having a maximum story drift of 0.88%. Comparing the damage costs these two buildings will experience, the base isolated building is expected to have $27,600 worth of damage while the 1st story isolated building is expected to have $35,300 worth of damage. There is a 28% difference between the costs.

However, these conclusions are limited. It is difficult to conclude which building may be more effective overall because only one ground motion was run. Also, the MATLAB program only allowed for braced frame buildings to be modeled, while the OPENSEES analyzes used moment frame buildings. When an OPENSEES analysis is run using a braced frame, the results are expected to be different. Braced frame buildings tend to have less story-drift and more accelerations in an earthquake. Therefore, if the components used in PACT II and MATLAB are kept constant, the isolated buildings may not reach any of the peaks. Since not all the performance groups were taken into account, however, the actual results may be substantially different. Therefore, once PACT II is complete, this program may be rerun.

BIBLIOGRAPHY[AMW1]

Applied Technology Council . (n.d.). *ATC-58*. Retrieved July 22, 2010, from ATC Applied Technology Council: http://www.atcouncil.org/index.php?option=com_content&view=article&id=85&Itemid=129

Bandyk, M. (2010, March 24). Why Natural Disasters Are More Expensive—But Less Deadly. *U.S. News and World Report* .

Becker, T. C., Furukawa, S., Mahin, S. A., & Nakashima, M. (2010). Comparison of US and Japanese Codes and Practices for Seismically Isolated. *Structures Congress 2010.* Orlando: American Society of Civil Engineers.

Chopra, A. (2007). *Dynamics of Structures: Theory and Applications to Earthquake Engineering, Third Edition.* Upper Saddle River: Prentice Hall.

Earthquake Protection Systems, Inc. (EPS). (2008). *Friction Pendulum Bearings*. Retrieved July 20, 2010, from Earthquake Protection Systems: http://www.earthquakeprotection.com/product.html

Enscoe, A. (2010). *Saving in Isolation: A preliminary study of the lifetime repair costs of base isolated and fixed-base buildings.* Berkeley.

Isolators Move Up to Allow Bigger Addition to Building. (2008, February 4). *Engineering News Records* , pp. 20-21.

Kelly, J. M. (1998). *Base Isolation: Origins and Development.* Berkeley: National Information Service for Earthquake Engineering.

Mahin, S. (2008). Sustainable Design Considerations in Earthquake Engineering. *The 14th World Conference on Earthquake Engineering.* Beijing.

Mahin, S., & Becker, T. C. (2010). The Effect of the Statistical Distribution of Isolator Properties. *14 European Conference on Earthquake Engineering 2010.* Ohrid.

Mayes, R. (2008). *Impediments to the Implementation of Seismic Isolation.* San Francisco.
Miranda, E. A. (2004). Assessment of Seismic Performance in Terms of Economic. *PEER* .
Morgan, T., & Mahin, S. (2007). *Performance-Based Design of Seismic Isolated Buildings Considering Multiple Performance Objectives.* Berkeley.

National Science Foundation. (2008, October 16). *NEESR-SG: TIPS - Tools to Facilitate Widespread Use of Isolation and Protective Systems, a NEES/E-Defense Collaboration* . Retrieved July 22, 2010, from National Science Foundation: http://www.nsf.gov/awardsearch/showAward.do?AwardNumber=0724208

NEES TIPS. (n.d.). *Introduction to Life Cycle Performance Evaluation and Cost/Benefit Study*. Retrieved July 23, 2010, from Tools for Isolation and Protective Systems (TIPS): http://www.neng.usu.edu/cee/faculty/kryan/NEESTIPS/PBEE_study.html

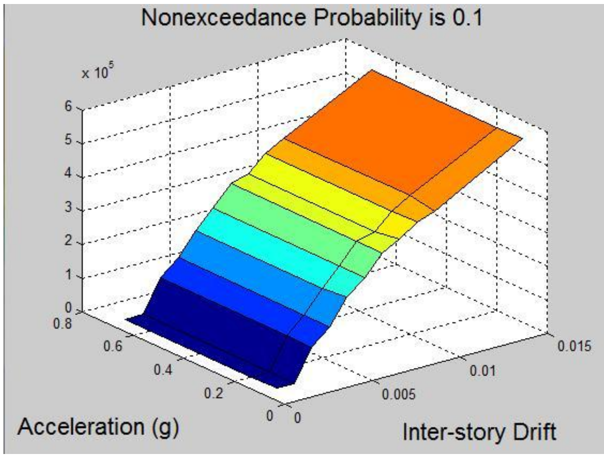
Sayani, P., & Ryan, K. *A First Attempt at Loss Evaluation in Fixed-Base and Seismically Isolated Buildings Using PACT.*

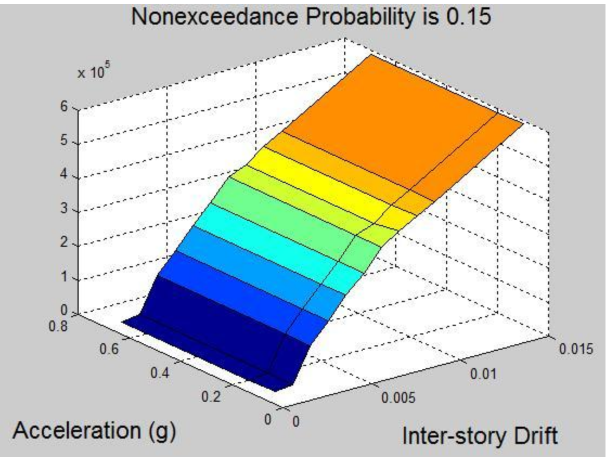
SDR Technology Co. Ltd . (n.d.). *Advantages of mid-story isolation over base isolation*. Retrieved August 4, 2010, from Seismic Design & Retrofit: http://www.sdr-tech.co.jp/tmg_advantage_e.html

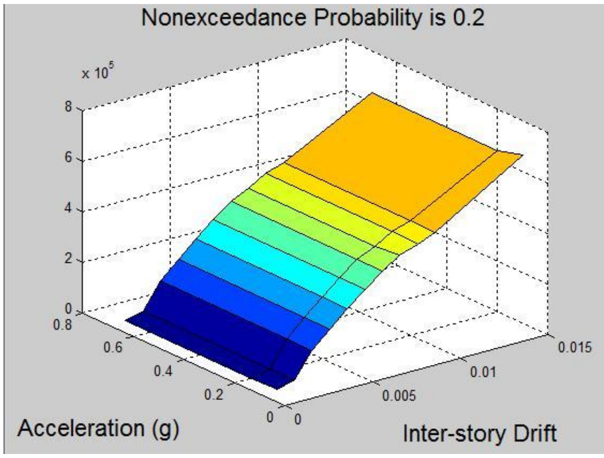
Taghavi, S., & Miranda, E. (2003). *Response Assessment of Nonstructual Building Elements.* Berkeley: PEER.

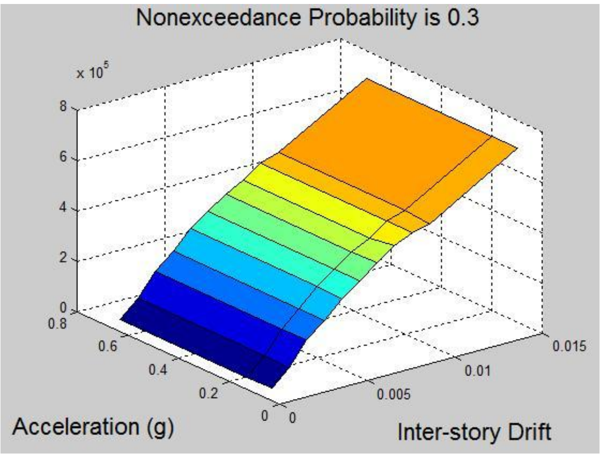
APPENDICES

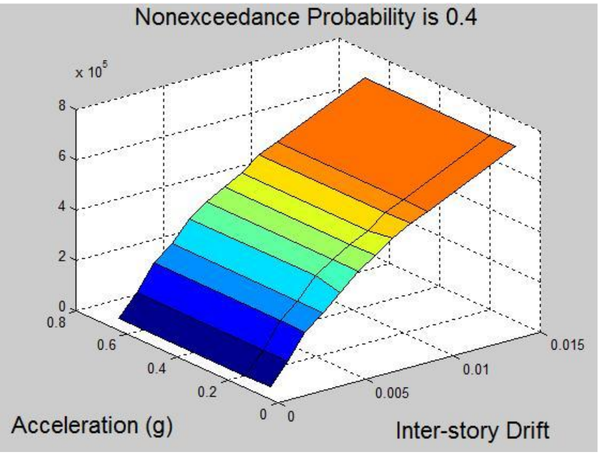
Appendix A: Graphs of Damage Costs Due to Acceleration and Inter-story Drift from PACT II

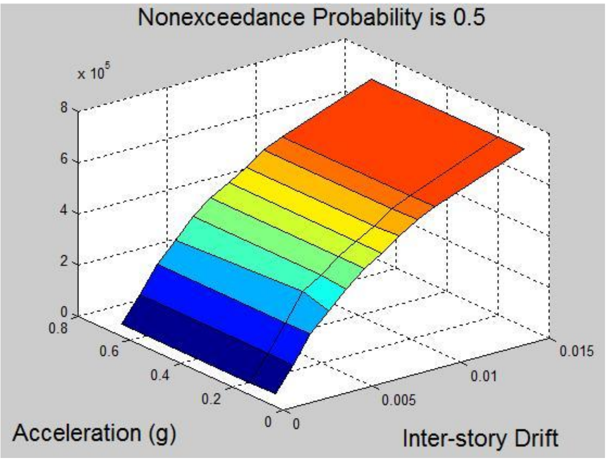


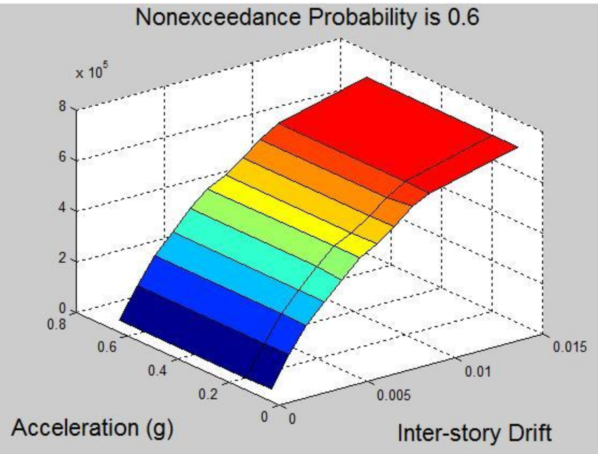


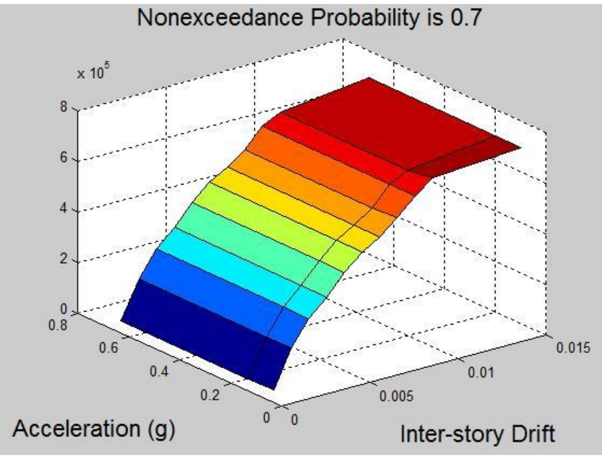


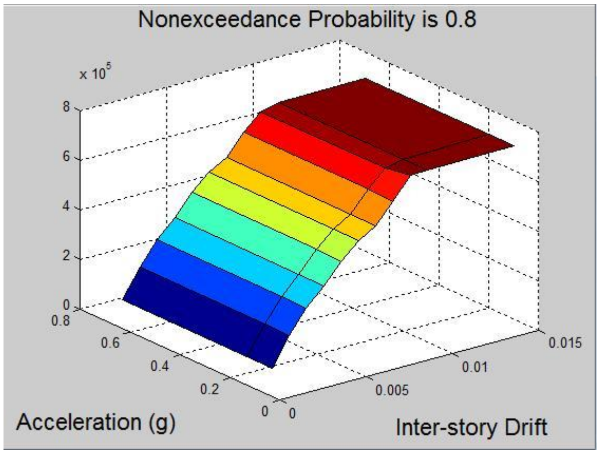


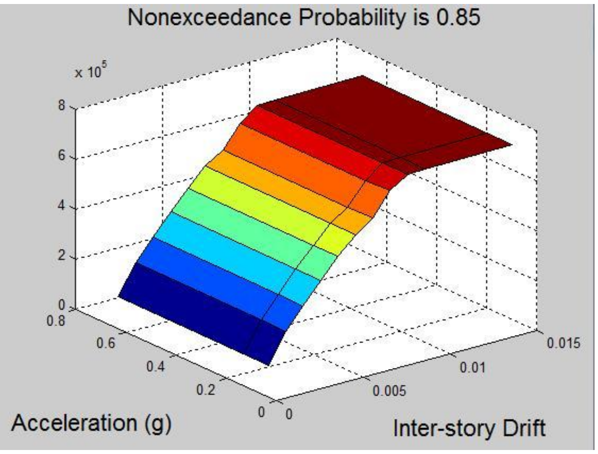


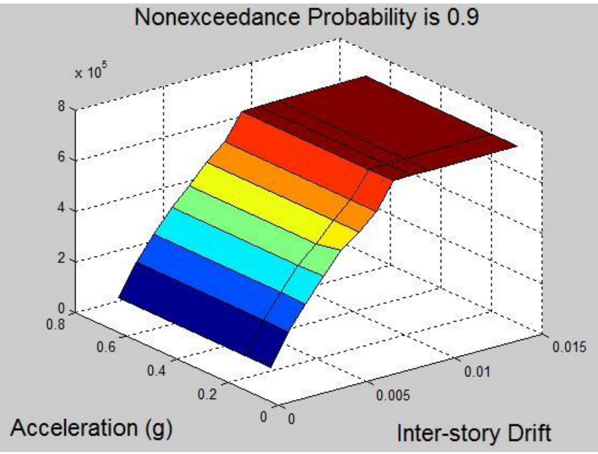



Nonexceedance Probability is 0.6
x 10^5
8
6
4
2
0
0.8
0.6
0.4
0.2
0
Acceleration (g)
0
0.005
0.01
0.015
Inter-story Drift

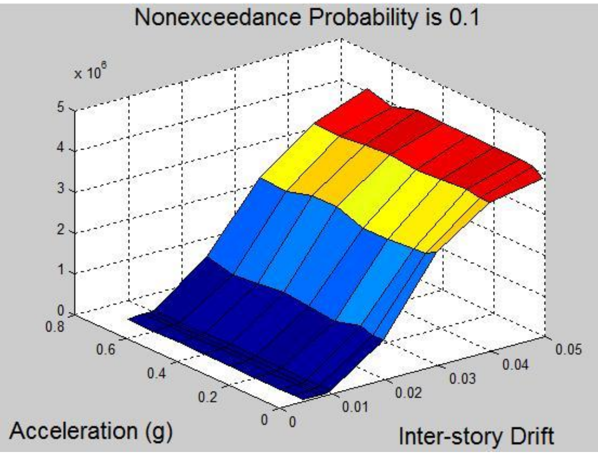

Nonexceedance Probability is 0.7
x 10^5
8
6
4
2
0
0.8
0.6
0.4
0.2
0
Acceleration (g)
0
0.005
0.01
0.015
Inter-story Drift

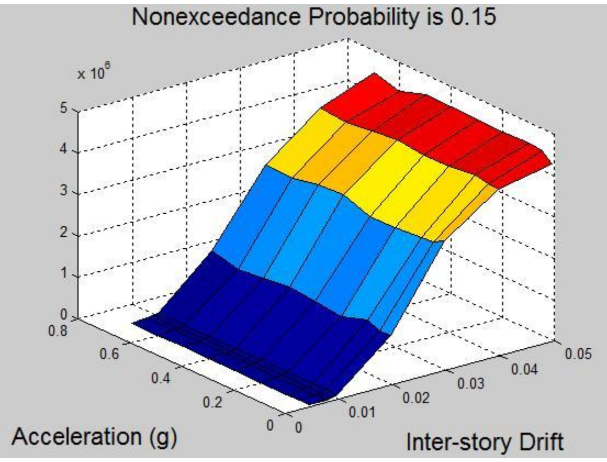

Nonexceedance Probability is 0.8
x 10^5
8
6
4
2
0
0.8
0.6
0.4
0.2
0
Acceleration (g)
0
0.005
0.01
0.015
Inter-story Drift

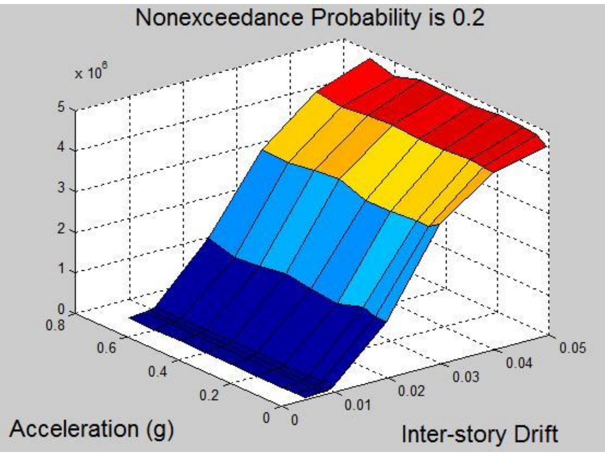

Nonexceedance Probability is 0.85
x 10^5
8
6
4
2
0
0.8
0.6
0.4
0.2
0
Acceleration (g)
0
0.005
0.01
0.015
Inter-story Drift

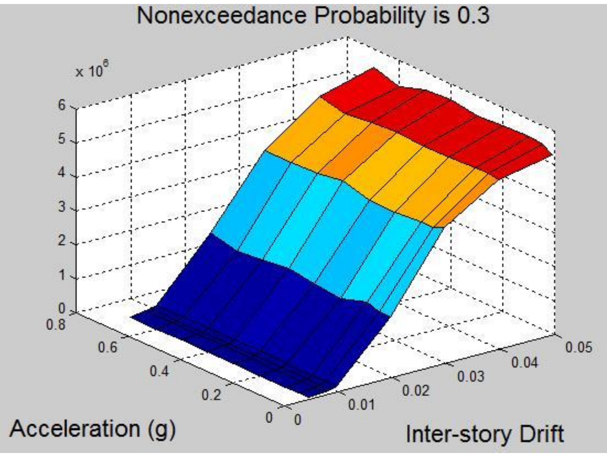

Nonexceedance Probability is 0.9
x 10^5
8
6
4
2
0
0.8
0.6
0.4
0.2
0
Acceleration (g)
0
0.005
0.01
0.015
Inter-story Drift

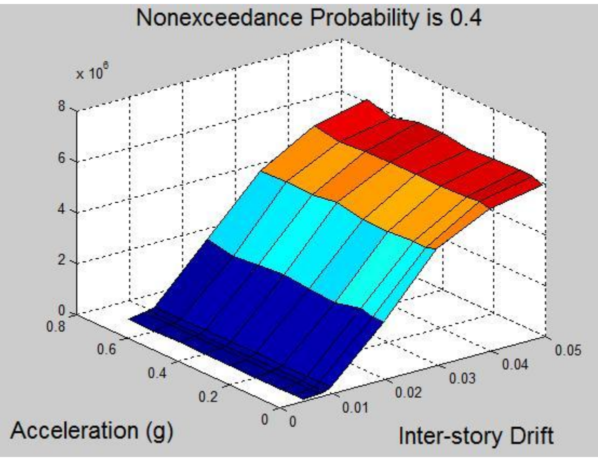
Appendix B: Graphs of Damage Costs Due to Acceleration and Inter-story Drift from Judith Mitrani-Reiser's MATLAB Program

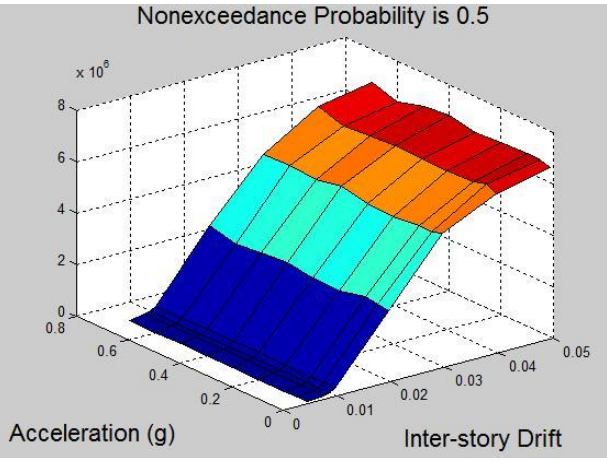


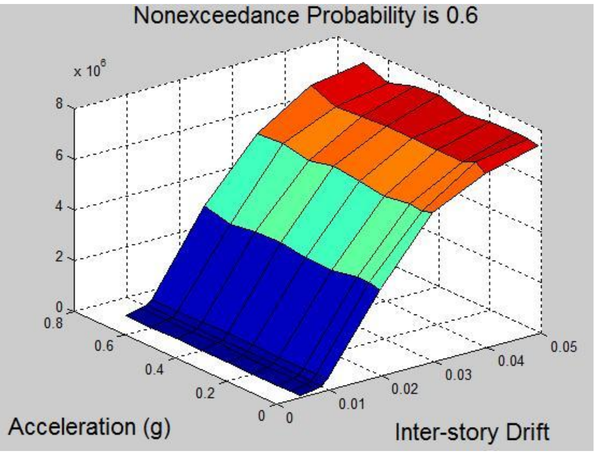


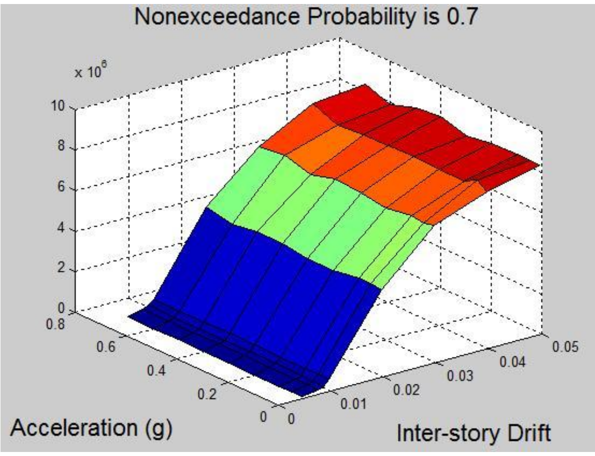


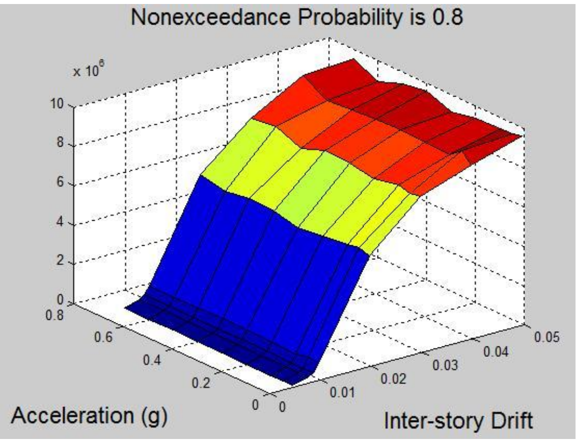


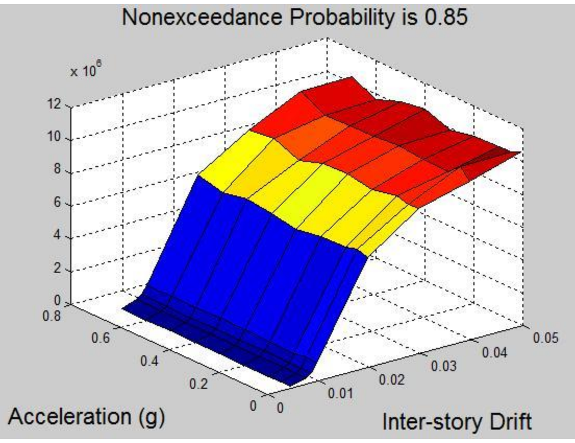


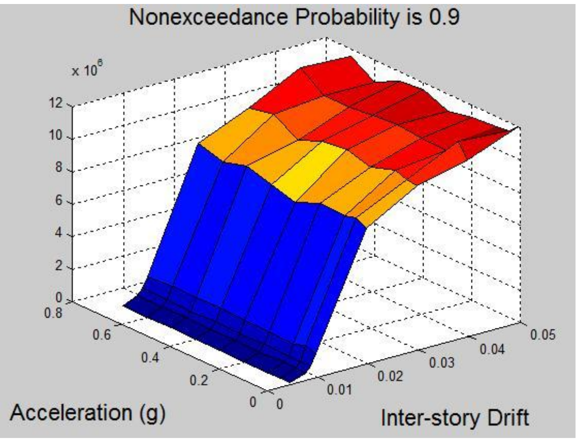



Nonexceedance Probability is 0.6
x 10^6
8
6
4
2
0
0.8
0.6
0.4
0.2
0
Acceleration (g)
0
0.01
0.02
0.03
0.04
0.05
Inter-story Drift


Nonexceedance Probability is 0.7
x 10^6
10
8
6
4
2
0
0.8
0.6
0.4
0.2
0
Acceleration (g)
0
0.01
0.02
0.03
0.04
0.05
Inter-story Drift


Nonexceedance Probability is 0.8
x 10^6
10
8
6
4
2
0
0.8
0.6
0.4
0.2
0
Acceleration (g)
0
0.01
0.02
0.03
0.04
0.05
Inter-story Drift


Nonexceedance Probability is 0.85
x 10^6
12
10
8
6
4
2
0
0.8
0.6
0.4
0.2
0
Acceleration (g)
0
0.01
0.02
0.03
0.04
0.05
Inter-story Drift


Nonexceedance Probability is 0.9
x 10^6
12
10
8
6
4
2
0
0.8
0.6
0.4
0.2
0
Acceleration (g)
0
0.01
0.02
0.03
0.04
0.05
Inter-story Drift